# Injury Potential Testing of Suited Occupants During Dynamic Spacecraft Flight Phases

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**In support of the NASA Constellation Program, a space-suit architecture was envisioned for support of Launch, Entry, Abort, Micro-g EVA, Post Landing crew operations, and under emergency conditions, survival. This space suit architecture is unique in comparison to previous launch, entry, and abort (LEA) suit architectures in that it utilized rigid mobility elements in the scye and the upper arm regions. The suit architecture also employed rigid thigh disconnect elements to allow for quick disconnect functionality above the knee which allowed for commonality of the lower portion of the suit across two suit configurations. This suit architecture was designed to interface with the Orion seat subsystem, which includes seat components, lateral supports, and restraints. Due to this unique configuration of spacesuit mobility elements, combined with the need to provide occupant protection during dynamic landing events, risks were identified with potential injury due to the suit characteristics described above. To address the risk concerns, a test series was developed to evaluate the likelihood and consequences of these potential issues. Testing included use of Anthropomorphic Test Devices (ATDs), Post Mortem Human Subjects (PMHS), and representative seat/suit hardware in combination with high linear acceleration events. The ensuing treatment focuses on detailed results of the testing that has been conducted under this test series thus far.**

## Nomenclature

| | | |
|---|---|---|
| *ACES* | = | *Advanced Crew Escape Suit* |
| *ATD* | = | *Anthropomorphic Test Device* |
| *BMD* | = | *Bone Mineral Density* |
| *CSSE* | = | *Constellation Space Suit Element* |
| *CT* | = | *Computed Tomography* |
| *Cx(P)* | = | *Constellation (Program)* |
| *EMU* | = | *Extravehicular Mobility Unit* |
| *ESR* | = | *Engineering System Reference* |
| *EVA* | = | *Extra-Vehicular Activity* |
| *HGE* | = | *HYdralic Gas Energized* |
| *IBRL* | = | *Injury Biomechanics Research Laboratory* |
| *JSC* | = | *Johnson Space Center* |
| *LEA* | = | *Launch Entry and Abort* |
| *MRI* | = | *Magnetic Resonance Imaging* |
| *NASA* | = | *National Aeronautics and Space Administration* |
| *OSU* | = | *(The) Ohio State University* |
| *PMHS* | = | *Post-Mortem Human Subject* |
| *RMS* | = | *Root Mean Squared* |
| *SSP* | = | *Space Shuttle Program* |
| *TRC* | = | *Transportation Research Center* |
| *VIE* | = | *Vehicle Interface Element* |

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## I. Introduction

THE Constellation Space Suit Element (CSSE) architecture discussed herein consisted of two suit configurations. Configuration 1 was to be designed for use during launch, entry, and abort (LEA) as well as during contingency microgravity extravehicular activity (EVA). Configuration 2 was to be designed for surface EVA operations. Although two separate suits were being developed, it was the primary design goal of the CSSE design team to provide as much modularity as possible between these two configurations. For example, the same gloves, boots, and helmet may be used for both suit configurations. This architecture differs from the Space Shuttle Program (SSP), which employs two very different suits with no common hardware; the Advanced Crew Escape Suit (ACES) is used for LEA, while the Extravehicular Mobility Unit (EMU) is used for microgravity EVA. Although there are large mass and volume drawbacks to this Shuttle architecture, the advantage is having two different suit designs, each optimized for its own environment.

The ACES is, with the exception of the neck ring, helmet, and glove disconnect, an all-soft suit that protects the crew during launch and reentry. Meanwhile, the EMU has many rigid elements to provide the required pressurized mobility to the crewmember during an EVA. Although the ACES is a fully pressurizable suit, it is not designed to afford the wearer much in the way of pressurized mobility. Luckily, the mobility required of the crew during a scenario where the ACES would be pressurized is considerably small and therefore not historically known to be a problem.

The Constellation Configuration 1 suit architecture described above, however, was to meet the occupant protection demands of an LEA suit as well as the pressurized mobility demands of an EVA suit in the same design. In addition, the landing loads predicted by the Constellation Program (CxP) were considerably higher than those seen by the SSP due to the fact that the Orion vehicle is designed for passive water landing under parachutes instead of an active runway landing like the Shuttle Orbiter. This is a significant engineering challenge.

To meet the various applicable requirements, the CSSE reference design for Configuration 1 [EVA System Reference (ESR) 2, shown depicted in Figure 1] called for a soft suit with specific rigid mobility elements in the scye and upper arm regions. Additionally, this architecture employed rigid thigh disconnects just above the knee, which provide a quick disconnect capability for the lower portion of the suit, which is common across both suit configurations (1).

There are unknowns, however, associated with placing these rigid elements in a suit designed for protecting the crew during nominal and off-nominal LEA modes. A test series was developed in response to a NASA risk being tracked that addressed these unknowns, particularly during the short period of time encompassed by landing, where loads could be high enough to cause injury in an otherwise soft suit. Injuries that raise the most concern are those that may inhibit crewmember egress from the vehicle in an emergency, such as bone fractures or nerve damage; however, any injury caused by the suit during a nominal landing is more or less considered unacceptable.

The objective of this test series is to qualify the risk associated with these baselined suit architectural features (i.e., scye bearing, upper arm bearing, and thigh disconnect).

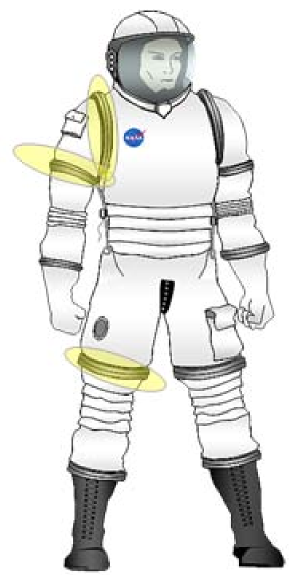

**Figure 1. ESR2 for Configuration 1.**

## II. Testing Methodology

Postmortem human subjects (PMHSs) were selected as the primary testing mechanism for this test series due to the higher level of correlation to a live crewmember over ATDs and the unique test scenarios for which ATDS have not been validated.

A common concern when debating between the use of ATDs and PMHSs is the issue of sample size. When testing with an ATD, an erroneous test can simply be redone, with little or marginal impact to cost and schedule. Furthermore, an ATD can be tested virtually an infinite number of times so as to provide a testing sample size deemed to be statistically significant. However, an erroneous test using a PMHS can easily result in major cost and scheduling problems, with lead times for subject procurement and instrumentation heading into weeks, if not months. Therefore, most test series employing PMHSs typically have a small sample size when compared to an

ATD test. For example, the regulations on air bags in the United States were defined using PMHS testing with a sample size of only 23. Between 1961 and 1990, of 108 studies performed employing whole-body PMHSs, the average sample size was 12.9 (2).

While cause for discussion, it was found to not be a cause for concern. First of all, it was determined that the benefits of using a PMHS (particularly the increase in bio-fidelity) outweighed the drawbacks. Furthermore, human spaceflight has an inherently more conservative risk posture than the automotive world. Subjects were selected for this test series based on anthropometry (approximate 50$^{th}$ percentile male), and acceptable results of bone mineral density (BMD) scans. For more detailed data and analysis regarding the use of postmortem human subjects and test subject selection, see the prefacing paper regarding this test series (3).

### A. Facilities

In order to simulate the required landing loads, testing is being conducted at the Transportation Research Center (TRC) in East Liberty, Ohio. The TRC has one of the few 24-inch hydraulically-controlled gas energized (HYGE™) sleds in the world, which is capable of test accelerations up to 100 g's in magnitude [shown in Figure 2 1: HYGE™ Crash Simulator (Lower Left = Actuator; Center = Test Article)]. The Ohio State University (OSU) Injury Biomechanics Research Laboratory (IBRL) in nearby Columbus, Ohio, provides the test subjects, medical and injury biomechanics expertise, subject instrumentation, pre- and post-test imaging of the subjects, and finally, post-test autopsy and report. For more detailed information on this test facility and its capabilties, see see the prefacing paper regarding this test series (3).

### B. Variables

Considering a set of 24 possible Orion landing events that were analyzed, a representative landing impact of 11.5Gs with an 80ms duration was selected as shown in Figure 3. The original test matrix allowed for twelve test subjects, many of which could be used for two test points; this provided for a total of 20 possible test points across all six orthogonal test directions:

- +X ("eyeballs in" – e.g., getting rear-ended)
- -X ("eyeballs out" – e.g., head-on collision)
- +/-Y ("eyeballs left/right" – e.g., side impact)
- +Z ("eyeballs down" – e.g., pushed into seat pan)
- -Z ("eyeballs up" – e.g., pulled out of seat pan)

For more detailed data and analysis regarding the test pulse selection and test subject/test point allocation, see the prefacing paper regarding this test series (3).

### C. Hardware

A substantial amount of new test hardware was required to support this test. Although the following is a brief synopsis of this hardware, a full treatment of each of the below items is available in the prefacing paper regarding this test series (3).

- A new test seat was required to accommodate subject anthropometric variability and multiple test directions.
- A suit analog was required to simulate the rigid components of the suit, but also to enable easy placement/removal of these components
- An off-the shelf five-point harness comparable to the current Orion design was used to restrain the test subject
- Data recording capability in the form of high speed imagery, seat accelerometers and load cells
- Test subject instrumentation in the form of bone-mounted accelerometers and strain gauges in the area of anthropometric focus (ribs, vertebrae, clavicles, scapulas, sternum, humerus) for each test point

### D. Procedure

Due to subject procurement and logistical restraints, it is only possible to test two or three subjects during a given test week. Several days prior to testing, the PMHSs are removed from the freezer, if necessary, for thawing and instrumentation. Also at this stage, a pre-test radiology of the relevant anatomical areas is performed using x-rays, MRI, or CT scans depending on test direction. All of this occurs at the OSU IBRL, and upon completion, the subject is transported to the TRC for acceleration testing.

Once at the testing facility, the subject is outfitted with the suit simulator and connected to the data acquisition system located off the seat on the HYGE™ carriage, while final system preparations are completed (subject positioning, camera adjustments, bolster and harness reconfiguration, etc.).

Before every collected test point, two test trial runs are completed. The first is a trial run with an empty seat. This “inertial pulse” provides the seat system with a means to exhibit any anomalous behavior resulting from the recent reconfiguration. It also provides a baseline against which to calibrate the load cells and accelerometers. Lastly, it allows the test team to view the output from the data acquisition system to look for any problems.

In the second trial run, called a “shakedown pulse,” a 50th percentile male Hybrid III ATD is placed into the seat and restrained with the harnesses. This trial run provides extra assurance of avoiding a problem that could negatively impact the PMHS test run. Secondly, the data from this trial run is also more analogous to the PMHS test, as the subject/seat impact can be observed and measured. Some of the images taken prior to a +Z, -Z, and +Y tests are shown in Figure 2,3, and 4, respectively.

**Figure 2: ATD Trial (+Z Configuration)**

**Figure 3: ATD Trial (-Z Configuration)**

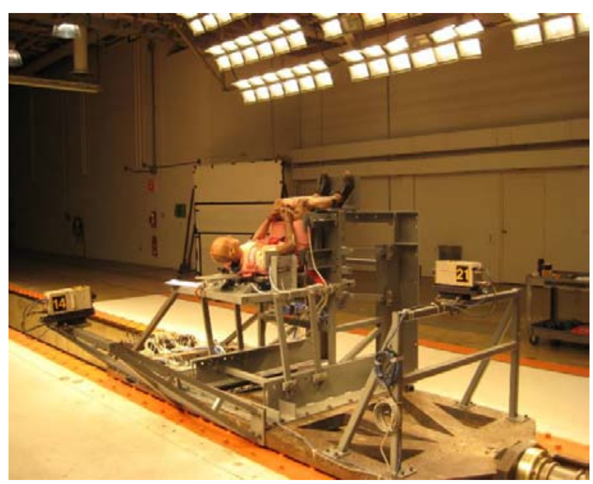

**Figure 4: ATD Trial (+Y Configuration)**

Once these trial runs are completed, the PMHS is inserted into the seat and restrained with the harnesses. Great care is taken to ensure consistent and representative positioning of the subject in the seat, the suit simulator on the subject, and the restraint harness. A soft cervical collar is used to keep the head of the subject in a semi-typical position, when necessary. The shoulder harnesses are placed directly over the scye bearings and all harnesses are tightened to 20 +/- 3 pounds of tension, as measured by the load cells at each harness attachment point.

Once this is complete, pre-test imagery is taken, and FARO® measurements are taken on the subject and the seat. The FARO® is used to define the subject’s coordinate system and initial positioning on the seat. The lungs of the PMHS are filled with air to ensure representative internal pressure of the pleural cavities on impact. Final checks are then performed and the test is executed. The complete test setup, as demonstrated by a live human test conductor during a hardware fit check, is shown in Figure 5: Live Fit Check (+X Configuration), and detail is provided in Figure 6: Detail from Live Fit Check.

Immediately after the acceleration event, post-test imagery is taken of the seat and PMHS for later comparison against the pre-test images. The subject is removed from the seat and transported back to the IBRL for post-test radiology. By performing both pre- and post-test imaging, it is possible to see injuries before an autopsy is performed, as well as to confirm that these injuries did not occur before the test.

The last and most important step in the testing process is the post-test autopsy. These are conducted by the OSU IBRL, often in conjunction with support from NASA, JSC Medical Operations Flight Surgeons who can provide insight into potential injuries as they relate to human spaceflight and the CxP architecture. For example, while an injury may have minimal impact to the inherent health or safety of a person in a car crash, it may have a much worse consequence for a crewmember that needs to be able to self-egress from the vehicle in an emergency scenario.

**Figure 5: Live Fit Check (+X Configuration)**

**Figure 6: Detail from Live Fit Check**

## III. Detailed Results

As of July 2011, 6 of the 12 subjects have been tested, as shown in the highlighted rows of Table 1. Across the 9 completed test points encompassed by these 6 subjects, multiple skeletal injuries to the thoracic cage and potential muscular and nerve injuries have been documented in the anatomical region correlating to the scye bearing. In this table, red highlighting indicates a test point that resulted in injury of some kind; green highlighting indicates a test point where no injury was observed, and grey indicates that the scheduled test point was not completed as originally planned. Test points labeled “VIE” indicate data collected by the Vehicle Interface Element and are not within the scope of this paper.

**Table 1: Test Status Matrix**

| Test Point | Subject | Direction | Area of Focus |
|---|---|---|---|
| 1 | A | +X | Posterior Shoulder |
| 2 | B | -X | Anterior Shoulder |
| 3 | C | -Z | Superior Shoulder |
| 4 | C | +Z | Thigh and Backbone |
| 5 | D | +X | Posterior Shoulder |
| 6 | E | -X | Anterior Shoulder |
| 7 | F | +Y | Rib, Shoulder, etc. |
| 8 | F | -Y | Rib, Shoulder, etc. |
| 9 | G | -Z | Superior Shoulder |
| 10 | | +Z | Thigh and Backbone |
| 11 | H | +X | Posterior Shoulder |
| 12 | | +Z | VIE |
| 13 | I | -X | Anterior Shoulder |
| 14 | | +X | VIE |
| 15 | J | -Z | Superior Shoulder |
| 16 | | +Z | Thigh and Backbone |
| 17 | K | +Y | Rib, Shoulder, etc. |
| 18 | | +X | VIE |
| 19 | L | +Z | VIE |
| 20 | L | +X | VIE |

Given the results from these test points coupled limited future funding, it was determined to cancel the remaining test points and consider the test series complete. Table 2: **Injury Summary** provides a brief synopsis of the injuries for each test case with injuries classified on the Abbreviated Injury Score (AIS) system. Test reports delivered to NASA by OSU indicate that the scye bearing is the primary injury mechanism in these injurious cases; the following sections provide detailed information on each test point and the injuries that resulted.

**Table 2: Injury Summary**

| Subject ID | Principal Axis | Observed Injuries | Injury Severity |
|---|---|---|---|
| A | +x | contusions, soft tissue injury, nerve damage | AIS 2-3 |
| B | -x | rib fractures (7) | AIS 4 (severe) |
| C | +z | none | N/A |
| C | -z | none | N/A |
| E | -x | rib fractures (3) | AIS 2 (moderate) |
| F | +y | none | N/A |
| F | -y | rib fractures (5); resulting collapsed lung on one side | AIS 4 (severe) |

## A. Subject A Results

Subject A was a 46 year old male, weighing 167 pounds and approximately 69.9" tall. BMD results from this subject indicate t-values of 0.7 and -0.07 for the whole body and lumbar spine, respectively; t-values indicate the standard deviations from the mean BMD for a 30 year old of the same race and gender. Typically when selecting test subjects we looked for BMDs within 1 standard deviation of the average 30 year old male. Figure 7 shows the instrumentation employed on Subject A.

The test subject was subjected to one test point, approximately 11.5g peak acceleration in the +X direction (analogous to a rear-end collision) with a total acceleration duration of 80ms. Below is a figure of the acceleration of the test sled.

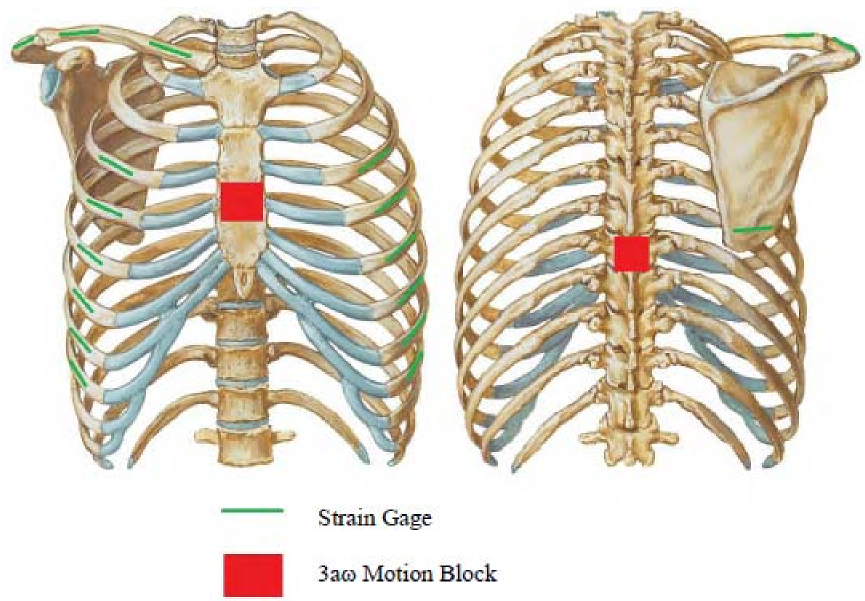


**Figure 7: Subject A Instrumentation**

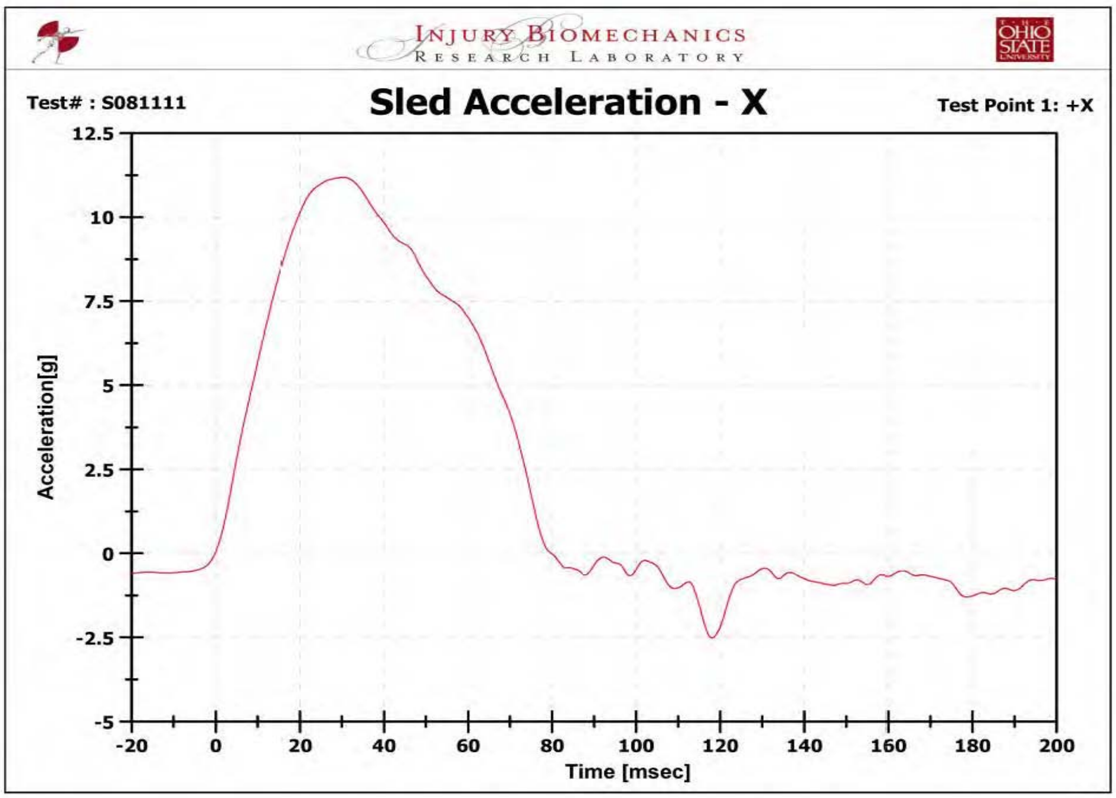


**Figure 8: Test Point 1 (Subject A) Acceleration**

Table 3 below shows the peak values of the instrumentation used for this test.

**Table 3: Test Point 1 (Subject A) Peak Values**

| Sled Instrumentation | | Subject Instrumentation | |
|---|---|---|---|
| **Channel** | **Maximum** | **Channel** | **Maximum** |
| Seat Back Fx | -2,450 lbf | Sternum Xg | 25 g |
| Seat Back Fy | 240 lbf | Sternum Yg | 5 g |
| Seat Back Fz | 380 lbf | Sternum Zg | 6 g |
| Seat Pan Fx | -5,800 lbf | T8 Xg | 18 g |
| Seat Pan Fy | 295 lbf | T8 Yg | 6 g |
| Seat Pan Fz | -750 lbf | T8 Zg | 10 g |
| Left Shoulder Harness | 122 lbf | Chest Compression | 1.57” |
| Right Shoulder Harness | 210 lbf | | |
| Left Pelvis Harness | 102 lbf | | |
| Right Pelvis Harness | 77 lbf | | |
| Harness 5th Point | 260 lbf | | |

Significant findings from this data are as follows.

**Seat Back**
• All of the force channels show a vibration during the event that was due to the construction and stability of the seat. Although the vibrations are significant in value, they are not significant in causing injuries to the subject.
• X-Axis Forces - The x-axis force plots of the seat back reveal that the subject loaded the back of the seat very uniformly.
• Y-Axis & Z-Axis Forces – These forces were slightly higher than expected due to the coupling of the 4 load cells by the steel plate that formed the seat back.

**Seat Pan**
• Looking at Table 3, the maximum value of -5,800 lbf for the force in the x-axis of the seat pan is alarming. However, upon review of the sled seat it was noted that the leg holders are linked to the pan, thus creating the large forces in the x-axis. In future tests this linkage was uncoupled to reduce this loading.

**Harness Loads**
• From the plots it appears the crotch strap loaded the subject at around 75 msec followed by the other 4 straps fairly uniformly at 100 msec. This is compared to the peak interaction of the seat back at 40 msec. The subject rebounded off the seat and into the harness given the impact was in the +x-direction.

**Strain Gages**
• The strain gages were configured incorrectly in the data acquisition system for this test point, thus they were not analyzed.

**3aω Motion Blocks**
• The peak acceleration for the sternum was 25 g in the x-axis. This was not surprising given the motion of the event in the +X direction.
• The x-axis acceleration of T8 was similar in the range of 18 g.
• The compression of the sternum in relation to T8 in the x-axis direction was calculated using the motion blocks, Figure 9. The maximum value recorded during the event is approximately 1.57”, a value below the injury threshold for the thorax used in car safety testing.

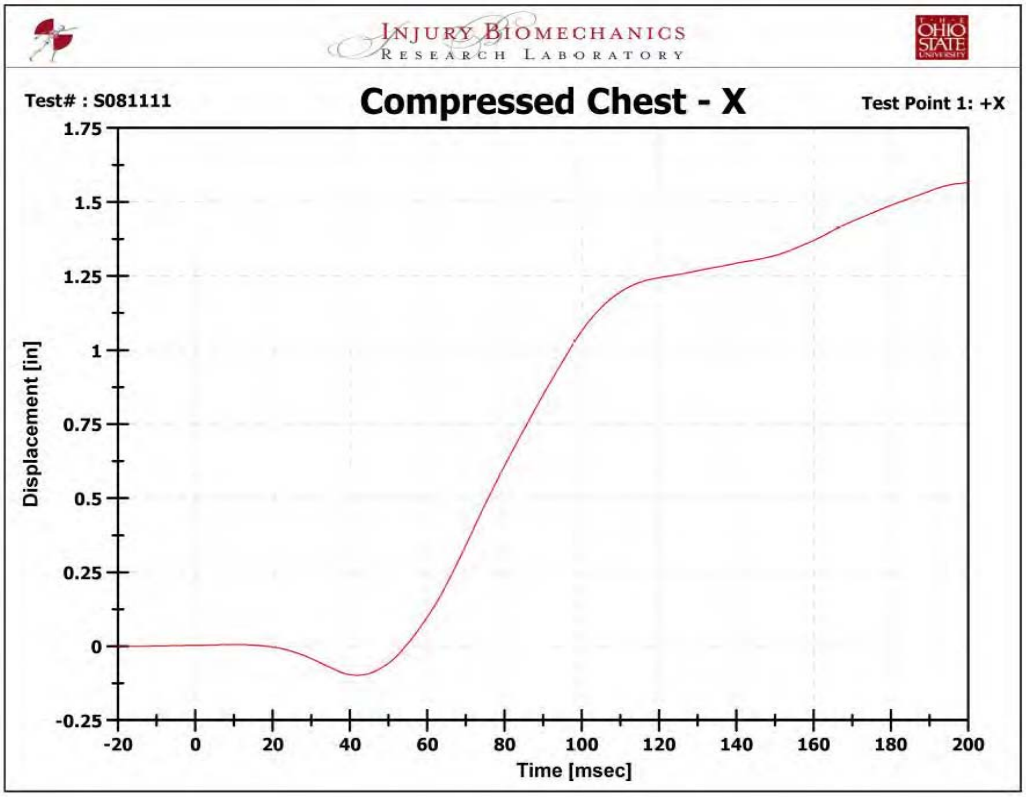


**Figure 9: Test Point 1 (Subject A) Chest Compression**

Post-test imaging did not show any potential injury or bone damage to the test subject as a result of the acceleration event. However, a full autopsy was conducted on Subject A, and the detailed results are as follows:

**Skin Surface**

- No noticeable markings on the external surface of the subject

**Musculature: (Both Right & Left – unless noted differently)**

- Deltoid – No Damage
- Pectoralis Major – No Damage
- Pectoralis Minor – No Damage
- Serratus Anterior – No Damage
- Trapezius
  - *Symmetric bruising 11cm from center & bruising along the spine of the scapula, both left and right sides*
  - *No evidence of being caused by instrumentation, possible scye bearing impact site*
- Supraspinatus
  - *Bruising on left and right Supraspinatus*
  - *Bruising is deeper on the right Supraspinatus*

- Infraspinatus
  - *Bruising on the right side only*
  - Suprascapular nerve – No damage

- Teres Major – No Damage
- Teres Minor – No Damage

- Subscapularis – No Damage

**Joints: (Both Right & Left – unless noted differently)**

- Glenohumeral Joint – No Damage
  - Joint Capsule (Rotator Cuff) – No Damage
  - Long head of biceps tendon – No Damage
  - Coracoacromial Ligament – No Damage
  - Coracoclavicular Ligaments
    - Conoid – No Damage
    - Trapezoid – No Damage
  - Coracohumeral Ligament – No Damage
- Acromioclavicular Joint – No Damage
  - Acromioclavicular Ligament – No Damage
- Sternoclavicular Joint – No Damage
  - Sternoclavicular Ligament – No Damage
  - Intraclavicular Ligament – No Damage
  - Costoclavicular Ligament – No Damage

**Skeletal: (Both Right & Left – unless noted differently)**

- Humerus – No Damage
- Scapula – No Damage
- Clavicle – No Damage
- Sternum – No Damage
- Ribs – No Damage

Due to the limited damage to the musculature and skeleton structure it was deemed unnecessary to autopsy the organs of the subject to look for internal damage. The deep bruising on the posterior aspect of the muscles that control the shoulder were caused by the interaction of the scye bearing and the occupant's thorax with the seat back during the event. In a living individual this impact would cause extreme bruising and pain from upper extremity and shoulder motion. However, no major joint, skeletal or nerve injury would be expected.

One possible complication that could result, but not demonstrated in this trial would be entrapment of the suprascapular nerve as it passes through the suprascapular notch. The bruising pattern indicates that this area could swell greatly following impact causing this entrapment to potentially occur. If this would occur following impact, the individual would lose the ability to abduct their arm without the aid of gravity and also affect their ability to rotate their upper limb laterally.

### Subject A Conclusion

This test was an 11.5 g, +X directed loading event using a 46 year old male post mortem human subject. The test data showed good interaction between the subject, the seat back and the harness. The seat did show vibrations due to insufficient stability on the buck. This issue was identified for resolution before future testing in this direction was completed. The vibrations were not deemed to have caused any injuries to the subject. The main injury to the subject was bruising over the muscles that cover the scapula on the posterior aspect of the subject caused by the scye bearing. This bruising would lead to swelling and minor pain during arm and shoulder motion if the individual had been living.

### B. Subject B Results

Subject B was a 56 year old male, weighing 181 pounds and approximately 68.5" tall. BMD results from this subject indicate t-values of 1.2 and -1.28 for the whole body and lumbar spine, respectively. Below is a figure of the instrumentation employed on Subject B.

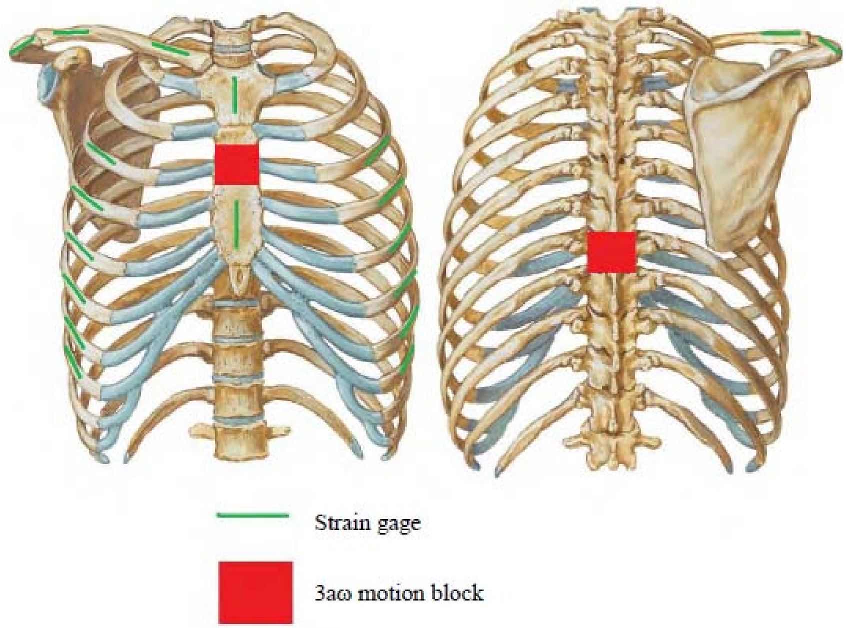


**Figure 10: Test Point 2 (Subject B) Instrumentation**

The test subject was subjected to one test point, approximately 10.8g peak acceleration in the -X direction (analogous to a head-on collision) with a total acceleration duration of 80ms. Figure 11 below shows the acceleration of the test sled.

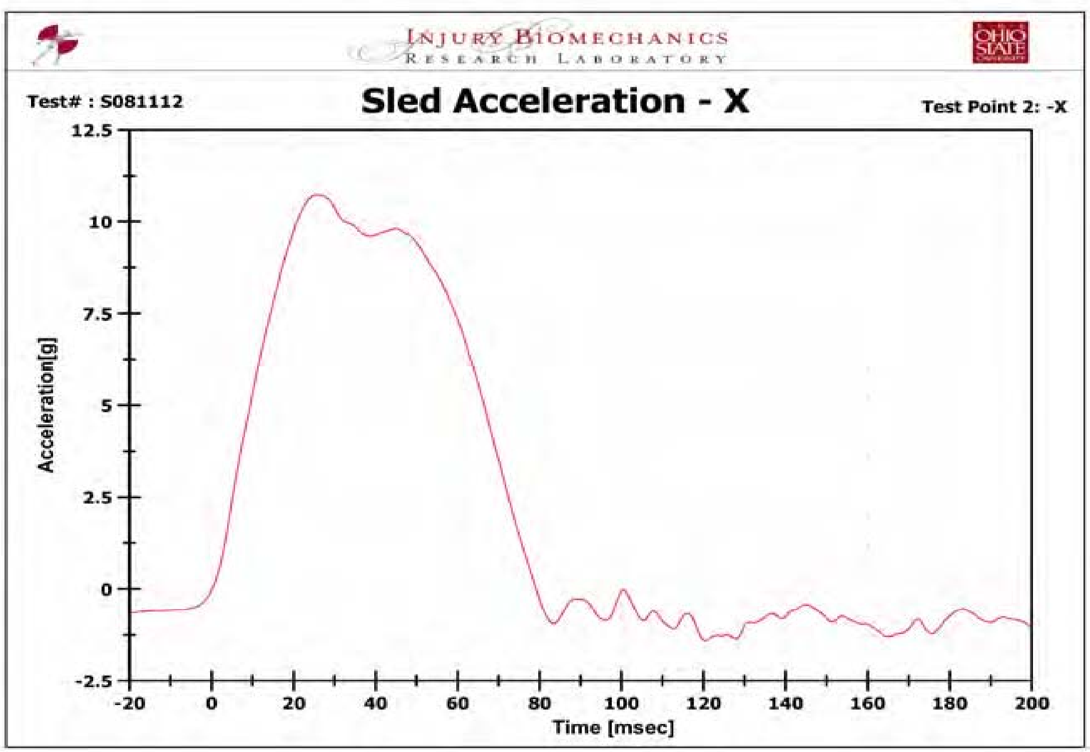


**Figure 11: Test Point 2 (Subject B) Acceleration**

Table 4 below shows the peak values of the instrumentation used for this test.

**Table 4: Test Point 2 (Subject B) Peak Values**

| Sled Instrumentation | | Subject Instrumentation | |
|---|---|---|---|
| **Channel** | **Maximum** | **Channel** | **Maximum** |
| Seat Back Fx | -1,100 lbf | Sternum Xg | -35 g |
| Seat Back Fy | -310 lbf | Sternum Yg | -20 g |
| Seat Back Fz | 725 lbf | Sternum Zg | -12 g |
| Seat Pan Fx | 1,050 lbf | T8 Xg | -27 g |
| Seat Pan Fy | -900 lbf | T8 Yg | -15 g |
| Seat Pan Fz | -2,800 lbf | T8 Zg | 10 g |
| Left Shoulder Harness | 980 lbf | Chest Compression | 1.57" ** |
| Right Shoulder Harness | 1,120 lbf | | |
| Left Pelvis Harness | 740 lbf | | |
| Right Pelvis Harness | 840 lbf | | |
| Harness 5th Point | N/A* | | |

* The crotch strap load cell was not used because of a lack of clearance in the seat for the belt and loadcell
** This number is approximated given error due to the double integration of the accelerometers

Significant findings from this data are as follows.

**Seat Back**

• All of the force channels show a vibration during the event that was due to the construction and stability of the seat. Although the vibrations are significant in value, they are not significant in causing injuries to the subject. It was deemed after this test that changes would need to be made to the seat before the next round of tests.

• X-Axis Forces - The x-axis force plots of the seat reveal less loads than recorded during the +X direction impact. This is due to the subject primarily loading the harness and not the back of the seat.

• Y-Axis & Z-Axis Forces – These forces were slightly higher than expected due to the coupling of the 4 load cells by the steel plate that formed the seat back.

**Seat Pan**

• Looking at Table 4, the maximum value of -2,800 lbf for the force in the z-axis of the seat pan is alarming. However, as noted in the previous +x testing the leg holders are linked to the pan, thus creating the large coupled forces. In future tests this linkage was uncoupled to reduce the loading.

• The loads through the seat pan are also not associated with any injury findings on the subject.

**Harness Loads**

• There was limited clearance in the seat for proper harness placement so the crotch strap load cell was removed for this test. The seat should be altered to allow for more room for both the harness and loadcell when the strap is in proper position.

• The other four harness load cells show uniform loading of the specimen into the harness at approximately 57 msec. The uniform loading shows that the harness was properly installed and distributed the loads of the event uniformly across the thorax of the subject.

**Strain Gages**

• A handful of the strain gages channels were lost during the set-up and testing of the subject and thus they cannot be analyzed. It was decided a new instrumentation technique must be developed before the next phase of testing. These channels include –

- o Right and left proximal humerus
- o Right and left distal humerus
- o Rib 3 right; Rib 4 right and left

• We would hope to see failure signs in the output from the following strain gages based on the rib fractures found in autopsy –

o Left rib 2 – not instrumented; should instrument in future test

o Left rib 3 – There is not a sharp change in strain which is the common sign of failure. This finding could be due to the failure occurring at the costochondral joint between the bone and the cartilage and not a fracture of the bone itself. This rib also contained a fracture at the mid-axillary line, which would complicated the local strain and potentially mask the time of failure.

o Left rib 4 – strain gage failure

o Right rib 3 – strain gage failure

o Right rib 4 – strain gage failure

o Right rib 5 – Does show a quick drop-off after 1500 μ-strain but not the standard "cliff-like" drop associated with fracture of the bone. This could also be due to the location of the failure at the costochondral joint, but it also could have been affected by the ante-mortem fracture documented during the instrumentation phase of the test. The ante-mortem fracture forced the strain gage to be located further away from the failure site thus reducing the local strain.

• The other strain gage channels all recorded under 2,000 μ-strain and did not display traits representative of bone failure. This coincides with the autopsy findings that no other fractures were found in the subject.

**3aω Motion Blocks**

• The peak acceleration for the sternum was -35 g in the x-axis. This was not surprising given the interaction of the subject and the harness during the –X axis event.

• The x-axis acceleration of T8 was similar in the range of -27 g.

• The compression of the sternum in relation to T8 in the x-axis direction was calculated using the motion blocks, Figure 12. The maximum value recorded during the event is approximately 1.57", during the initial 200 msec of the event. The compression cannot be calculated accurately beyond this time due to mathematical error introduced when integrating accelerometers into displacements.

A full autopsy was conducted on Subject B, and the detailed results are as follows:

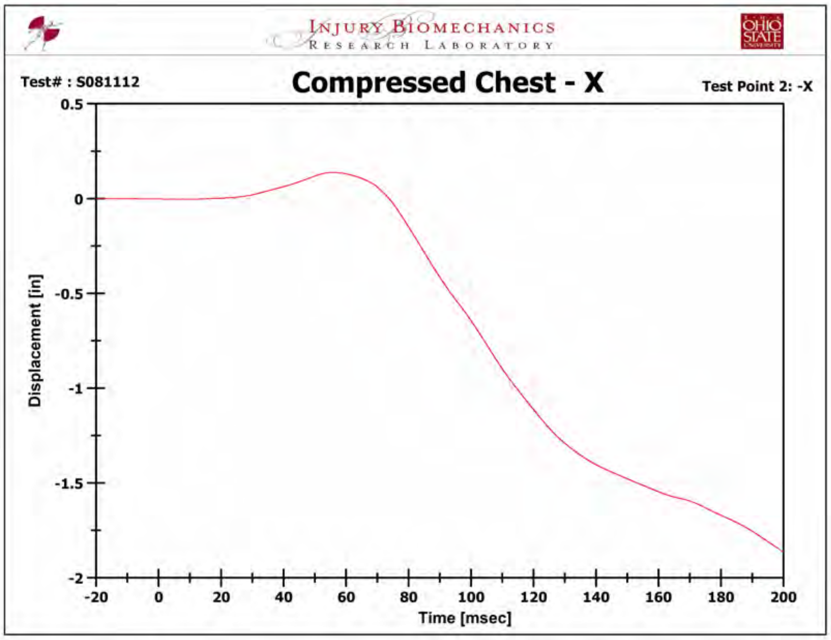


**Figure 12: Test Point 2 (Subject B) Chest Compression**

**Skin Surface**

- No noticeable markings on the external surface of the subject

**Musculature: (Both Right & Left – unless noted differently)**

- Deltoid – No Damage
- Pectoralis Major – No Damage
- Pectoralis Minor – No Damage
- Serratus Anterior – No Damage
- Trapezius – No Damage
- Supraspinatus – No Damage

- Infraspinatus – No Damage
- Teres Major – No Damage
- Teres Minor – No Damage
- Subscapularis – No Damage

**Joints: (Both Right & Left – unless noted differently)**

- Glenohumeral Joint – No Damage
  - Joint Capsule (Rotator Cuff) – No Damage
  - Long head of biceps tendon – No Damage
  - Coracoacromial Ligament – No Damage
  - Coracoclavicular Ligaments
    - Conoid – No Damage
    - Trapezoid – No Damage
  - Coracohumeral Ligament – No Damage
- Acromioclavicular Joint – No Damage
  - Acromioclavicular Ligament – No Damage
- Sternoclavicular Joint – No Damage
  - Sternoclavicular Ligament – No Damage
  - Intraclavicular Ligament – No Damage
  - Costoclavicular Ligament – No Damage

**Skeletal: (Both Right & Left – unless noted differently)**

- Humerus – No Damage
- Scapula – No Damage
- Clavicle – No Damage
- Sternum – No Damage
- Ribs
  - Left Side
    - *Disarticulation fractures of 2, 3 & 4 at the costochondral joint*
    - *Fracture at mid-axillary line of rib #3*
  - Right Side
    - *Disarticulation fractures of 3, 4 & 5 at the costochondral joint*

The multiple rib fractures on both sides of the thorax equate to an abbreviated injury score (AIS) of 450240.4, which is considered to be a severe injury. Upon removal of the thoracic plate, no further damage was documented to the lungs, heart or great vessels. The injuries sustained to this subject are due to the interactions between the scye bearings, the 5-point harness and the occupant. Based on the acceleration levels recorded at the sternum and T-8 and the thoracic compression measured during the event, past testing with an occupant restrained by a 5-point harness tells us this subject should not have been injured. It was determined that more testing in this configuration should be conducted to examine this injury mechanism further.

**Subject B Conclusion**

This test was a 10.8 g, -X directed loading event using a 56 year old male post mortem human subject. The test data showed good interaction between the subject, the seat back and the harness. The seat did show vibrations due to insufficient stability on the buck. This issue should be resolved before future testing in this direction is completed. The vibrations were not deemed to have caused any injuries to the subject. The main finding of the testing was a severe injury involving the failure of six ribs, three on each hemi-thorax. The fractures occurred between the bone and cartilage at the costochondral junctions, in line with the scye bearings on the occupant. The harness showed equal restraint on the load cells, but the scye bearings between the shoulder straps and the occupant's thorax kept the occupant from being restrained properly. The harness straps caused point loading of the scye bearings on the ribs of the occupant which resulted in fractures.

### C. Subject C Results

Subject C was a 74 year old male, weighing 175 pounds and approximately 69.3” tall. BMD results from this subject indicate t-values of 0.6 and 0.07 for the whole body and lumbar spine, respectively. Figure 13 shows the instrumentation employed on Subject C.

The test subject was subjected to two test points. The first was an approximately 11.0g peak acceleration in the +Z direction (resulting in spinal compression) with a total acceleration duration of 80ms. The second was an approximately 11.2g peak acceleration in the –Z direction (resulting in spinal compression). Below in Figure 14 the acceleration of the test sled is shown for the +Z test only.

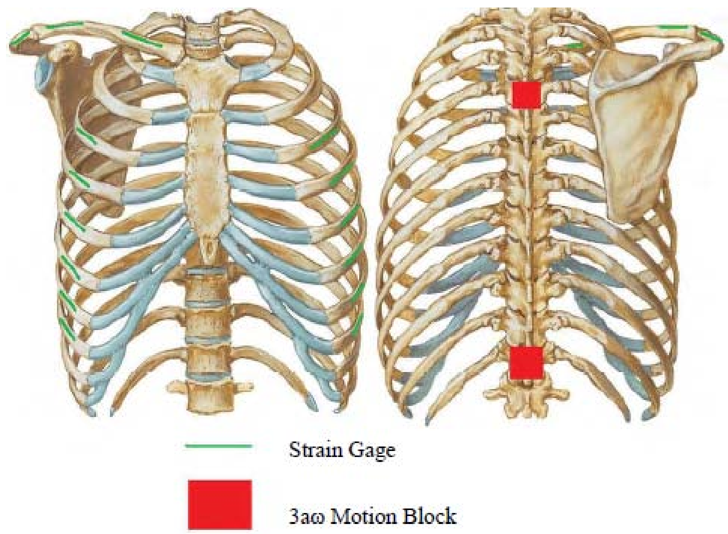


**Figure 13: Test Point 3-4 (Subject C) Instrumentation**

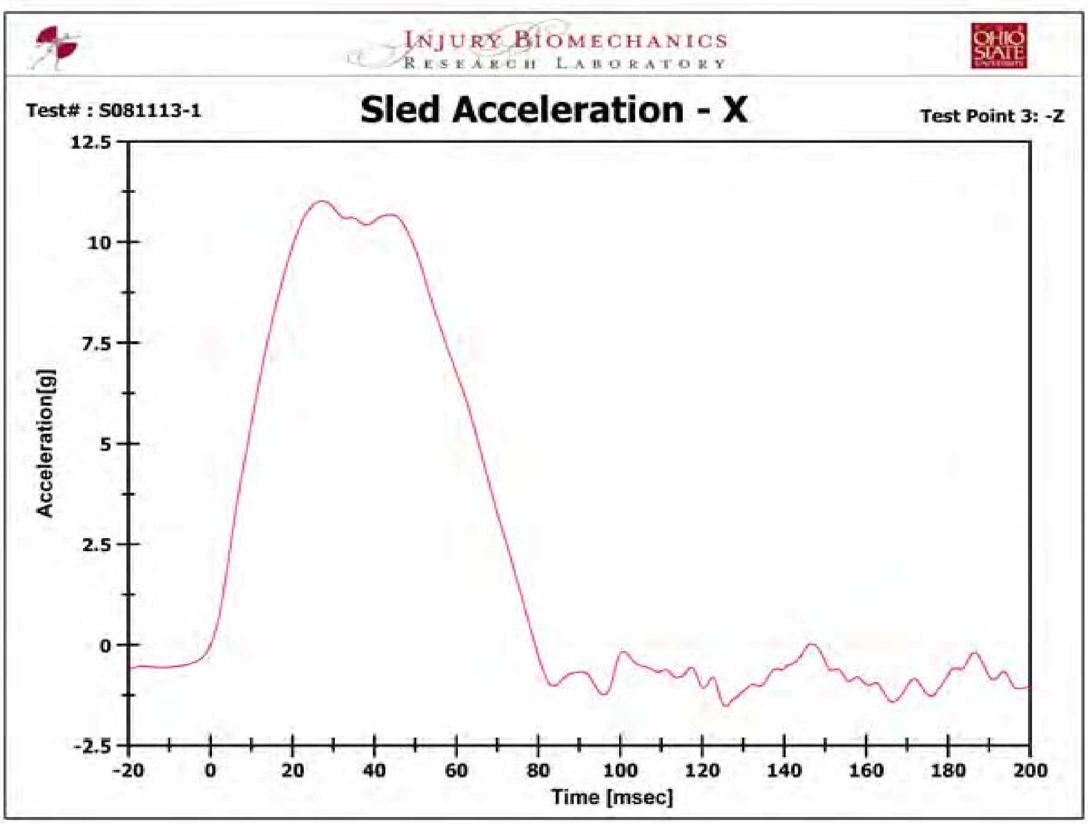


**Figure 14: Test Point 3 (Subject C) Acceleration**

Table 5 below shows the peak values of the instrumentation used for this +Z test.

**Table 5: Test Point 3 (Subject C) Peak Values**

| Sled Instrumentation | | Subject Instrumentation | |
|---|---|---|---|
| **Channel** | **Maximum** | **Channel** | **Maximum** |
| Seat Back Fx | 2,604 lbf | T4 Xg | 11 g |
| Seat Back Fy | 309 lbf | T4 Yg | -8 g |
| Seat Back Fz | -304 lbf | T4 Zg | 18 g |
| Seat Pan Fx | 371 lbf | T12 Xg | 6 g |
| Seat Pan Fy | 349 lbf | T12 Yg | 3 g |
| Seat Pan Fz | -3,043 lbf | T12 Zg | 19 g |
| Left Shoulder Harness | 171 lbf | S1 Xg | 9 g |
| Right Shoulder Harness | 185 lbf | S1 Yg | -2 g |
| Left Pelvis Harness | 114 lbf | S1 Zg | 16 g |
| Right Pelvis Harness | 150 lbf | Compression T4 to T12 | 0.04 in* |
| Harness 5th Point | 164 lbf | Compression T4 to S1 | 0.12 in* |

* This number is approximated given error due to the double integration of the accelerometers

Significant findings from this data are as follows.

**Seat Back**

• All of the force channels show a vibration during the event that was due to the construction and stability of the seat. Although the vibrations are significant in value, they are not significant in causing injuries to the subject.

• The x-axis channel recorded abnormally high readings due to the construction of the seat. The occupant was sliding on top of the seat back, thus these forces were driven by the struts attaching the seatback to the buck. This is verified by the vibrational swings that the load cell plot shows.

**Seat Pan**

• Looking at Table 5, the maximum value of 3,043 lbf for the force in the z-axis of the seat pan occurs at approximately 50 msec. This is the main load path to the occupant for this testing direction.

• The x-axis and y-axis loads through the seat pan are not associated with any injury findings on the subject.

**Harness Loads**

• The harness restrains the occupant after it rebounds off of the seat pan. The harness loads reach their peak approximately 10 msec following the peak force through the seat pan.

• The peak loads on the harness straps are about 1/5 of what was recorded in the +z testing direction.

• The shoulder harness straps and pelvis straps recorded similar peak forces revealing the occupant was uniformly positioned onto the seat..

**Strain Gages**

• A handful of the strain gages channels were lost during the set-up and testing of the subject and thus they cannot be analyzed. It was decided a new instrumentation technique must be developed before the next phase of testing. These channels include –

- o Left medial clavicle
- o Right & left distal & proximal femur
- o Right acromion process
- o Rib 3 left; Rib 4 right; Rib 5 right; Rib 8 right

• The remaining strain gage signals did not show signs of bone failure, which corresponded to the autopsy findings.

**3aω Motion Blocks**

• The peak acceleration for the spine was 19 g in the z-direction at the T-12 vertebra. The z-axis accelerations for T-4 and S-1 were similar at 18 g and 16 g respectively.

• The spinal accelerations were less than what was recorded in the +z-axis testing.

• This acceleration led to a spinal compression of only 0.12”, Figure 15. The compression cannot be calculated accurately beyond this time due to mathematical error introduced when integrating accelerometers into displacements.

• Typically, 0.12” of spinal deflection would not equate to serious spinal injury.

The subject was then transported to the OSU Medical Center for thoracic CT scans before the –Z direction test was conducted. The data showed good interaction between the occupant, the harness and the thigh bearings. The main load path in this scenario was through the seat pan followed by the harness straps.

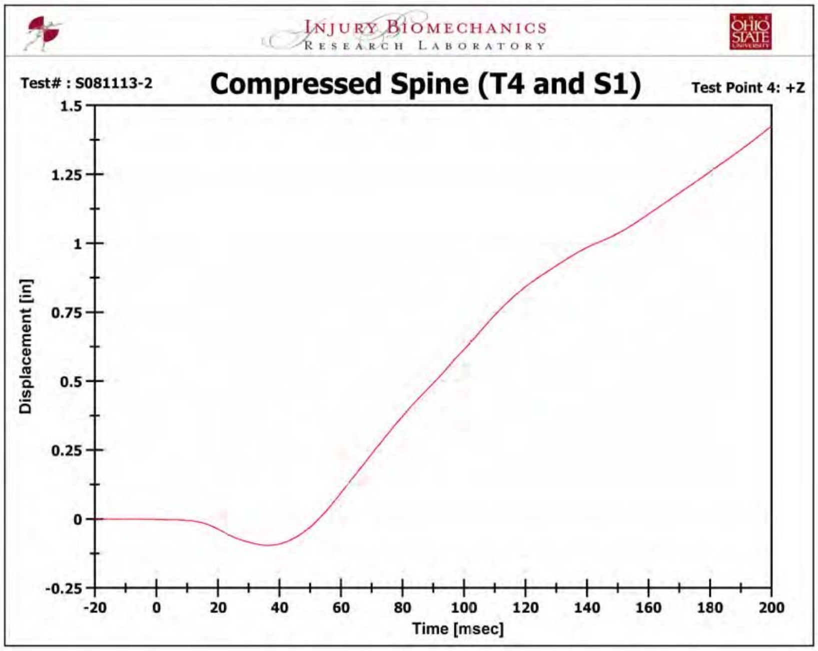


**Figure 15: Test Point 3 (Subject C) Spinal Compression**

A full autopsy was conducted on Subject C, and the detailed results are as follows:

**Skin Surface**

- No noticeable markings on the external surface of the subject

**Musculature: (Both Right & Left – unless noted differently)**

- Deltoid – No Damage
- Pectoralis Major – No Damage
- Pectoralis Minor – No Damage
- Serratus Anterior – No Damage
- Trapezius – No Damage
- Supraspinatus – No Damage
- Infraspinatus – No Damage
- Teres Major – No Damage
- Teres Minor – No Damage
- Subscapularis – No Damage

**Joints: (Both Right & Left – unless noted differently)**

- Glenohumeral Joint – No Damage
    - Joint Capsule (Rotator Cuff) – No Damage
    - Long head of biceps tendon – No Damage
    - Coracoacromial Ligament – No Damage
    - Coracoclavicular Ligaments
        - Conoid – No Damage
        - Trapezoid – No Damage
    - Coracohumeral Ligament – No Damage

- Acromioclavicular Joint – No Damage
    - Acromioclavicular Ligament – No Damage
- Sternoclavicular Joint – No Damage
    - Sternoclavicular Ligament – No Damage
    - Intraclavicular Ligament – No Damage
    - Costoclavicular Ligament – No Damage

**Skeletal: (Both Right & Left – unless noted differently)**

- Humerus – No Damage
- Scapula – No Damage
- Clavicle – No Damage
- Sternum – No Damage
- Ribs – No Damage

There were no injuries found during the autopsy of the PMHS following the two loading conditions. These findings were echoed both by post-test radiology and the strain gage instrumentation.

**Subject C Conclusion**

This test was a 11.0 g, +Z directed loading event, followed by a 11.2 g, -Z directed loading event, using a 74 year old male post mortem human subject. The test data showed good interaction between the subject, the seat back and the harness. The seat did show vibrations due to insufficient stability on the buck. The vibrations were not deemed to have caused any injuries to the subject. On the +Z test the main loading path into the occupant was through the 5-point harness system, while a secondary load was through the seat pan. On the –Z test, the main load path was through the seat pan followed by the harness straps.

The PMHS was not injured in either testing scenario. Minimal spinal accelerations were recorded during the impact events and the compression of the spine was below injury thresholds. The femora of the subject were also uninjured during the –z-axis impact. It does not appear from this initial testing that neither +z or –z axis loading would cause injury to the occupant through the bearings in the suit simulator.

**D. Subject E Results**

Subject E was a 60 year old male, weighing 161 pounds and approximately 69” tall. BMD results from this subject indicate t-values of -1.0 and -0.8 for the whole body and lumbar spine, respectively. The instrumentation used on Subject E is shown in Figure 16 at right.

The test subject was subjected to one test point, approximately 12.0g peak acceleration in the -X direction (analogous to a head-on collision) with a total acceleration duration of 80ms. Shown below in Figure 17 is the acceleration of the test sled, as well as the seat back and seat pan. Shown in Figure 18 is the integrated velocity taken from the same data.

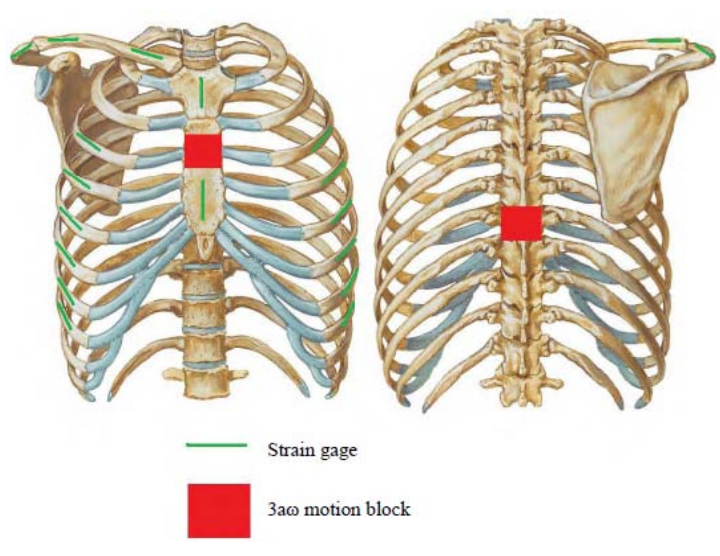


**Figure 16: Test Point 6 (Subject E) Instrumentation**

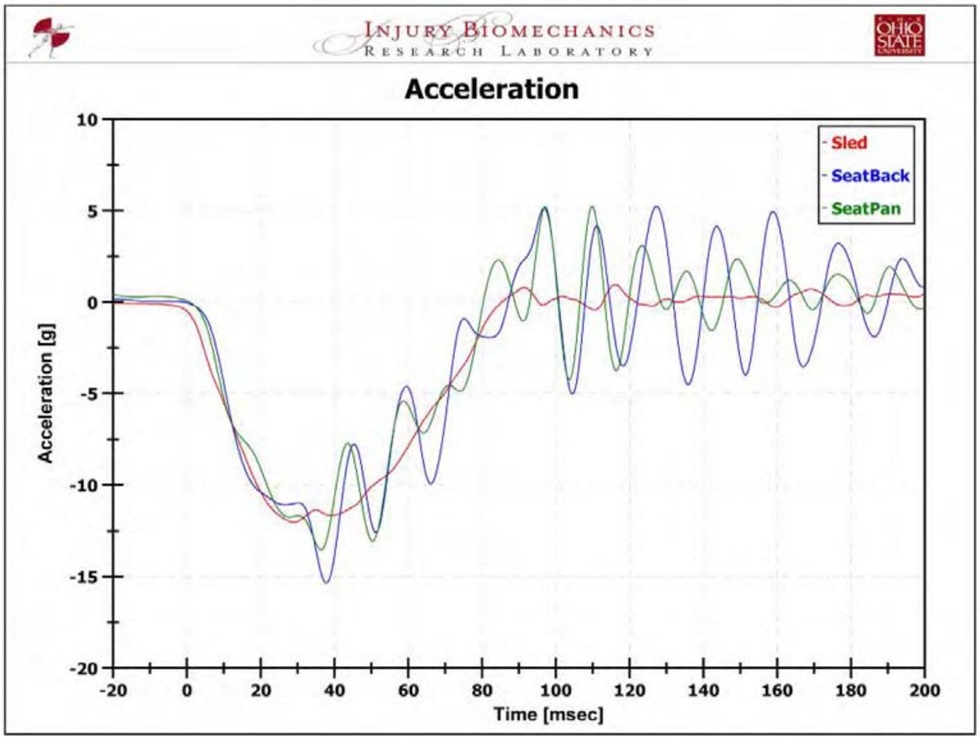


**Figure 17: Test Point 6 (Subject E) Acceleration**

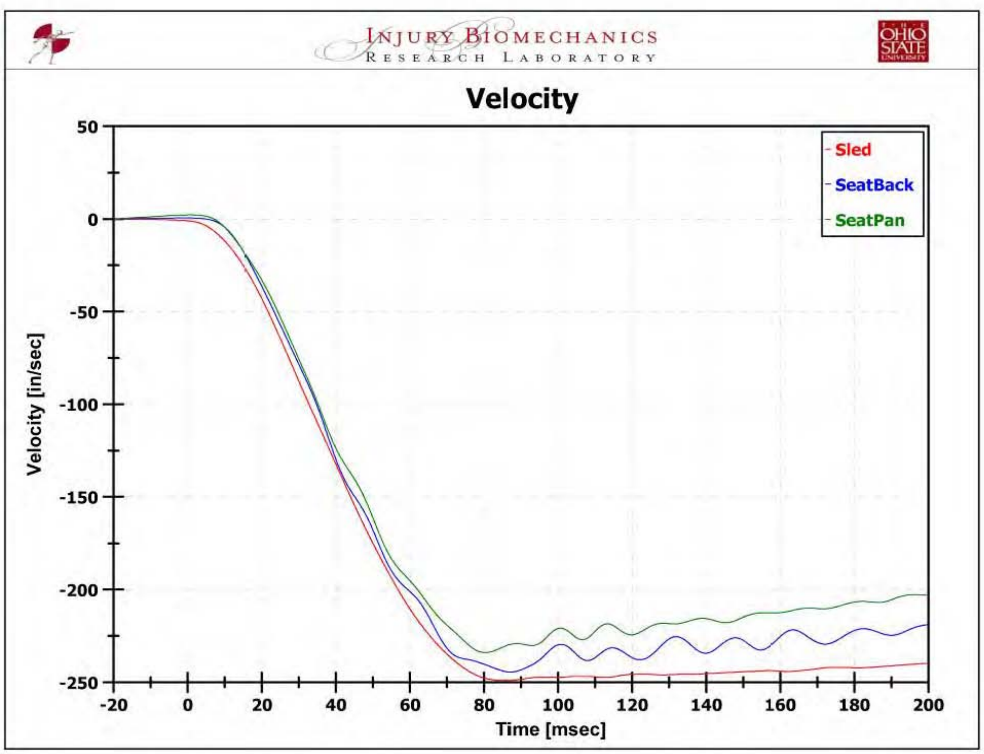


**Figure 18: Test Point 6 (Subject E) Velocity**

Table 6 below shows the peak values of the instrumentation used for this test.

**Table 6: Test Point 6 (Subject E) Peak Values**

| Sled Instrumentation | | Subject Instrumentation | |
|---|---|---|---|
| **Channel** | **Maximum** | **Channel** | **Maximum** |
| Seat Back Fx | -583 lbf | Sternum Xg | -28 g |
| Seat Back Fy | -125 lbf | Sternum Yg | 2 g |
| Seat Back Fz | 208 lbf | Sternum Zg | 7 g |
| Seat Pan Fx | 399 lbf | T8 Xg | -25 g |
| Seat Pan Fy | 95 lbf | T8 Yg | 5 g |
| Seat Pan Fz | -1,060 lbf | T8 Zg | -20 g |
| Left Shoulder Harness | 845 lbf | Chest Compression | -2.25 in * |
| Right Shoulder Harness | 758 lbf | | |
| Left Pelvis Harness | 725 lbf | | |
| Right Pelvis Harness | 838 lbf | | |
| Harness 5$^{th}$ Point | 639 lbf | | |

* This number is approximated given error due to the double integration of the accelerometers

Significant findings from this data are as follows.

**Seat Back**

• All of the force channels show a vibration during the event that was due to the construction and lack of stability of the seat for use in this direction. The increased stability of the seat for this round of testing decreased the vibrations that were recorded during phase I testing. As in the previous testing, the vibrations are not significant in causing injuries to the subject.

• X-Axis Forces - The x-axis force plots of the seatback reveal similar loads as to what was recorded in the –x-direction testing of subject B. These loads, which are less than what is seen in +x-direction testing, are due to the subject primarily loading the harness prior to the back of the seat. The peak load in the x-axis is recorded at approximately 120 msec when the subject has offloaded the harness and is interacting with the seat back.

• Y-Axis & Z-Axis Forces – These forces were slightly higher than expected due to the coupling of the 4 load cells by the steel plate that formed the seat back.

**Seat Pan**

• Looking at Table 3, the maximum value of 1,060 lbf for the force in the z-axis of the seat pan is alarming. However, as noted in the previous -x testing the leg holders are linked to the pan, thus creating the large coupled forces. In future tests these should be uncoupled to reduce this loading.

• The loads through the seat pan are also not associated with any injury findings on the subject.

**Harness Loads**

• The harness load cells show uniform loading of the specimen into the harness at approximately 57 msec, similar again to the timing and loads documented in the –X direction test for subject B.

• The uniform loading shows that the harness was properly installed and distributed the loads of the event uniformly across the thorax of the subject.

**Strain Gages**

• As previously mentioned a new technique using electrical tape to better reinforce the leads of the gage onto the gage itself was developed to decrease the number of broken gages in a test. This technique did reduce the number of broken gages, but not to the extent as we had hoped.

• A handful of the strain gages channels were lost during the set-up and testing of the subject and thus they cannot be analyzed. These channels include –

o Right & left proximal humerus & right distal humerus – these instrumentation sites are deep to subcutaneous tissue and muscle and therefore it is hard to glue the gages onto the bone properly. An alternative method should be developed to better instrument the humerus without dissecting more of the soft tissue.

o Left acromion process – This site was altered due to the pre-existing sutures and did not allow enough space to properly glue the gage onto the bone.

o Left rib 3 – The strain gage glue did not hold during the test.

o Left rib 6 – The strain gage was found to be attached but the lead wires were disconnected.

o Left rib 8 – The strain gage glue did not hold during the test.

o Right rib 3 - The strain gage glue did not hold during the test.

o The glue not holding could either be a function of the bone not being properly clean and dry before the cement was applied or the gage was not held long enough for the cement to cure properly. These steps were closely monitored in the testing following subject E and the results were greatly improved.

• We would hope to see failure signs in the output from the following strain gages based on the rib fractures found in autopsy –

o Left rib 3 – Failed

o Left rib 4 – The output from the strain gage appears to be very suspect even though the channel passed pre-test shunt checks and appeared to be intact at autopsy. The channel only recorded a peak of 112 μ-strain, which is a factor of more than 10 below normal bone thresholds. The noise in the channel also reveals that the instrumentation was not recording properly during the test.

o Right rib 7 – Does show the standard “cliff-like” drop associated with fracture of the bone at approximately 55 msec. This timing is very close to the maximum harness loads recorded around 57-58 msec. The timing of this fracture points to the injury mechanism being the transfer of the load from the shoulder harness straps to the scye bearings and into the occupant’s thoracic cage.

• The other strain gage channels all recorded under 4,000 μ-strain and did not display traits representative of bone failure. This coincides with the autopsy findings that no other fractures were found in the subject.

**3aω Motion Blocks**

• It was documented that the sternum x-axis angular rate sensor failed during the impact event. The failure occurred near 50 msec prior to the peak loading of the occupant by the harness system.

• The peak acceleration for the sternum was -28 g(s) in the x-axis. This was not surprising given the interaction of the subject and the harness during the –X axis event.

• The x-axis acceleration of T8 was similar in the range of -25 g(s).

• The compression of the sternum in relation to T8 in the x-axis direction was calculated using the motion blocks, Figure 19. The maximum value recorded during the event is approximately 2.25”, during the initial 200 msec of the event. The compression cannot be calculated accurately beyond this time due to mathematical error introduced when integrating accelerometers into displacements.The peak acceleration for the sternum was -35 g in the x-axis. This was not surprising given the interaction of the subject and the harness during the –X axis event.

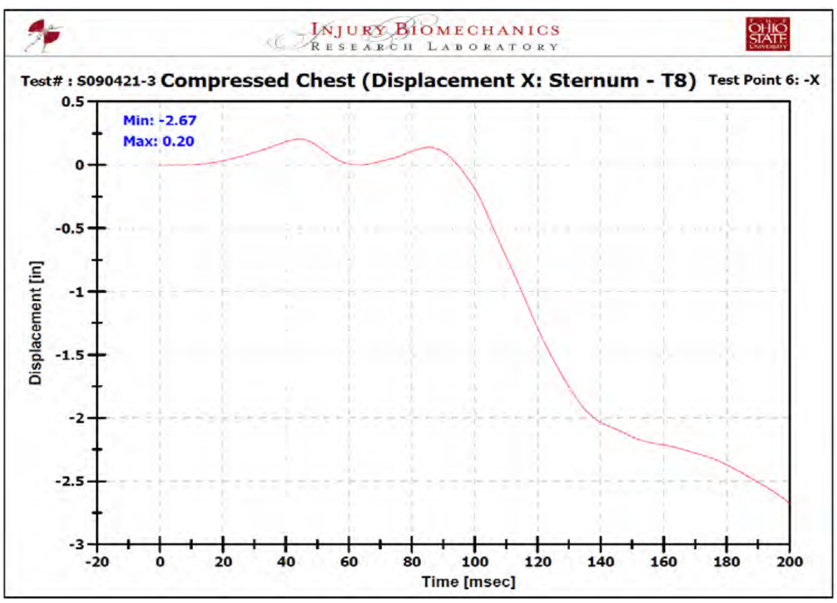


**Figure 19: Test Point 6 (Subject E) Chest Compression**

A full autopsy was conducted on Subject E, and the detailed results are as follows:

**Skin Surface**
- No noticeable markings on the external surface of the subject

**Musculature: (Both Right & Left – unless noted differently)**
- Deltoid – No Damage
- Pectoralis Major – No Damage
- Pectoralis Minor – No Damage
- Serratus Anterior – No Damage
- Trapezius – No Damage
- Supraspinatus – No Damage
- Infraspinatus – No Damage
- Teres Major – No Damage
- Teres Minor – No Damage
- Subscapularis – No Damage

**Joints: (Both Right & Left – unless noted differently)**
- Glenohumeral Joint – No Damage
    - Joint Capsule (Rotator Cuff) – No Damage
    - Long head of biceps tendon – No Damage
    - Coracoacromial Ligament – No Damage
    - Coracoclavicular Ligaments
        - Conoid – No Damage
        - Trapezoid – No Damage
    - Coracohumeral Ligament – No Damage
- Acromioclavicular Joint – No Damage
    - Acromioclavicular Ligament – No Damage
- Sternoclavicular Joint – No Damage
    - Sternoclavicular Ligament – No Damage
    - Intraclavicular Ligament – No Damage
    - Costoclavicular Ligament – No Damage

**Skeletal: (Both Right & Left – unless noted differently)**
- Humerus – No Damage
- Scapula – No Damage
- Clavicle – No Damage
- Sternum – No Damage
- Ribs
    - Left Side
        - *Non-displaced fracture on the pleural surface, 5.12” from the midline*
        - *The fracture was not evident on the cutaneous surface*
    - Right Side
        - *Non-displaced fracture on the cutaneous surface, 6.69” from the midline (mid-axillary line)*

The multiple rib fractures on both sides of the thorax equate to an abbreviated injury score (AIS) of 450210.2. Upon removal of the thoracic plate, no further damage was documented to the lungs, heart or great vessels. The injuries sustained to this subject are injuries similar to those documented in the –x-direction test with subject B. This subject’s AIS score is slightly less than documented with subject B, but the three rib fractures on both sides of the thorax would still be very painful and debilitating to occupants trying to escape a capsule.

**Subject E Conclusion**

This test was a 12.0 g, -X directed loading event using a 60 year old male post mortem human subject. The test data showed good interaction between the subject, the seat back and the harness. The seat did show vibrations due to insufficient stability on the buck. The vibrations were not deemed to have caused any injuries to the subject. The main finding of the testing was fractured ribs 3 & 4 on the left aspect of the thorax and rib 7 on the right aspect. These fractures were in line with the scye suit bearings on the occupant. The harness showed equal restraint on the load cells, but the scye bearings between the shoulder straps and the occupant's thorax kept the occupant from being restrained properly. The harness straps caused point loading of the scye bearings on the ribs of the occupant which resulted in fractures.

Subject B also underwent similar –x-axis loading and had more severe injuries due to the failure of three ribs on each aspect of the thorax. In that testing the bearings kept the thorax from being properly restrained and a similar injury mechanism resulted in an AIS level 4 injury. These two tests both reveal that the bearings do not allow for proper restraint of the subject's thorax resulting in serious injury to the occupant. Many tests have been done at these impact levels with occupants wearing similar 5-point harnesses and rib fractures are not normally prevalent.

### E. Subject F Results

Subject F was a 71 year old male, weighing 194 pounds and approximately 67.3" tall. BMD results from this subject indicate t-values of 0.7 and 1.0 for the whole body and lumbar spine, respectively. Figure 20 at right shows the instrumentation employed on Subject F.

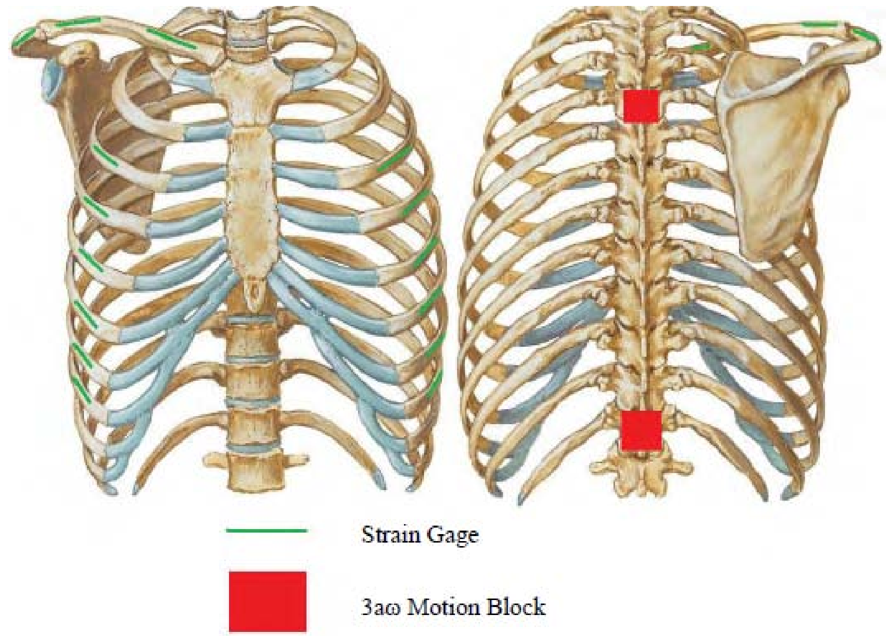


**Figure 20: Test Point 7-8 (Subject F) Instrumentation**

The test subject was subjected to two test points. The first was an approximately 11.7g peak acceleration in the +Y direction (side impact) with a total acceleration duration of 80ms. The second was also an approximately 11.7g peak acceleration in the -Y direction (side impact). Below in Figure 21 the acceleration of the test sled is shown for the +Y test only.

Table 7 shows the peak values of the instrumentation used for this +Y test.

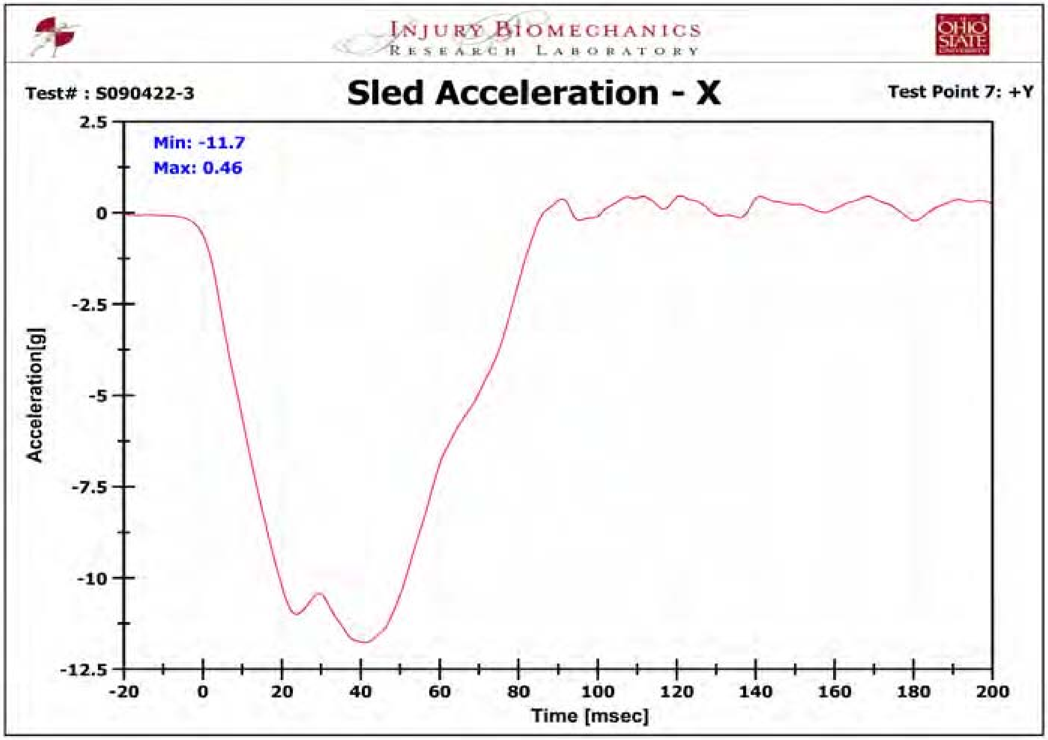


**Figure 21: Test Point 7 (Subject E) Acceleration**

Table 7 below shows the peak values of the instrumentation used for this test.

**Table 7: Test Point 7 (Subject E) Peak Values**

| Sled Instrumentation | | Subject Instrumentation | |
|---|---|---|---|
| **Channel** | **Maximum** | **Channel** | **Maximum** |
| Seat Back Fx | -1,660 lbf | T4 Xg | 11 g |
| Seat Back Fy | -973 lbf | T4 Yg | -27 g |
| Seat Back Fz | -353 lbf | T4 Zg | 7 g |
| Seat Pan Fx | -211 lbf | T12 Xg | 6 g |
| Seat Pan Fy | -474 lbf | T12 Yg | -27 g |
| Seat Pan Fz | -898 lbf | T12 Zg | -9 g |
| Left Shoulder Harness | 264 lbf | S1 Xg | -7 g |
| Right Shoulder Harness | 261 lbf | S1 Yg | -27 g |
| Left Pelvis Harness | 707 lbf | S1 Zg | -5 g |
| Right Pelvis Harness | 142 lbf | Lateral Flexion T4 to S1 | -0.18 in* |
| Harness 5$^{th}$ Point | 295 lbf | | |
| Shoulder Support Plate | 903 lbf | | |
| Pelvis Support Plate | 653 lbf | | |
| Knee Support Plate | 714 lbf | | |

* This number is approximated given error due to the double integration of the accelerometers

Significant findings from this data are as follows.

**Seat Back**

• All of the force channels show a large vibration during the event that was due to the construction and lack of stability of the seat for use in this direction. Although the vibrations are significant in value, they are not significant in causing injuries to the subject.
• The occupant was sliding on top of the seat back, thus these forces were driven by the struts attaching the seatback to the buck. This is verified by the vibrational swings that the load cell plots show in all three directions.

**Seat Pan**
• Looking at Table 7, the seat pan loads are very similar and negligible in value when compared to other directions of loading.
• The loads through the seat pan are not associated with any injury findings on the subject.

**Harness Loads**
• The harness restrains the occupant after it rebounds off of the seat pan. The harness loads reach their peak approximately 10 msec following the peak force through the seat pan.
• These harness loads are also very similar to what was recorded with subject C.
• The shoulder harness straps and pelvis straps recorded similar peak forces revealing the occupant was uniformly positioned onto the seat.

**Strain Gages**
• As previously mentioned a new technique using electrical tape to better reinforce the leads of the gage onto the gage itself was developed to decrease the number of broken gages in a test. This technique did reduce the number of broken gages down to only 2 –
  o Left rib 4
  o Left rib 6
• The gages show peak strain around 50-55 msec which is timed with the maximum load into the seat pan.
• None of the strain gage signals displayed signs of bone failure, which corresponded to the autopsy findings eported later in this section.

**3aω Motion Blocks**
• The peak acceleration for the spine was 41 g in the z-direction at the T-6 vertebra. The z-axis acceleration for T S-1 was similar at 28 g.
• The spinal accelerations were also similar to what was recorded by subject C in phase I testing.
• This acceleration led to a spinal compression of only .20”, Figure 22. The compression cannot be calculated accurately beyond this time due to mathematical error introduced when integrating accelerometers into displacements.

The subject was then transported to the OSU Medical Center for thoracic CT scans before the –Y direction test was conducted. Figure 23 shows the acceleration of the test sled for the -Y test only.

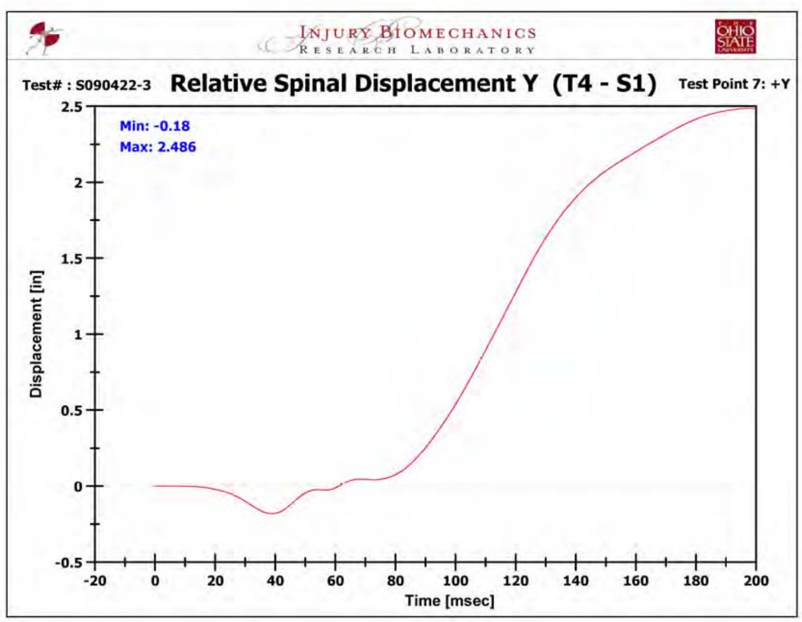


**Figure 22: Test Point 7 (Subject F) Spinal Displacement**

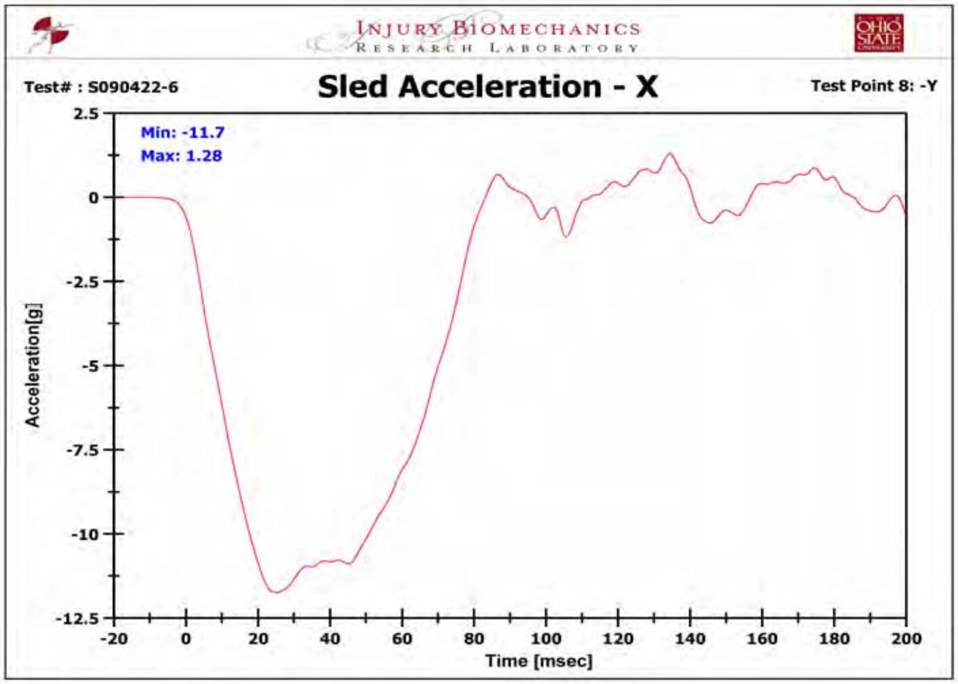


**Figure 23: Test Point 8 (Subject F) Acceleration**

Table 8 below shows the peak values of the instrumentation used for this +Y test.

**Table 8: Test Point 8 (Subject F) Peak Values**

| Sled Instrumentation | | Subject Instrumentation | |
|---|---|---|---|
| **Channel** | **Maximum** | **Channel** | **Maximum** |
| Seat Back Fx | -1,941 lbf | T4 Xg | -13 g |
| Seat Back Fy | 776 lbf | T4 Yg | 28 g |
| Seat Back Fz | -258 lbf | T4 Zg | 11 g |
| Seat Pan Fx | -319 lbf | T12 Xg | -7 g |
| Seat Pan Fy | 360 lbf | T12 Yg | 28 g |
| Seat Pan Fz | -1,072 lbf | T12 Zg | 17 g |
| Left Shoulder Harness | 352 lbf | S1 Xg | 7 g |
| Right Shoulder Harness | 137 lbf | S1 Yg | 38 g |
| Left Pelvis Harness | 49 lbf | S1 Zg | -5 g |
| Right Pelvis Harness | 691 lbf | Lateral Flexion T4 to S1 | -0.35 in |
| Harness 5th Point | 332 lbf | | |
| Shoulder Support Plate | 1,348 lbf | | |
| Pelvis Support Plate | 1,405 lbf | | |
| Knee Support Plate | 912 lbf | | |

* This number is approximated given error due to the double integration of the accelerometers

Significant findings from this data are as follows.

**Seat Back**

• All of the force channels show a vibration during the event that was due to the construction and stability of the seat. Although the vibrations are significant in value, they are not significant in causing injuries to the subject.

• X-Axis Forces - The x-axis force plot of the seat back reveal that the subject loaded the back of the seat at 50 msec with almost 3,000 lbf. This is the main load path into the occupant for this direction.
• Y-Axis & Z-Axis Forces – These forces were slightly higher than expected due to the coupling of the 4 load cells by the steel plate that formed the seat back.

**Seat Pan**
• Looking at Table 8, the maximum value of -1,072 lbf for the force in the z-axis of the seat pan is slightly high given the subject sliding along the pan. The vibrations and slightly inflated forces are once again due to the coupling of the four load cells under the seat pan.

**Harness Loads**
• It appears that the right shoulder harness load cell might have caught up on the seat structure. It shows an irregular loading increase at 80 msec. The value of the load cell seems to be correct when compared to the others, but the slope of the increase, being almost linear, does not appear to be correct.
• The other harness load cells are similar and show a uniform restraint of the subject.

**Strain Gages**
• As previously mentioned a new technique using electrical tape to better reinforce the leads of the gage onto the gage itself was developed to decrease the number of broken gages in a test. This technique did reduce the number of broken gages down to only 2 –
  o Left rib 4
  o Left rib 6
• The gages show peak strain around 45 msec which is timed with the maximum load into the harness after rebounding off of the seat back.
• Several of the strain gage signals displayed signs of bone failure, which corresponded to the autopsy findings reported later in this section.

**3aω Motion Blocks**
• The peak acceleration for the sternum was 20 g in the x-axis. This was not surprising given the motion of the event in the +X direction. It is slightly less than the 25g recorded by subject A in a similar loading scenario.
• The x-axis acceleration of T6 was similar in the range of 17 g.
• The compression of the sternum in relation to T6 in the x-axis direction was calculated using the motion blocks, Figure 24. The maximum value recorded during the event is approximately 1.26”, a value below the injury threshold for the thorax used in car safety testing. In fact, it is less than the 1.57” of compression recorded by subject A even with the umbilical connector in addition to the harness.

A full autopsy was conducted on Subject F, and the detailed results are as follows:

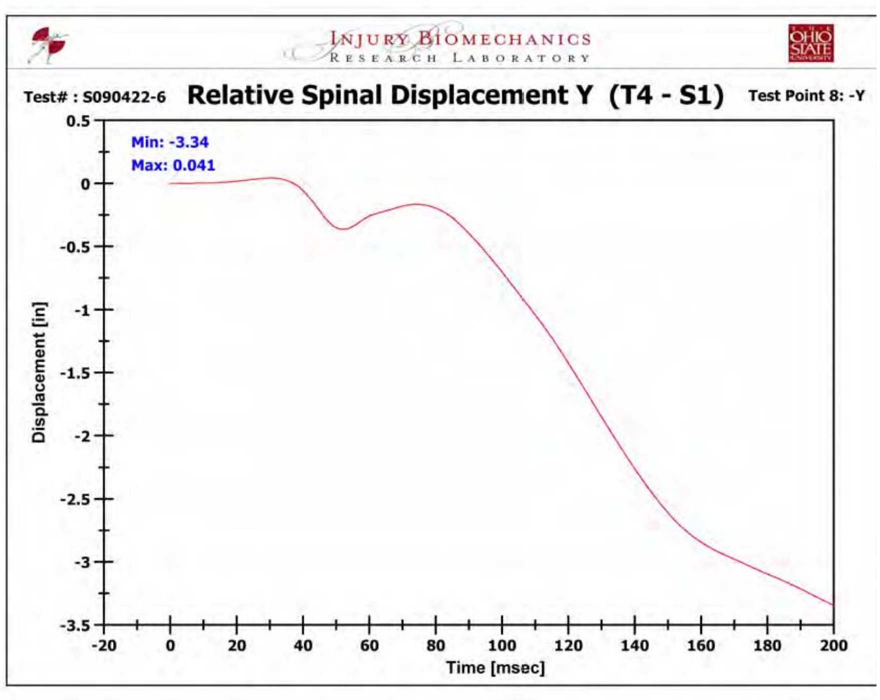


**Figure 24: Test Point 8 (Subject F) Spinal Displacement**

**Skin Surface**

- No noticeable markings on the external surface of the subject

**Musculature: (Both Right & Left – unless noted differently)**

- Deltoid – No Damage
- Pectoralis Major – No Damage
- Pectoralis Minor – No Damage
- Serratus Anterior – No Damage
- Trapezius – No Damage
- Supraspinatus – No Damage
- Infraspinatus – No Damage
- Teres Major – No Damage
- Teres Minor – No Damage
- Subscapularis – No Damage

**Joints: (Both Right & Left – unless noted differently)**

- Glenohumeral Joint – No Damage
    - Joint Capsule (Rotator Cuff) – No Damage
    - Long head of biceps tendon – No Damage
    - Coracoacromial Ligament – No Damage
    - Coracoclavicular Ligaments
        - Conoid – No Damage
        - Trapezoid – No Damage
    - Coracohumeral Ligament – No Damage
- Acromioclavicular Joint – No Damage
    - Acromioclavicular Ligament – No Damage
- Sternoclavicular Joint – No Damage
    - Sternoclavicular Ligament – No Damage
    - Intraclavicular Ligament – No Damage
    - Costoclavicular Ligament – No Damage

**Skeletal: (Both Right & Left – unless noted differently)**

- Humerus – No Damage
- Scapula – No Damage
- Clavicle – No Damage
- Sternum –
    - Ribs – Left Side
        - Rib 6 – *displaced fracture 5.90” from midline*
            - *Pneumo-thorax*
        - Rib 7 – 2 fractures
            - *Non-displaced fracture 5.12” from midline*
            - *Non-displaced fracture 8.66” from midline*
        - Rib 8 – 2 fractures
            - *Non-displaced fracture 5.12” from midline*
            - *Non-displaced fracture 9.45” from midline*
    - Right Side – no injuries
- Pelvis – No Damage
- Femora – No Damage

The multiple rib fractures on both sides of the thorax equate to the highest abbreviated injury score (AIS) of all tests performed thus far. Upon removal of the thoracic plate, it was documented that the left lung sustained a pneumo-thorax (collapsed lung) due to the fracture of Rib 6. The injuries sustained to this subject would not only be painful, they would be potentially life threatening without immediate medical care. The pneumo-thorax and pain would make egress out of a capsule and into the water difficult if not impossible.

### Subject F Conclusion

This test was a 11.7 g, +Y directed loading event, followed by a 11.7 g, -Y directed loading event, using a 71 year old male post mortem human subject. The test data showed good interaction between the subject, the seat back and the harness. The seat did show vibrations due to insufficient stability on the buck. The vibrations were not deemed to have caused any injuries to the subject. On both events the primary loading path into the occupant was the three side support plates located at the shouler, pelvis and knee, while a secondary load was through the 5-point harness.

The PMHS suffered major injuries as a result of these loading events. Due to the severity of the injuries (AIS 4), the fact that the subject received CT imaging between the two tests, coupled with the higher loads seen into the side bolster restraints on the second test, it is concluded that the injuries were sustained primarily or entirely on the second (-Y) test. After thorough pre and post test imaging analysis, as well as video analysis, the primary injury mechanism for these injuries was determined to be the scye bearing. However, it is possible that the upper arm bearing may have contributed as well.

## F. Subject L Results

Subject L was a test conducted in conjuction with the Constellation Vehicle Interface Element (VIE) team to assess injury potential of umbilical connectors located at different places on the body; as Subject L was not wearing the suit simulator for the accelerations events in question, it is not within the scope of this paper.

## G. Acceleration Analysis

In order to recharacterize the testing loads with respect to expected Orion vehicle landing loads, and to capture any changes to landing load estimates after the beginning of the test series, each tested data point was plotted against a subset of 24 Orion water landings (1 chute out, high winds) and land landing cases. As the OSU tests were single-direction only, and all Orion landing cases are multi-directional in nature (i.e., simultaneous components of X, Y, and Z), the Brinkley beta value was used to compare the expected Orion cases to the OSU test cases.

The Brinkley beta value is a non-dimensional number calculated by a root mean squared (RMS) calculation comparing accelerations in each discrete direction with respective limits. By using the beta value, it is possible to roughly compare the injury potential of a single-axis landing event to the injury potential of a multi-axis landing event.

The result of this comparison is shown in Figure 25: Landing Load Comparison. In this figure, a beta (low) value of less than or equal to 1.0 correlates to less than a 0.5 percent risk of injury; while a beta value (low) of more than 1.0 correlates to a 5 percent risk of injury.

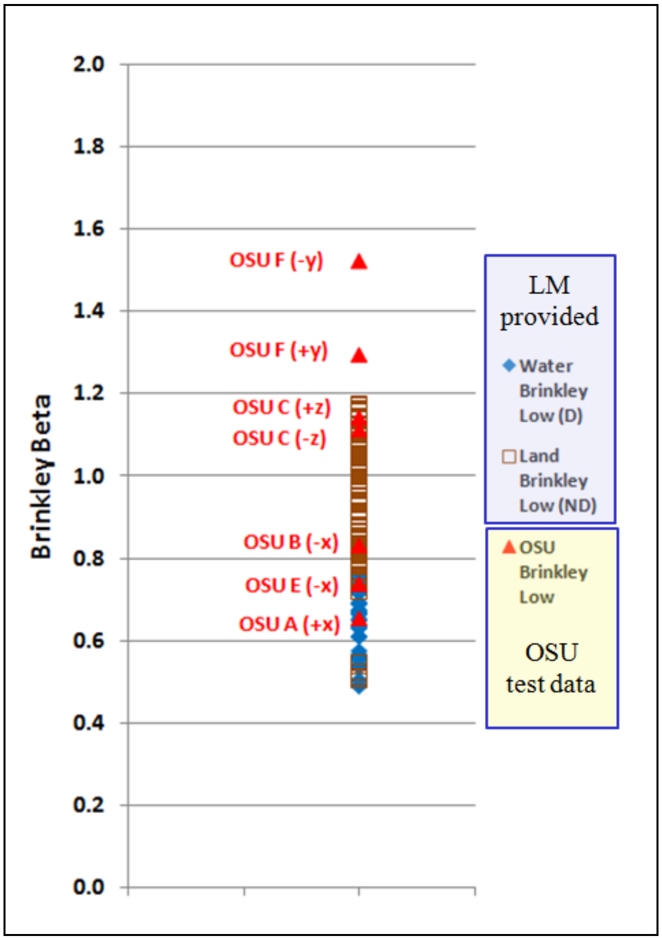


**Figure 25: Landing Load Comparison**

As shown in the graph, the Brinkley beta (low) values of the OSU test cases ranged from 0.6 to 1.5, correlating to a 5 percent (Y test cases) or a 0.5 percent (all other test cases) risk of injury. With the exception of the Y cases, all OSU landing loads were commensurate to landing loads currently estimated by Orion.

This graph communicates two things: (1) that the loads subjected upon the test subject were comparable to what is estimated by Orion; and (2) that all the test cases, when ran through the Brinkley injury assessment model, correlated to a 0.5 or 5 percent risk of injury despite the fact that the real-world tests demonstrated an injury rate of ~50 percent. Conclusions that can be drawn from this analysis are as follows:

- The Brinkley injury model is not sufficient at predicting injury when hard suit elements are placed on the subject
- These hard suit elements increase the risk of injury somewhere between one and two orders of magnitude based on the test results

### H. Suit Hardware Injury Risk Analysis

Most notable of all OSU test cases is Test Point 1 (Subject A in the +X direction) and Test Point 6 (Subject E in the –X direction). In these cases, the estimated Brinkley beta values were 0.65 and 0.74, respectively, correlating to less than 0.5 percent risk of injury; however, both tests showed substantial injuries in the anatomical region corresponding to the scye bearing (chest, thoracic cage, and rear shoulder). These two data points, when taken together, provide strong evidence that the scye bearing, as implemented in this test series, is the direct mechanism for these injuries. It should be noted that this does not necessarily mean a scye bearing in any implantation would cause injury; however, it demonstrates a large risk mitigation effort would be required to protect an occupant wearing a scye bearing under the designated landing loads.

The arm bearing is less evident. Although the injuries in the X directions can be directly attributed to the scye bearing alone, the injury in the Y direction may have been caused by the arm bearing, the scye bearing, or a combination of both. In addition, the landing cases in the Y direction correlated to a much higher inherent risk of injury (5 percent) than the other test directions (0.5 percent). Looking at the high-speed video and other data, it is difficult to determine with absolute certainty the exact injury mechanism in Test Point 8 (Subject F in the –Y direction). However, it is the opinion of the test team that the scye bearing played a role, and an arm bearing alone would probably not have caused injury. This opinion is based on video analysis that shows the interactions between the scye and upper arm bearings on impact with the side bolster, and the lack of restraint provided to the subject when the scye bearing is in place; the shoulder harnesses run over the scye bearing instead of the shoulder, which would be preferred.

Based on this information, an upper arm bearing alone would likely not cause injury to the test subject in the –Y direction when representative Orion landing loads are applied. However, without further testing with an upper arm bearing alone, it is impossible to say with absolute certainty.

Due to the fact that no observable injuries were found in the thigh region for any test points, it is apparent that a thigh disconnect or thigh bearing is not a credible risk injury mechanism.

## IV. Conclusion

In response to specific injury risks identified due to the incorporation of hard mobility elements in an otherwise soft suit, coupled with nominal or off-nominal Orion vehicle landing loads, a test series was conducted in conjuction with The Ohio State University's Injury Biomechanical Research Laboratory at Transportation Research Center. This test series consisted of placing post-mortem human subjects in a suit simulator designed to replicate the size and position of these hard mobility elements. These test subjects were then subjected to linear acceleration events on the order of 12g peak with a total duration of ~80ms to evaluate potential for injury.

Due to the results of the first seven test points in which the suit simulator was used, coupled with limited funding, the test series was terminated earlier than anticipated; however, the data that was collected provided enough information for the principal investigators to draw several conclusions.

Across these seven test points, multiple severe skeletal and muscular injuries were observed in the anatomical region correlating to the scye bearing. In conclusion, under acceleration events similar in magnitude to those tested, a scye bearing is a very credible injury mechanism and may result in life threatening injuries if not mitigated properly. While it was not determined to absolute certainty, an upper arm bearing may present a credible injury mechanism in a Y-direction acceleration event, which is compounded if a scye bearing is also present. Although an upper arm bearing may present injury alone in these cases, it is considered a much lower risk due to the fact that the scye bearing was identified as the injury mechanism in +X and –X tests as well.

## Acknowledgments

S.McFarland thanks Dr. John Bolte and the entire test team at The Ohio State University's Injury Biomechanical Research Laboratory for their tireless effort and very late testing hours.

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