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# Test Device for Human Occupant Restraint (THOR) Multi-Directional Biodynamic Response Testing

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# Table of Contents


1.0 Background ..... 1
2.0 Purpose ..... 1
3.0 Methods ..... 1
3.1 Seat and Restraints ..... 3
3.2 THOR Anthropomorphic Test Device ..... 4
3.3 Aerospace Hybrid III Anthropomorphic Test Device ..... 4
3.4 Wright-Patterson Horizontal Impact Accelerator ..... 5
4.0 Measurements ..... 6
4.1 Seat Instrumentation List ..... 6
4.2 Hybrid-III AERO Instrumentation List ..... 6
4.3 THOR Instrumentation List ..... 7
4.4 Data Analysis ..... 7
4.4.1 WPAFB –X (Frontal) Impact Runs ..... 7
4.4.2 WPAFB –Y (Lateral) Impact Runs ..... 8
4.4.3 WPAFB +Z (Spinal) Impact Runs ..... 9
4.4.4 IR-TRACC Calculations ..... 10
4.4.5 Resultant and Summation Calculations ..... 10
5.0 Results ..... 11
5.1 Objective 1: Assess the Linearity, Reproducibility and Frequency Response of the THOR ATD in Each Axes ..... 11
5.1.1 Sled Acceleration Reproducibility ..... 11
5.1.2 Thoracic Spine Axial Force ..... 11
5.1.3 Response Linearity ..... 12
5.2 Objective 2: Collect Validation Data for the THOR ATD Finite Element Model in Development ..... 17
5.3 Objective 3: Compare the THOR responses to historical human test data ..... 19
5.4 Objective 4: Compare the THOR Responses to ATD Test Data Collected from Previous Test Regimes including Data Collected from the 50th Percentile Male Hybrid III Automotive ATD, the 50th Percentile Male Hybrid III Aerospace ATD, and the EuroSID2re 50th Percentile Male Side Impact Dummy ..... 20
5.4.1 THOR K and Hybrid III Aero ..... 20
5.4.2 Lateral Comparison ..... 20
6.0 Specific Test Comments ..... 24
6.1 Head/Neck Mounting Platform ..... 24

6.2 Neck Cable Damage ..... 25
6.3 Lumbar Spine Damage ..... 26
6.4 Aerospace Hybrid III Comments ..... 27
6.5 General Comments ..... 28
7.0 References ..... 29
8.0 Appendices ..... 29
A. THOR Frontal Tests ..... 30
B. THOR Lateral Tests ..... 46
C. THOR Spinal Tests ..... 62
D. Aerospace Hybrid III Frontal Tests ..... 78
E. Aerospace Hybrid III Lateral Tests ..... 87
F. Aerospace Hybrid III Spinal Tests ..... 96

# 1.0 Background

Reaching space requires an extreme amount of kinetic energy and effective systems to dissipate this energy on the return to Earth. While most of this energy is controlled, dissipated, or absorbed by the vehicle, some amount of kinetic energy may be transmitted to the occupants aboard the spacecraft. This energy, if not properly managed, may cause injury to the crewmembers. Particular flight-phases of concern include pad abort, launch, ascent abort, reentry, and landing.

With the retirement of the Space Shuttle, NASA is developing the Multi-Purpose Crew Vehicle (MPCV) also known as Orion, as well as working with commercial partners in developing new spacecraft for NASA's use. Because each has unique dynamic loading, and those loads are different than current vehicles in the automotive, commercial aviation, and military industries, new methods are needed to assess crew injury risk.

In addition, NASA's injury risk posture is different than most other vehicles. Nominal dynamic loads expected in capsule-based crew vehicles are more akin to crashes or ejections in other vehicles. The differences between automotive, military, and NASA operational environments make it important to consider the *overall acceptable probability of injury*, given that occupants in a space vehicle will incur impact conditions every time the vehicle returns to Earth.

Currently, NASA requirements for new vehicles are based on the Brinkley Dynamic Response Criterion and Hybrid III Anthropomorphic Test Device (ATD) limits [NASA TM-2013-217380]. Because of the limitations to this approach, new methods are desired to mitigate the risk of injury to the crew. After a careful review of the available injury assessment methods [Evidence Book], the Test Device for Human Occupant Restraint (THOR) was chosen as a candidate for further investigation. The testing outlined in this report was conducted to assess the THOR response in various orientations and dynamics for its applicability to the NASA environment. In addition, these data were collected to provide validation data for concurrent development of a Finite Element model of the THOR in cooperation with the National Highway Traffic Safety Administration (NHTSA).

# 2.0 Purpose

The purpose of this test regimen was to evaluate the THOR ATD in spaceflight-specific orientations and accelerations. The following were the objectives of the testing:

1. Assess the linearity, reproducibility, and frequency response of the THOR ATD in each axes.
2. Collect validation data for the THOR ATD finite element model in development.
3. Compare the THOR responses to historical human test data.
4. Compare the THOR responses to ATD test data collected from previous test regimens including data collected from the 50$^{th}$ percentile male Hybrid III automotive ATD, the 50$^{th}$ percentile male Hybrid III aerospace ATD, and the EuroSID2re 50$^{th}$ percentile male Side Impact Dummy (SID).

# 3.0 Methods

The test protocol shown below in Table 1 (-X tests), Table 2 (-Y tests), and Table 3 (+Z tests) was conducted on the Horizontal Impact Accelerator at 711th Human Performance Wing of the Air Force Research Laboratory from January 17 to February 4, 2013. In all, 46 tests were conducted during the campaign in 3 different orientations at various peak-G levels and rise times. Testing was conducted with the THOR and 50$^{th}$ Percentile Aerospace Hybrid III ATDs.

**Table 1. THOR -X Axis Testing**

| Test | ATD | Orientation | G-Level [G] | Pulse Width [ms] | Condition |
|---|---|---|---|---|---|
| *8678* | *Aerospace Hybrid III* | *-X* | *8.0* | *100* | *Air Force Helmet* |
| *8679* | *THOR* | *-X* | *8.0* | *100* | *No Helmet* |
| *8680* | *THOR* | *-X* | *8.0* | *100* | *No Helmet* |
| *8681* | *THOR* | *-X* | *8.0* | *100* | *Air Force Helmet* |
| *8682* | *THOR* | *-X* | *9.9* | *100* | *Air Force Helmet* |
| *8683* | *Aerospace Hybrid III* | *-X* | *7.9* | *100* | *No Helmet* |
| *8698* | *THOR* | *-X* | *20.4* | *70* | *No Helmet* |
| *8699* | *THOR* | *-X* | *20.3* | *70* | *No Helmet* |
| *8700* | *THOR* | *-X* | *9.9* | *70* | *No Helmet* |
| *8701* | *THOR* | *-X* | *10.0* | *70* | *No Helmet* |
| *8702* | *THOR* | *-X* | *10.0* | *70* | *No Helmet* |
| *8703* | *Aerospace Hybrid III* | *-X* | *20.1* | *70* | *No Helmet* |

**Table 2. THOR -Y Axis Testing**

| Test | ATD | Orientation | G-Level [G] | Pulse Width [ms] | Condition |
|---|---|---|---|---|---|
| *8684* | *Aerospace Hybrid III* | *-Y* | *10.9* | *100* | *No Helmet* |
| *8685* | *Aerospace Hybrid III* | *-Y* | *9.9* | *100* | *No Helmet* |
| *8686* | *THOR* | *-Y* | *10.2* | *100* | *No Helmet* |
| *8687* | *THOR* | *-Y* | *10.1* | *100* | *No Helmet* |
| *8688* | *THOR* | *-Y* | *10.1* | *40* | *No Helmet* |
| *8689* | *THOR* | *-Y* | *10.0* | *40* | *No Helmet* |
| *8690* | *Aerospace Hybrid III* | *-Y* | *10.2* | *40* | *No Helmet* |
| *8691* | *Aerospace Hybrid III* | *-Y* | *10.7* | *70* | *No Helmet* |
| *8692* | *Aerospace Hybrid III* | *-Y* | *10.1* | *70* | *No Helmet* |
| *8693* | *THOR* | *-Y* | *10.3* | *70* | *No Helmet* |
| *8694* | *THOR* | *-Y* | *10.1* | *70* | *No Helmet* |
| *8695* | *THOR* | *-Y* | *20.3* | *70* | *No Helmet* |
| *8696* | *THOR* | *-Y* | *20.6* | *70* | *No Helmet* |
| *8697* | *THOR* | *-Y* | *19.9* | *70* | *No Helmet* |

**Table 3.THOR +Z Axis Testing**

| Test | ATD | Orientation | G-Level [G] | Pulse Width [ms] | Condition |
|---|---|---|---|---|---|
| *8658* | *THOR* | *+Z* | *10.0* | *40* | *No Helmet* |
| *8659* | *THOR* | *+Z* | *10.0* | *40* | *No Helmet* |
| *8660* | *THOR* | *+Z* | *10.0* | *40* | *Air Force Helmet* |
| *8661* | *Aerospace Hybrid III* | *+Z* | *10.0* | *40* | *Air Force Helmet* |
| *8662* | *Aerospace Hybrid III* | *+Z* | *10.9* | *70* | *Air Force Helmet* |
| *8663* | *Aerospace Hybrid III* | *+Z* | *10.5* | *70* | *Air Force Helmet* |
| *8664* | *Aerospace Hybrid III* | *+Z* | *10.2* | *70* | *Air Force Helmet* |
| *8665* | *THOR* | *+Z* | *9.7* | *70* | *Air Force Helmet* |
| *8666* | *THOR* | *+Z* | *9.8* | *70* | *No Helmet* |
| *8667* | *THOR* | *+Z* | *10.1* | *70* | *No Helmet* |
| *8668* | *THOR* | *+Z* | *21.8* | *70* | *No Helmet* |
| *8669* | *THOR* | *+Z* | *21.4* | *70* | *No Helmet* |
| *8670* | *THOR* | *+Z* | *9.4* | *100* | *No Helmet* |
| *8671* | *THOR* | *+Z* | *9.9* | *100* | *No Helmet* |
| *8672* | *THOR* | *+Z* | *9.9* | *100* | *No Helmet* |
| *8673* | *THOR* | *+Z* | *10.0* | *100* | *Air Force Helmet* |
| *8674* | *THOR* | *+Z* | *10.9* | *100* | *Air Force Helmet* |
| *8675* | *THOR* | *+Z* | *12.2* | *100* | *Air Force Helmet* |
| *8676* | *THOR* | *+Z* | *8.0* | *100* | *Air Force Helmet* |
| *8677* | *Aerospace Hybrid III* | *+Z* | *9.9* | *100* | *Air Force Helmet* |

## 3.1 Seat and Restraints

All testing was conducted with the Baseline 2 seat. The seat consisted of a flat seat pan without padding, a seat back with 2 individual loading plates without padding, and a headrest with minimal padding. The seat pan and seat back angle was set at 90 degrees, and the seat could be oriented on the sled buck to achieve the appropriate orientation for testing. For lateral testing, additional side panels were added on the right side of the seat. These panels were positioned as close as possible to the ATD head, shoulder, pelvis, and knee to minimize any closing velocity that may occur at the test initiation. All seat surfaces were supported by load cells, which allow the measurement of forces imparted on the seat. A picture of the seat with the side supports in shown in Figure 1. Before each test, the ATD was removed from the seat to zero the seat instrumentation, and then repositioned in the seat.

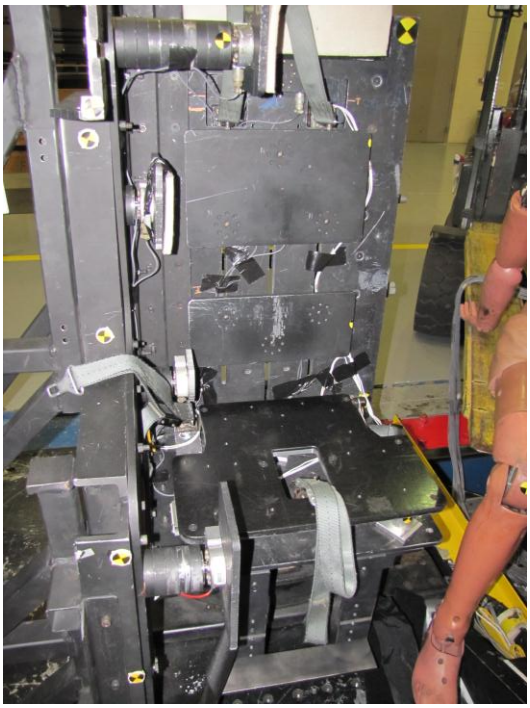


**Figure 1. Baseline 2 seat with side supports.**

The restraint system was a standard Air Force MB-6 4-point harness with an added crotch strap. Each restraint was anchored to a 3-axis load cell. The belts were pretensioned before each test to 20 lbf by technicians by monitoring the output of the load cells on a monitor.

## 3.2 THOR Anthropomorphic Test Device

Testing was conducted using a NHTSA 50$^{th}$ percentile male THOR-K ATD (Figure 3). The THOR-K (S/N 015) includes all of the Modification Kit upgrades to the THOR-NT, excluding the SD-3 shoulder [1, 2].

The THOR was developed as a frontal impact ATD and was not designed to be used in other orientations; however, based on our review of all of the current ATDs available, the THOR is the best available ATD for performance in all 3 axes [3]. The purpose of this testing was to evaluate the THOR-K in spinal and lateral impact conditions.

## 3.3 Aerospace Hybrid III Anthropomorphic Test Device

The 50$^{th}$ percentile male Aerospace Hybrid III

Figure 2) was used for comparison to the THOR-K for all impact orientations. The inclusion of this ATD was to allow comparison to other previous impact conditions using the Aerospace Hybrid III along with other ATDs and humans.

The Aerospace modification includes replacement of the lumbar spine with a straight spine and a standing pelvis. A comparison of the Aerospace Hybrid III and the FAA Hybrid III was recently published [4].

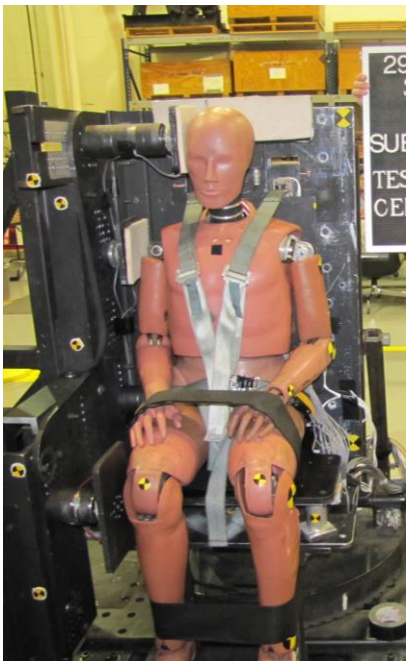


Figure 2. Aerospace Hybrid III.

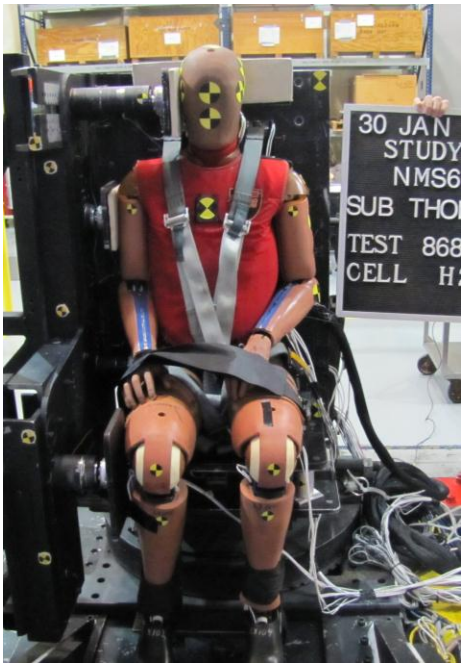



Figure 3. THOR ATD.

## 3.4 Wright-Patterson Horizontal Impact Accelerator

The Horizontal Impulse Accelerator (HIA) (Figure 4) is capable of accelerations up to 150 G, maximum velocities of 53 m/s, and pulse durations of 10 to 300 ms. This device is human rated and more than 2500 human tests have been performed. The HIA begins with no initial velocity, is accelerated to the prescribed level, and was used for all testing [5].

Figure 4. Horizontal Impulse Accelerator.

# 4.0 Measurements

For each sled run, pretest photographs were taken of the configuration. During the test, 2 high-speed cameras collected photogrammetry data. Post-test, additional photographs were taken to document the changes that occurred during the test. In addition, FARO arm data were collected on each seat orientation to assist with post-test analysis.

Data were collected using a Diversified Technical Systems (DTS) TDAS PRO 64-channel system and 32-channel TDAS G5 system for a total of 96 channels. All 96 channels were used for the THOR tests, and 63 channels were collected for the Aerospace Hybrid III tests. High-speed video was collected at 500 frames per second.

## 4.1 Seat Instrumentation List

For each test, the channels noted in Table 4 were collected from the test fixture, with the exception of the lateral load cells. These channels were only collected for the –Y axis tests, since they are part of the test fixture added from those tests. In addition, for tests conducted with the Aerospace Hybrid III, the channels shown in Table 5 were collected for each test, and for test conducted with the THOR, the channels in Table 6 were collected.

**Table 4: Test Fixture Channels**

| *Recorded Test Fixture Channels* |
|---|
| *Sled X Acceleration* |
| *Left, Right, & Center Headrest X Force* |
| *Left, Right, & Center Upper Back Plate X Force* |
| *Left, Right, & Center Lower Back Plate X Force* |
| *Left, Right, & Center Seat Pan Z Force* |
| *Right Headrest Lateral Y Force* |
| *Right Shoulder Plate Lateral Y Force* |
| *Right Pelvis Plate Lateral Y Force* |
| *Right Knee Plate Lateral Y Force* |
| *Left & Right Shoulder Restraint X, Y, & Z Force* |
| *Left & Right Lap Restraint X, Y, & Z Force* |
| *Crotch Strap Restraint X, Y, & Z Force* |
| *2 High Speed Video Cameras* |
| *Denotes channels only collected during –Y axis tests* |

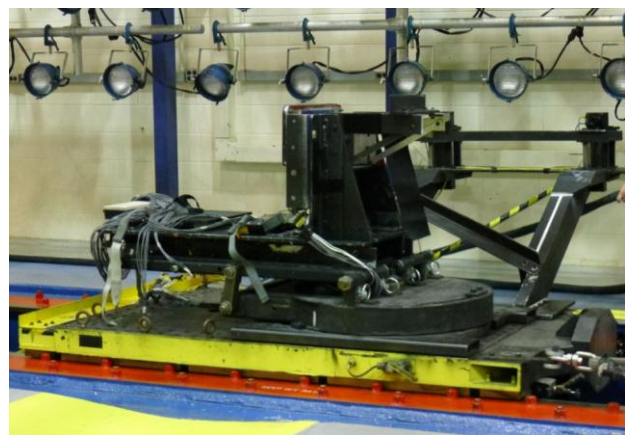


**Figure 5. Sled in Z axis position.**

## 4.2 Hybrid-III AERO Instrumentation List

**Table 5: Hybrid III Channels Collected**

| *ATD Channels to Record* |
|---|
| *Head X, Y, & Z Acceleration* |
| *Head Y Rotational Acceleration* |
| *Upper Neck X, Y, & Z Force* |
| *Upper Neck X, Y, & Z Moment* |
| *Chest X, Y, & Z Acceleration* |
| *Chest Y Angular Acceleration* |
| *Lumbar X, Y, & Z Force* |
| *Lumbar X, Y, & Z Moment* |
| *Pelvis X, Y, & Z Acceleration* |

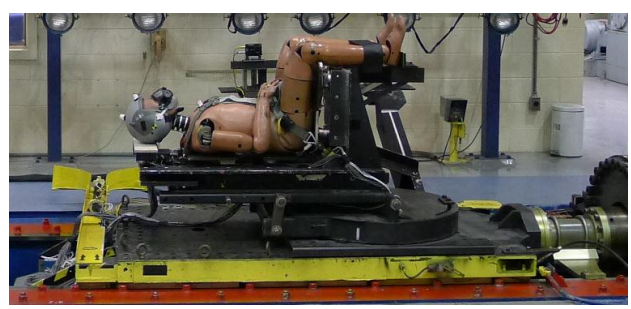


**Figure 6. Hybrid III Aero.**

## 4.3 THOR Instrumentation List

**Table 6: THOR Channels Collected**

| *Recorded THOR Channels* |
|---|
| *Head X, Y, & Z Linear Acceleration* |
| *Head X, Y, & Z Angular Velocity* |
| *Occipital Condyle Rotation* |
| *Upper Neck X, Y, & Z Force* |
| *Upper Neck X, Y, & Z Moment* |
| *Lower Neck X, Y, & Z Force* |
| *Lower Neck X, Y, & Z Moment* |
| *Front & Rear Neck Spring Force* |
| *T1 X, Y, & Z Acceleration* |
| *Left Clavicle Lateral X & Y Force* |
| *Left Clavicle Medial X & Y Force* |
| *Upper Left Chest Deflection & Rotation* |
| *Upper Right Chest Deflection & Rotation* |
| *Lower Left Chest Deflection & Rotation* |
| *Lower Right Chest Deflection & Rotation* |
| *Mid Sternum Acceleration* |
| *Chest CG (T6) X, Y, & Z Acceleration* |
| *T12 X, Y, & Z Acceleration* |
| *T12 X, Y, & Z Force* |
| *T12 X & Y Moment* |
| *Right Acetabular X, Y, & Z Force* |
| *Pelvis X, Y, & Z Acceleration* |
| *Left & Right Ankle X, Y, & Z Rotations* |

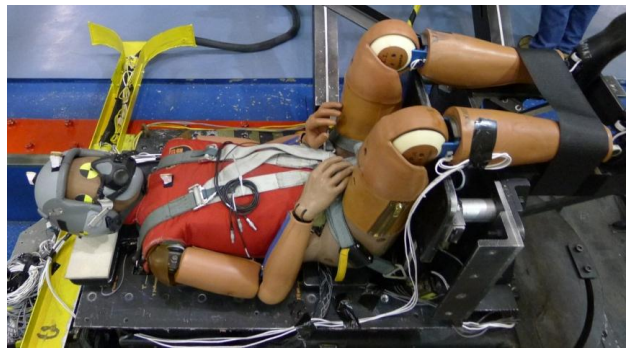


**Figure 7. THOR ATD in seat.**

## 4.4 Data Analysis

All data collected during the sled testing were processed per SAE J/211-1 [6], with a few exceptions. The data were collected in English Units, and the accelerometers were collected with the Air Force Research Laboratory coordinate system convention (see below). All of the data were analyzed using MATLAB [7]. Note that for all tests, regardless of orientation, the sled acceleration is labeled as "SLED X ACC." This acceleration is recorded in a global sled reference frame and thus does not change with seat orientation.

### 4.4.1 *WPAFB –X (Frontal) Impact Runs*

For this test condition, the ATD was facing the ram with its back toward the end of the track (Figure 8). Equations 1-3 allow conversion from the seat coordinate system to the SAE coordinate system.

**Equation 1. WPAFB –X to Sled Coordinate Transformation**

$$\vec{a}_{sled} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \vec{a}_{-X}$$

**Equation 2. WPAFB Sled to SAE Coordinate Transformation**

$$\vec{a}_{SAE} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \vec{a}_{sled}$$

**Equation 3. WPAFB –X to SAE Coordinate Transformation**

$$\vec{a}_{SAE} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \vec{a}_{-X}$$

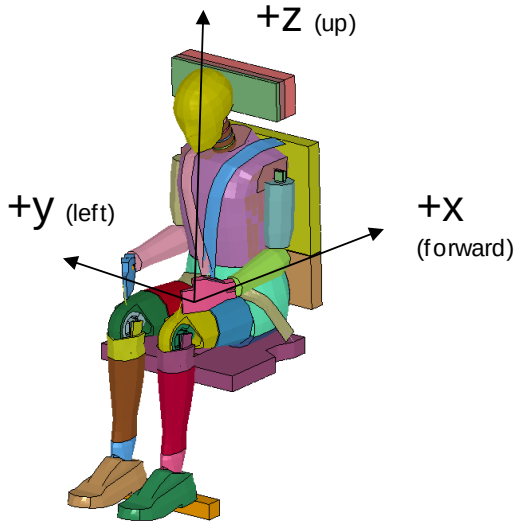



**Figure 8. WPAFB horizontal sled –X (frontal) test condition coordinate system.**

### 4.4.2 *WPAFB –Y (Lateral) Impact Runs*

For this test condition, the ATD was facing to the right with the left shoulder toward the end of the track (Figure 9). Equations 4-6 allow conversion from seat coordinate system to the SAE coordinate system.

**Equation 4. WPAFB –Y to Sled Coordinate Transformation**

$$\vec{a}_{sled} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \vec{a}_{-Y}$$

**Equation 5. WPAFB Sled to SAE Coordinate Transformation**

$$\vec{a}_{SAE} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \vec{a}_{sled}$$

**Equation 6. WPAFB –Y to SAE Coordinate Transformation**

$$\vec{a}_{SAE} = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \vec{a}_{-Y}$$

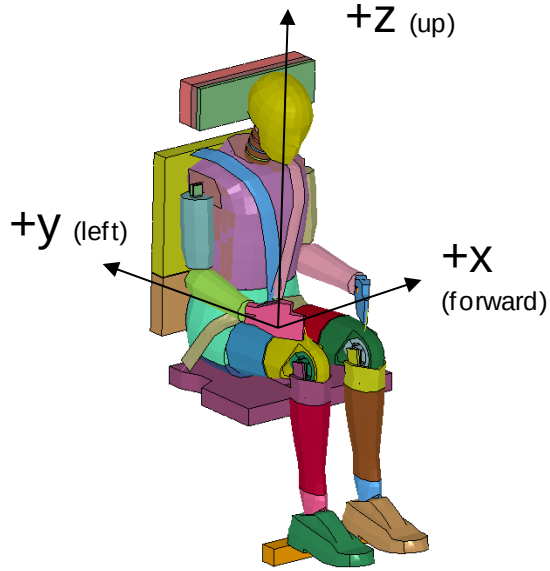



**Figure 9. WPAFB horizontal sled –Y (lateral) test condition coordinate system.**

### 4.4.3 *WPAFB +Z (Spinal) Impact Runs*

For this test condition, the ATD was facing up with the head toward the end of the track (Figure 10). Equations 7-9 allow conversion from the seat coordinate system to the SAE coordinate system.

**Equation 7. WPAFB +Z to Sled Coordinate Transformation**

$$\vec{a}_{sled} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \vec{a}_{+Z}$$

**Equation 8. WPAFB Sled to SAE Coordinate Transformation**

$$\vec{a}_{SAE} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \vec{a}_{sled}$$

**Equation 9. WPAFB +Z to SAE Coordinate Transformation**

$$\vec{a}_{SAE} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \vec{a}_{+Z}$$

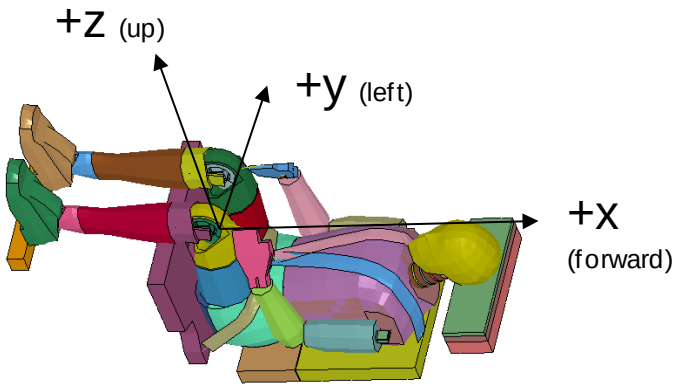



**Figure 10. WPAFB horizontal sled +Z (spinal) test condition coordinate system.**

### 4.4.4 *IR-TRACC Calculations*

The following values (Table 7) were provided by NHTSA for calculation of chest displacement from the IR-TRACC raw data. These calculations are included in the EV5 files submitted to NHTSA.

**Table 7. IR-TRACC Calibration Data**

| Location | $S_{Cal}$ | $O_{cal}$ | $D_{Design}$ | $E_{cal}$ | $\delta$ |
|---|---|---|---|---|---|
| *Upper Left Chest* | *-35.615* | *123.90* | *155.7* | *-0.4675* | *15.5* |
| *Upper Right Chest* | *-34.998* | *124.14* | *155.7* | *-0.4675* | *15.5* |
| *Lower Left Chest* | *-34.612* | *123.46* | *155.7* | *-0.4675* | *15.5* |
| *Lower Right Chest* | *-34.804* | *123.24* | *155.7* | *-0.4675* | *15.5* |
| *Lower Right Abdomen* | *-31.788* | *153.09* | *176* | *-0.47131* | *1* |
| *Lower Left Abdomen* | *-42.499* | *153.68* | *176* | *-0.45142* | *1* |

Using the equations supplied by NHTSA, the 3 dimensional displacements of the chest were calculated.

### 4.4.5 *Resultant and Summation Calculations*

In addition to the recorded channels, additional channels are included for resultants and for force summations from the seat fixture.

# 5.0 Results

The analyses of the results of these tests are still ongoing. Initial results will be presented here and more detail results will be released in the future. The full data sets are plotted in Appendices A-F.

## 5.1 Objective 1: Assess the Linearity, Reproducibility and Frequency Response of the THOR ATD in Each Axes

### 5.1.1 *Sled Acceleration Reproducibility*

Before assessing the reproducibility of the ATD, the sled pulses must first be investigated to assure the input to the tests were similar; otherwise, any differences seen in the ATD responses might be due to the input acceleration differences.

Acceleration profiles delivered from the horizontal impulse accelerator are shown below in Figure 11. These particular pulses were for +Z axis tests. Note the varying rise times (across the top) as well as the varied peak acceleration (down the side). Overall, the pulses were very repeatable. In the 10-G, 100-ms rise-time condition, there is some variability in the peak G, which was due to repeat tests to match the G levels. The final tests that were accepted in each case were well matched.

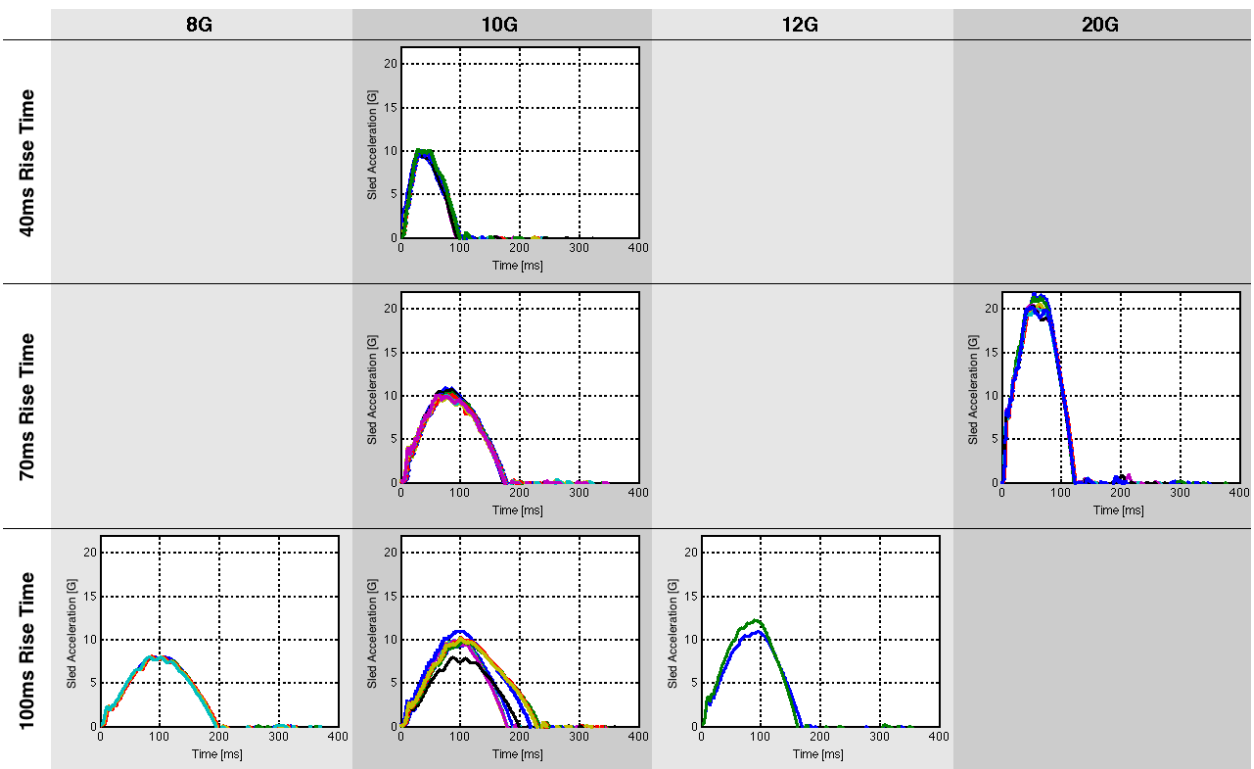



**Figure 11. Sled accelerations from horizontal impulse accelerator.**

### 5.1.2 *Thoracic Spine Axial Force*

Comparing similar THOR test runs shows good repeatability in the thoracic spine axial force, which is an important metric for spacecraft dynamics (Figure 12). Other metrics have similar repeatability (see Appendices).

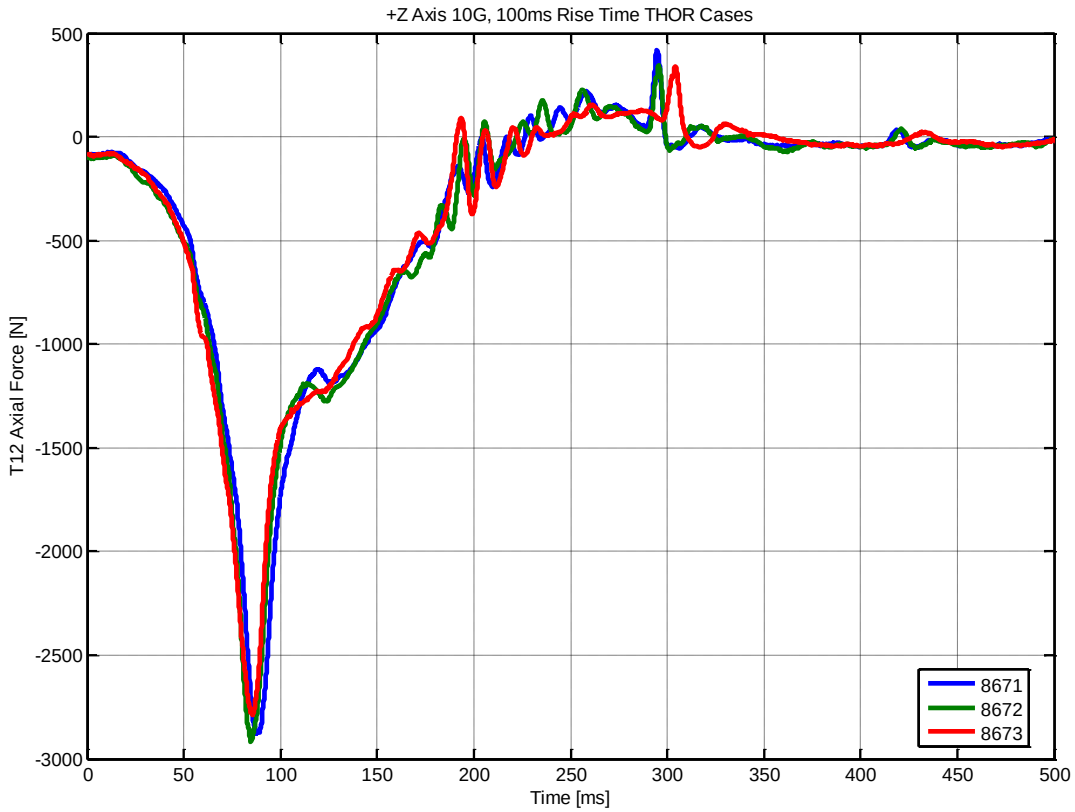



**Figure 12. THOR-K spinal loading.**

### 5.1.3 *Response Linearity*

Figure 13 shows example time histories of THOR chest acceleration. Note the rise in peak chest acceleration for each seat acceleration level (8 G-blue, 10 G-green, 12 G-red).

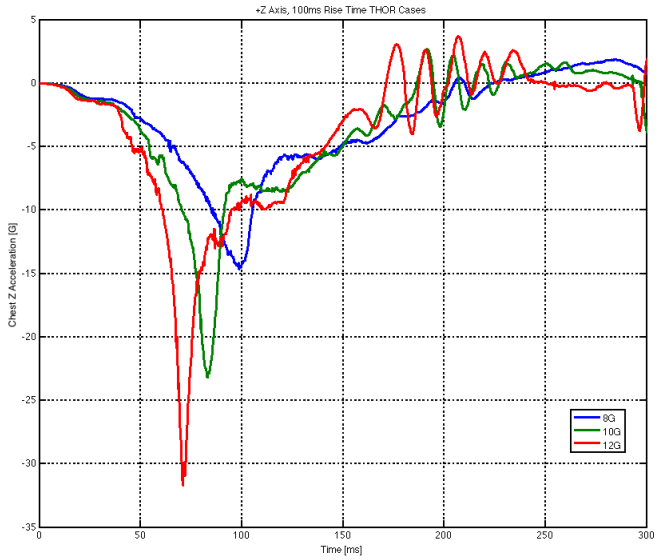



**Figure 13. Chest acceleration in Z axis for the THOR.**

Figure 14 shows peak head acceleration versus peak seat acceleration for each condition tested. Note that for head X acceleration, the THOR X tests show much higher responses at the 20-G seat level than at the lower-G levels (red symbols). Similar trends can be seen in the Y axis (green symbols) and Z axis (blue symbols). The Hybrid III responses were also included for comparison. Figures 15-18 show similar effects for the chest acceleration, pelvis acceleration, neck dynamics, and thoracic spinal force.

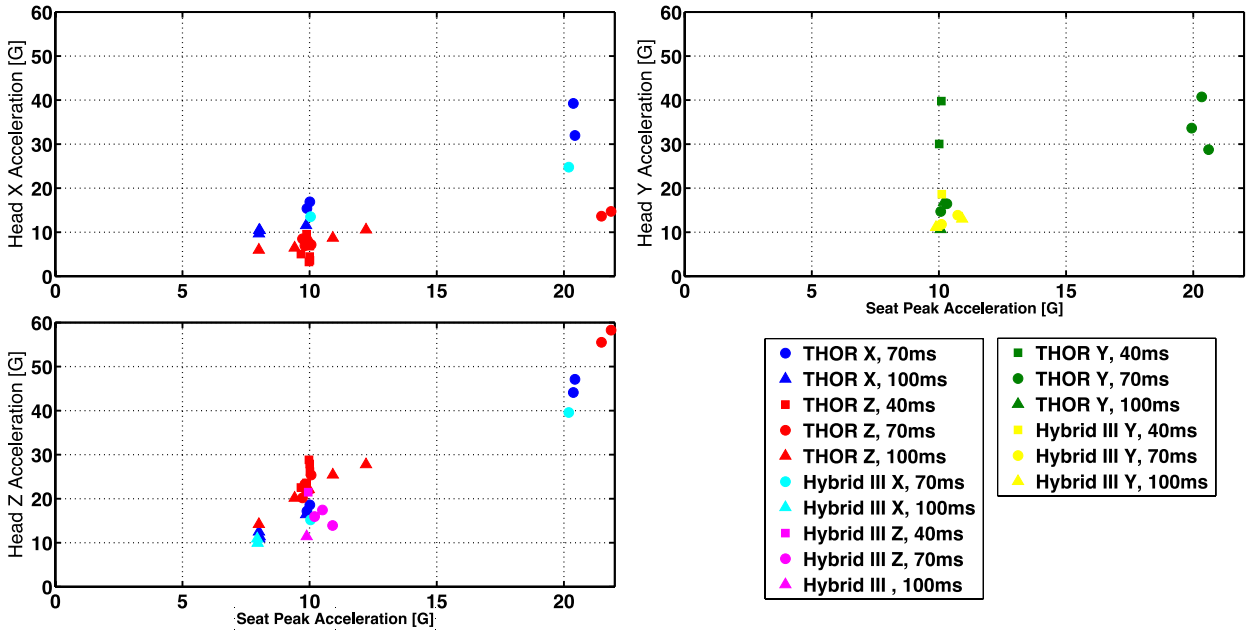



**Figure 14. Head acceleration.**

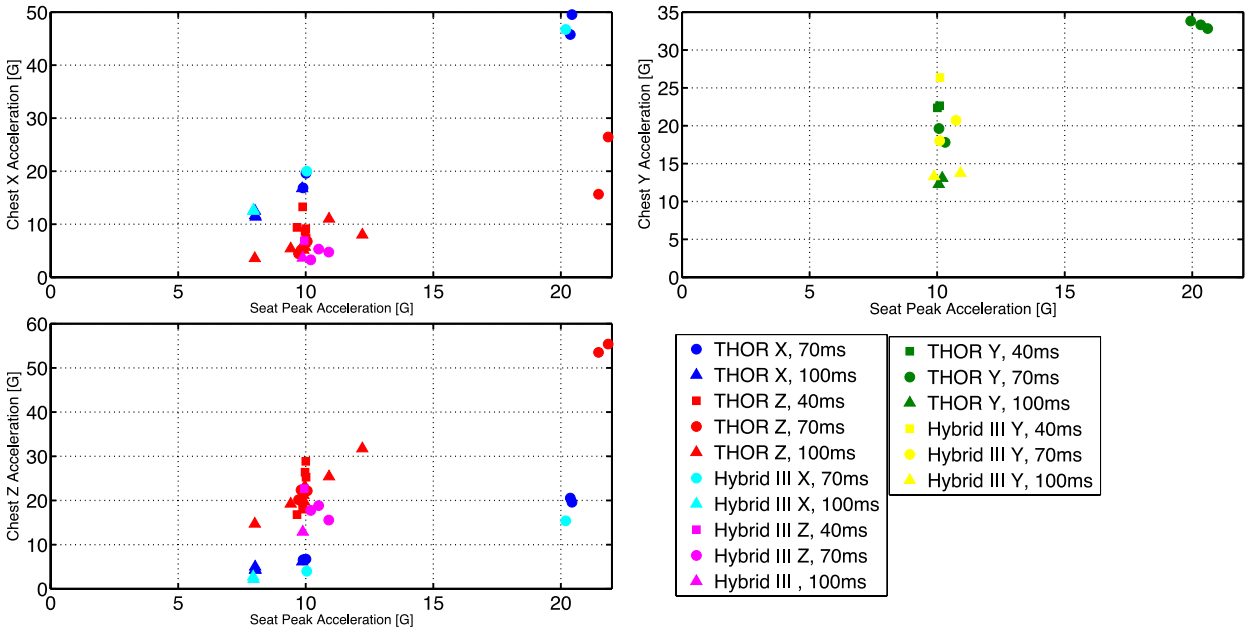



**Figure 15. Chest acceleration.**

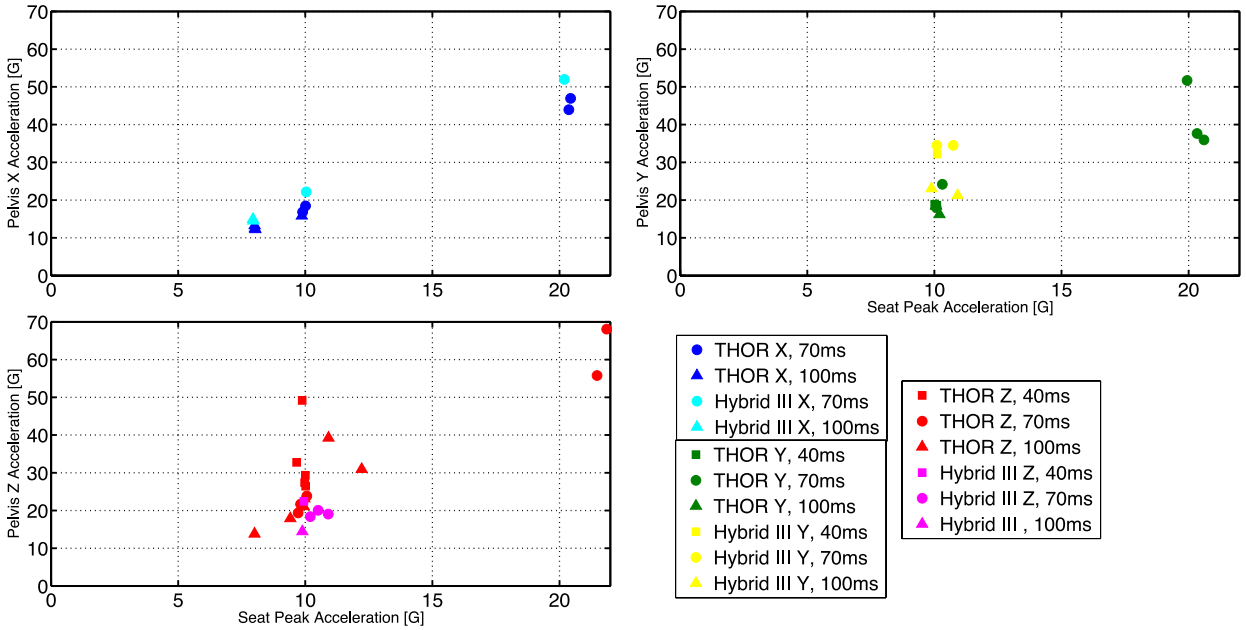



**Figure 16. Pelvis acceleration.**

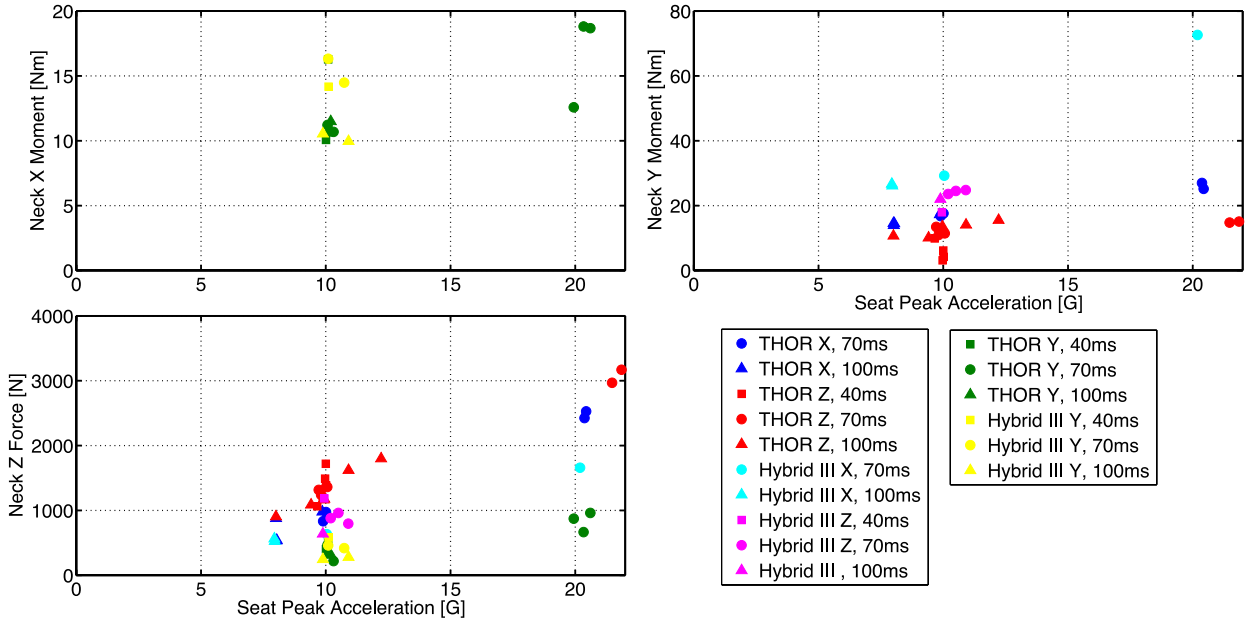



**Figure 17. Neck dynamics.**

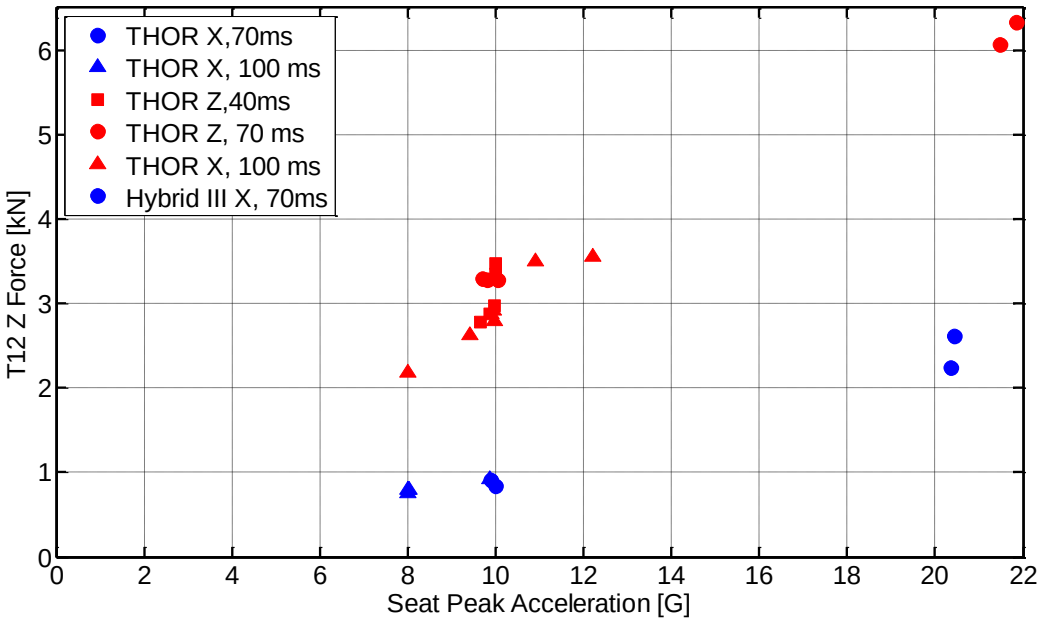



**Figure 18. Thoracic spine response.**

In addition, when comparing the thoracic spine axial force to the Dynamic Response Index (DRI), the response is highly linear. A preliminary comparison is shown between the THOR Mod Kit (THOR-K) and other ATD responses (Figure 19).

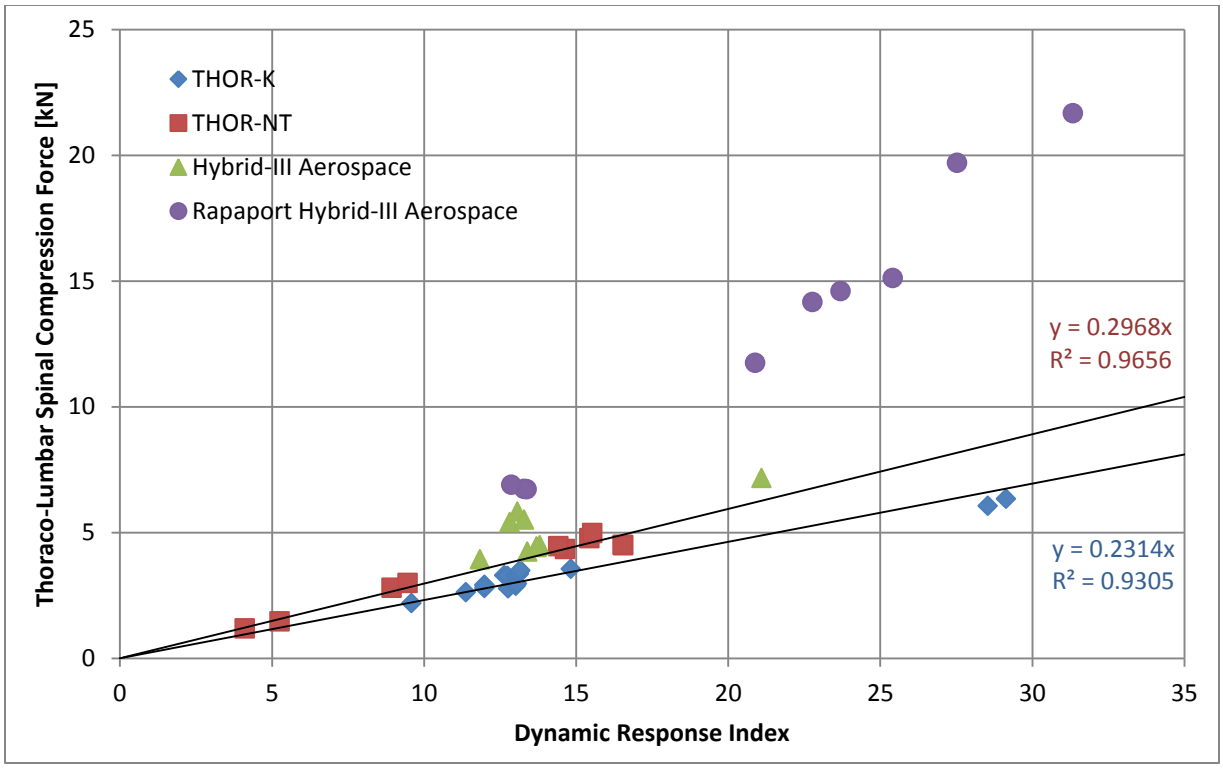



**Figure 19. THOR lumbar load comparison.**

## 5.2 Objective 2: Collect Validation Data for the THOR ATD Finite Element Model in Development

The THOR Finite Element (FE) model was developed initially by the University of Virginia for the NHTSA [8].

In parallel with the THOR ATD testing, updates were made to the THOR FE model to incorporate the modification kit. NASA, in particular, was responsible for updating the head and neck model and assessing the responses [9, 10].

Currently, an optimization of the model is being performed to match the FE-model responses to the physical ATD. Initial results are shown in Figure 20.

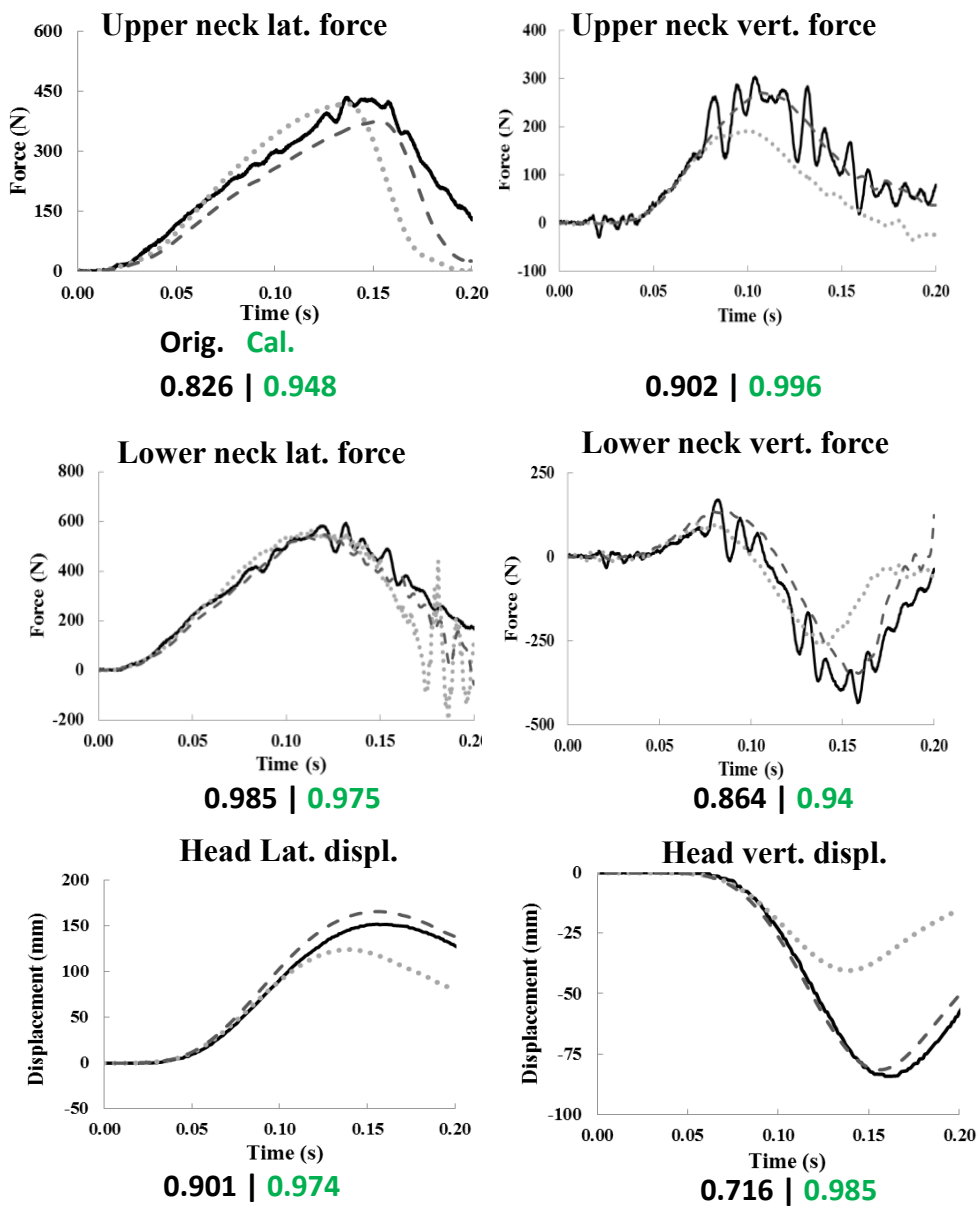



**Figure 20. Head and neck model optimization results.**

During evaluation of the entire THOR FE model, it was determined that the material properties for the pelvis flesh were too stiff (Figure 21). Revised material properties (Figure 22) were used to improve the FE-model response, particularly in the +Z axis loading cases.

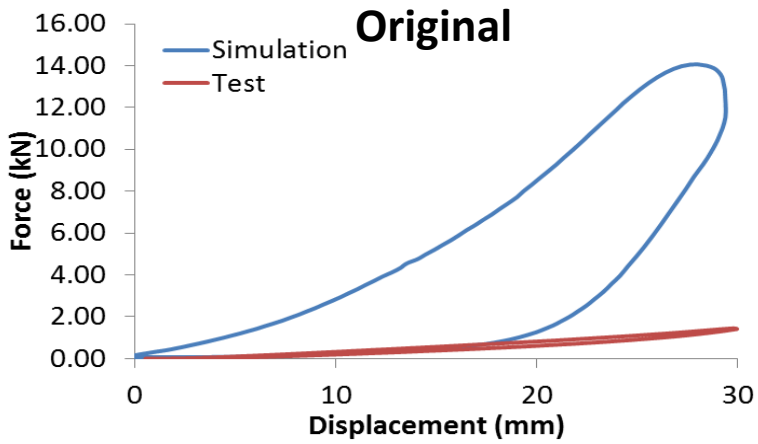



**Figure 21. Original FE model pelvis foam material properties.**

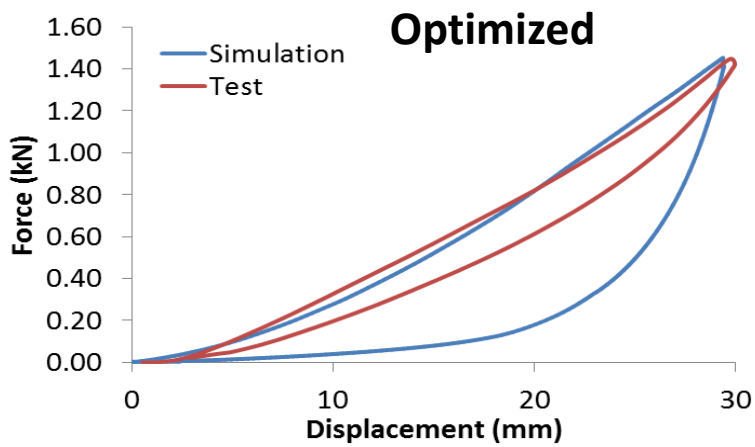



**Figure 22. Revised FE model pelvis foam material properties.**

Results from the revised model are currently being analyzed and will be published separately when completed.

## 5.3 Objective 3: Compare the THOR responses to historical human test data

A detailed comparison of the test data collected and historical human test data has been published recently [2]. The findings show that although the THOR was designed to be biofidelic in frontal impacts, the dynamics studied along with subject bracing resulted in poor correlation in many metrics.

## 5.4 Objective 4: Compare the THOR Responses to ATD Test Data Collected from Previous Test Regimes including Data Collected from the 50th Percentile Male Hybrid III Automotive ATD, the 50th Percentile Male Hybrid III Aerospace ATD, and the EuroSID2re 50th Percentile Male Side Impact Dummy

### 5.4.1 *THOR K and Hybrid III Aero*

Figure 23 compares the chest accelerations for the THOR-K and the Hybrid III. All seat pan accelerations were 10G and varied in rise time at 40, 70, and 100 ms. The THOR-K peak chest accelerations were predominately higher than Hybrid-III. Also notable, the Hybrid-III responded earlier to the impact relative to the THOR-K.

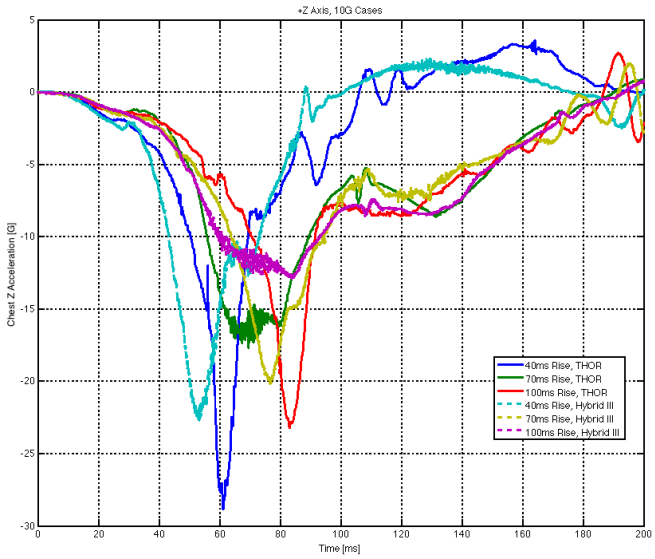



**Figure 23. Chest acceleration THOR versus Hybrid-III.**

### 5.4.2 *Lateral Comparison*

Figures 24-28 show a comparison of cases run in similar lateral conditions as the Automotive Hybrid III, Aerospace Hybrid III, and the EuroSID2re. The THOR responses are comparable to the other ATDs in most metrics. Additional metrics will be investigated to compare the lateral contact forces of the THOR with these ATDs.

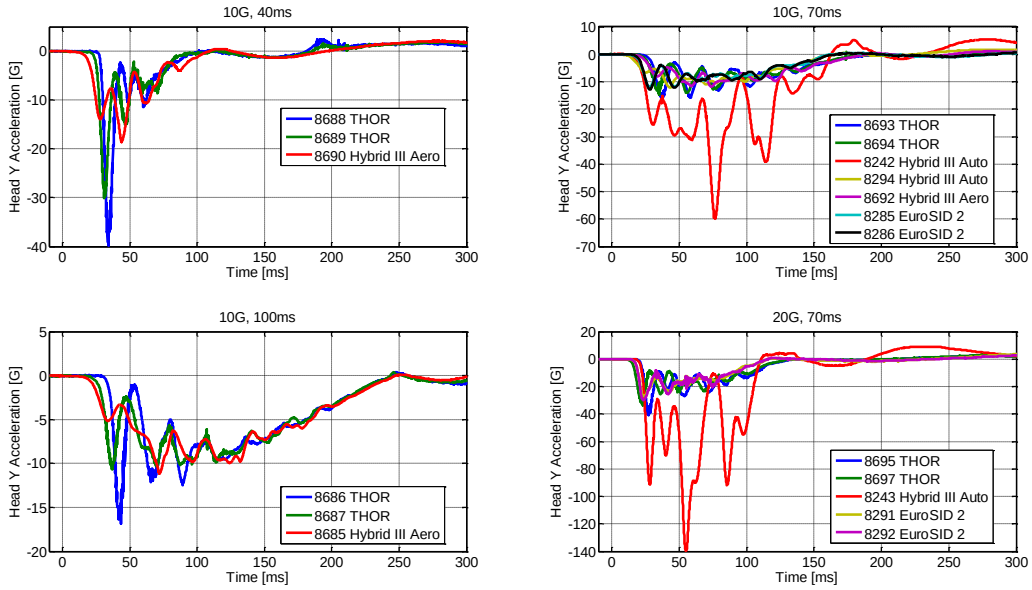



**Figure 24. Lateral head acceleration comparison.**

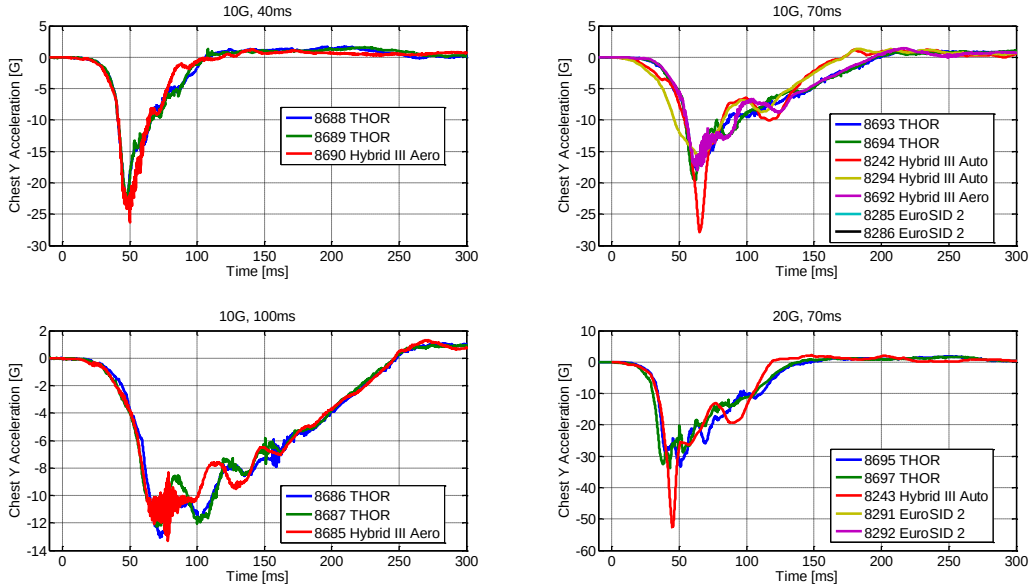



**Figure 25. Lateral chest acceleration comparison.**

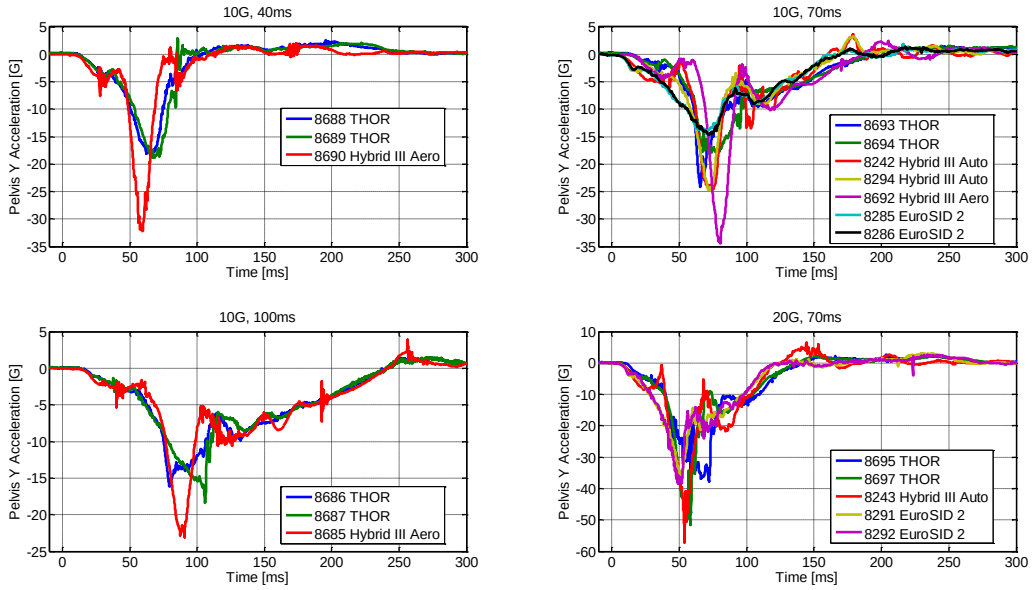



**Figure 26. Lateral pelvis acceleration comparison.**

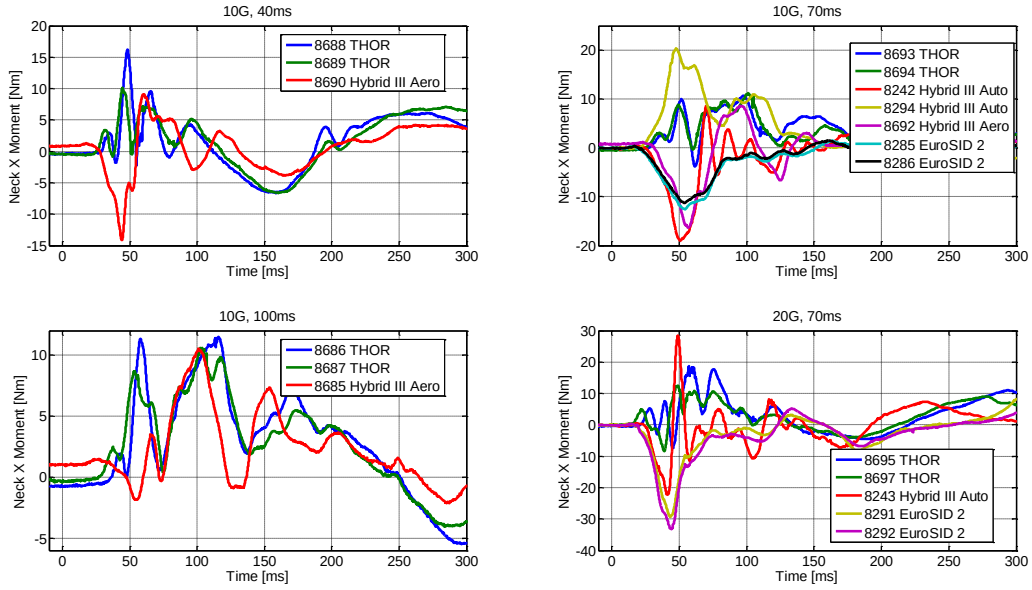



**Figure 27. Lateral neck moment comparison.**

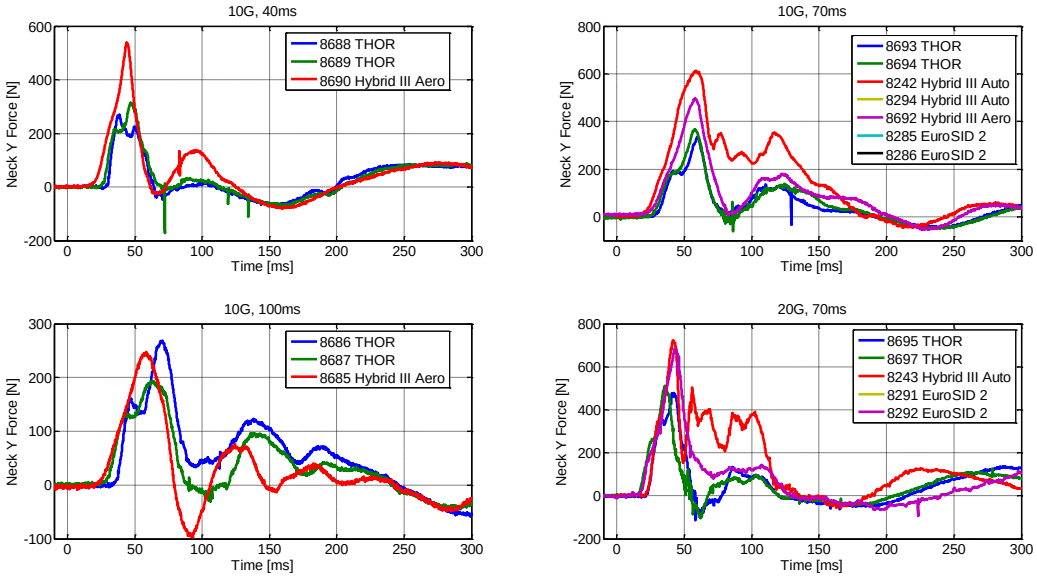



**Figure 28. Lateral neck shear force comparison.**

# 6.0 Specific Test Comments

After testing, it was determined that the THOR-K sustained damage that may impact some of the data collected. The following areas were shown with damage.

## 6.1 Head/Neck Mounting Platform

Upon post-testing inspection, a crack was found in the head/neck mounting platform (Figure 29). The crack is located where the rear cable attaches, but the crack did not propagate all the way across the part. Based on the initial inspection of the rear neck spring force, there does not appear to be any effect on the data (Figure 30).

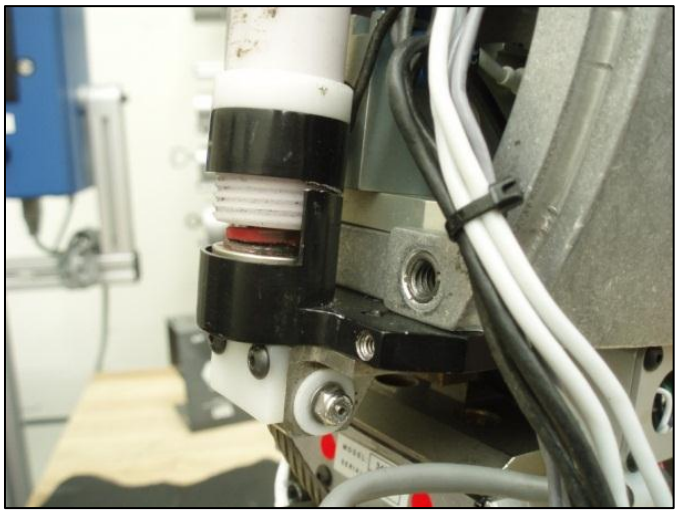


**Figure 29. Head/neck mounting platform damage.**

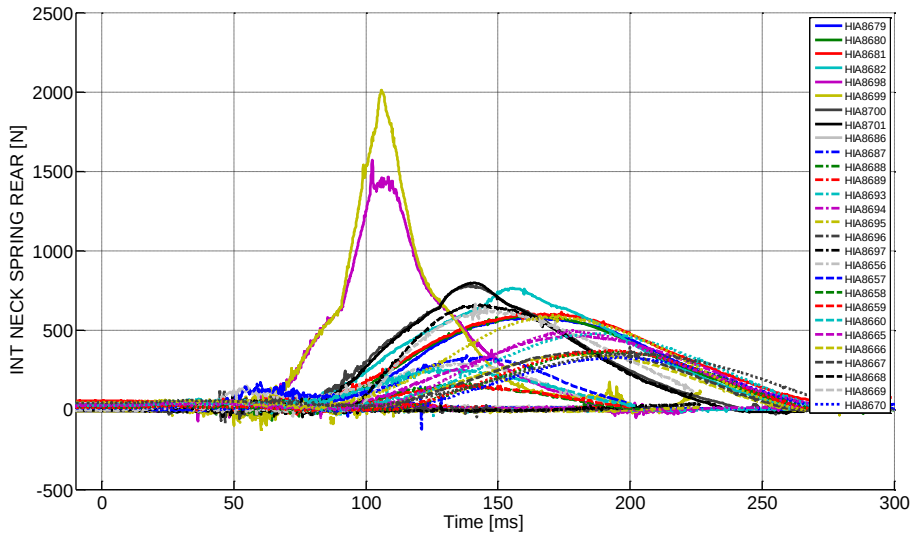



**Figure 30. THOR rear neck spring force in Newtons.**

## 6.2 Neck Cable Damage

Upon post-test inspection of the THOR-K, both neck cables were removed and damage was noted (Figure 16). Both cables showed signs of the braid untwisting and had permanent bends in the cables. It is unclear whether the current testing was the cause, but it is assumed as this damage wasn't noted previous to the testing. Based on the initial inspection of the rear and front neck spring force, there does not appear to be any effect on the data (Figures 31 and 32, respectively).

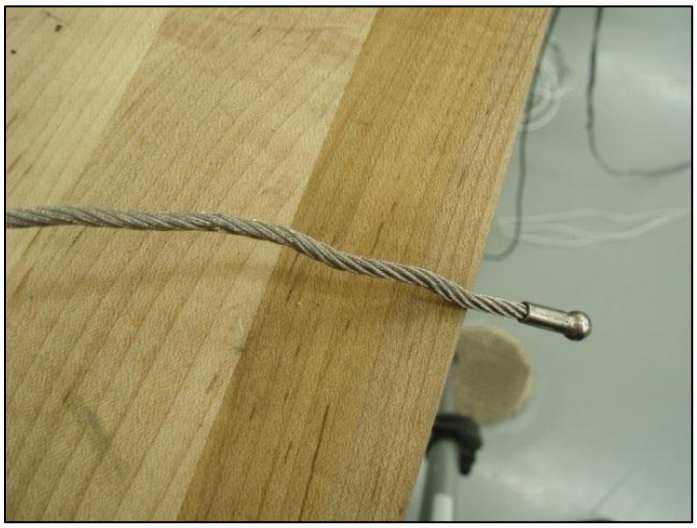


**Figure 31. Example THOR neck cable damage.**

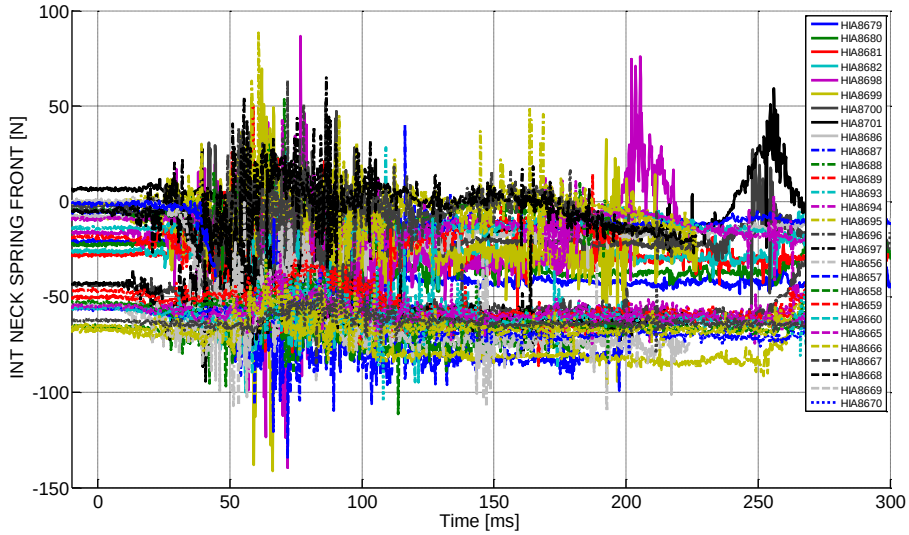



**Figure 32. THOR front neck spring force in Newtons.**

## 6.3 Lumbar Spine Damage

The lumbar spine rubber suffered cracks, as shown in Figure 33, which have been seen previously in other THORs. It is unclear whether the lateral testing was the cause. The spinal loading data (Figure 34) appear unaffected by the damage.

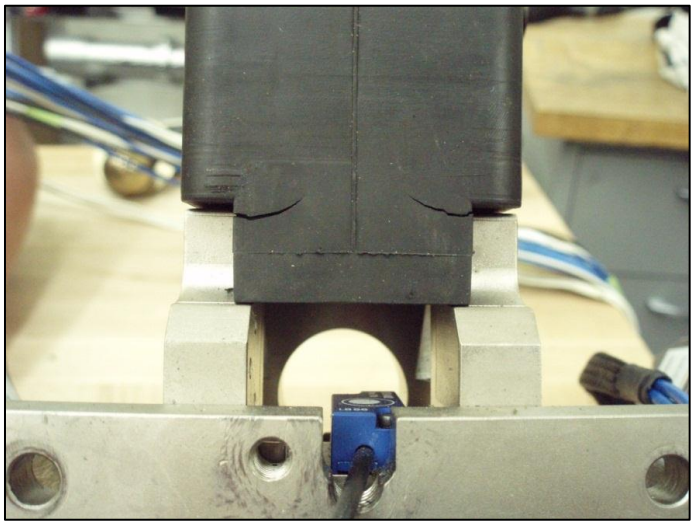


**Figure 33. Lumbar spine element damage.**

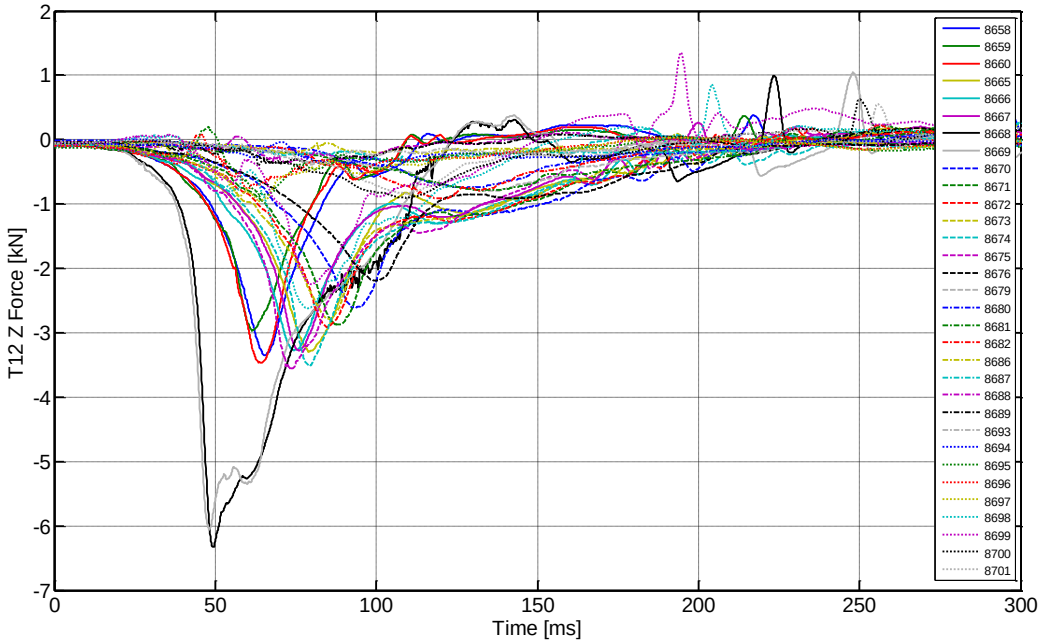



**Figure 34. Thoracic spine axial force.**

## 6.4 Aerospace Hybrid III Comments

The Aerospace Hybrid III also suffered a failure of the Head X accelerometer (Figure 35) during several of the tests (see Table 8). The sensor failed on the first Hybrid III run (8661) and then appears to function normally for runs 8662 and 8663. It then failed again, until it was repaired after run 8683. It functioned correctly for the remainder of the Hybrid III tests.

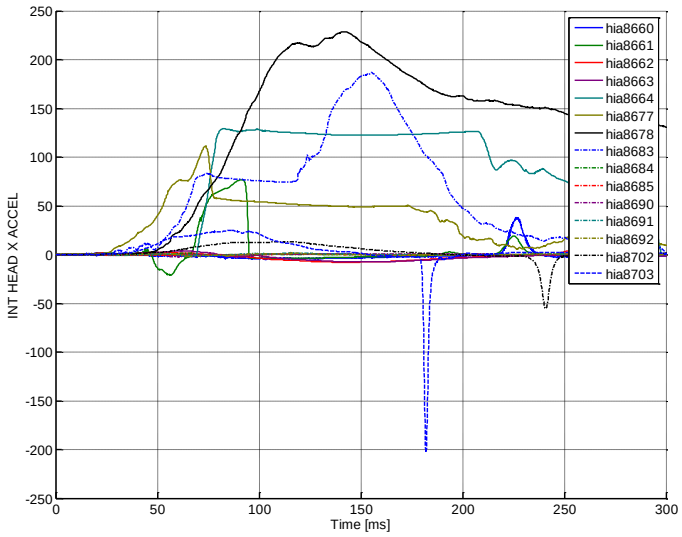



**Figure 35. Aerospace Hybrid III Head X acceleration comparison [G].**

## 6.5 General Comments

Any additional comments noted during testing are documented in Table 8.

**Table 8. Individual Test Run Comments**

| Test Run | Comment |
|---|---|
| *8656* | *Proof Testing. No belt loads or video* |
| *8657* | *Proof Testing. No belt loads or video* |
| *8658* | *Initial issues with scaling factors. Corrected post-test* |
| *8661* | *Head X Linear Accelerometer sensor failed* |
| *8662* | *Test pulse was too large, Head X accelerometer appears to function correctly* |
| *8663* | *Test pulse was too large, Head X accelerometer appears to function correctly* |
| *8664* | *Head X Linear Accelerometer sensor failed* |
| *8668* | *Test pulse was too large. Not rerun because comparison data were also collected as similar levels* |
| *8669* | *Test pulse was too large. Not rerun because comparison data were also collected as similar levels* |
| *8670* | *Test pulse was too low* |
| *8674* | *Test pulse was too low* |
| *8677* | *Head X Linear Accelerometer sensor failed* |
| *8678* | *Head X Linear Accelerometer sensor failed* |
| *8683* | *Head X Linear Accelerometer sensor failed* |
| *8684* | *Test pulse was too large* |
| *8691* | *Test pulse was too large* |
| *8692* | *Right hand not adequately restrained and came loose during run* |
| *8693* | *Left Ankle Y Rotational sensor data were suspect. Determined to be loose connector. Fixed before next run* |
| *8696* | *Test pulse was too large* |
| *8698* | *Right hand not adequately restrained and came loose during run* |
| *8699* | *Right leg not adequately restrained and kicked out during run* |

# 7.0 References


[1] Ridella S, Parent D. (2011). Modifications to improve durability, usability and biofidelity of the THOR-NTDummy. *Proceedings of the 22nd International ESV Conference, 11-0312*.

[2] Newby N, Somers J, Caldwell E, Perry C, Littell J, Gernhardt M. (2013). Assessing biofidelity of the test device for human occupant restraint (THOR) against historic human data. *Stapp Car Crash Journal,* vol. 56.

[3] Rangarajan N, Shams T, Artis M, Huang T, Haffner M, Eppinger R, Maltese M. (2000). Oblique and side impact performance on the THOR dummy. in *IRCOBI*, Montpellier, France, pp. 31-40.

[4] Pellettiere JA, Moorcroft D, Olivares G. (2011). Anthropomorphic test dummy lumbar load variability. *Proceedings of the 22nd International ESV Conference, 11-0157*.

[5] Shaffer JT. (1976). The impulse accelerator: an impact sled facility for human research and safety systems testing. Wright-Patterson AFB, OH: AeroMedical Research Laboratory, AMRL-TR-76-8.

[6] SAE International. (2007). Instrumentation for Impact Test - Part 1 - Electronic Instrumentation. Warrendale, PA: J211/1.

[7] The Mathworks. (2012). MATLAB, Vol. R2012b, Natick, MA.

[8] Untaroiu C, Lim YL, Shin J, Crandall J, Malone D, Tannous R. (2009). Evaluation of a finite element model of the THOR-NT dummy in frontal crash environment. In: *21st International Techincal Conference on the Enhanced Safety of Vehicles (09-0272)*, Stuttgart, Germany.

[9] Putnam J, Untaroiu C, Somers J. (2013). Development, validation and sensitivity analysis of a finite element model of THOR head-neck dummy. *Traffic Injury Prevention (In Review)*.

[10] Parent D. (2012). NHTSA THOR update. National High Traffic Safety Administration.


# 8.0 Appendices

All data shown have been scaled, transformed, and filtered per J211/1 standards.

Appendix A THOR Frontal Tests

Appendix B THOR Lateral Tests

Appendix C THOR Spinal Tests

Appendix D Aerospace Hybrid III Frontal Tests

Appendix E Aerospace Hybrid III Lateral Tests

Appendix F Aerospace Hybrid III Spinal Tests

# A. THOR Frontal Tests

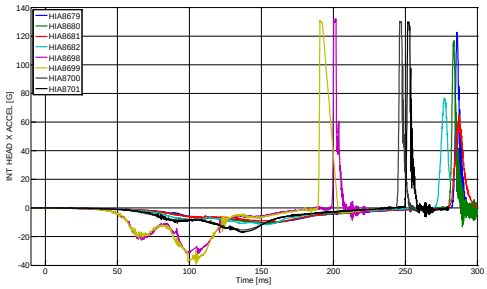



**Figure A-1. INT HEAD X ACCEL**

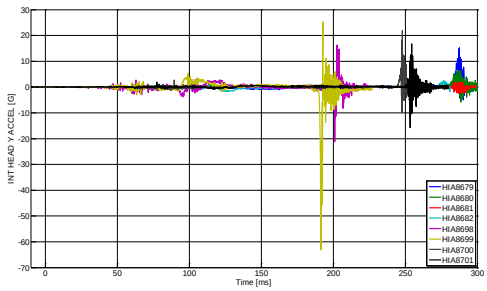



**Figure A-2. INT HEAD Y ACCEL**

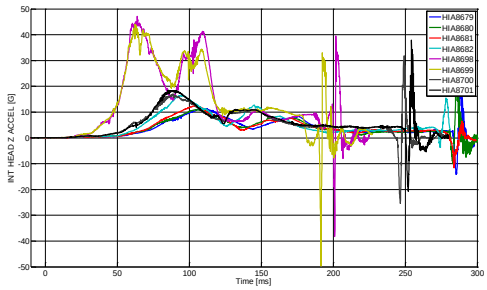



**Figure A-3. INT HEAD Z ACCEL**

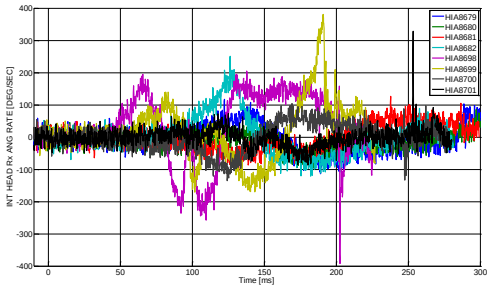



**Figure A-4. INT HEAD Rx ANG RATE**

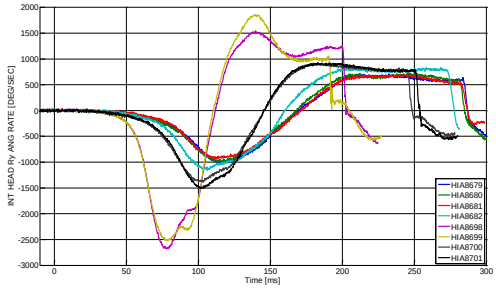



**Figure A-5. INT HEAD Ry ANG RATE**

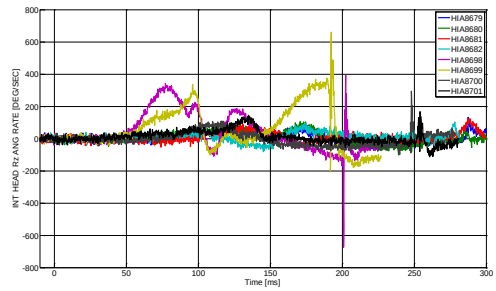



**Figure A-6. INT HEAD Rz ANG RATE**

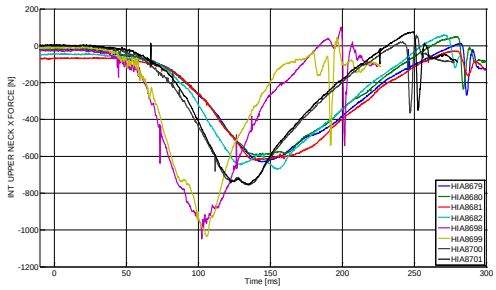



**Figure A-7. INT UPPER NECK X FORCE**

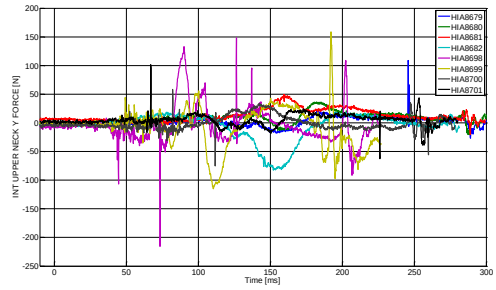



**Figure A-8. INT UPPER NECK Y FORCE**

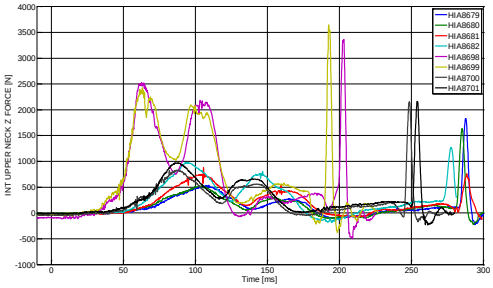



**Figure A-9. INT UPPER NECK Z FORCE**

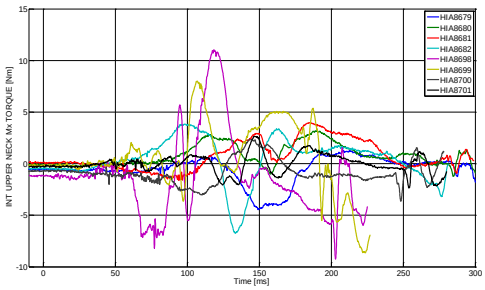



**Figure A-10. INT UPPER NECK Mx TORQUE**

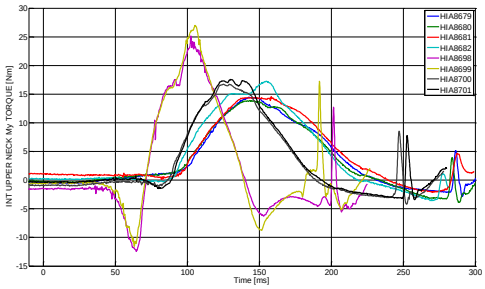



**Figure A-11. INT UPPER NECK My TORQUE**

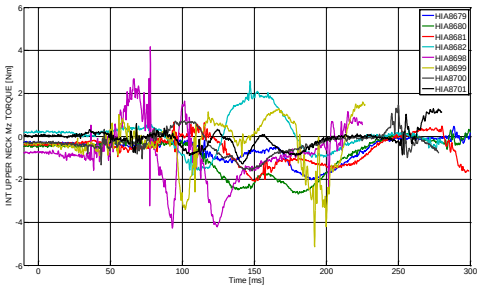



**Figure A-12. INT UPPER NECK Mz TORQUE**

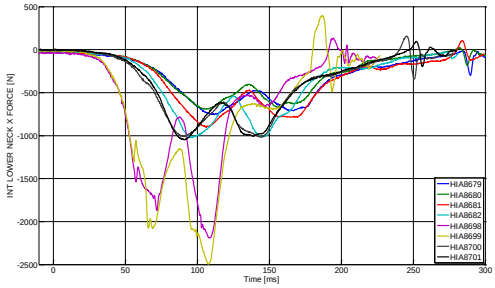



**Figure A-13. INT LOWER NECK X FORCE**

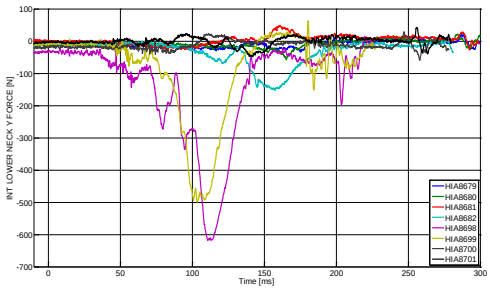



**Figure A-14. INT LOWER NECK Y FORCE**

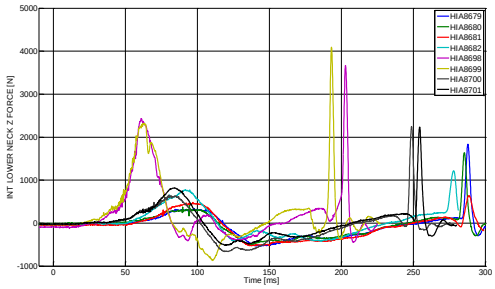



**Figure A-15. INT LOWER NECK Z FORCE**

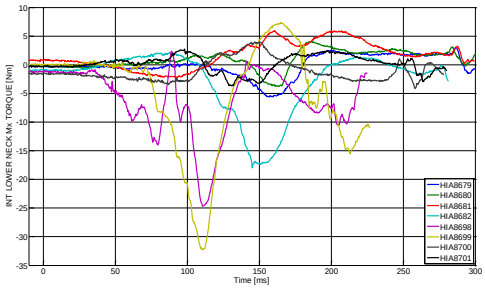



**Figure A-16. INT LOWER NECK Mx TORQUE**

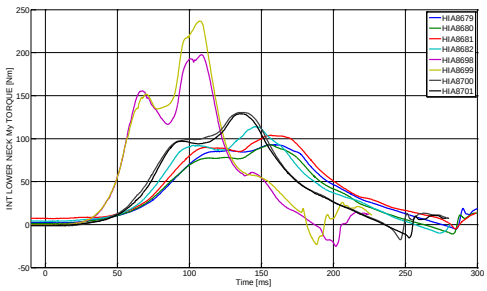



**Figure A-17. INT LOWER NECK My TORQUE**

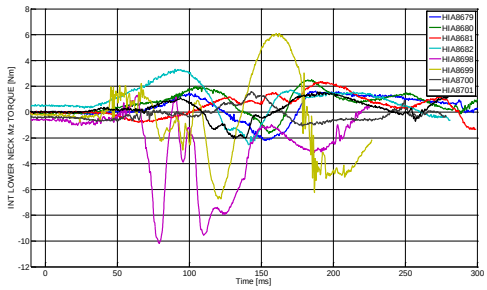



**Figure A-18. INT LOWER NECK Mz TORQUE**

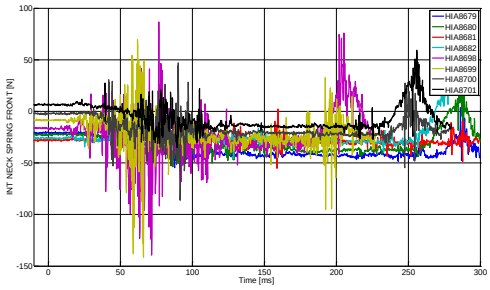



**Figure A-19. INT NECK SPRING FRONT**

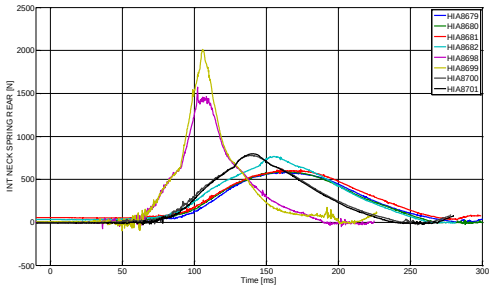



**Figure A-20. INT NECK SPRING REAR**

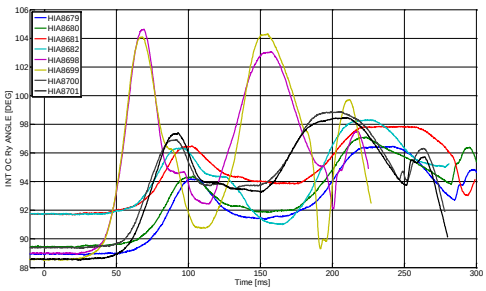



**Figure A-21. INT OC Ry ANGLE**

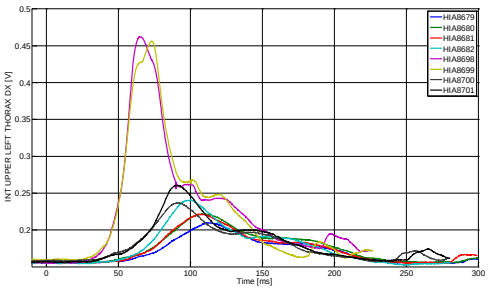



**Figure A-22. INT UPPER LEFT THORAX DX**

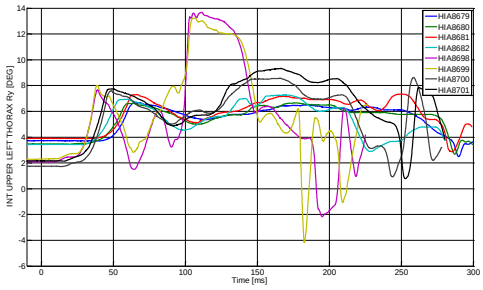



**Figure A-23. INT UPPER LEFT THORAX Ry**

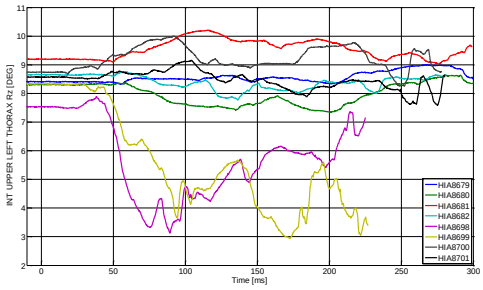



**Figure A-24. INT UPPER LEFT THORAX Rz**

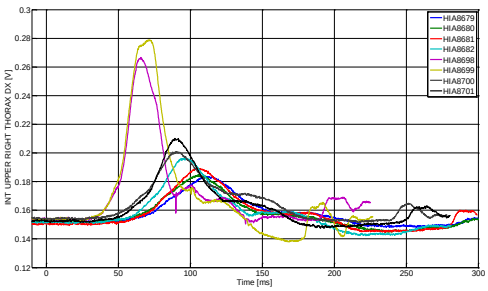



**Figure A-25. INT UPPER RIGHT THORAX DX**

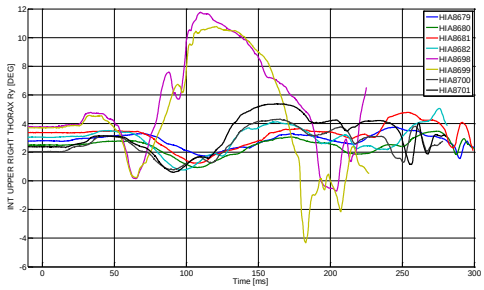



**Figure A-26. INT UPPER RIGHT THORAX Ry**

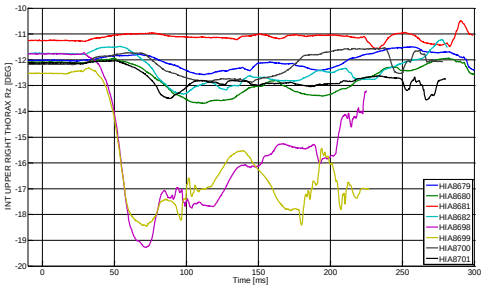



**Figure A-27. INT UPPER RIGHT THORAX Rz**

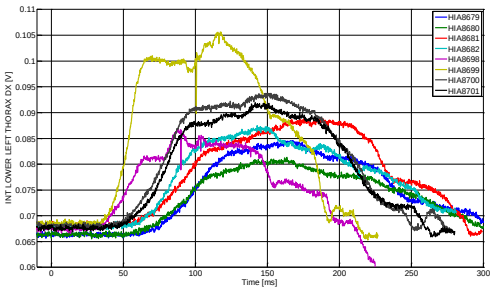



**Figure A-28. INT LOWER LEFT THORAX DX**

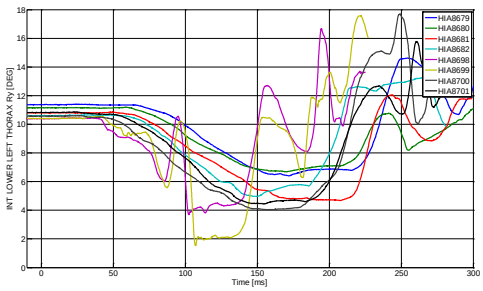



**Figure A-29. INT LOWER LEFT THORAX Ry**

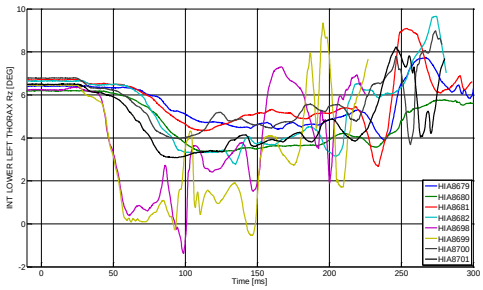



**Figure A-30. INT LOWER LEFT THORAX Rz**

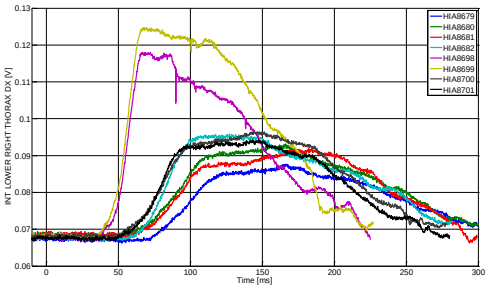



**Figure A-31. INT LOWER RIGHT THORAX DX**

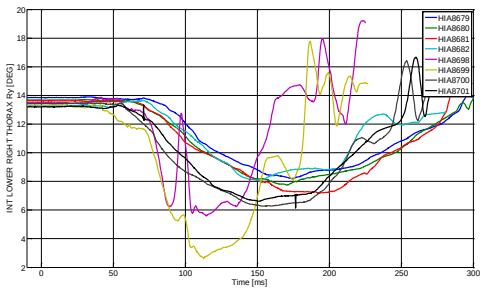



**Figure A-32. INT LOWER RIGHT THORAX Ry**

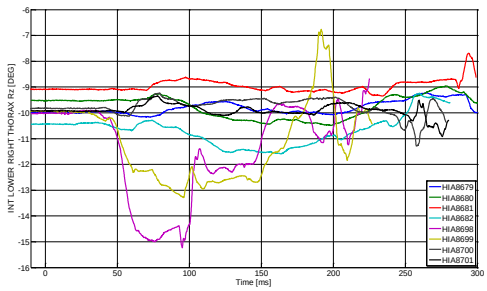



**Figure A-33. INT LOWER RIGHT THORAX Rz**

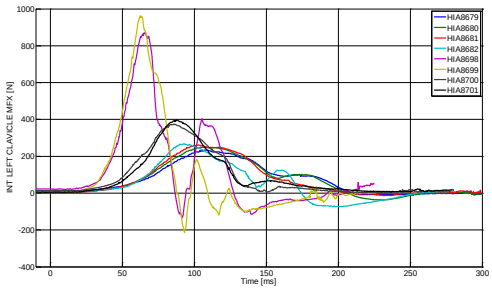



**Figure A-34. INT LEFT CLAVICLE MFX**

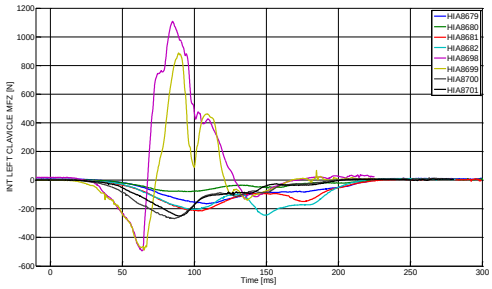



**Figure A-35. INT LEFT CLAVICLE MFZ**

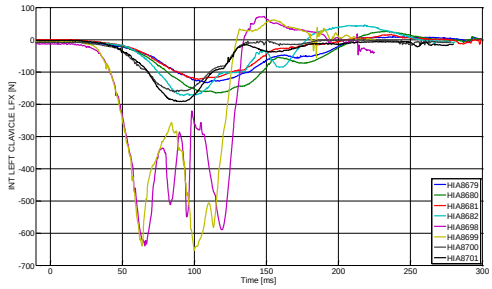



**Figure A-36. INT LEFT CLAVICLE LFX**

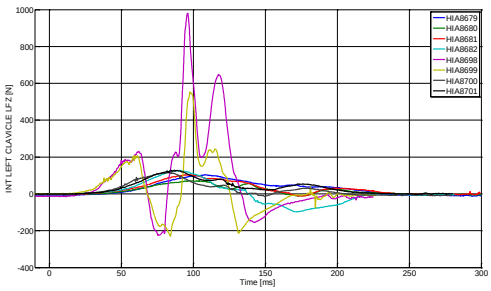



**Figure A-37. INT LEFT CLAVICLE LFZ**

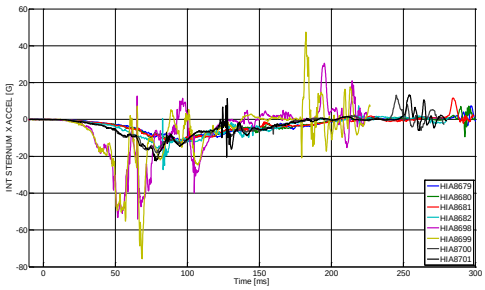



**Figure A-38. INT STERNUM X ACCEL**

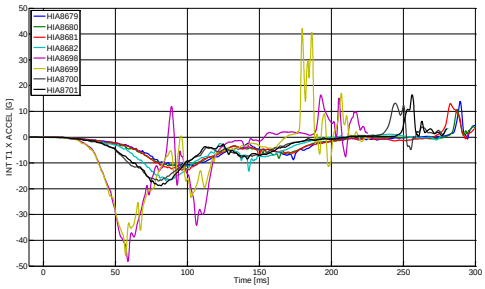



**Figure A-39. INT T1 X ACCEL**

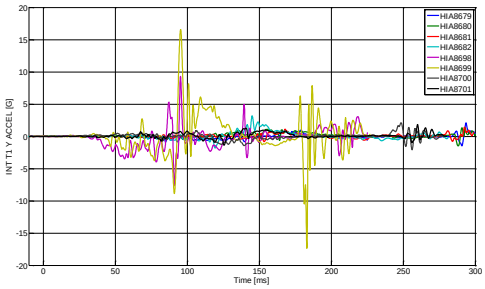



**Figure A-40. INT T1 Y ACCEL**

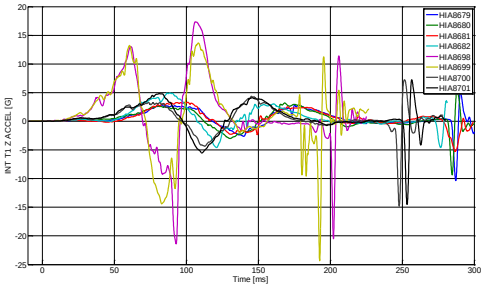



**Figure A-41. INT T1 Z ACCEL**

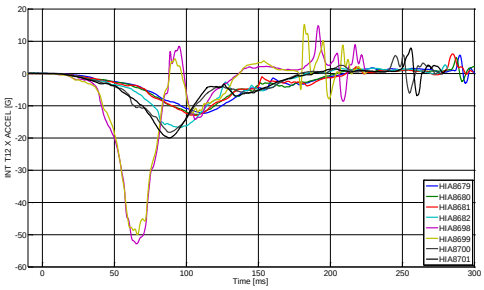



**Figure A-42. INT T12 X ACCEL**

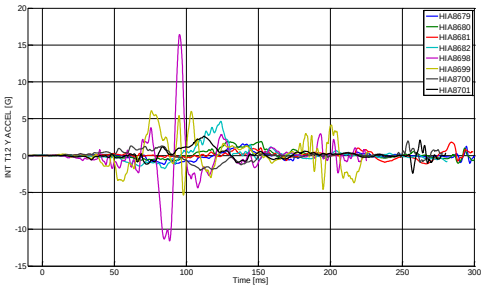



**Figure A-43. INT T12 Y ACCEL**

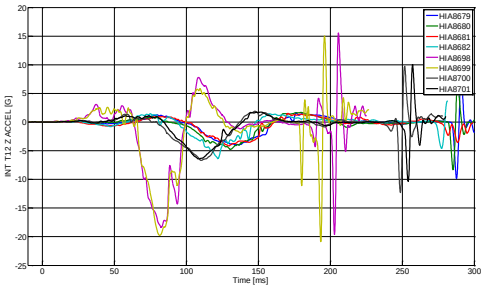



**Figure A-44. INT T12 Z ACCEL**

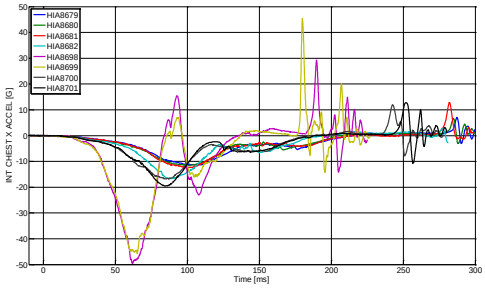



**Figure A-45. INT CHEST X ACCEL**

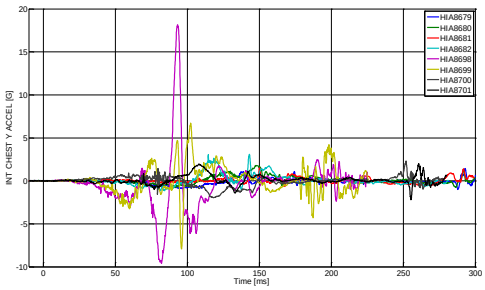



**Figure A-46. INT CHEST Y ACCEL**

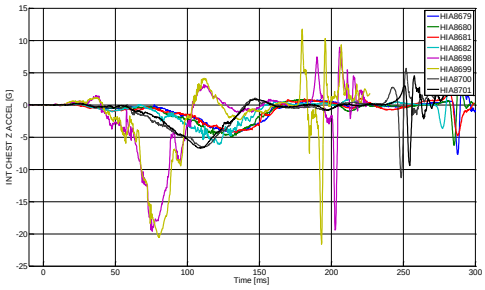



**Figure A-47. INT CHEST Z ACCEL**

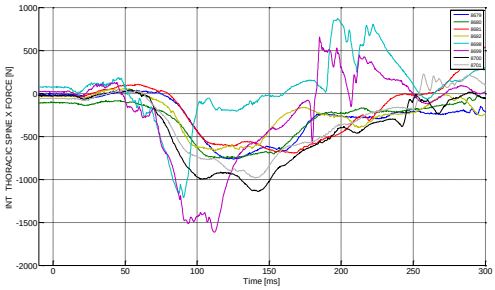



**Figure A-48. INT THORACIC SPINE X FORCE**

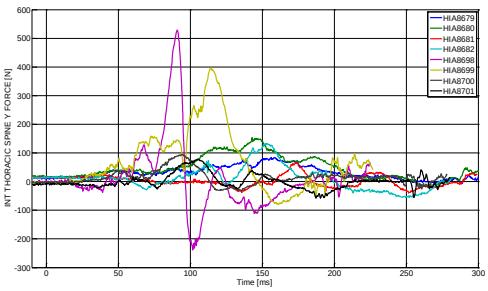



**Figure A-49. INT THORACIC SPINE Y FORCE**

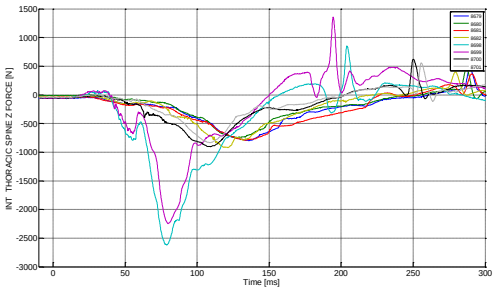



**Figure A-50. INT THORACIC SPINE Z FORCE**

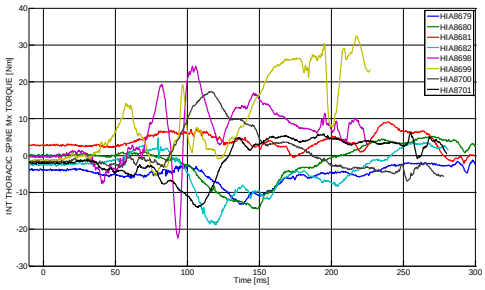



**Figure A-51. INT THORACIC SPINE Mx TORQUE**

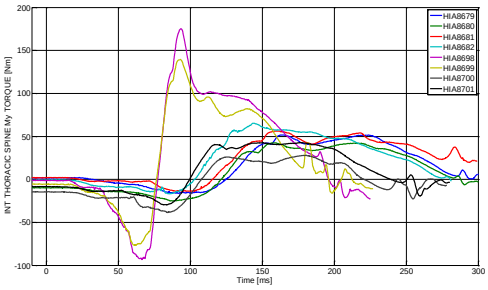



**Figure A-52. INT THORACIC SPINE My TORQUE**

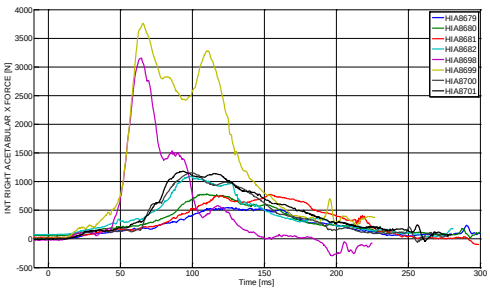



**Figure A-53. INT RIGHT ACETABULAR X FORCE**

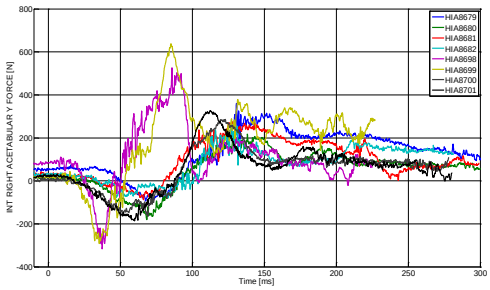



**Figure A-54. INT RIGHT ACETABULAR Y FORCE**

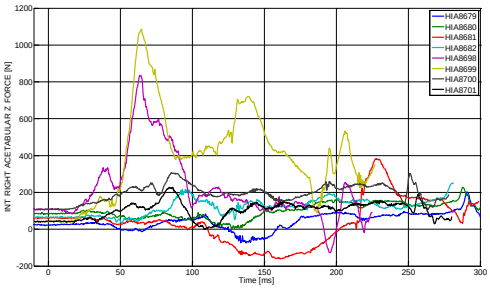



**Figure A-55. INT RIGHT ACETABULAR Z FORCE**

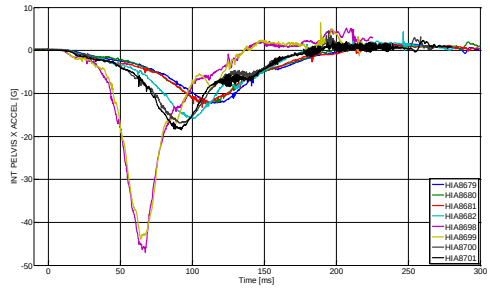



**Figure A-56. INT PELVIS X ACCEL**

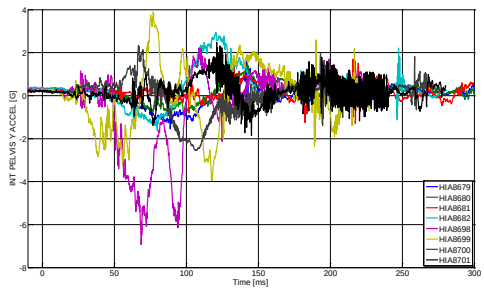



**Figure A-57. INT PELVIS Y ACCEL**

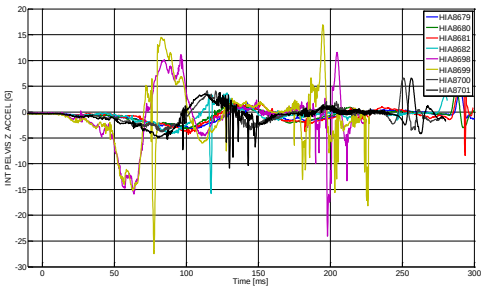



**Figure A-58. INT PELVIS Z ACCEL**

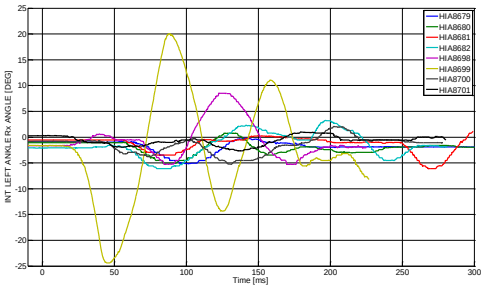



**Figure A-59. INT LEFT ANKLE Rx ANGLE**

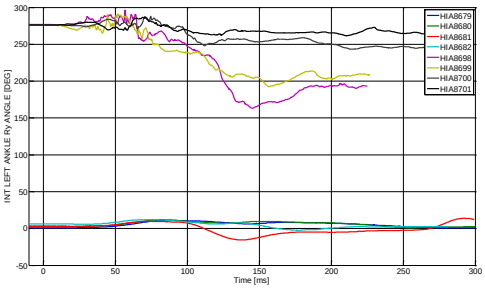



**Figure A-60. INT LEFT ANKLE Ry ANGLE**

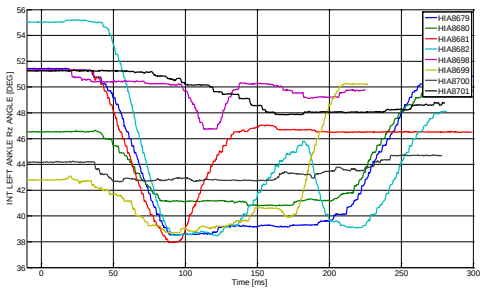



**Figure A-61. INT LEFT ANKLE Rz ANGLE**

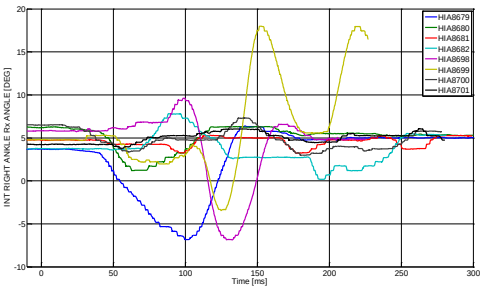



**Figure A-62. INT RIGHT ANKLE Rx ANGLE**

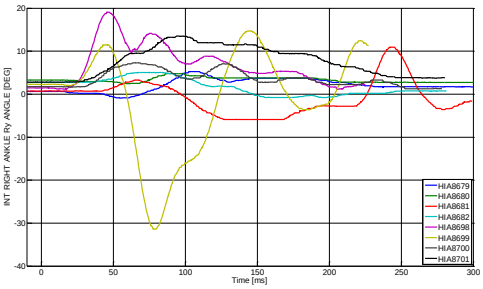



**Figure A-63. INT RIGHT ANKLE Ry ANGLE**

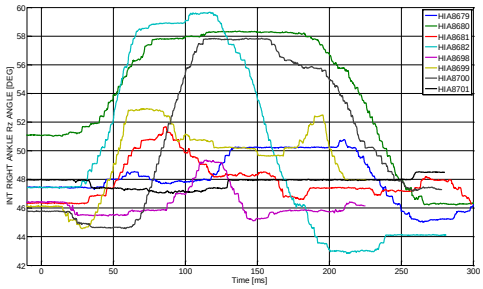



**Figure A-64. INT RIGHT ANKLE Rz ANGLE**

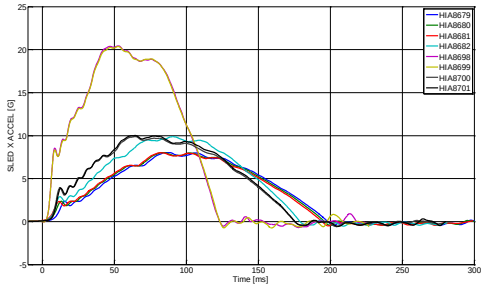



**Figure A-65. SLED X ACCEL**

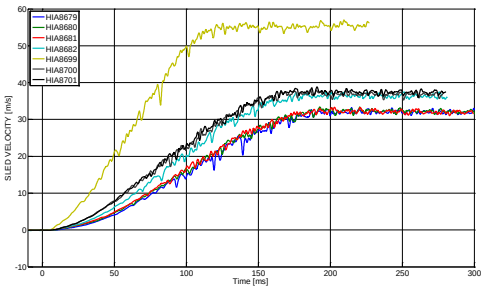



**Figure A-66. SLED VELOCITY**

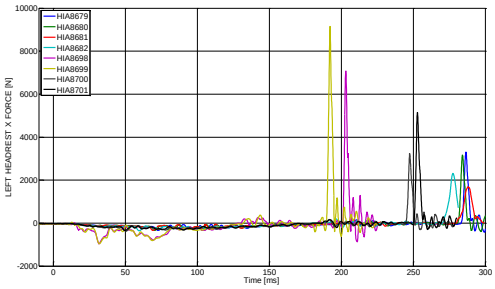



**Figure A-67. LEFT HEADREST X FORCE**

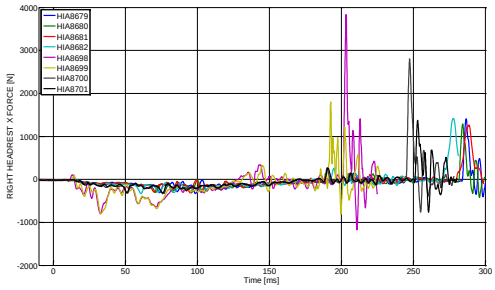



**Figure A-68. RIGHT HEADREST X FORCE**

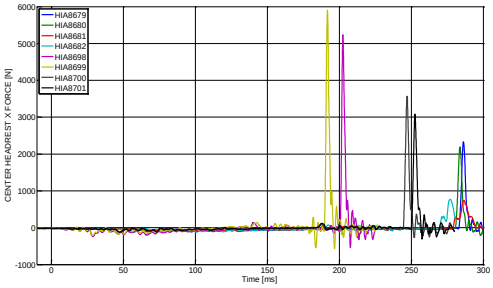



**Figure A-69. CENTER HEADREST X FORCE**

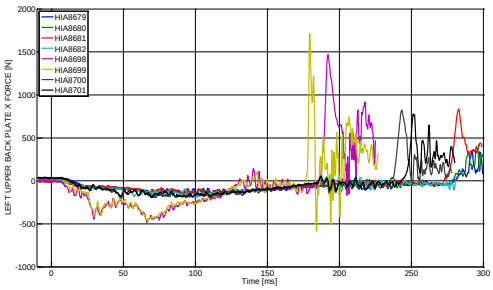



**Figure A-70. LEFT UPPER BACK PLATE X FORCE**

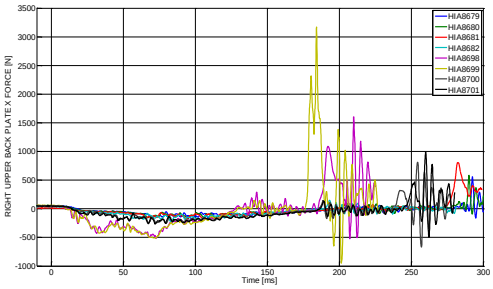



**Figure A-71. RIGHT UPPER BACK PLATE X FORCE**

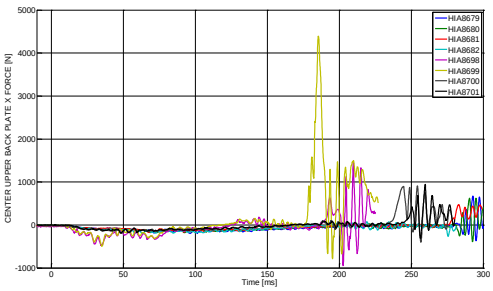



**Figure A-72. CENTER UPPER BACK PLATE X FORCE**

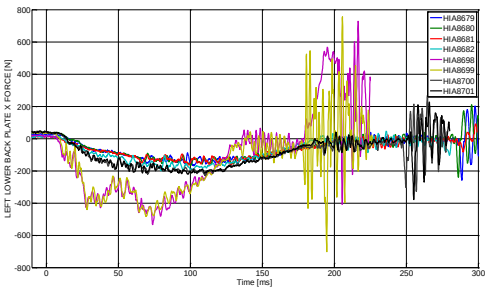



**Figure A-73. LEFT LOWER BACK PLATE X FORCE**

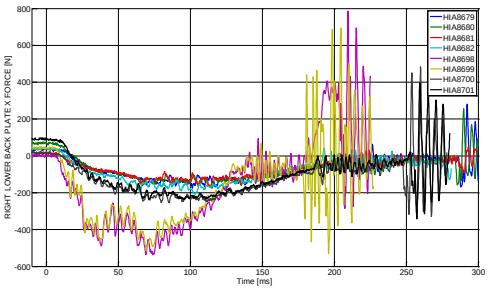



**Figure A-74. RIGHT LOWER BACK PLATE X FORCE**

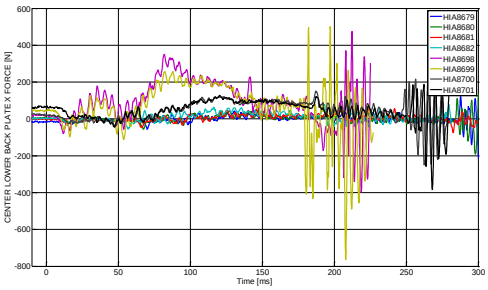



**Figure A-75. CENTER LOWER BACK PLATE X FORCE**

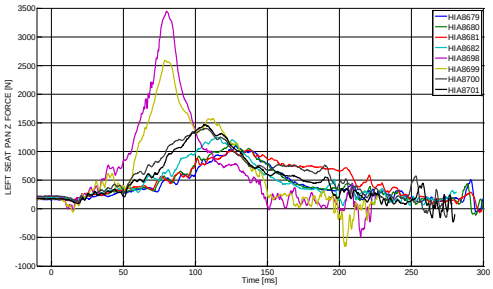



**Figure A-76. LEFT SEAT PAN Z FORCE**

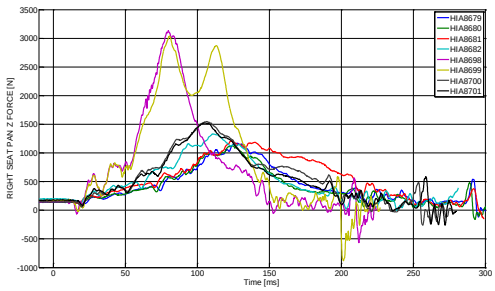



**Figure A-77. RIGHT SEAT PAN Z FORCE**

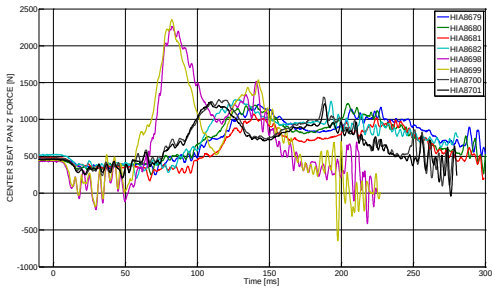



**Figure A-78. CENTER SEAT PAN Z FORCE**

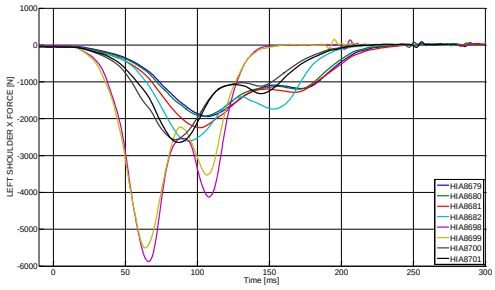



**Figure A-79. LEFT SHOULDER X FORCE**

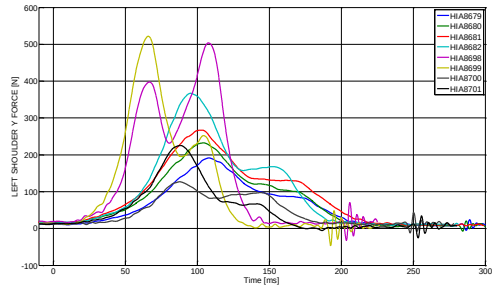



**Figure A-80. LEFT SHOULDER Y FORCE**

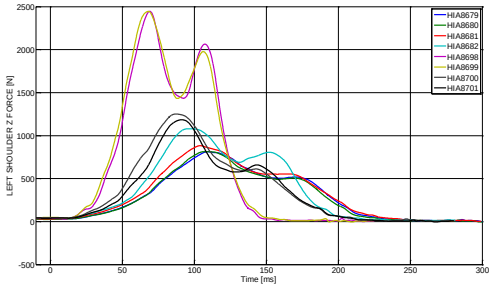



**Figure A-81. LEFT SHOULDER Z FORCE**

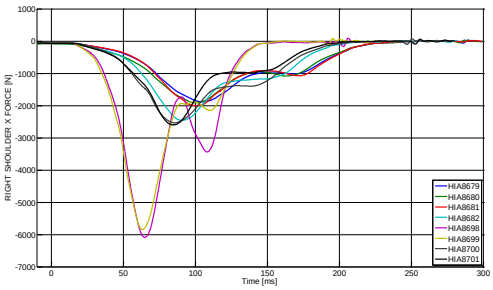



**Figure A-82. RIGHT SHOULDER X FORCE**

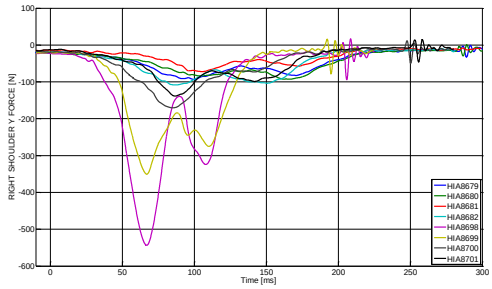



**Figure A-83. RIGHT SHOULDER Y FORCE**

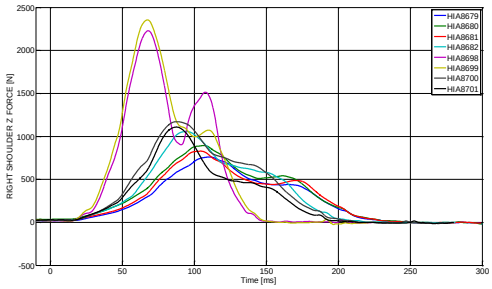



**Figure A-84. RIGHT SHOULDER Z FORCE**

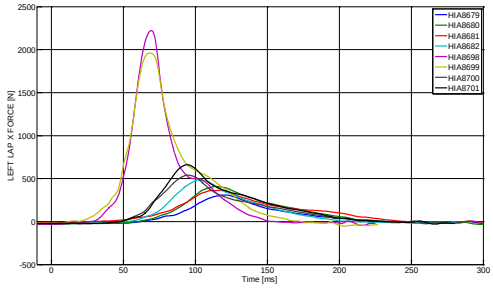



**Figure A-85. LEFT LAP X FORCE**

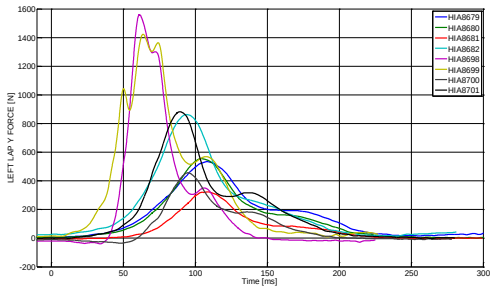



**Figure A-86. LEFT LAP Y FORCE**

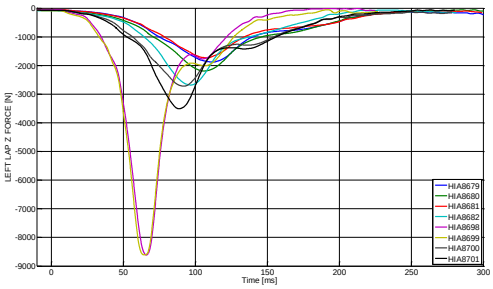



**Figure A-87. LEFT LAP Z FORCE**

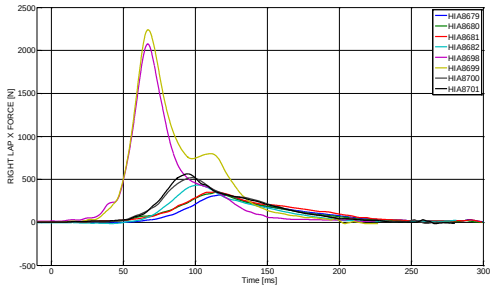



**Figure A-88. RIGHT LAP X FORCE**

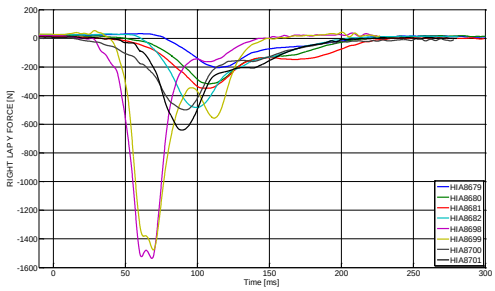



**Figure A-89. RIGHT LAP Y FORCE**

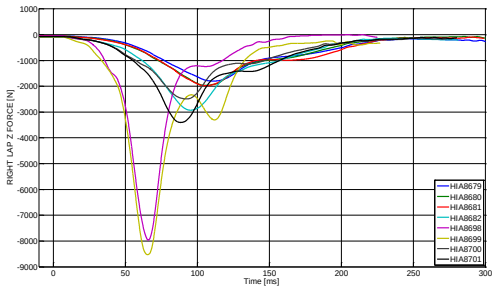



**Figure A-90. RIGHT LAP Z FORCE**

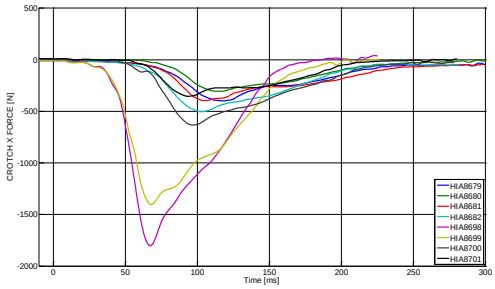



**Figure A-91. CROTCH X FORCE**

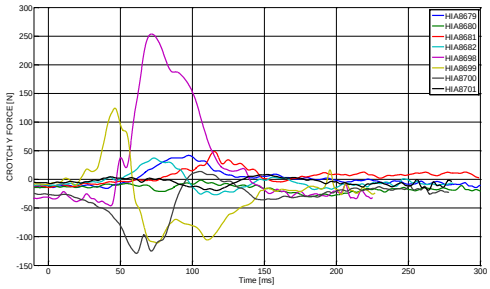



**Figure A-92. CROTCH Y FORCE**

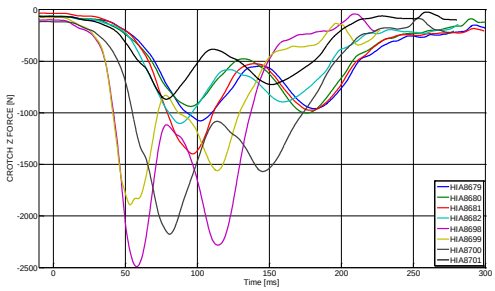



**Figure A-93. CROTCH Z FORCE**

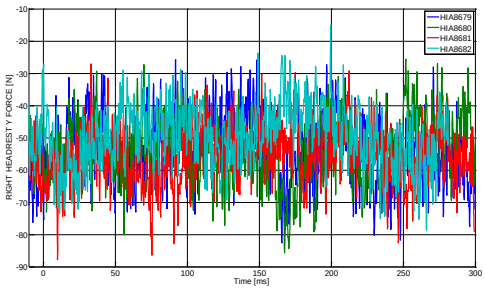



**Figure A-94. RIGHT HEADREST Y FORCE**

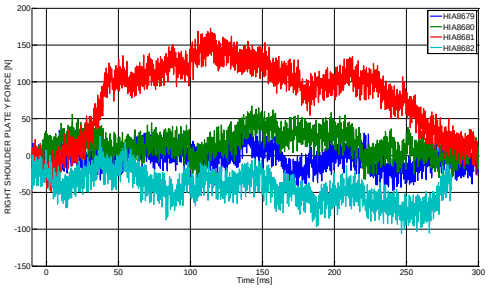



**Figure A-95. RIGHT SHOULDER PLATE Y FORCE**

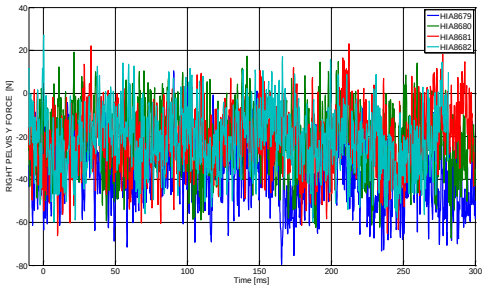



**Figure A-96. RIGHT PELVIS Y FORCE**

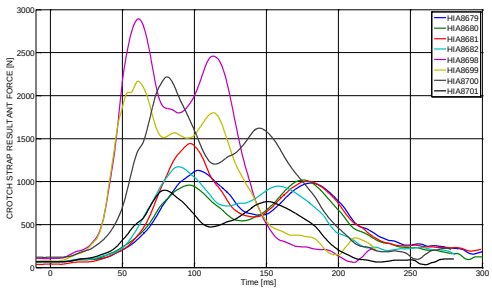



**Figure A-97. CROTCH STRAP RESULTANT FORCE**

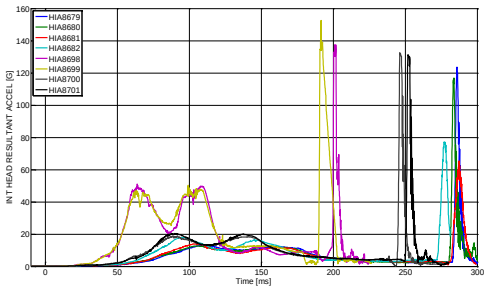



**Figure A-98. INT HEAD RESULTANT ACCEL**

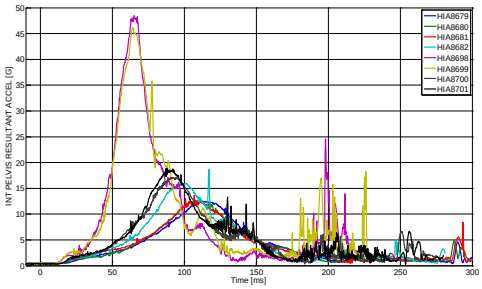



**Figure A-99. INT PELVIS RESULTANT ACCEL**

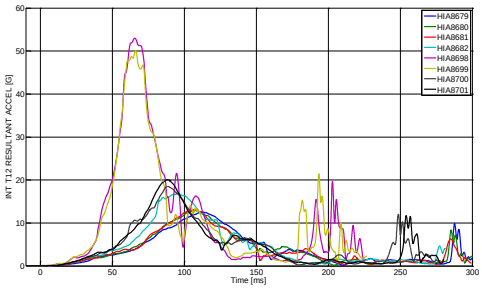



**Figure A-100. INT T12 RESULTANT ACCEL**

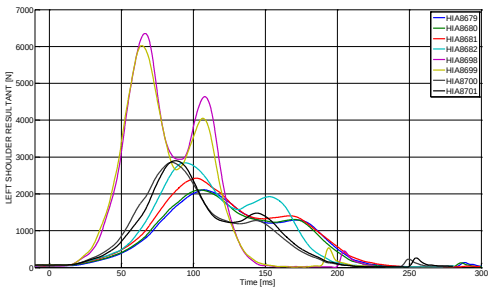



**Figure A-101. LEFT SHOULDER RESULTANT**

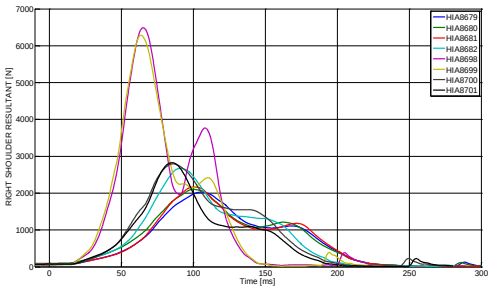



**Figure A-102. RIGHT SHOULDER RESULTANT**

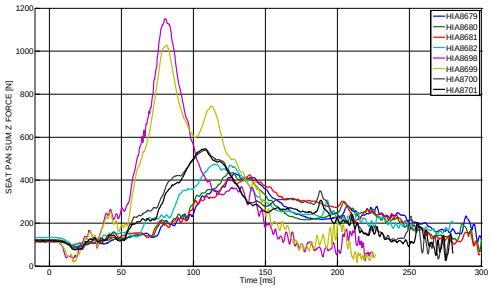



**Figure A-103. SEAT PAN SUM Z FORCE**

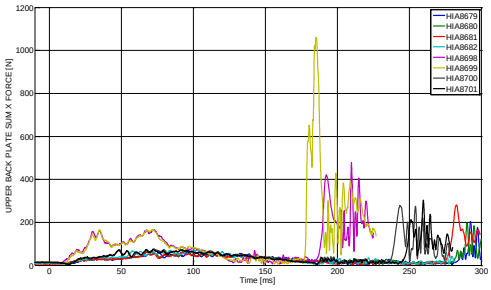



**Figure A-104. UPPER BACK PLATE SUM X FORCE**

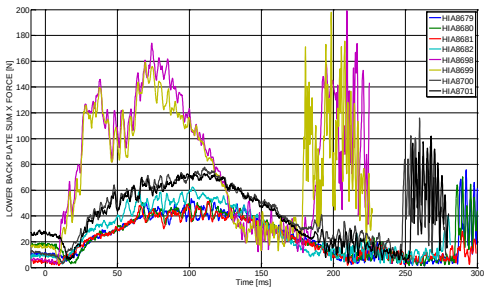



**Figure A-105. LOWER BACK PLATE SUM X FORCE**

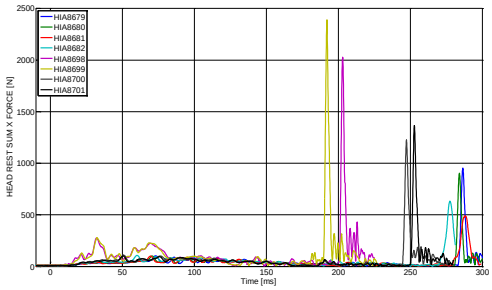



**Figure A-106. HEAD REST SUM X FORCE**

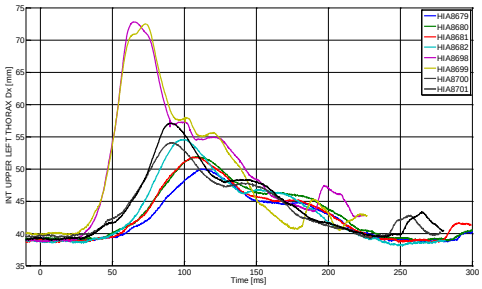



**Figure A-107. INT UPPER LEFT THORAX Dx**

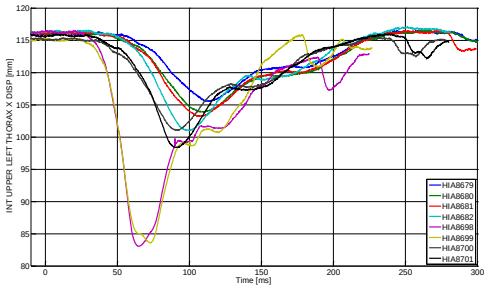



**Figure A-108. INT UPPER LEFT THORAX X DISP**

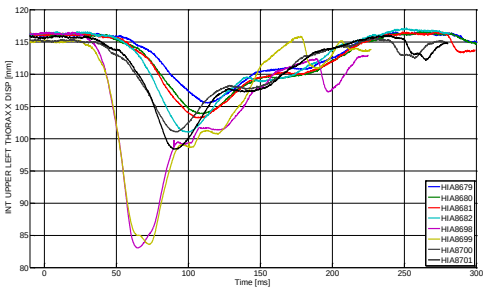



**Figure A-109. INT UPPER LEFT THORAX X DISP**

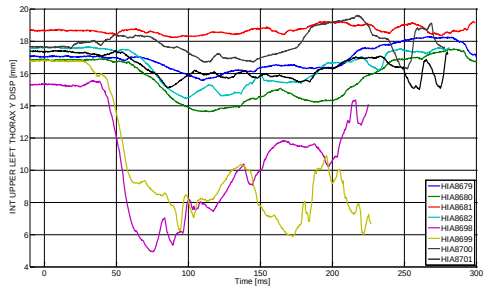



**Figure A-110. INT UPPER LEFT THORAX Y DISP**

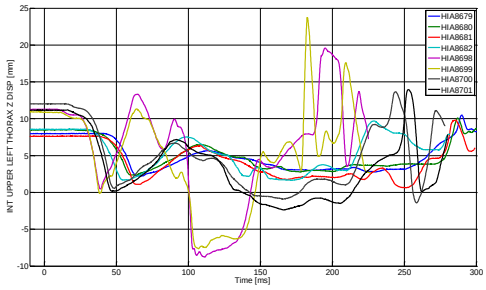



**Figure A-111. INT UPPER LEFT THORAX Z DISP**

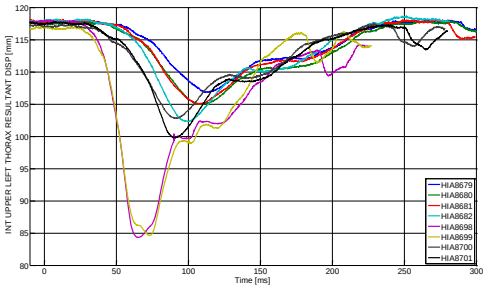



**Figure A-112. INT UPPER LEFT THORAX RESULTANT DISP**

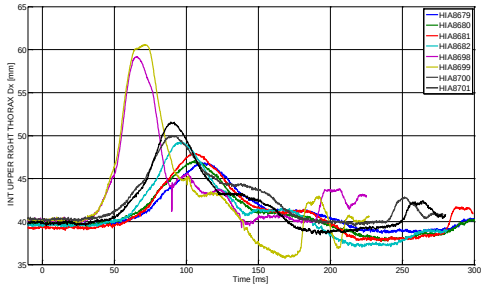



**Figure A-113. INT UPPER RIGHT THORAX Dx**

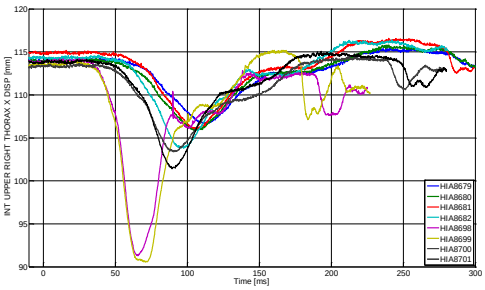



**Figure A-114. INT UPPER RIGHT THORAX X DISP**

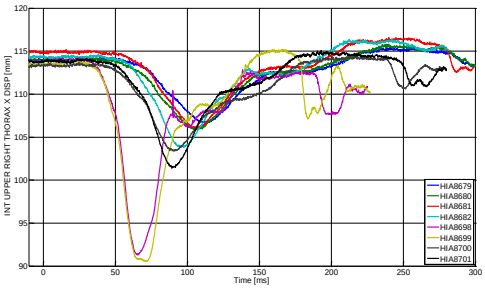



**Figure A-115. INT UPPER RIGHT THORAX X DISP**

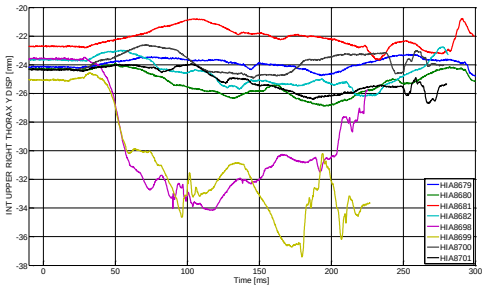



**Figure A-116. INT UPPER RIGHT THORAX Y DISP**

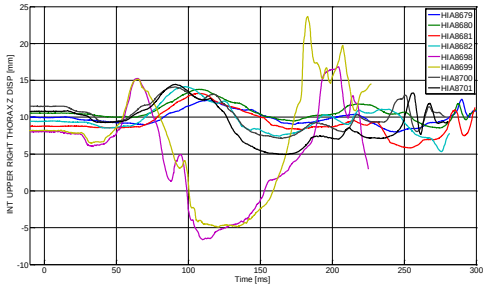



**Figure A-117. INT UPPER RIGHT THORAX Z DISP**

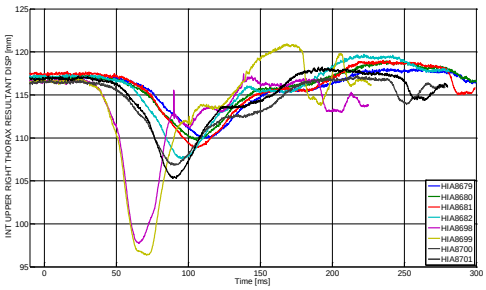



**Figure A-118. INT UPPER RIGHT THORAX RESULTANT DISP**

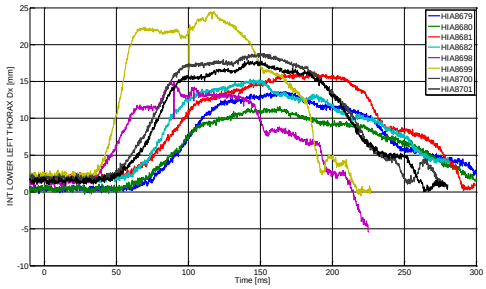



**Figure A-119. INT LOWER LEFT THORAX Dx**

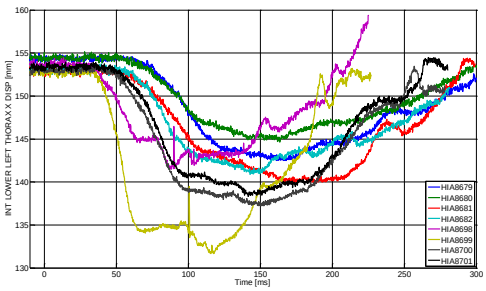



**Figure A-120. INT LOWER LEFT THORAX X DISP**

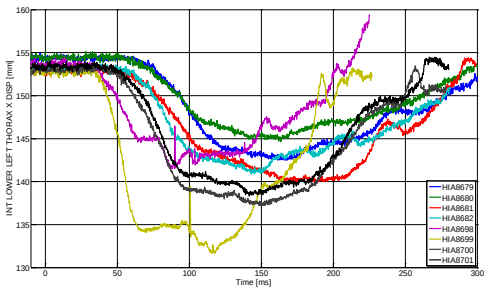



**Figure A-121. INT LOWER LEFT THORAX X DISP**

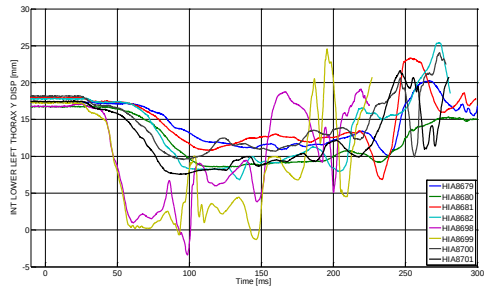



**Figure A-122. INT LOWER LEFT THORAX Y DISP**

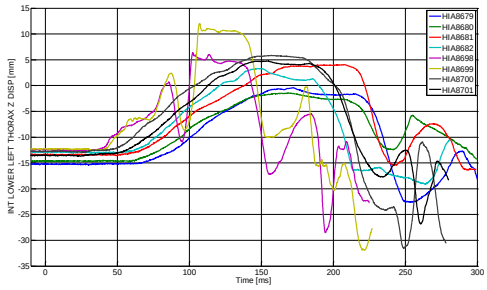



**Figure A-123. INT LOWER LEFT THORAX Z DISP**

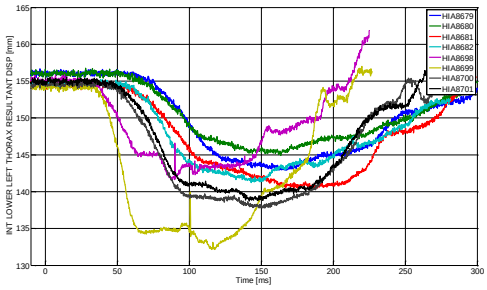



**Figure A-124. INT LOWER LEFT THORAX RESULTANT DISP**

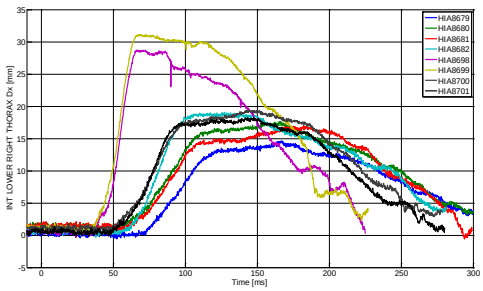



**Figure A-125. INT LOWER RIGHT THORAX Dx**

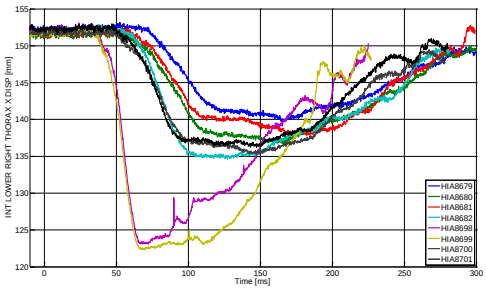



**Figure A-126. INT LOWER RIGHT THORAX X DISP**

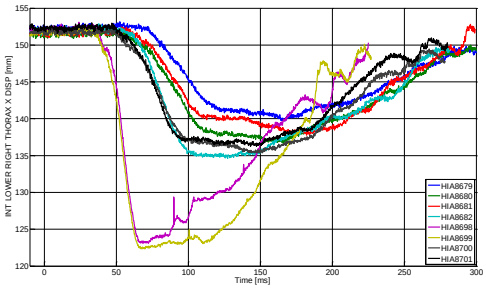



**Figure A-127. INT LOWER RIGHT THORAX X DISP**

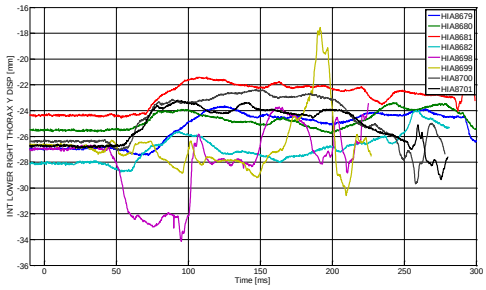



**Figure A-128. INT LOWER RIGHT THORAX Y DISP**

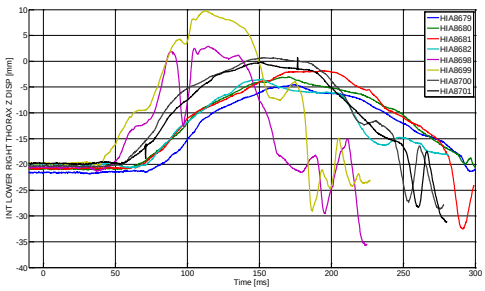



**Figure A-129. INT LOWER RIGHT THORAX Z DISP**

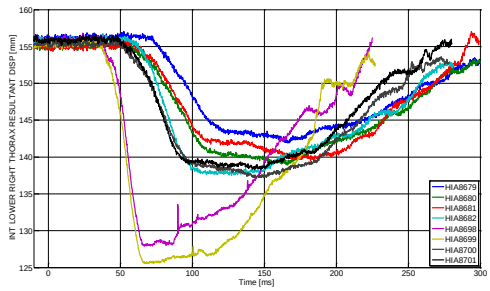



**Figure A-130. INT LOWER RIGHT THORAX RESULTANT DISP**

## B. THOR Lateral Tests

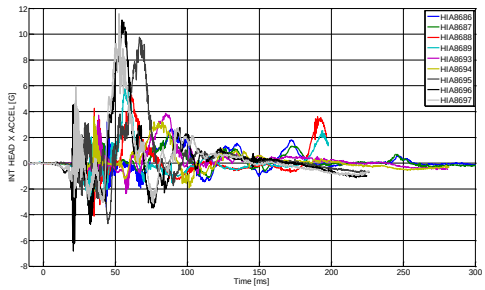



**Figure B-1. INT HEAD X ACCEL**

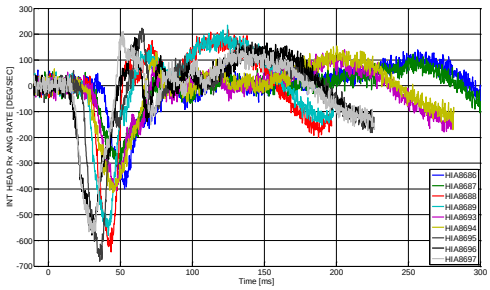



**Figure B-4. INT HEAD Rx ANG RATE**

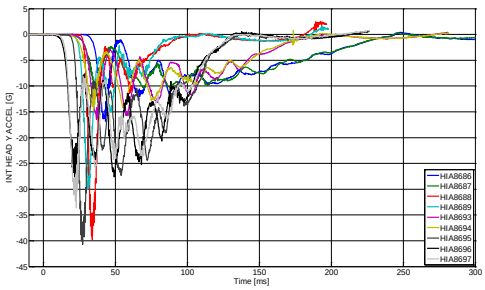



**Figure B-2. INT HEAD Y ACCEL**

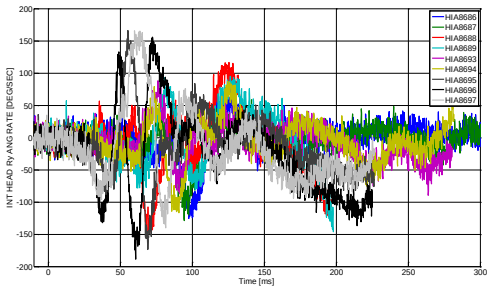



**Figure B-5. INT HEAD Ry ANG RATE**

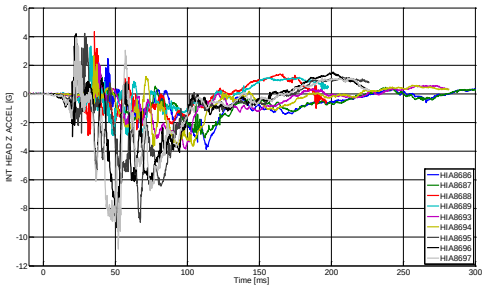



**Figure B-3. INT HEAD Z ACCEL**

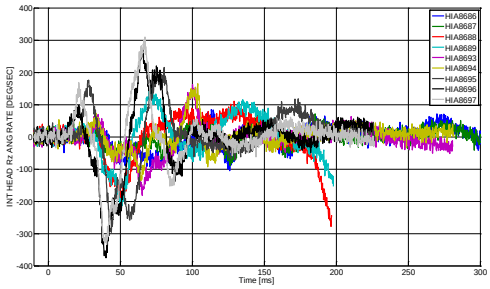



**Figure B-6. INT HEAD Rz ANG RATE**

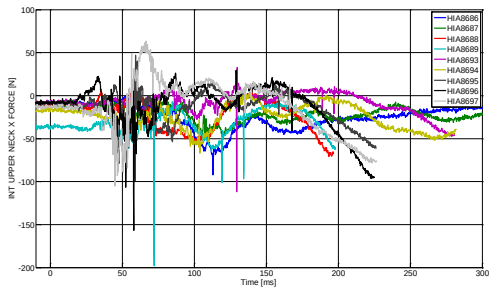



**Figure B-7. INT UPPER NECK X FORCE**

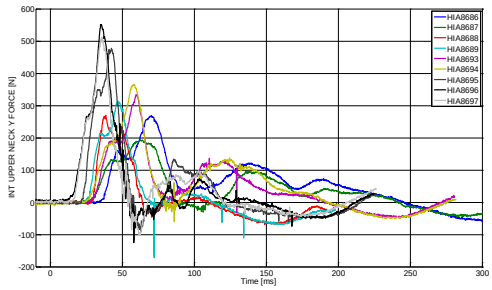



**Figure B-8. INT UPPER NECK Y FORCE**

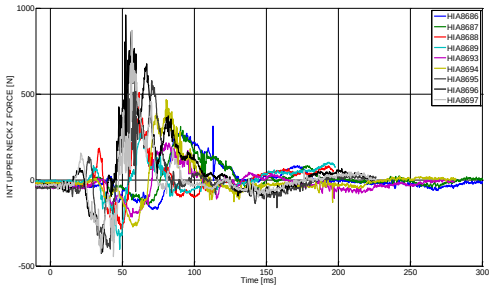



**Figure B-9. INT UPPER NECK Z FORCE**

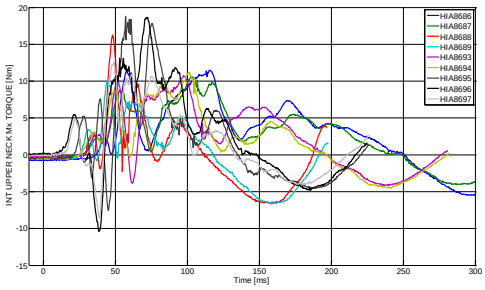



**Figure B-10. INT UPPER NECK Mx TORQUE**

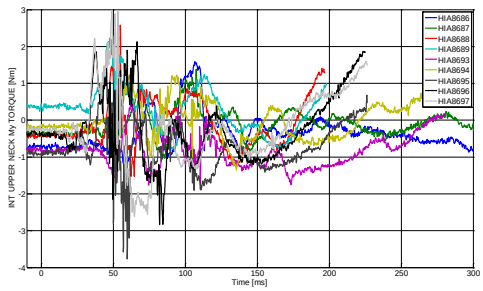



**Figure B-11. INT UPPER NECK My TORQUE**

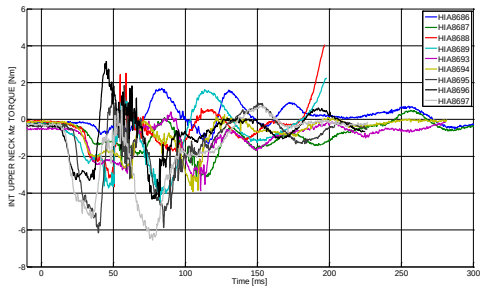



**Figure B-12. INT UPPER NECK Mz TORQUE**

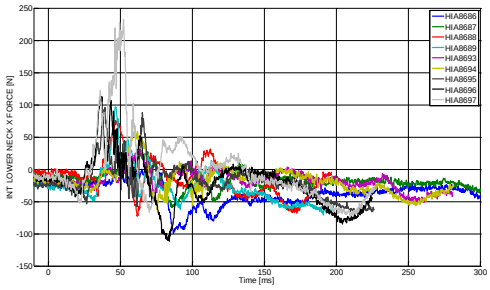



**Figure B-13. INT LOWER NECK X FORCE**

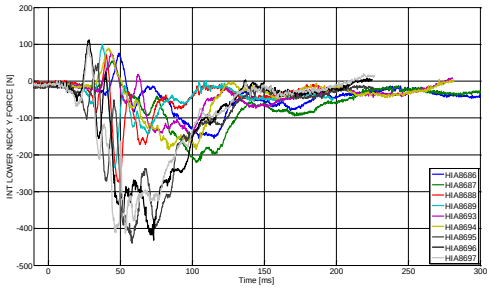



**Figure B-14. INT LOWER NECK Y FORCE**

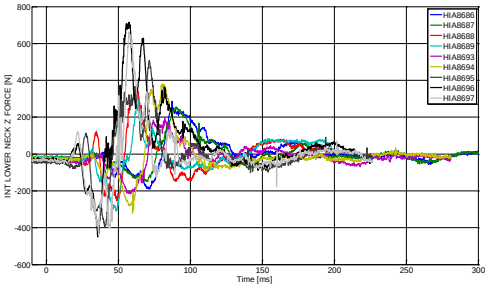



**Figure B-15. INT LOWER NECK Z FORCE**

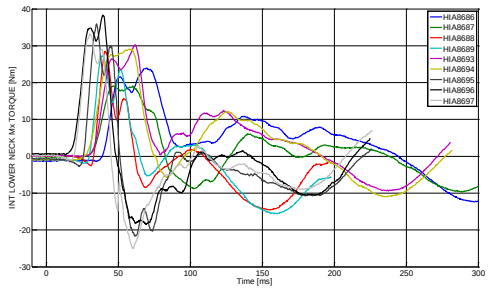



**Figure B-16. INT LOWER NECK Mx TORQUE**

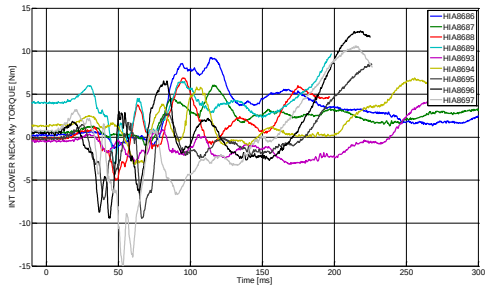



**Figure B-17. INT LOWER NECK My TORQUE**

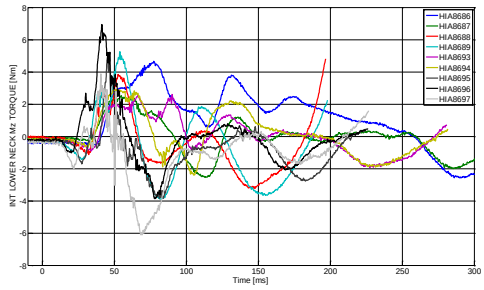



**Figure B-18. INT LOWER NECK Mz TORQUE**

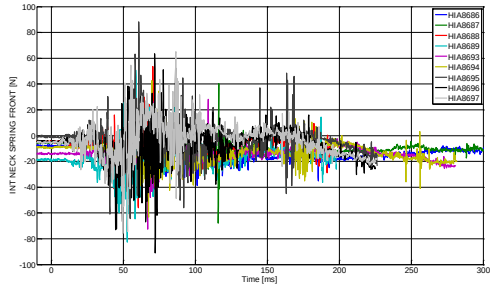



**Figure B-19. INT NECK SPRING FRONT**

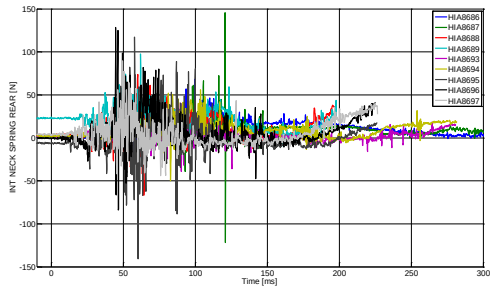



**Figure B-20. INT NECK SPRING REAR**

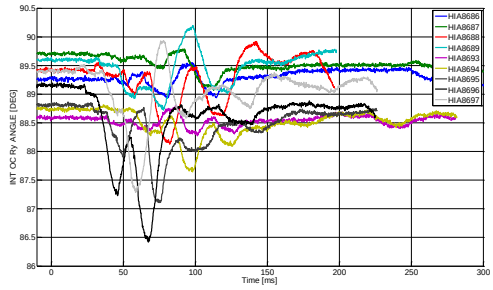



**Figure B-21. INT OC Ry ANGLE**

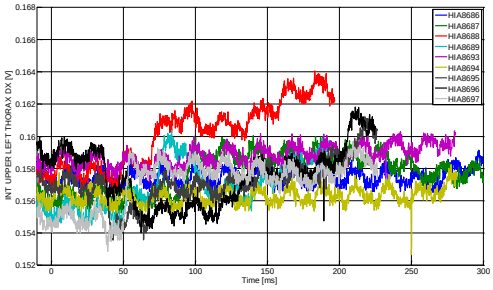



**Figure B-22. INT UPPER LEFT THORAX DX**

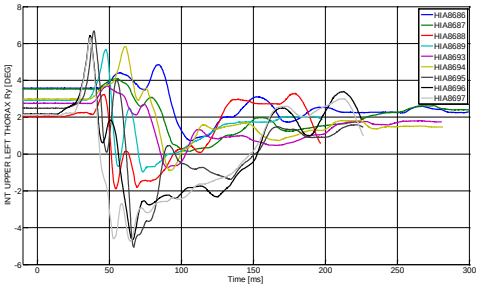



**Figure B-23. INT UPPER LEFT THORAX Ry**

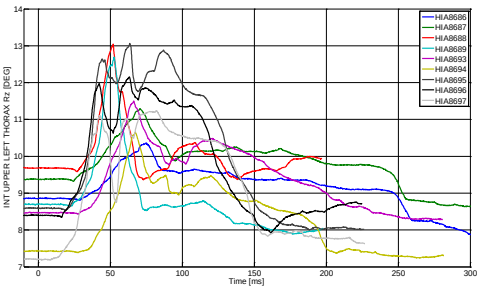



**Figure B-24. INT UPPER LEFT THORAX Rz**

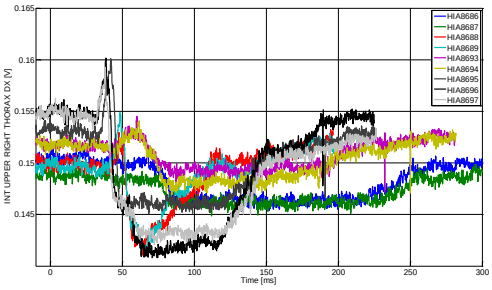



**Figure B-25. INT UPPER RIGHT THORAX DX**

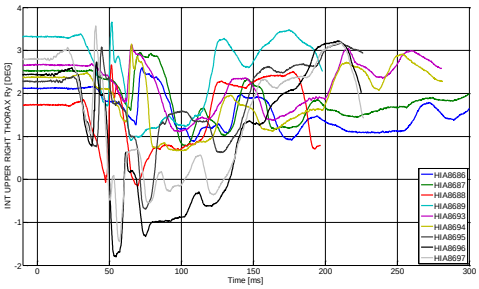



**Figure B-26. INT UPPER RIGHT THORAX Ry**

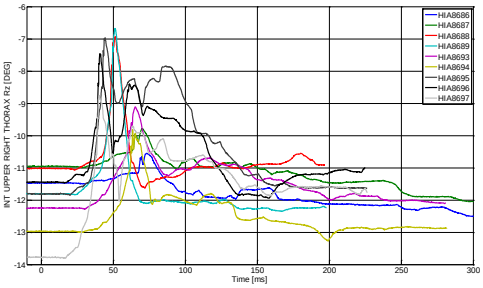



**Figure B-27. INT UPPER RIGHT THORAX Rz**

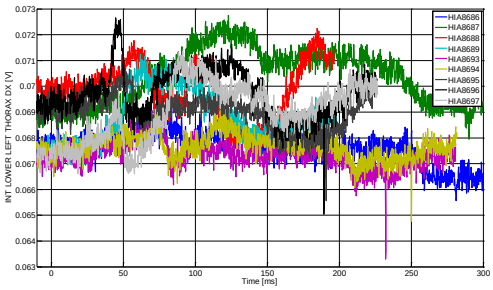



**Figure B-28. INT LOWER LEFT THORAX DX**

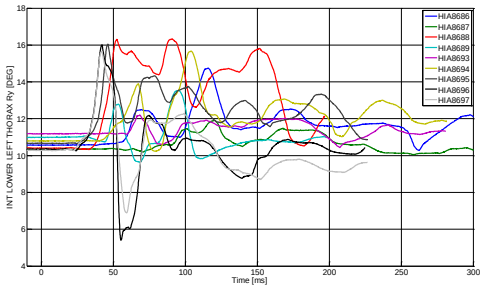



**Figure B-29. INT LOWER LEFT THORAX Ry**

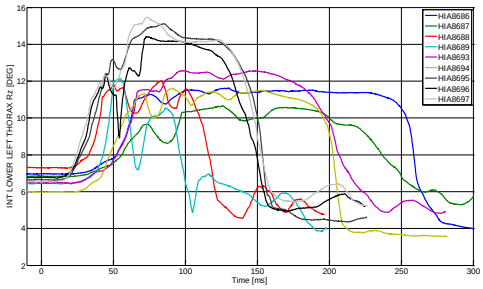



**Figure B-30. INT LOWER LEFT THORAX Rz**

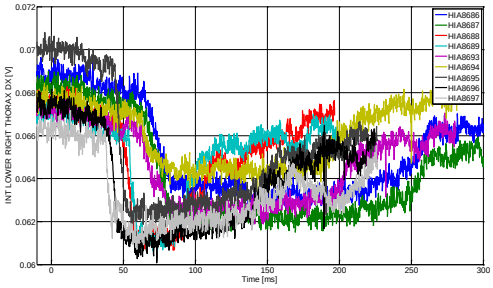



**Figure B-31. INT LOWER RIGHT THORAX DX**

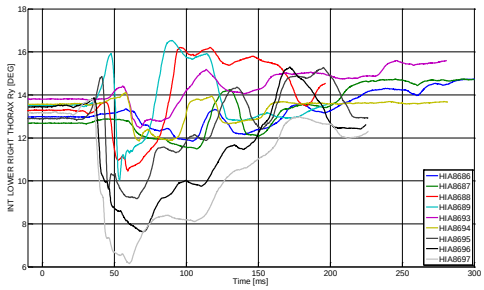



**Figure B-32. INT LOWER RIGHT THORAX Ry**

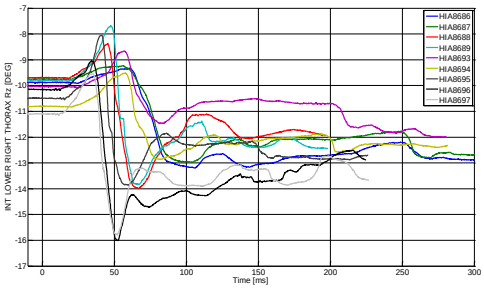



**Figure B-33. INT LOWER RIGHT THORAX Rz**

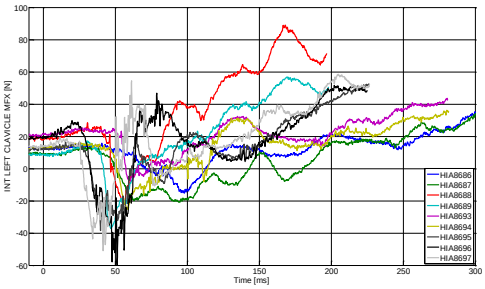



**Figure B-34. INT LEFT CLAVICLE MFX**

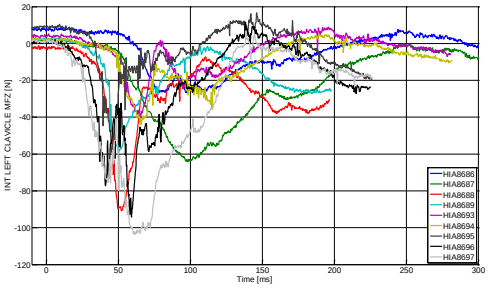



**Figure B-35. INT LEFT CLAVICLE MFZ**

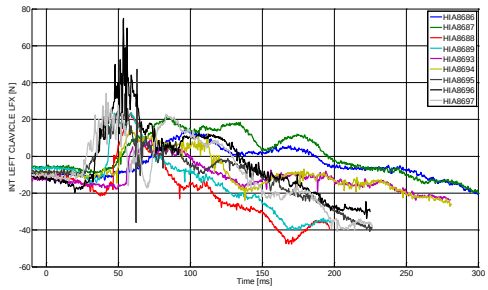



**Figure B-36. INT LEFT CLAVICLE LFX**

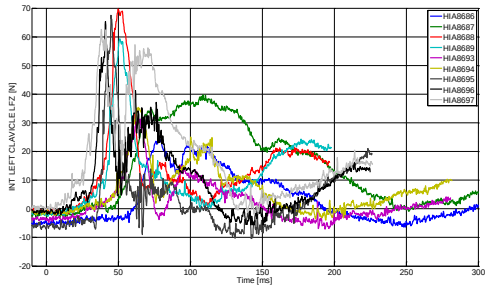



**Figure B-37. INT LEFT CLAVICLE LFZ**

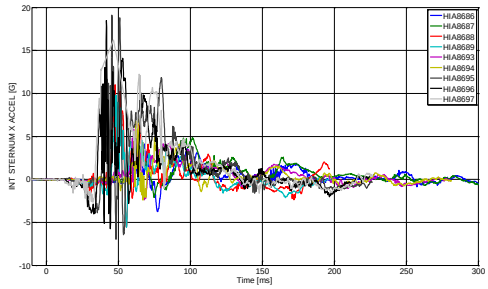



**Figure B-38. INT STERNUM X ACCEL**

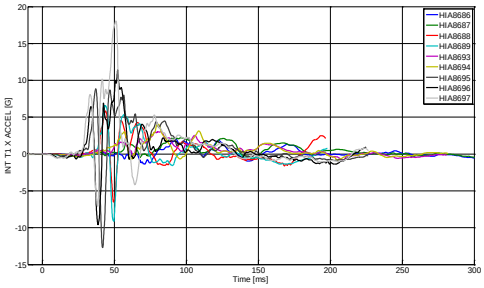



**Figure B-39. INT T1 X ACCEL**

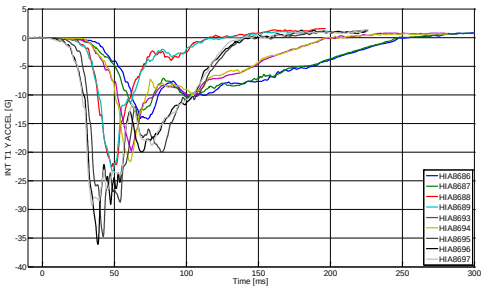



**Figure B-40. INT T1 Y ACCEL**

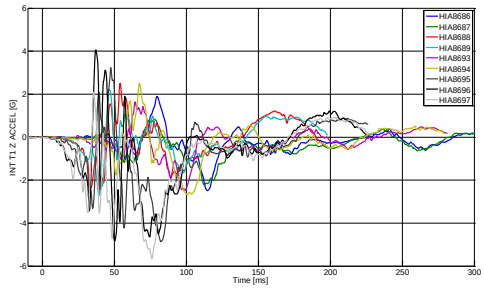



**Figure B-41. INT T1 Z ACCEL**

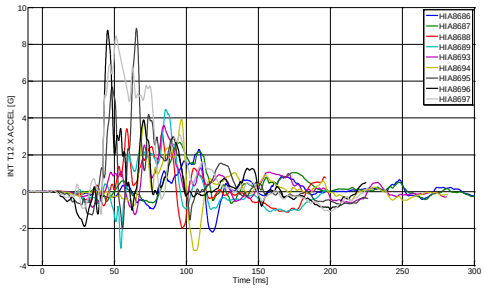



**Figure B-42. INT T12 X ACCEL**

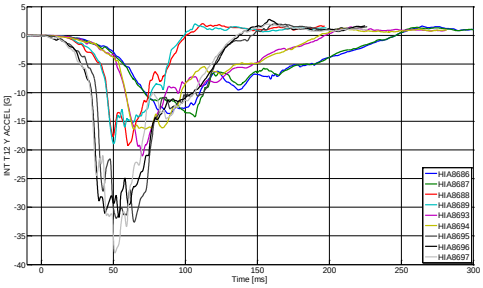



**Figure B-43. INT T12 Y ACCEL**

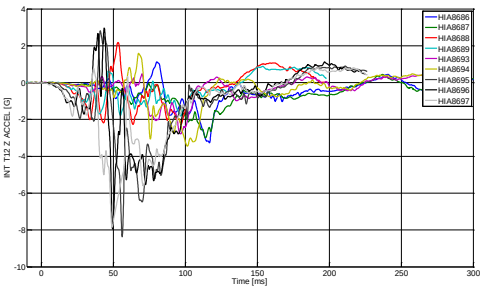



**Figure B-44. INT T12 Z ACCEL**

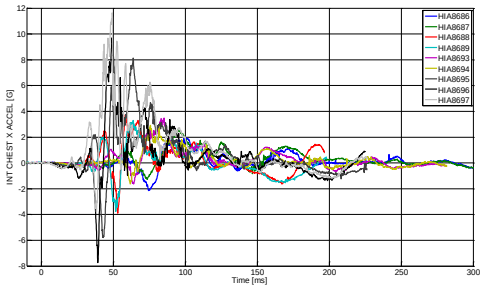



**Figure B-45. INT CHEST X ACCEL**

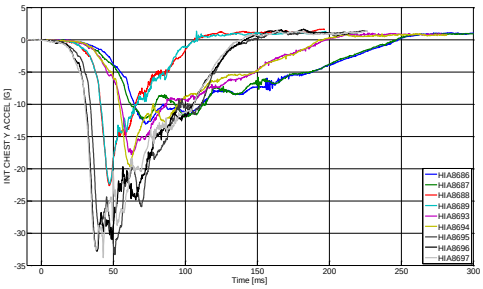



**Figure B-46. INT CHEST Y ACCEL**

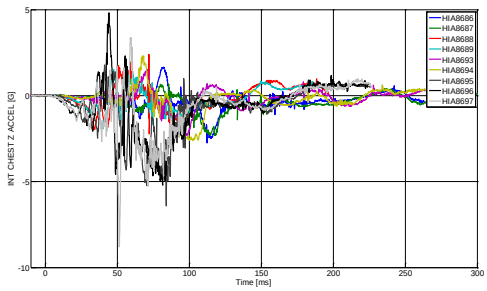



**Figure B-47. INT CHEST Z ACCEL**

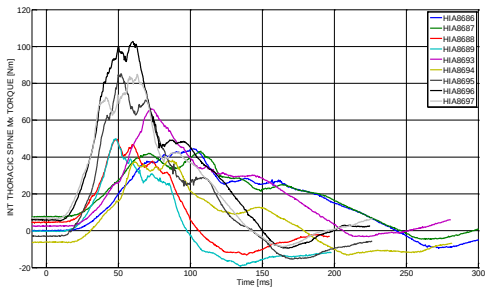



**Figure B-51. INT THORACIC SPINE Mx TORQUE**

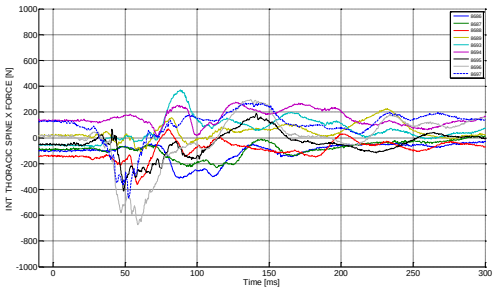



**Figure B-48. INT THORACIC SPINE X FORCE**

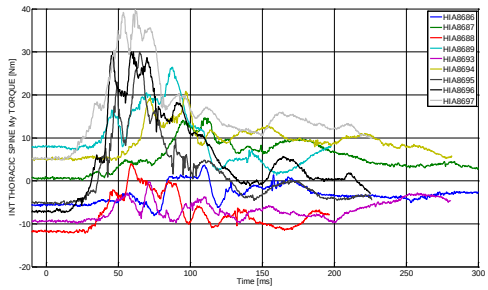



**Figure B-52. INT THORACIC SPINE My TORQUE**

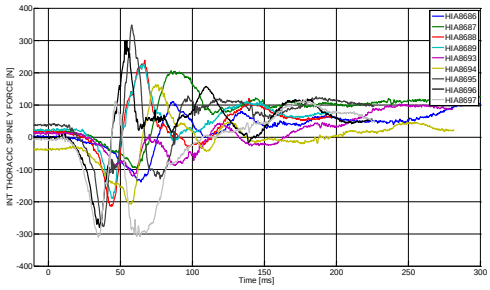



**Figure B-49. INT THORACIC SPINE Y FORCE**

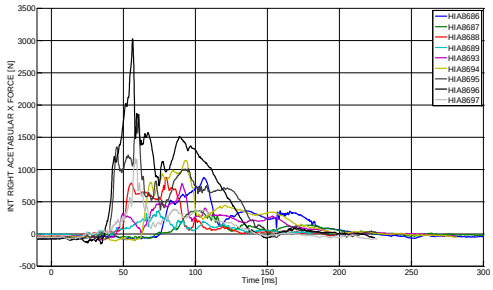



**Figure B-53. INT RIGHT ACETABULAR X FORCE**

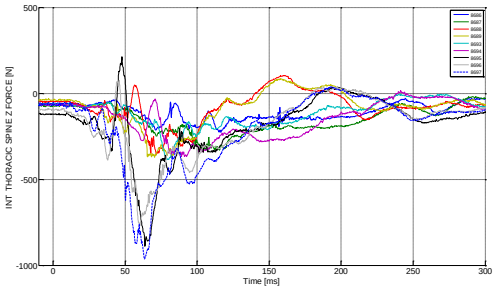



**Figure B-50. INT THORACIC SPINE Z FORCE**

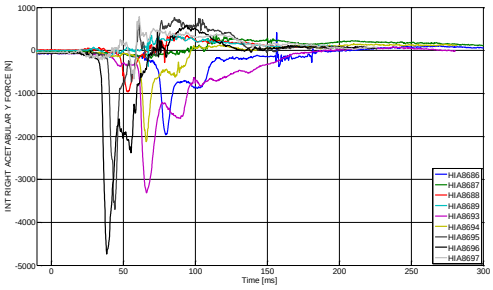



**Figure B-54. INT RIGHT ACETABULAR Y FORCE**

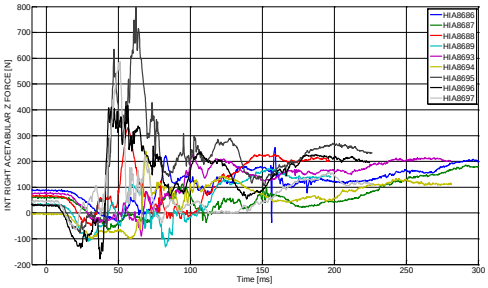



**Figure B-55. INT RIGHT ACETABULAR Z FORCE**

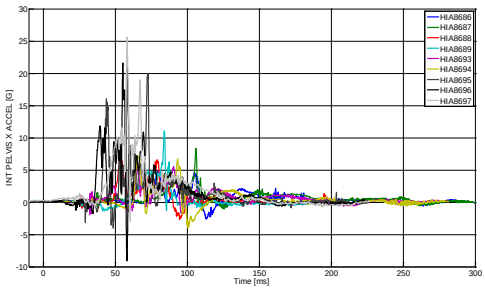



**Figure B-56. INT PELVIS X ACCEL**

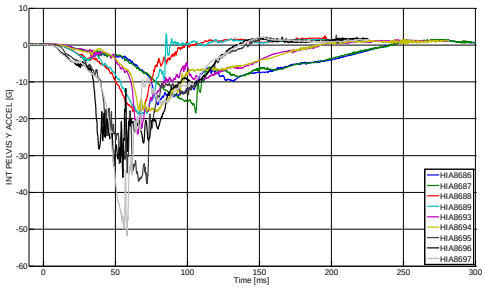



**Figure B-57. INT PELVIS Y ACCEL**

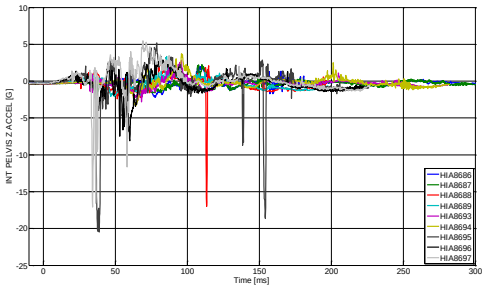



**Figure B-58. INT PELVIS Z ACCEL**

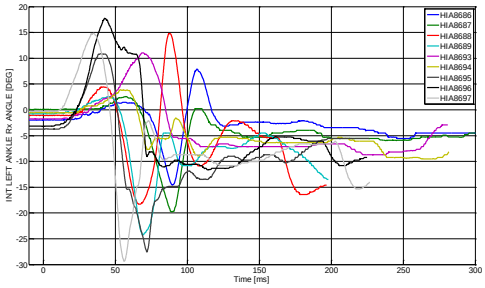



**Figure B-59. INT LEFT ANKLE Rx ANGLE**

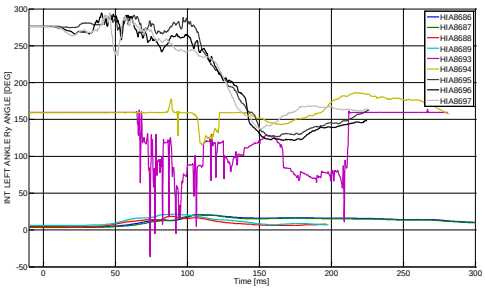



**Figure B-60. INT LEFT ANKLE Ry ANGLE**

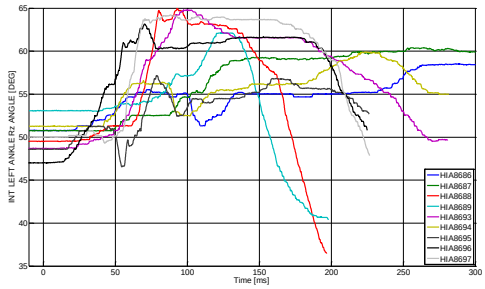



**Figure B-61. INT LEFT ANKLE Rz ANGLE**

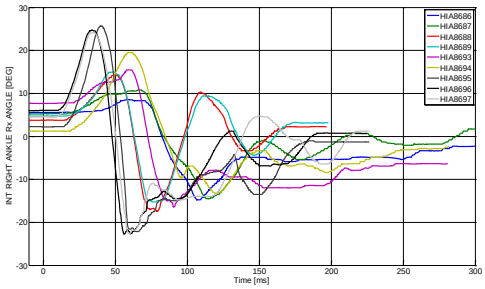



**Figure B-62. INT RIGHT ANKLE Rx ANGLE**

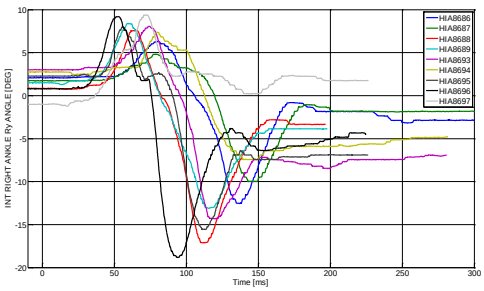



**Figure B-63. INT RIGHT ANKLE Ry ANGLE**

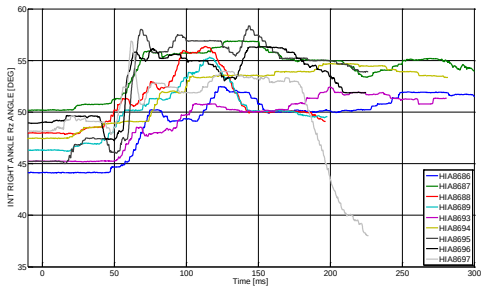



**Figure B-64. INT RIGHT ANKLE Rz ANGLE**

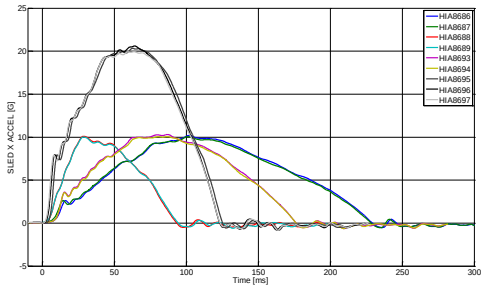



**Figure B-65. SLED X ACCEL**

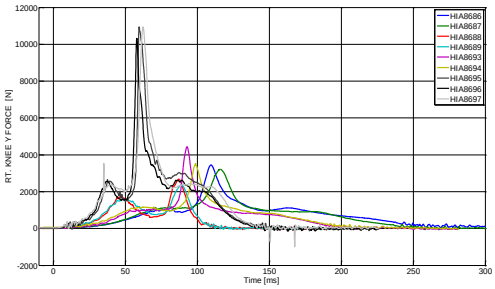



**Figure B-66. RT. KNEE Y FORCE**

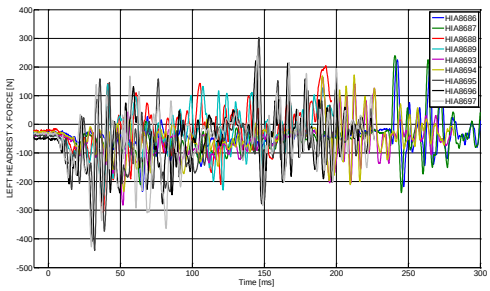



**Figure B-67. LEFT HEADREST X FORCE**

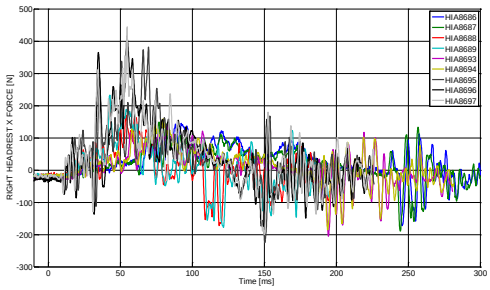



**Figure B-68. RIGHT HEADREST X FORCE**

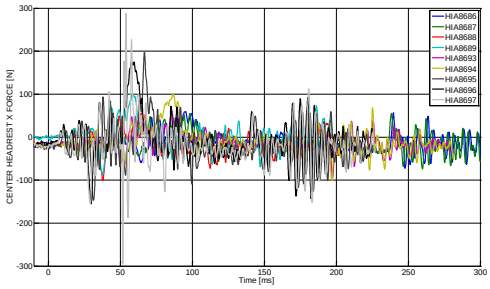



**Figure B-69. CENTER HEADREST X FORCE**

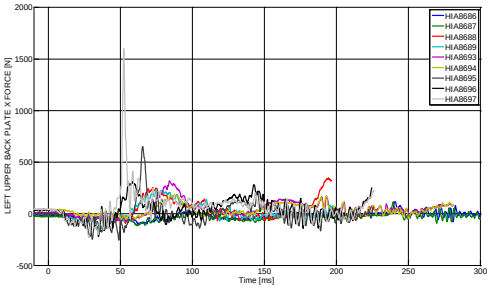



**Figure B-70. LEFT UPPER BACK PLATE X FORCE**

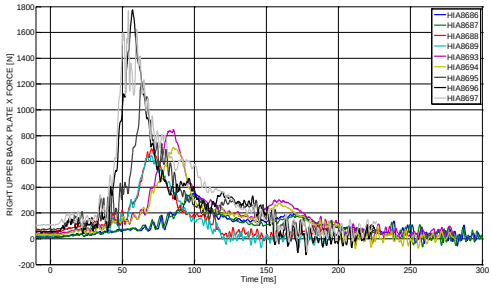



**Figure B-71. RIGHT UPPER BACK PLATE X FORCE**

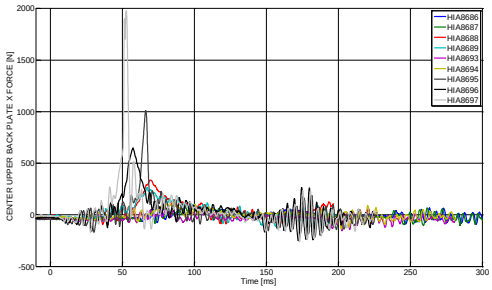



**Figure B-72. CENTER UPPER BACK PLATE X FORCE**

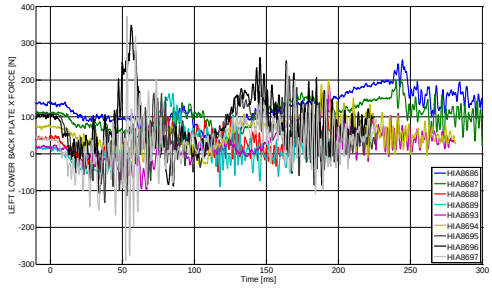



**Figure B-73. LEFT LOWER BACK PLATE X FORCE**

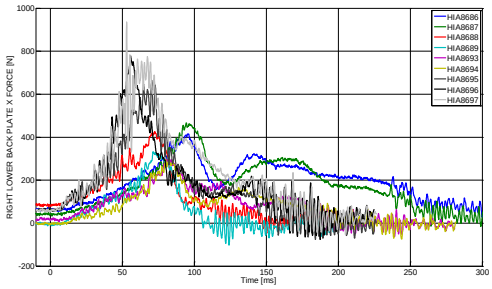



**Figure B-74. RIGHT LOWER BACK PLATE X FORCE**

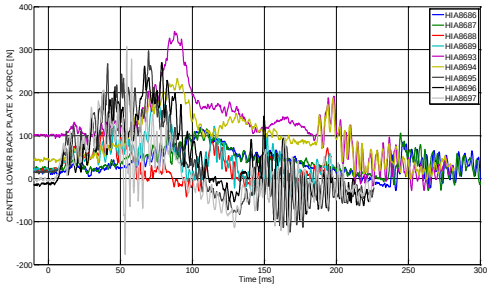



**Figure B-75. CENTER LOWER BACK PLATE X FORCE**

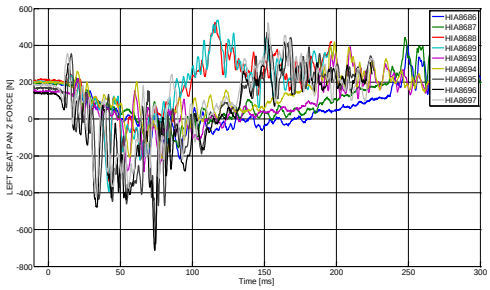



**Figure B-76. LEFT SEAT PAN Z FORCE**

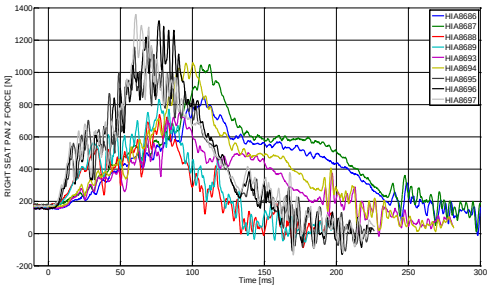



**Figure B-77. RIGHT SEAT PAN Z FORCE**

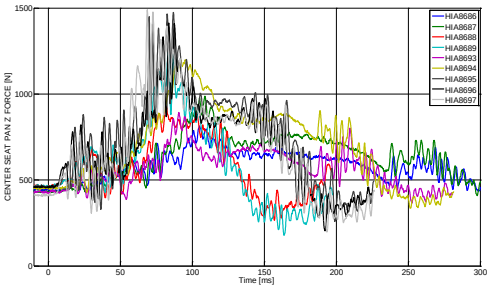



**Figure B-78. CENTER SEAT PAN Z FORCE**

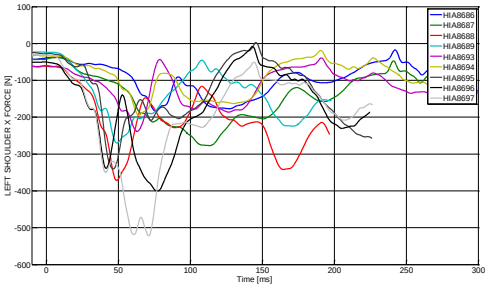



**Figure B-79. LEFT SHOULDER X FORCE**

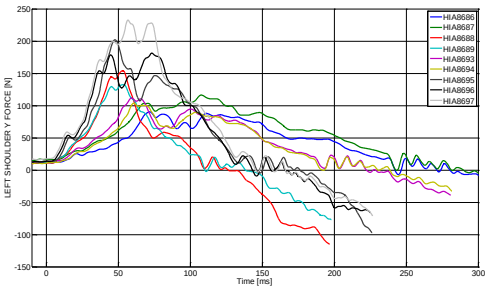



**Figure B-80. LEFT SHOULDER Y FORCE**

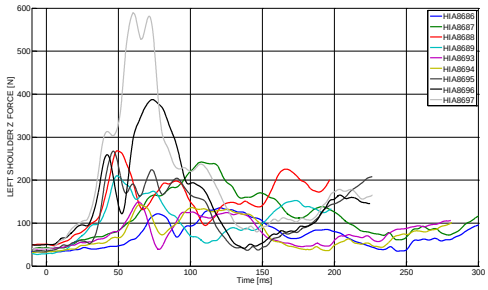



**Figure B-81. LEFT SHOULDER Z FORCE**

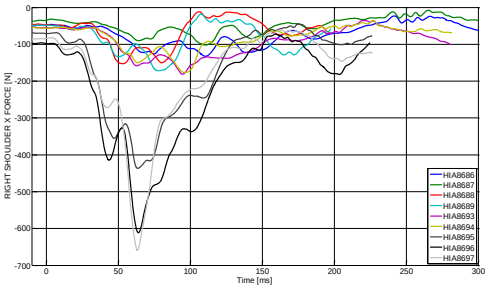



**Figure B-82. RIGHT SHOULDER X FORCE**

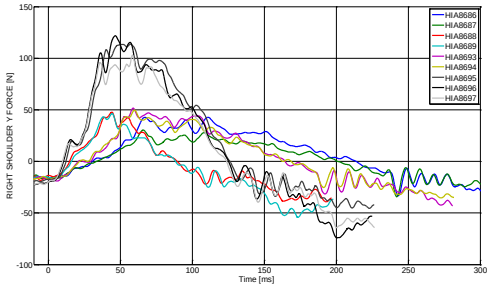



**Figure B-83. RIGHT SHOULDER Y FORCE**

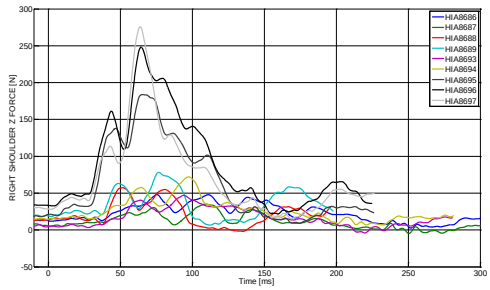



**Figure B-84. RIGHT SHOULDER Z FORCE**

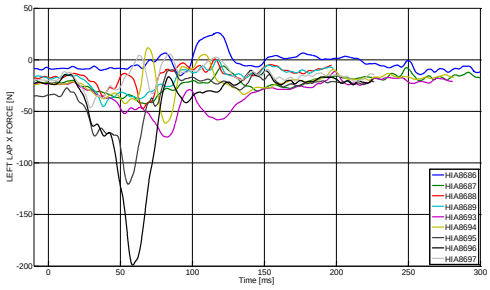



**Figure B-85. LEFT LAP X FORCE**

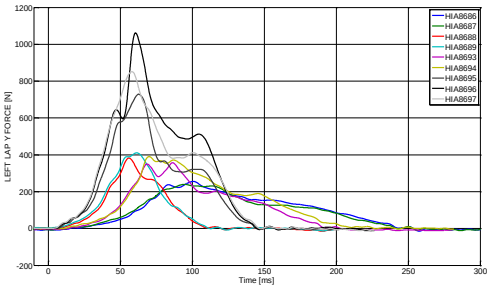



**Figure B-86. LEFT LAP Y FORCE**

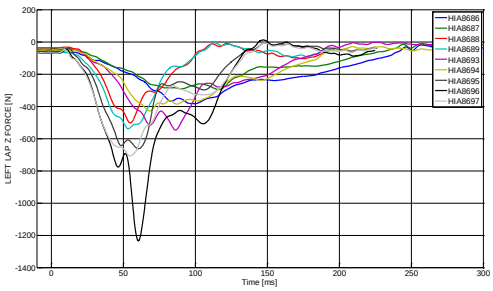



**Figure B-87. LEFT LAP Z FORCE**

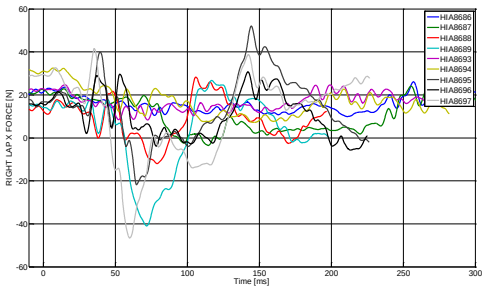



**Figure B-88. RIGHT LAP X FORCE**

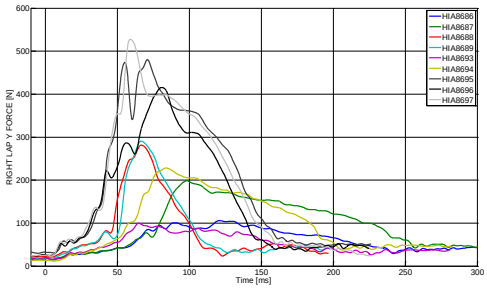



**Figure B-89. RIGHT LAP Y FORCE**

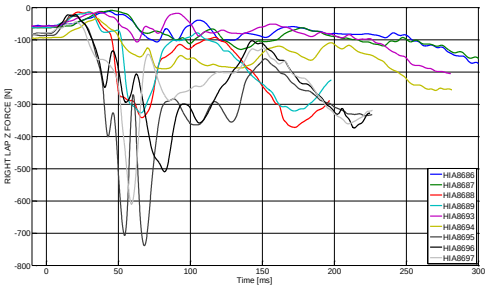



**Figure B-90. RIGHT LAP Z FORCE**

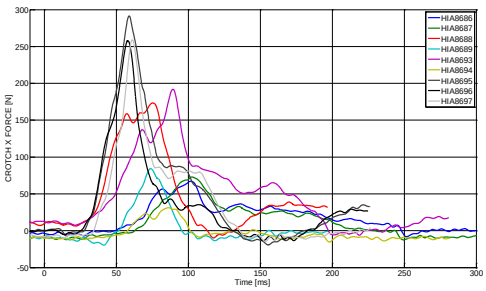



**Figure B-91. CROTCH X FORCE**

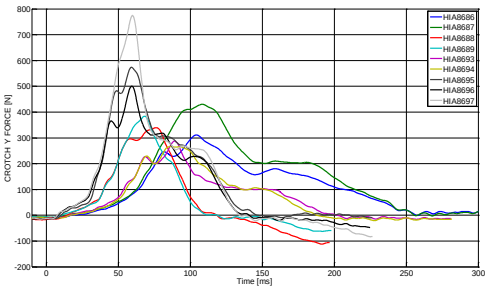



**Figure B-92. CROTCH Y FORCE**

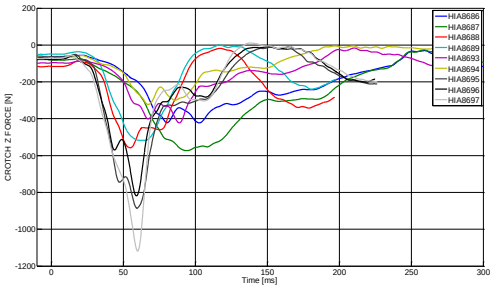



**Figure B-93. CROTCH Z FORCE**

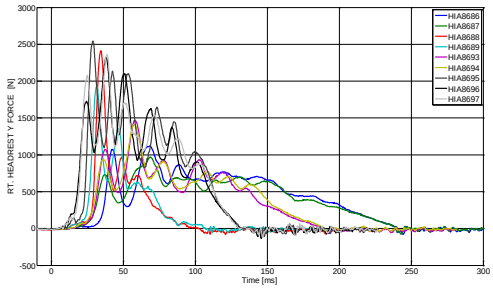



**Figure B-94. RT. HEADREST Y FORCE**

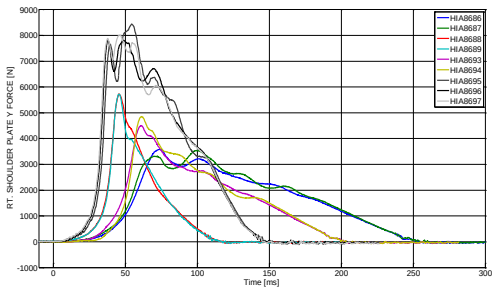



**Figure B-95. RT. SHOULDER PLATE Y FORCE**

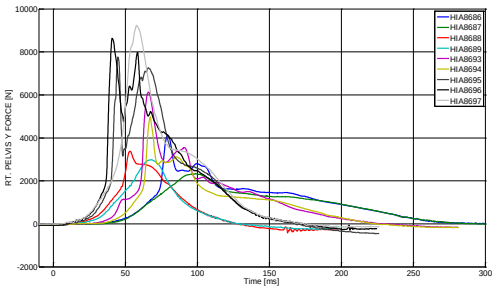



**Figure B-96. RT. PELVIS Y FORCE**

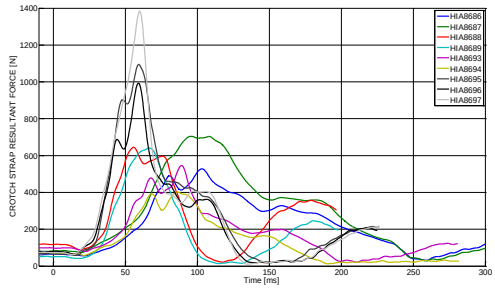



**Figure B-97. CROTCH STRAP RESULTANT FORCE**

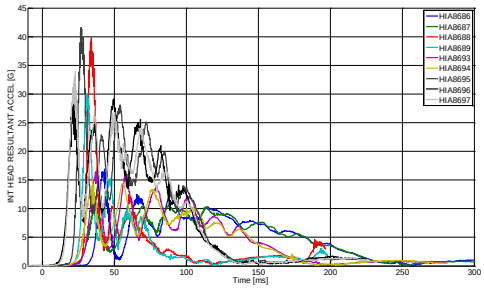



**Figure B-98. INT HEAD RESULTANT ACCEL**

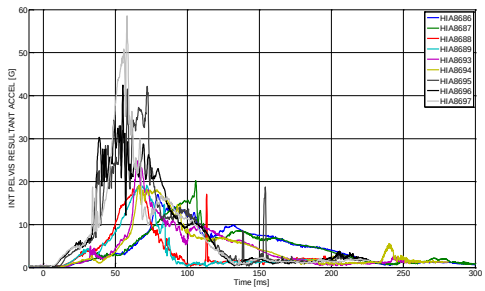



**Figure B-99. INT PELVIS RESULTANT ACCEL**

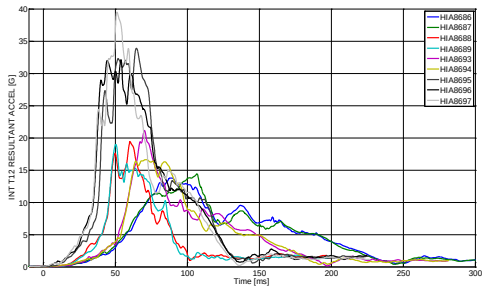



**Figure B-100. INT T12 RESULTANT ACCEL**

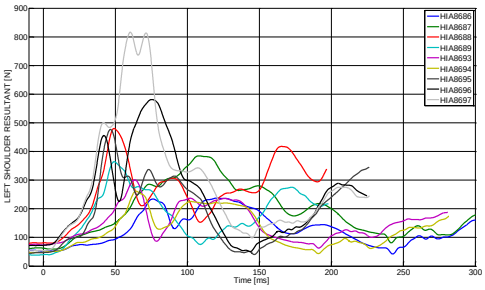



**Figure B-101. LEFT SHOULDER RESULTANT**

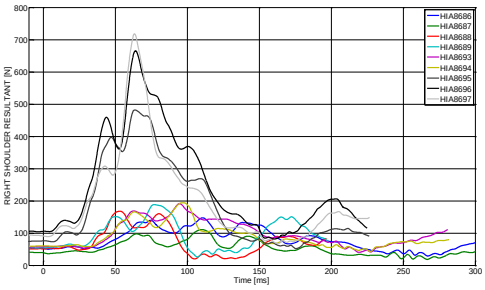



**Figure B-102. RIGHT SHOULDER RESULTANT**

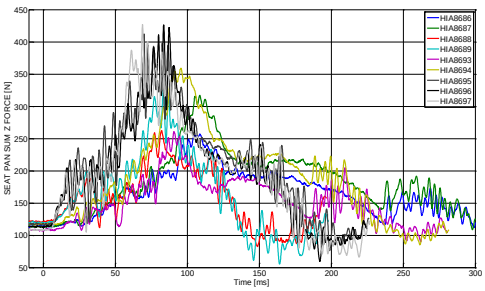



**Figure B-103. SEAT PAN SUM Z FORCE**

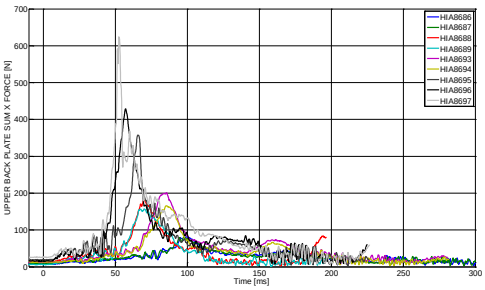



**Figure B-104. UPPER BACK PLATE SUM X FORCE**

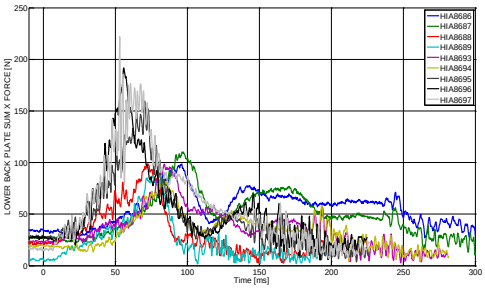



**Figure B-105. LOWER BACK PLATE SUM X FORCE**

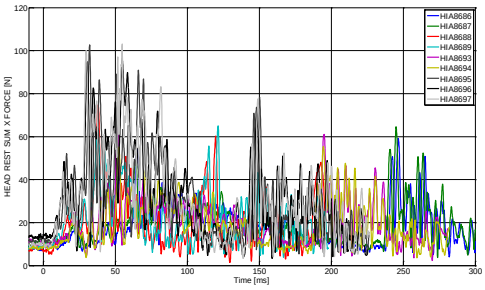



**Figure B-106. HEAD REST SUM X FORCE**

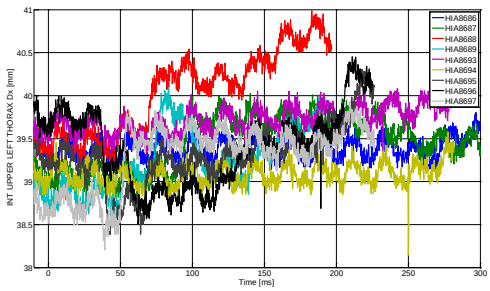



**Figure B-107. INT UPPER LEFT THORAX Dx**

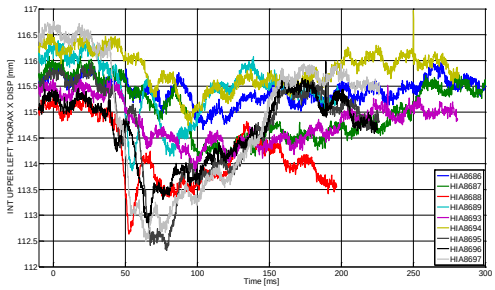



**Figure B-108. INT UPPER LEFT THORAX X DISP**

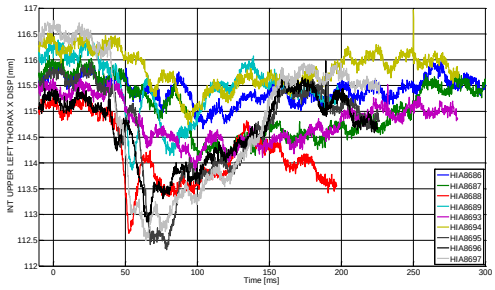



**Figure B-109. INT UPPER LEFT THORAX X DISP**

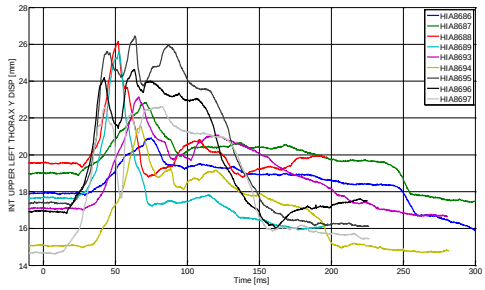



**Figure B-110. INT UPPER LEFT THORAX Y DISP**

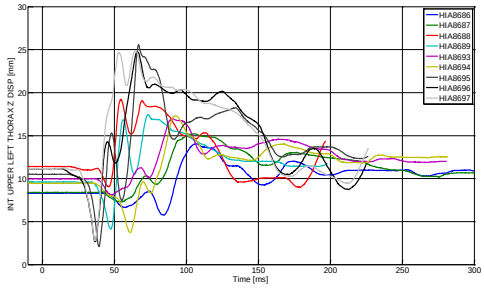



**Figure B-111. INT UPPER LEFT THORAX Z DISP**

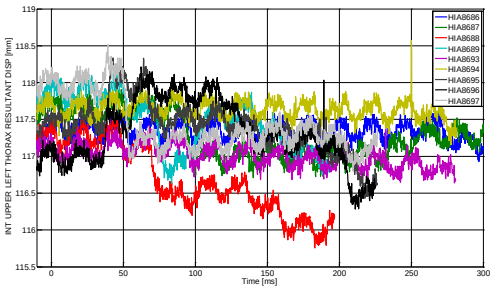



**Figure B-112. INT UPPER LEFT THORAX RESULTANT DISP**

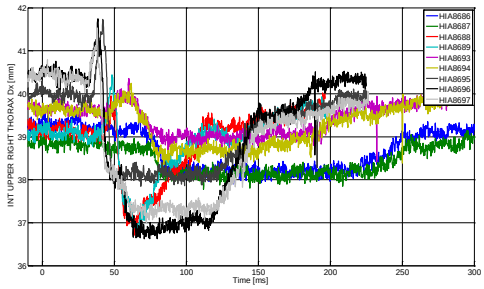



**Figure B-113. INT UPPER RIGHT THORAX Dx**

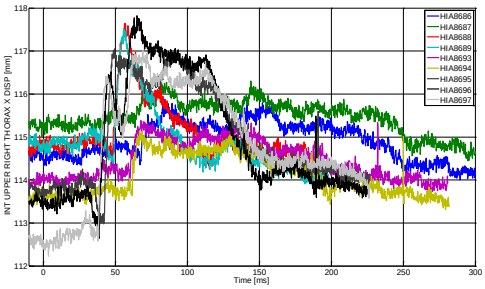



**Figure B-114. INT UPPER RIGHT THORAX X DISP**

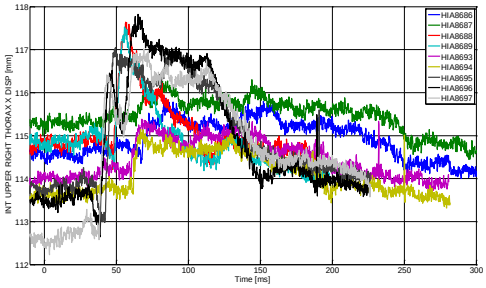



**Figure B-115. INT UPPER RIGHT THORAX X DISP**

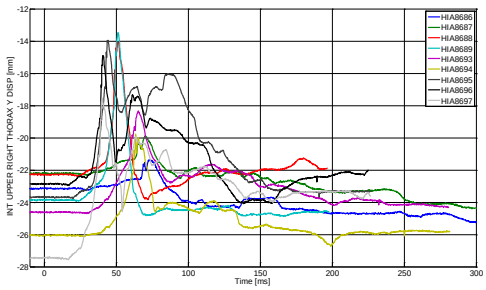



**Figure B-116. INT UPPER RIGHT THORAX Y DISP**

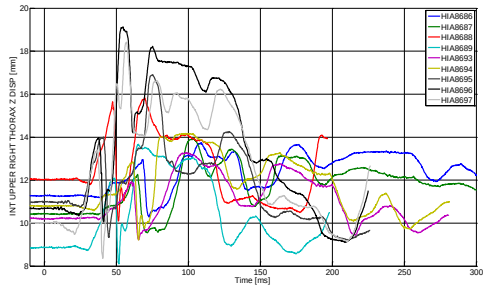



**Figure B-117. INT UPPER RIGHT THORAX Z DISP**

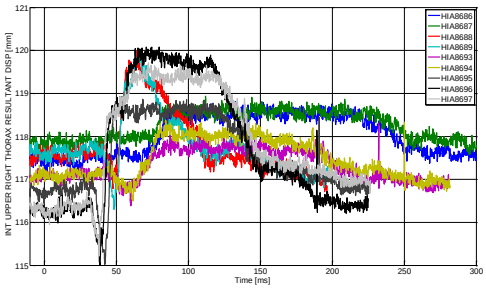



**Figure B-118. INT UPPER RIGHT THORAX RESULTANT DISP**

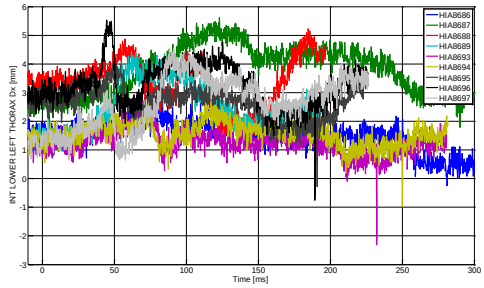



**Figure B-119. INT LOWER LEFT THORAX Dx**

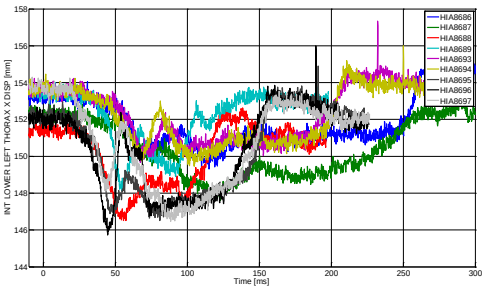



**Figure B-120. INT LOWER LEFT THORAX X DISP**

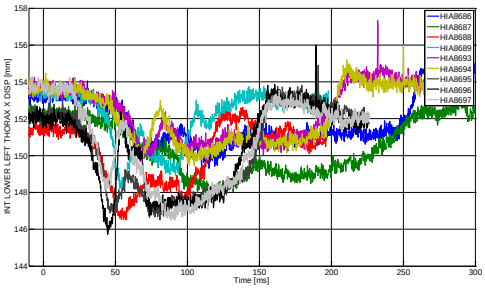



**Figure B-121. INT LOWER LEFT THORAX X DISP**

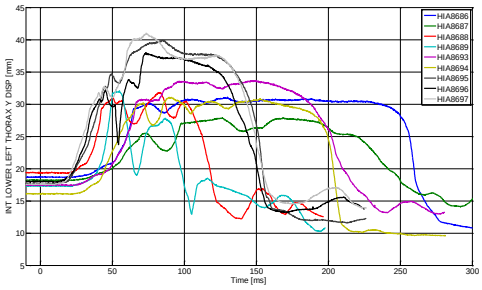



**Figure B-122. INT LOWER LEFT THORAX Y DISP**

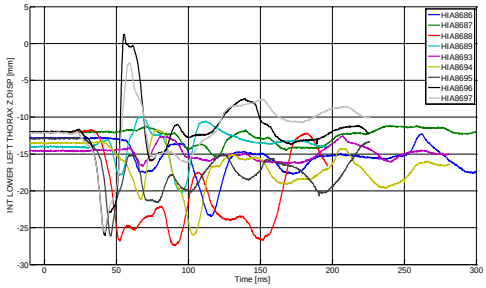



**Figure B-123. INT LOWER LEFT THORAX Z DISP**

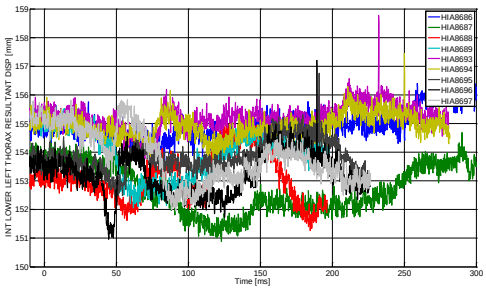



**Figure B-124. INT LOWER LEFT THORAX RESULTANT DISP**

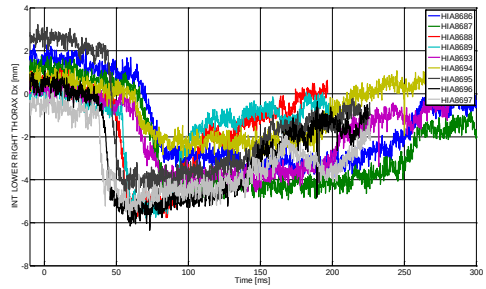



**Figure B-125. INT LOWER RIGHT THORAX Dx**

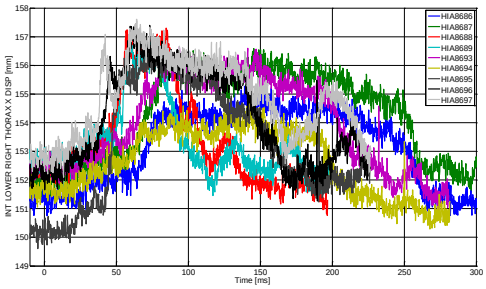



**Figure B-126. INT LOWER RIGHT THORAX X DISP**

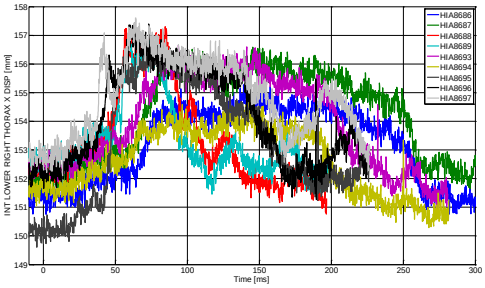



**Figure B-127. INT LOWER RIGHT THORAX X DISP**

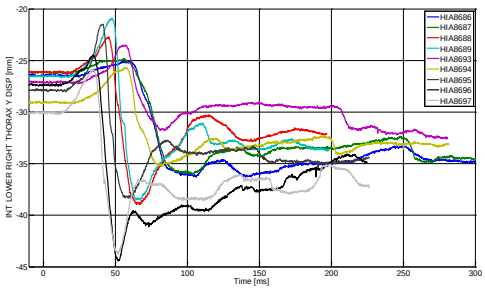



**Figure B-128. INT LOWER RIGHT THORAX Y DISP**

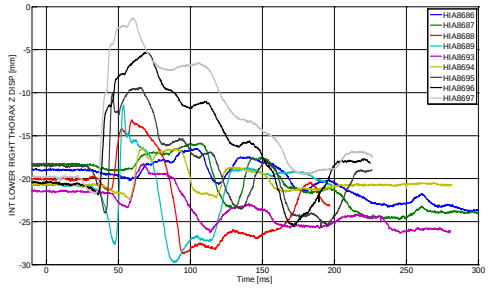



**Figure B-129. INT LOWER RIGHT THORAX Z DISP**

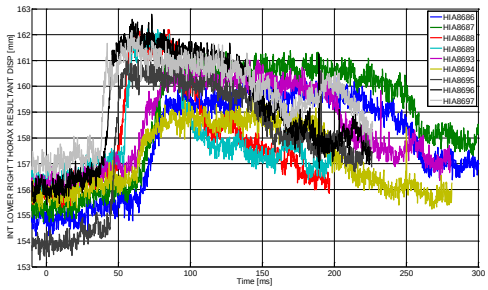



**Figure B-130. INT LOWER RIGHT THORAX RESULTANT DISP**

## C. THOR Spinal Tests

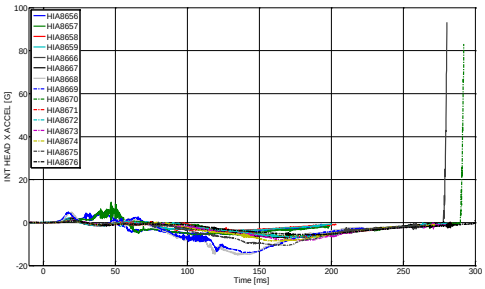



**Figure C-1. INT HEAD X ACCEL**

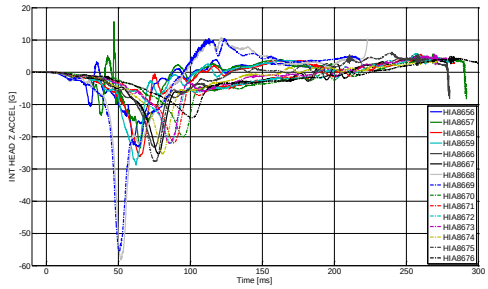



**Figure C-3. INT HEAD Z ACCEL**

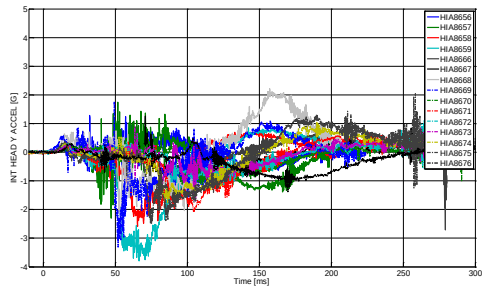



**Figure C-2. INT HEAD Y ACCEL**

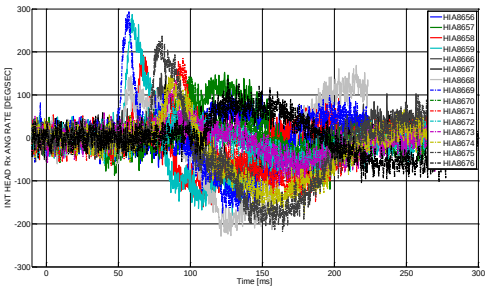



**Figure C-4. INT HEAD Rx ANG RATE**

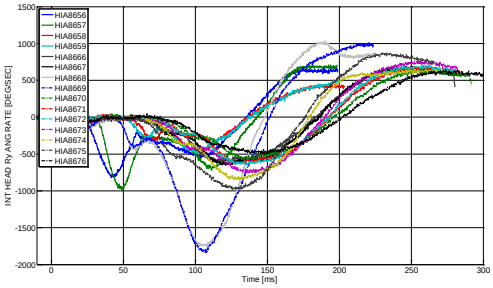



**Figure C-5. INT HEAD Ry ANG RATE**

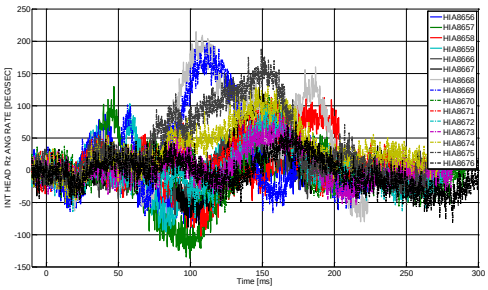



**Figure C-6. INT HEAD Rz ANG RATE**

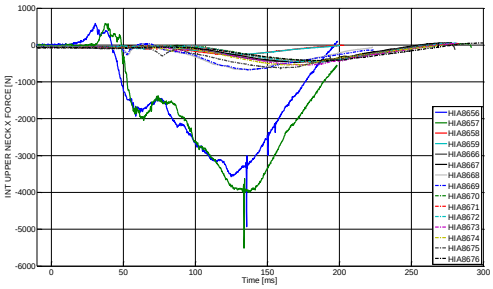



**Figure C-7. INT UPPER NECK X FORCE**

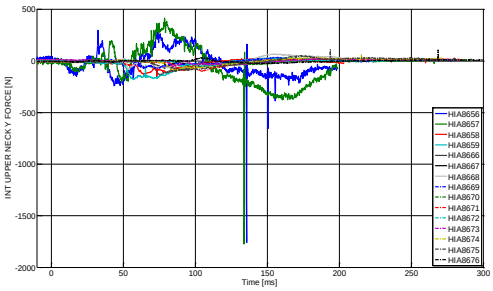



**Figure C-8. INT UPPER NECK Y FORCE**

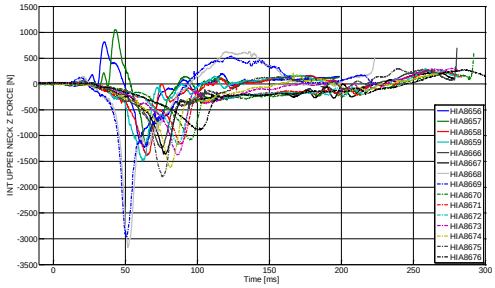



**Figure C-9. INT UPPER NECK Z FORCE**

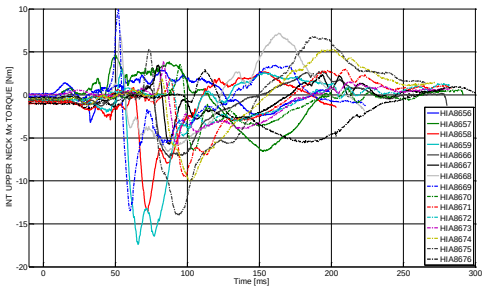



**Figure C-10. INT UPPER NECK Mx TORQUE**

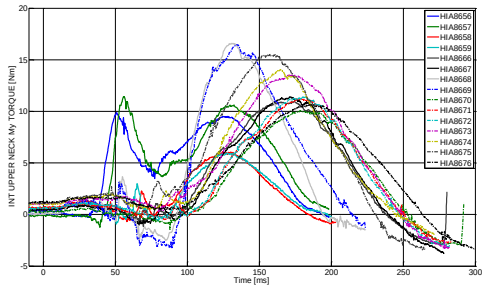



**Figure C-11. INT UPPER NECK My TORQUE**

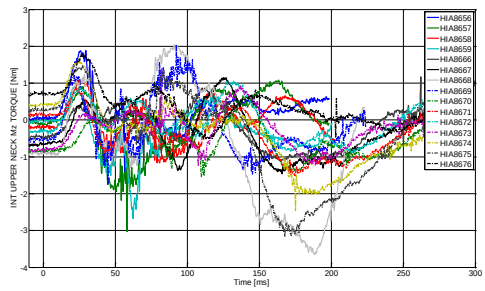



**Figure C-12. INT UPPER NECK Mz TORQUE**

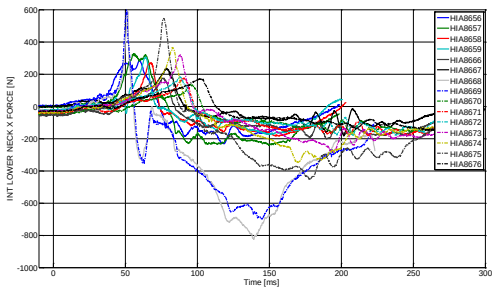



**Figure C-13. INT LOWER NECK X FORCE**

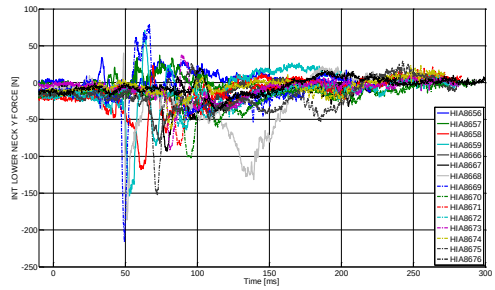



**Figure C-14. INT LOWER NECK Y FORCE**

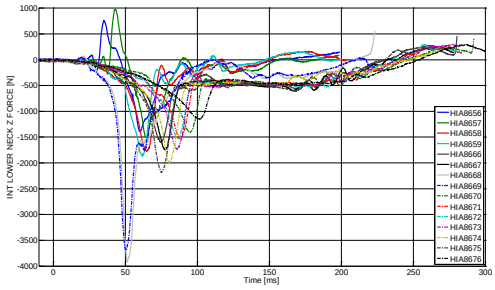



**Figure C-15. INT LOWER NECK Z FORCE**

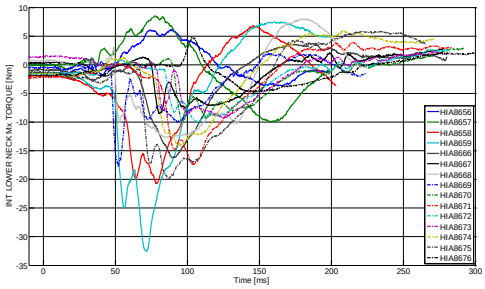



**Figure C-16. INT LOWER NECK Mx TORQUE**

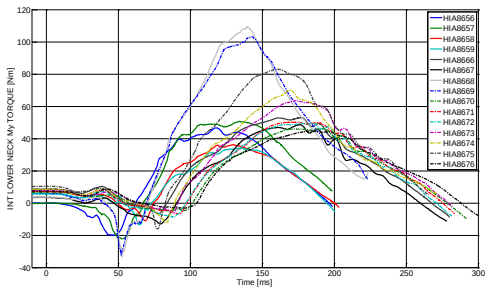



**Figure C-17. INT LOWER NECK My TORQUE**

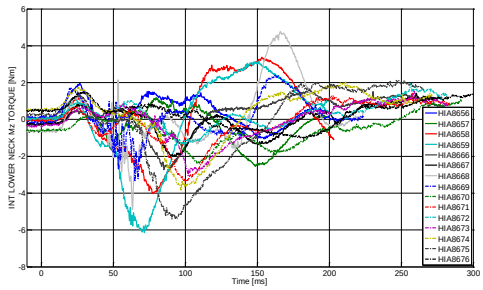



**Figure C-18. INT LOWER NECK Mz TORQUE**

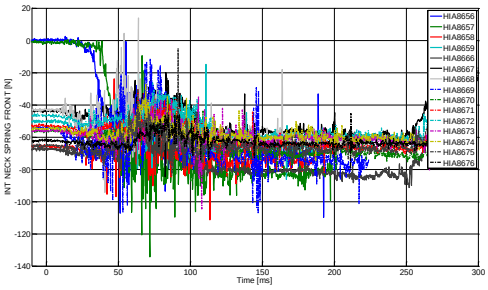



**Figure C-19. INT NECK SPRING FRONT**

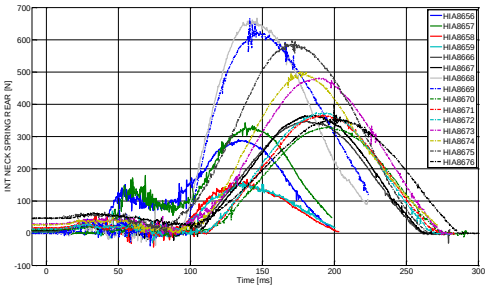



**Figure C-20. INT NECK SPRING REAR**

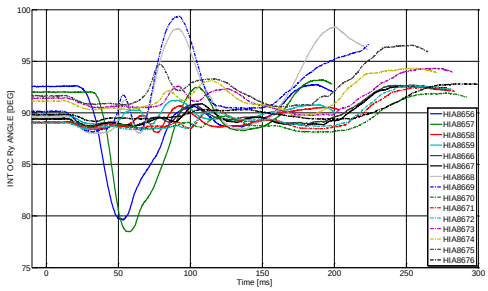



**Figure C-21. INT OC Ry ANGLE**

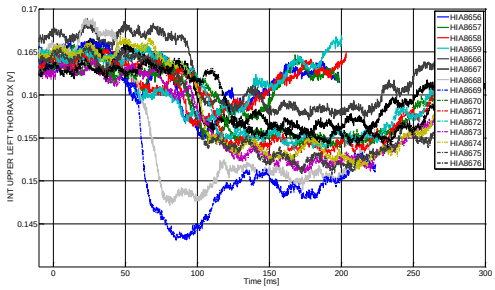



**Figure C-22. INT UPPER LEFT THORAX DX**

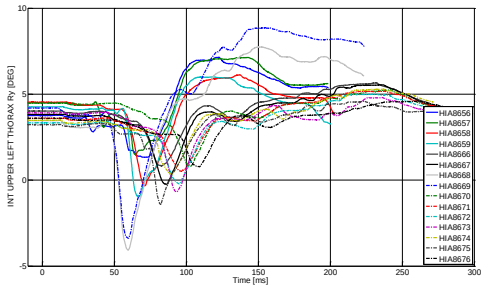



**Figure C-23. INT UPPER LEFT THORAX Ry**

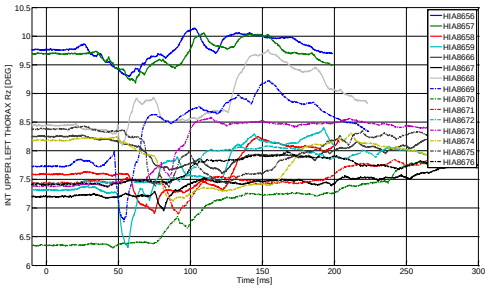



**Figure C-24. INT UPPER LEFT THORAX Rz**

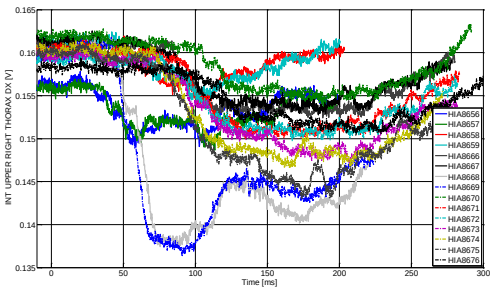



**Figure C-25. INT UPPER RIGHT THORAX DX**

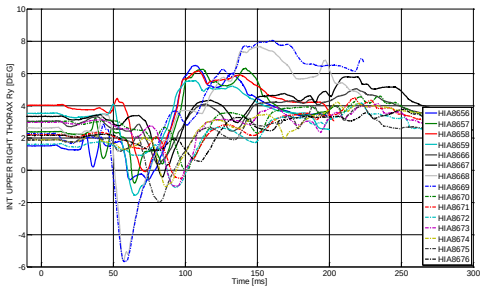



**Figure C-26. INT UPPER RIGHT THORAX Ry**

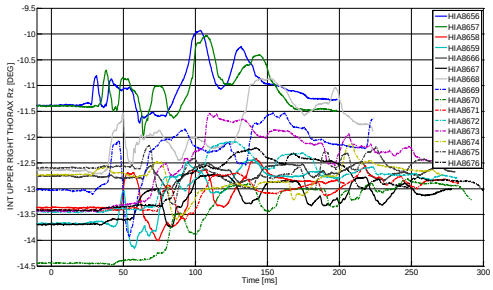



**Figure C-27. INT UPPER RIGHT THORAX Rz**

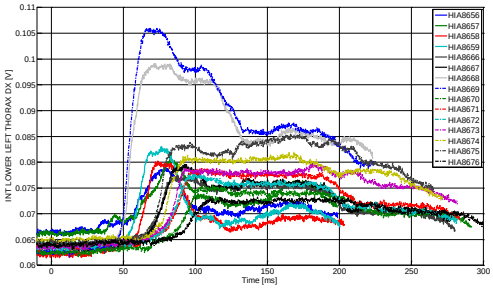



**Figure C-28. INT LOWER LEFT THORAX DX**

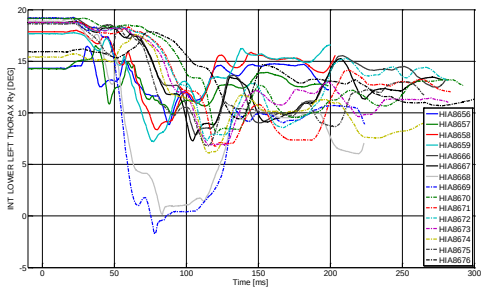



**Figure C-29. INT LOWER LEFT THORAX Ry**

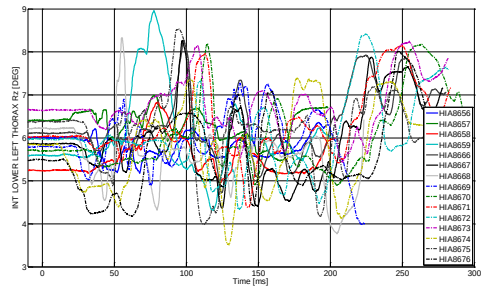



**Figure C-30. INT LOWER LEFT THORAX Rz**

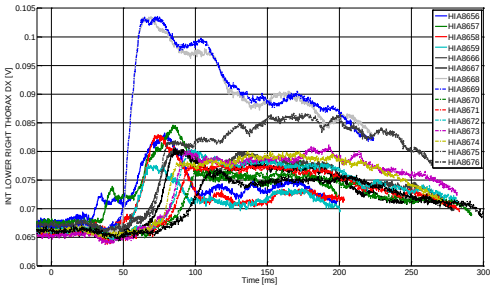



**Figure C-31. INT LOWER RIGHT THORAX DX**

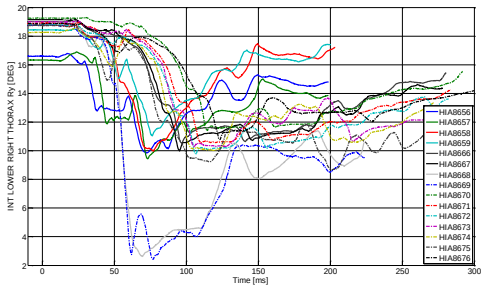



**Figure C-32. INT LOWER RIGHT THORAX Ry**

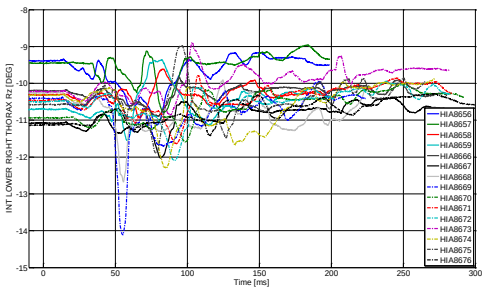



**Figure C-33. INT LOWER RIGHT THORAX Rz**

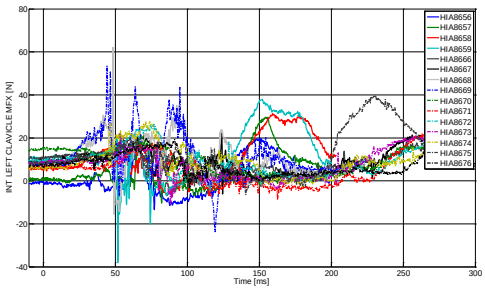



**Figure C-34. INT LEFT CLAVICLE MFX**

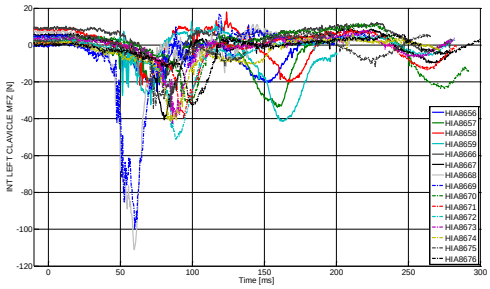



**Figure C-35. INT LEFT CLAVICLE MFZ**

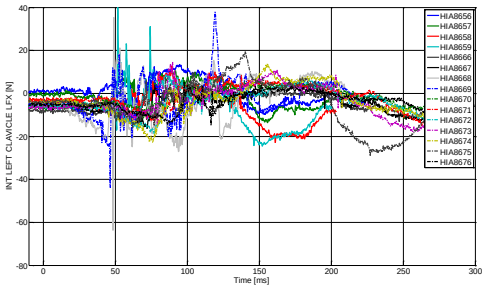



**Figure C-36. INT LEFT CLAVICLE LFX**

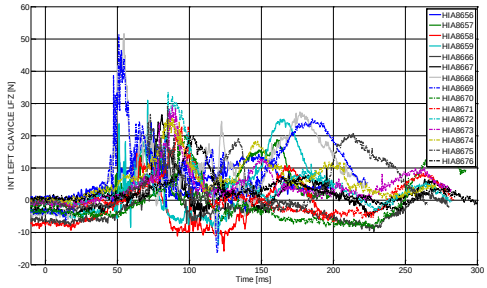



**Figure C-37. INT LEFT CLAVICLE LFZ**

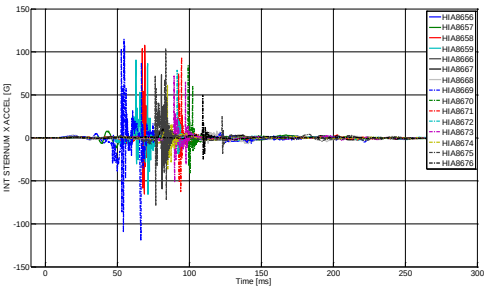



**Figure C-38. INT STERNUM X ACCEL**

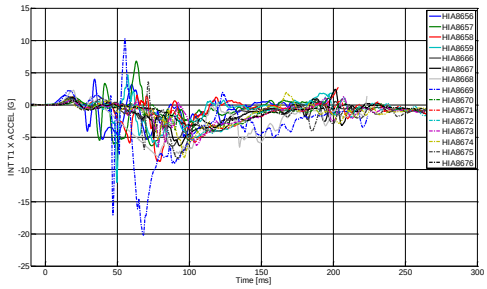



**Figure C-39. INT T1 X ACCEL**

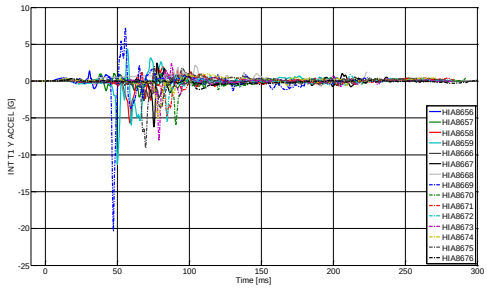



**Figure C-40. INT T1 Y ACCEL**

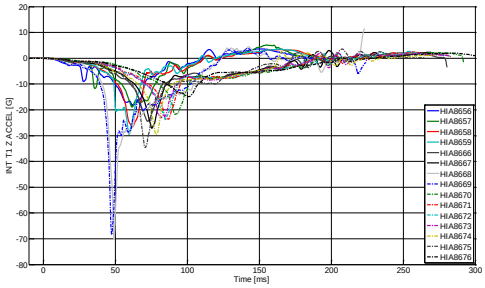



**Figure C-41. INT T1 Z ACCEL**

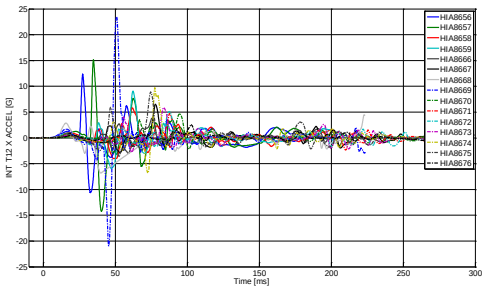



**Figure C-42. INT T12 X ACCEL**

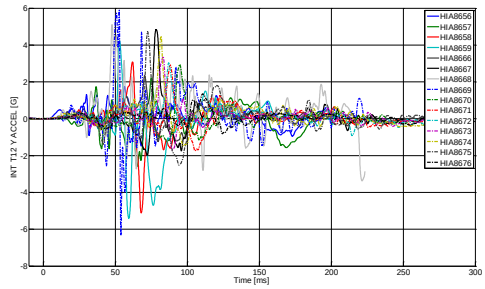



**Figure C-43. INT T12 Y ACCEL**

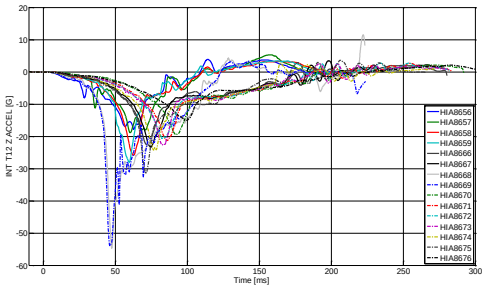



**Figure C-44. INT T12 Z ACCEL**

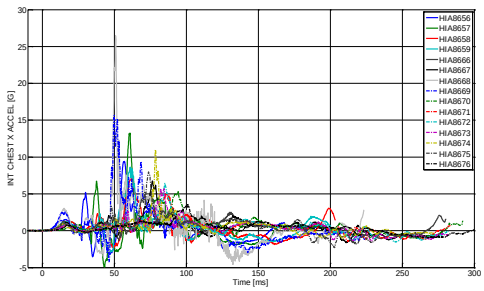



**Figure C-45. INT CHEST X ACCEL**

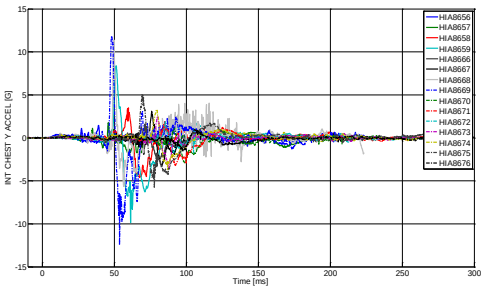



**Figure C-46. INT CHEST Y ACCEL**

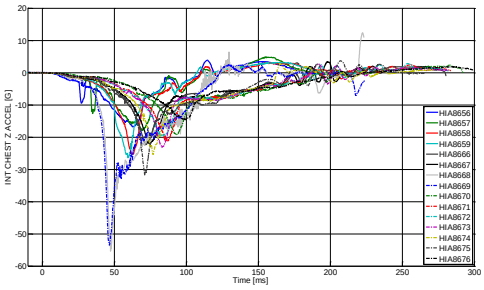



**Figure C-47. INT CHEST Z ACCEL**

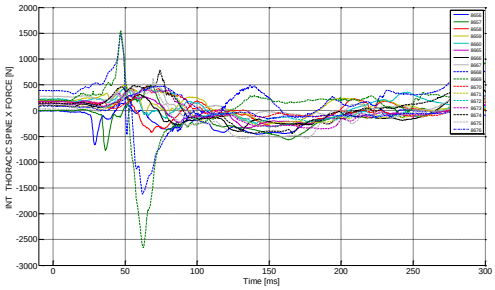



**Figure C-48. INT THORACIC SPINE X FORCE**

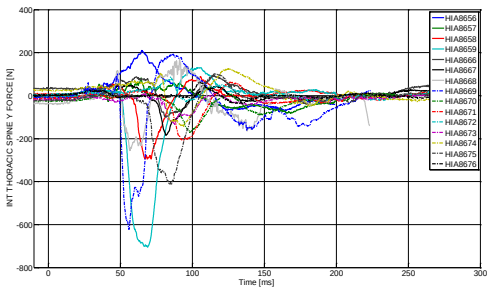



**Figure C-49. INT THORACIC SPINE Y FORCE**

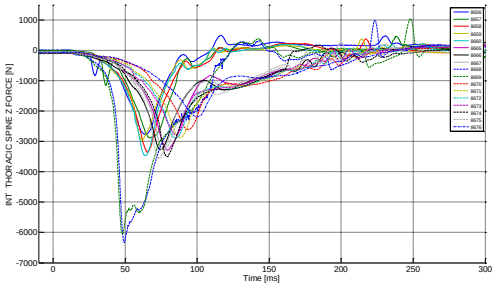



**Figure C-50. INT THORACIC SPINE Z FORCE**

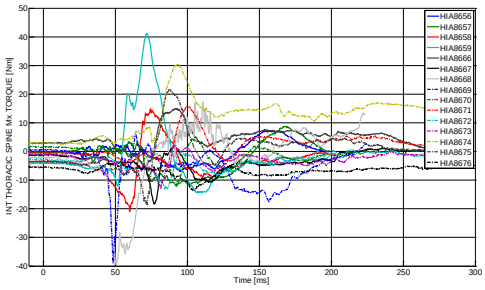



**Figure C-51. INT THORACIC SPINE Mx TORQUE**

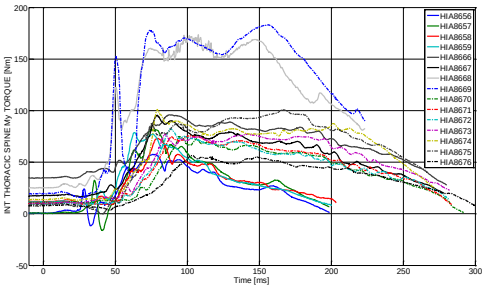



**Figure C-52. INT THORACIC SPINE My TORQUE**

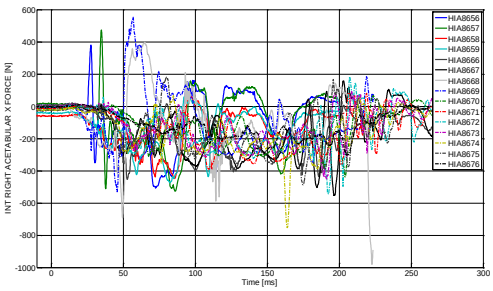



**Figure C-53. INT RIGHT ACETABULAR X FORCE**

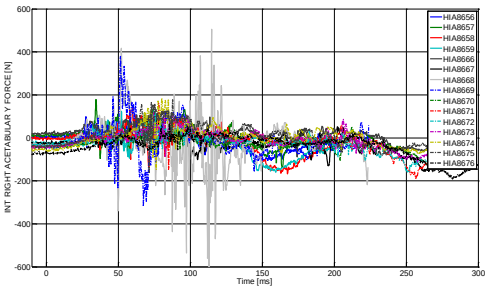



**Figure C-54. INT RIGHT ACETABULAR Y FORCE**

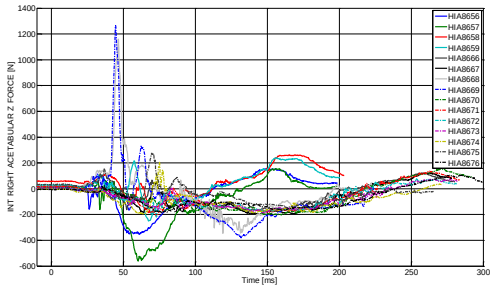



**Figure C-55. INT RIGHT ACETABULAR Z FORCE**

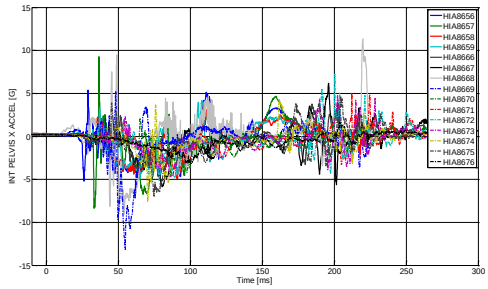



**Figure C-56. INT PELVIS X ACCEL**

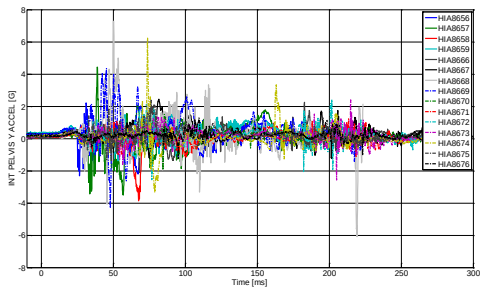



**Figure C-57. INT PELVIS Y ACCEL**

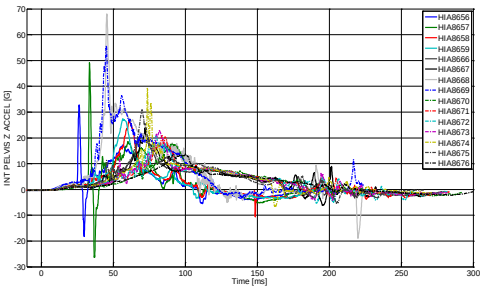



**Figure C-58. INT PELVIS Z ACCEL**

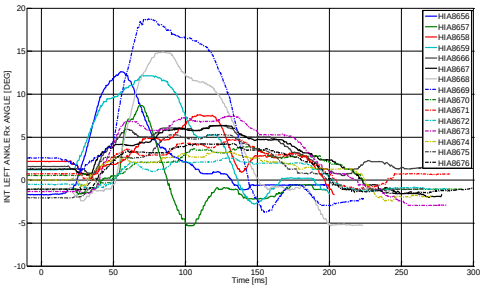



**Figure C-59. INT LEFT ANKLE Rx ANGLE**

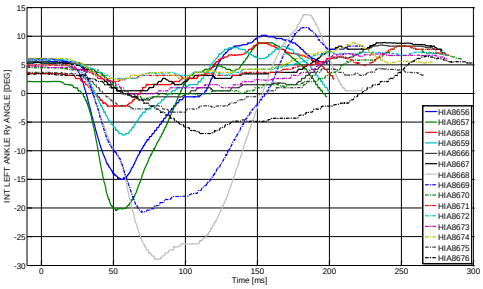



**Figure C-60. INT LEFT ANKLE Ry ANGLE**

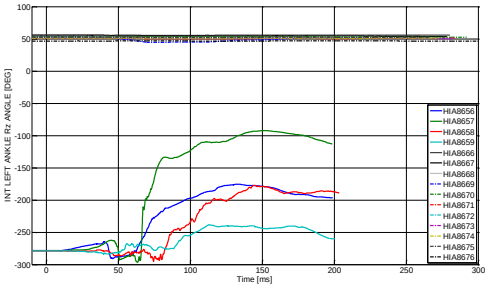



**Figure C-61. INT LEFT ANKLE Rz ANGLE**

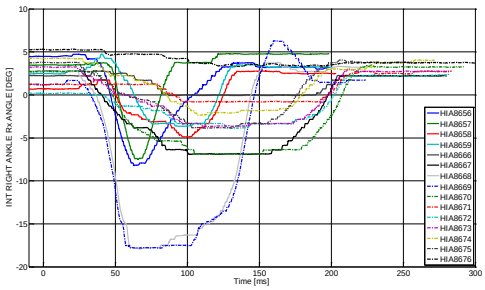



**Figure C-62. INT RIGHT ANKLE Rx ANGLE**

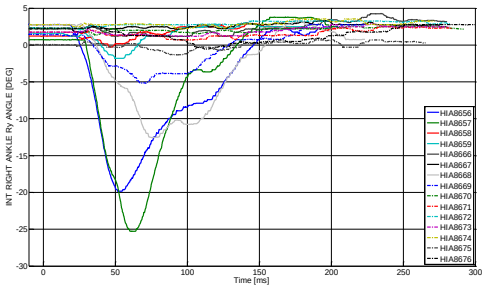



**Figure C-63. INT RIGHT ANKLE Ry ANGLE**

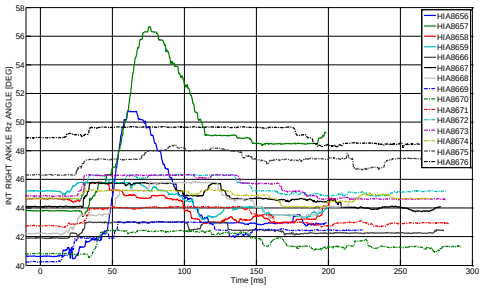



**Figure C-64. INT RIGHT ANKLE Rz ANGLE**

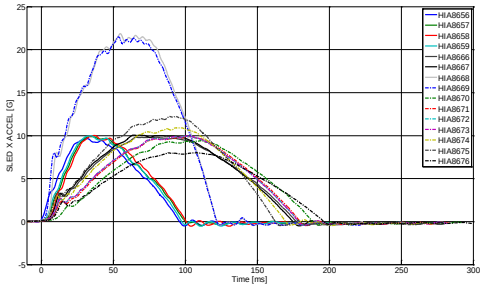



**Figure C-65. SLED X ACCEL**

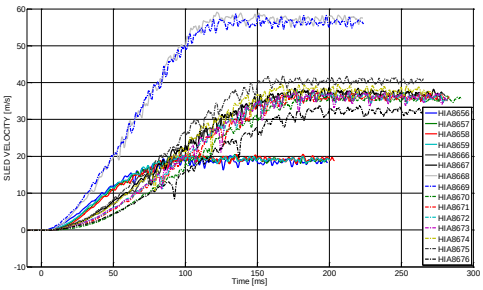



**Figure C-66. SLED VELOCITY**

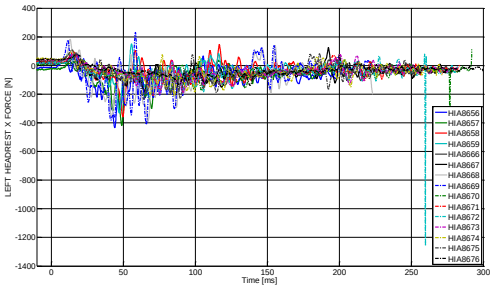



**Figure C-67. LEFT HEADREST X FORCE**

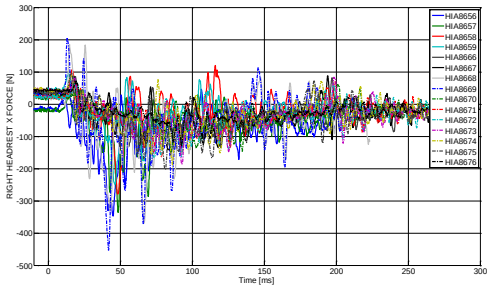



**Figure C-68. RIGHT HEADREST X FORCE**

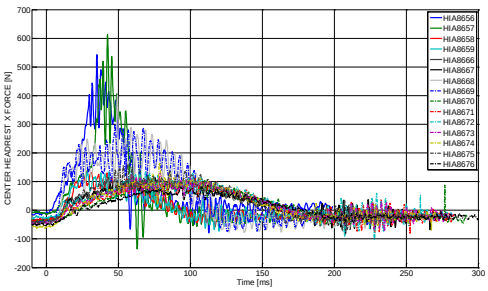



**Figure C-69. CENTER HEADREST X FORCE**

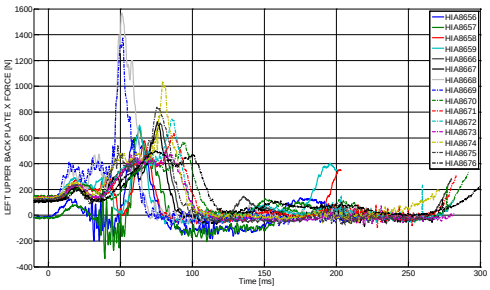



**Figure C-70. LEFT UPPER BACK PLATE X FORCE**

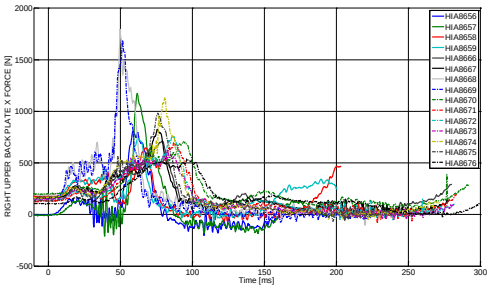



**Figure C-71. RIGHT UPPER BACK PLATE X FORCE**

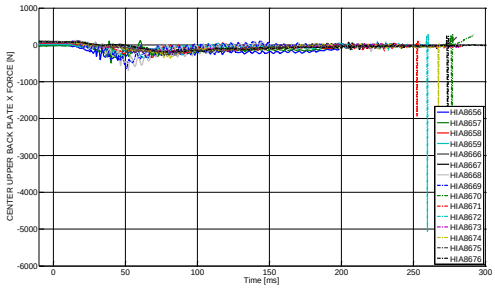



**Figure C-72. CENTER UPPER BACK PLATE X FORCE**

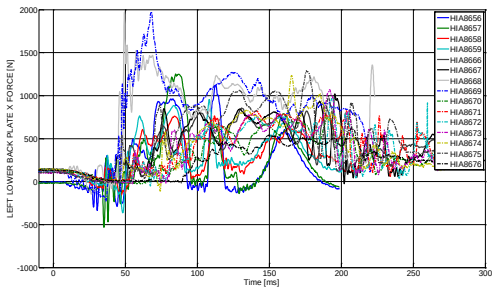



**Figure C-73. LEFT LOWER BACK PLATE X FORCE**

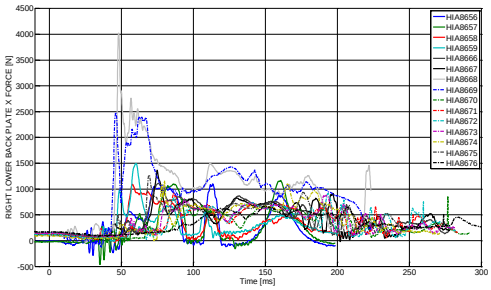



**Figure C-74. RIGHT LOWER BACK PLATE X FORCE**

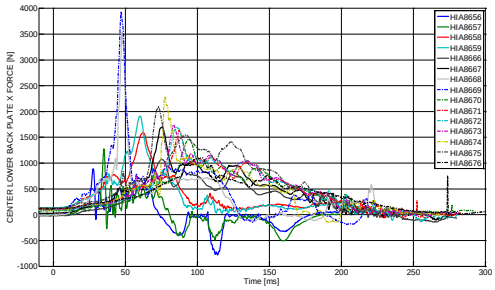



**Figure C-75. CENTER LOWER BACK PLATE X FORCE**

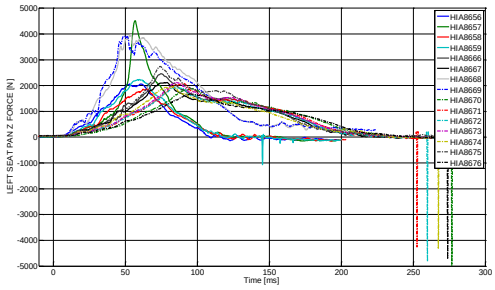



**Figure C-76. LEFT SEAT PAN Z FORCE**

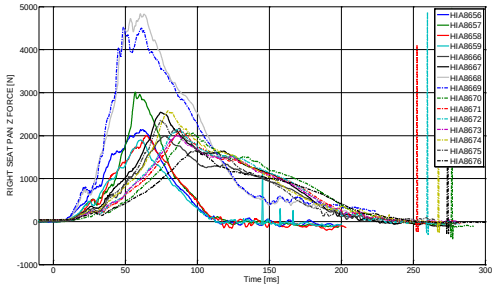



**Figure C-77. RIGHT SEAT PAN Z FORCE**

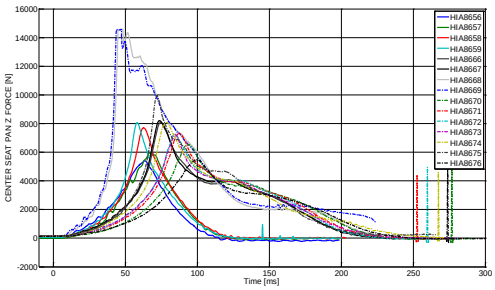



**Figure C-78. CENTER SEAT PAN Z FORCE**

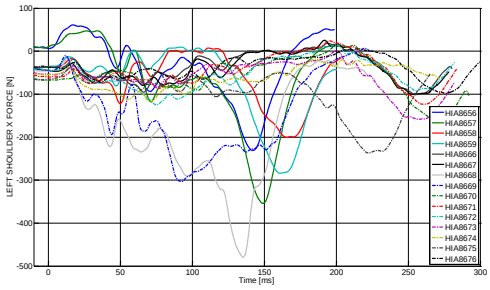



**Figure C-79. LEFT SHOULDER X FORCE**

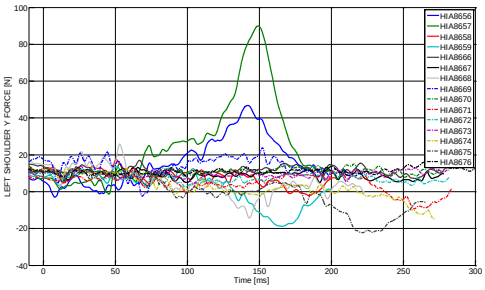



**Figure C-80. LEFT SHOULDER Y FORCE**

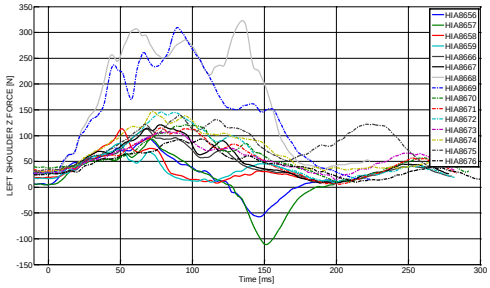



**Figure C-81. LEFT SHOULDER Z FORCE**

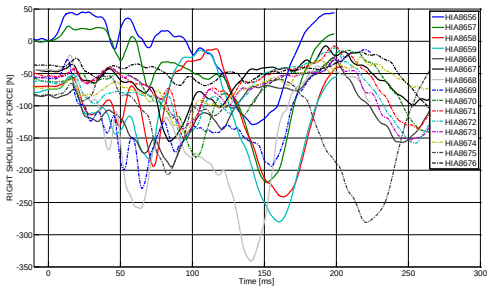



**Figure C-82. RIGHT SHOULDER X FORCE**

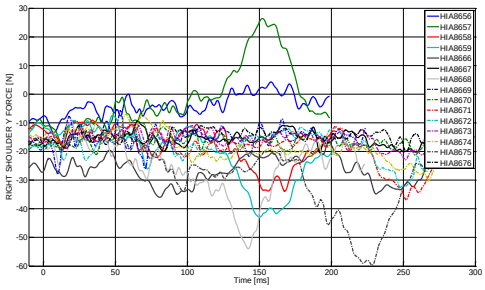



**Figure C-83. RIGHT SHOULDER Y FORCE**

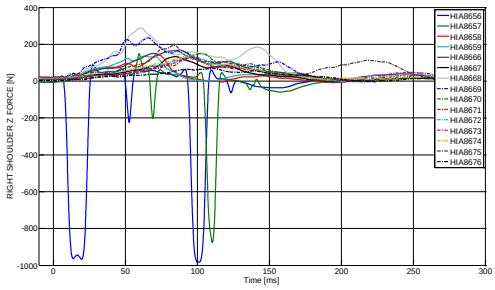



**Figure C-84. RIGHT SHOULDER Z FORCE**

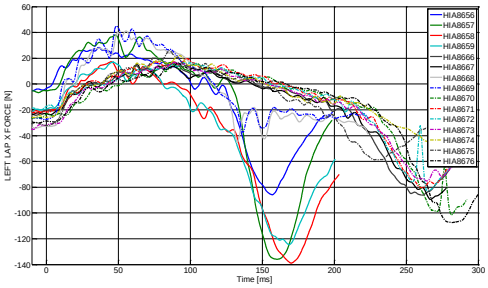



**Figure C-85. LEFT LAP X FORCE**

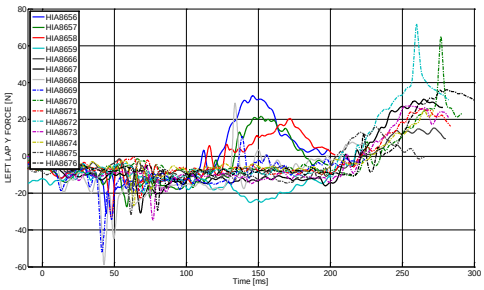



**Figure C-86. LEFT LAP Y FORCE**

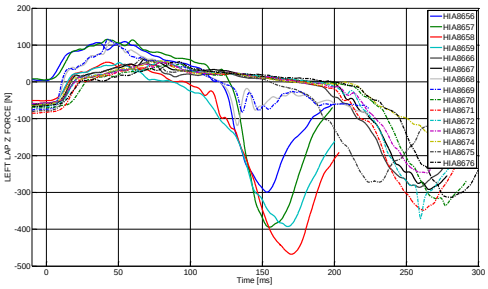



**Figure C-87. LEFT LAP Z FORCE**

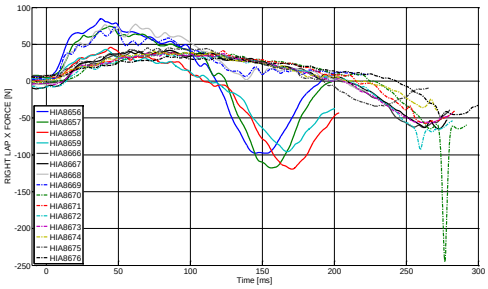



**Figure C-88. RIGHT LAP X FORCE**

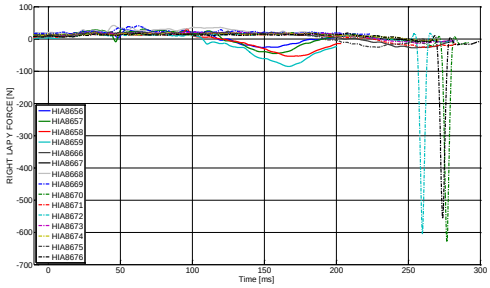



**Figure C-89. RIGHT LAP Y FORCE**

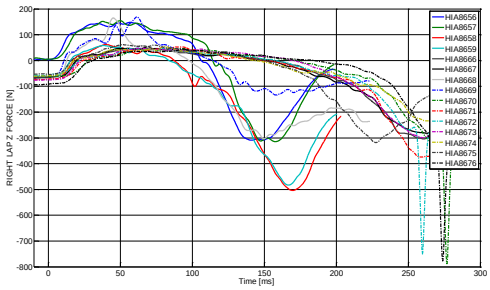



**Figure C-90. RIGHT LAP Z FORCE**

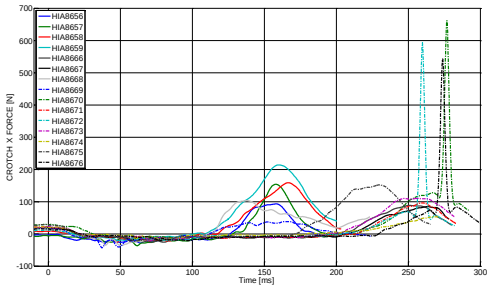



**Figure C-91. CROTCH X FORCE**

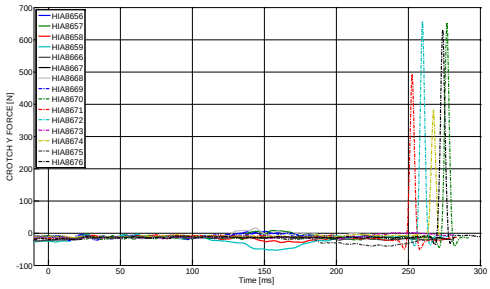



**Figure C-92. CROTCH Y FORCE**

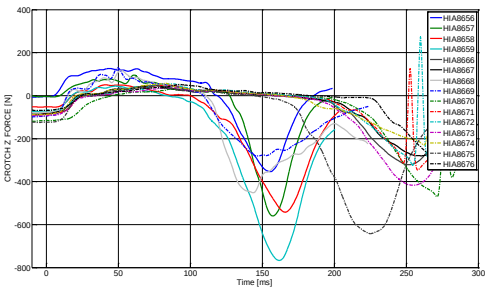



**Figure C-93. CROTCH Z FORCE**

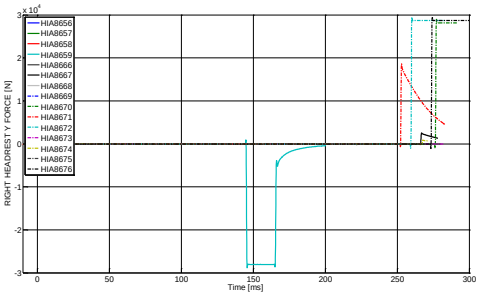



**Figure C-94. RIGHT HEADREST Y FORCE**

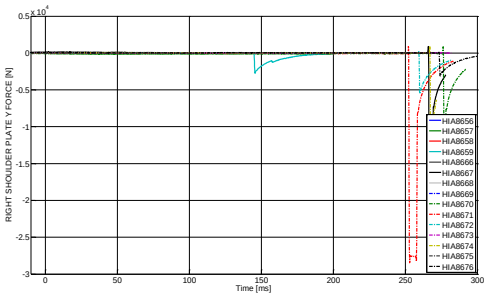



**Figure C-95. RIGHT SHOULDER PLATE Y FORCE**

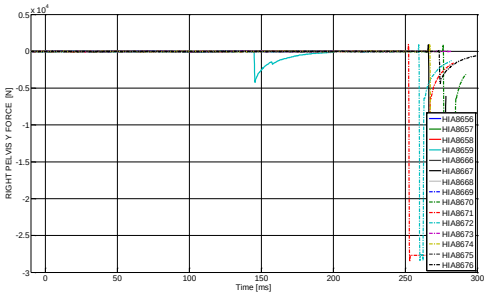



**Figure C-96. RIGHT PELVIS Y FORCE**

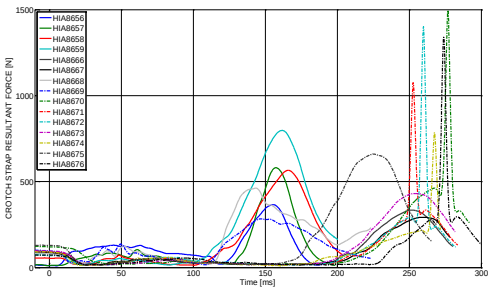



**Figure C-97. CROTCH STRAP RESULTANT FORCE**

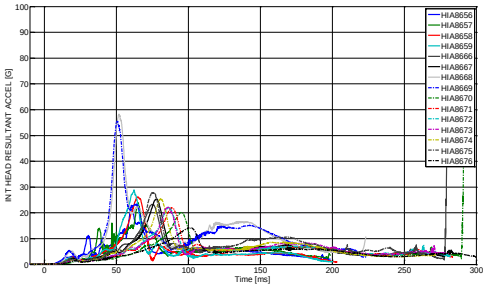



**Figure C-98. INT HEAD RESULTANT ACCEL**

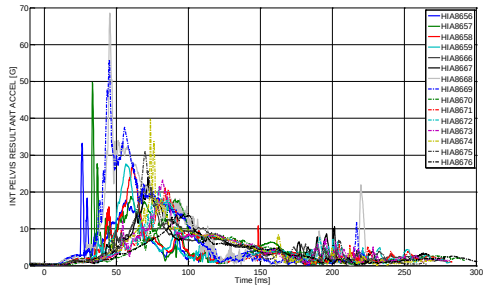



**Figure C-99. INT PELVIS RESULTANT ACCEL**

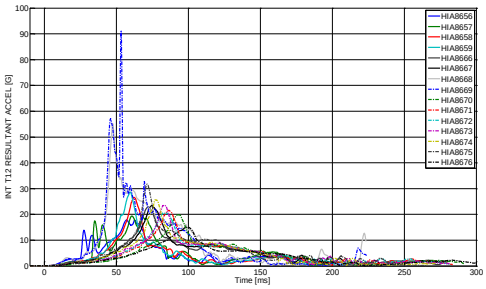



**Figure C-100. INT T12 RESULTANT ACCEL**

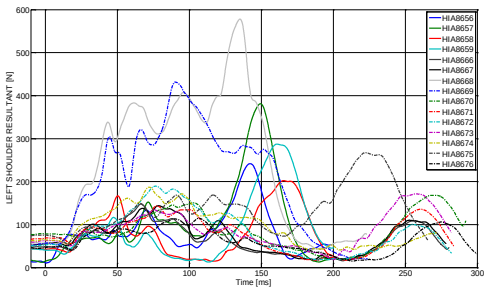



**Figure C-101. LEFT SHOULDER RESULTANT**

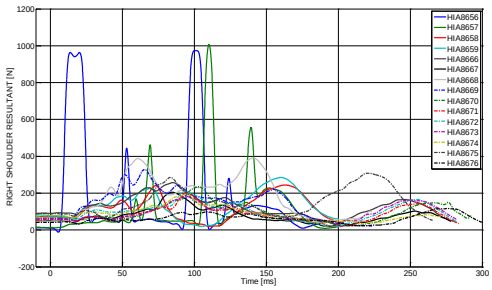



**Figure C-102. RIGHT SHOULDER RESULTANT**

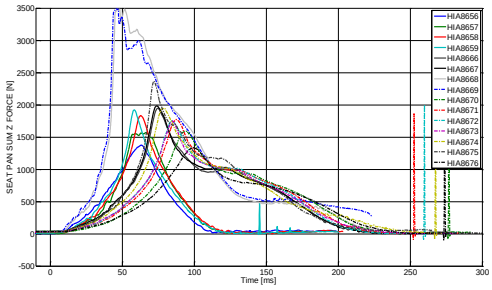



**Figure C-103. SEAT PAN SUM Z FORCE**

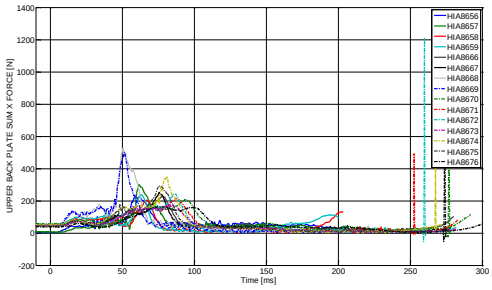



**Figure C-104. UPPER BACK PLATE SUM X FORCE**

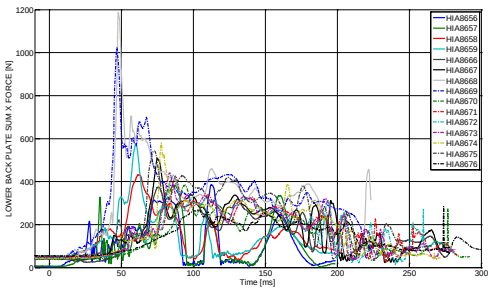



**Figure C-105. LOWER BACK PLATE SUM X FORCE**

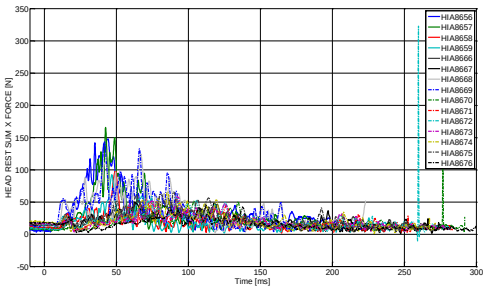



**Figure C-106. HEAD REST SUM X FORCE**

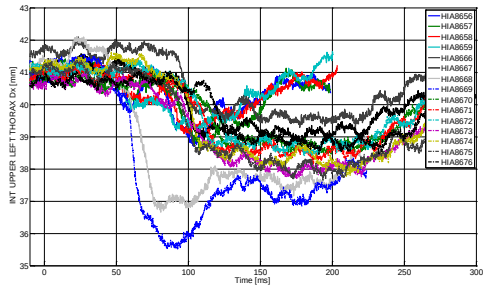



**Figure C-107. INT UPPER LEFT THORAX Dx**

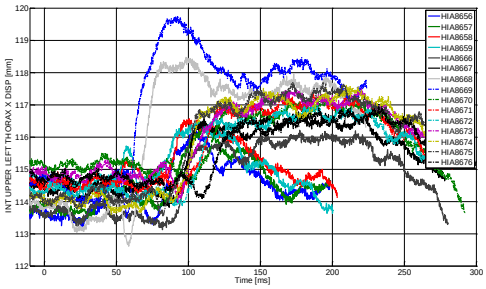



**Figure C-108. INT UPPER LEFT THORAX X DISP**

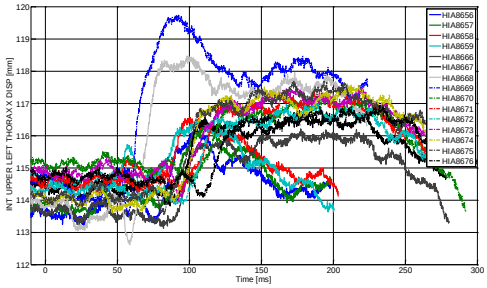



**Figure C-109. INT UPPER LEFT THORAX X DISP**

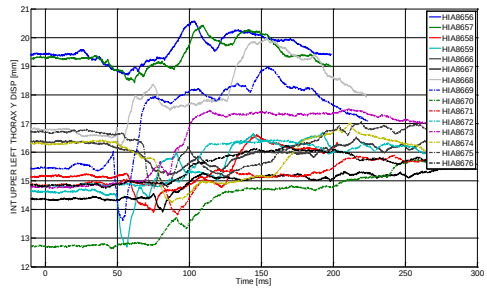



**Figure C-110. INT UPPER LEFT THORAX Y DISP**

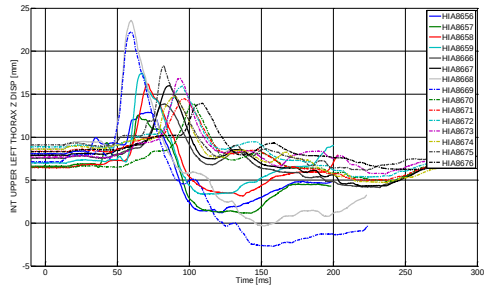



**Figure C-111. INT UPPER LEFT THORAX Z DISP**

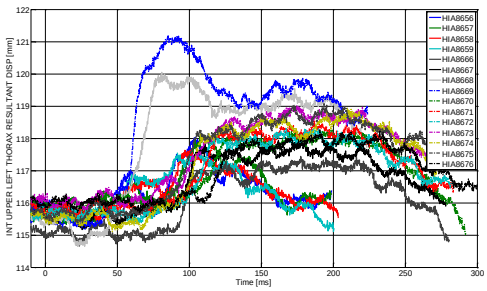



**Figure C-112. INT UPPER LEFT THORAX RESULTANT DISP**

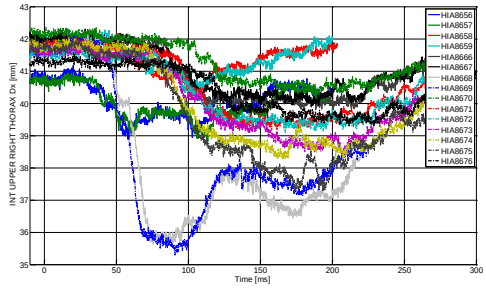



**Figure C-113. INT UPPER RIGHT THORAX Dx**

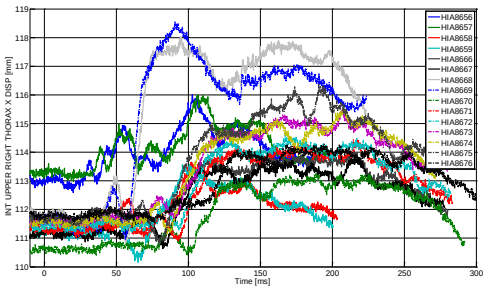



**Figure C-114. INT UPPER RIGHT THORAX X DISP**

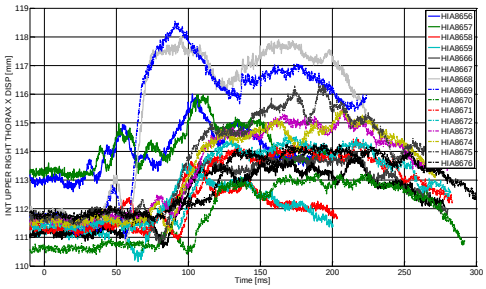



**Figure C-115. INT UPPER RIGHT THORAX X DISP**

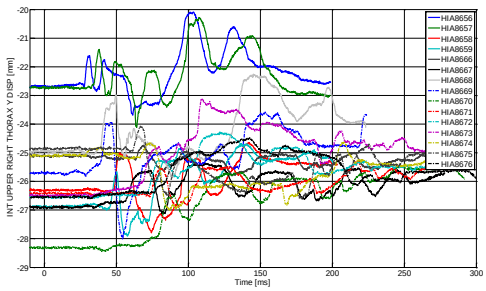



**Figure C-116. INT UPPER RIGHT THORAX Y DISP**

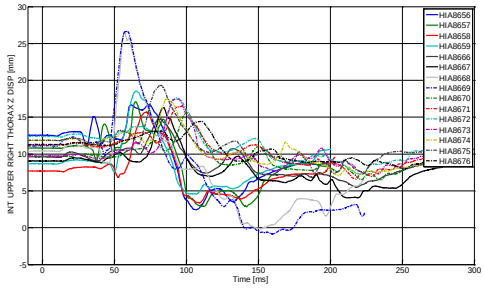



**Figure C-117. INT UPPER RIGHT THORAX Z DISP**

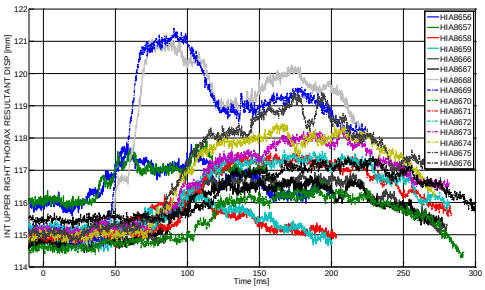



**Figure C-118. INT UPPER RIGHT THORAX RESULTANT DISP**

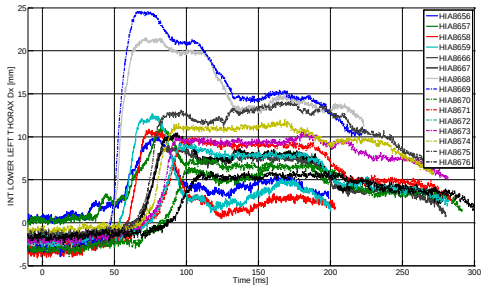



**Figure C-119. INT LOWER LEFT THORAX Dx**

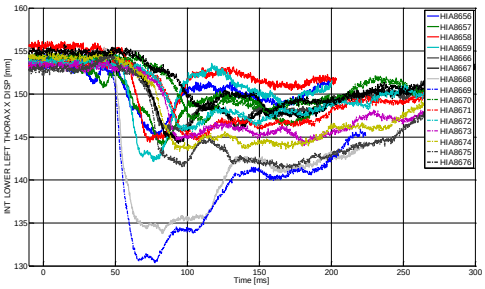



**Figure C-120. INT LOWER LEFT THORAX X DISP**

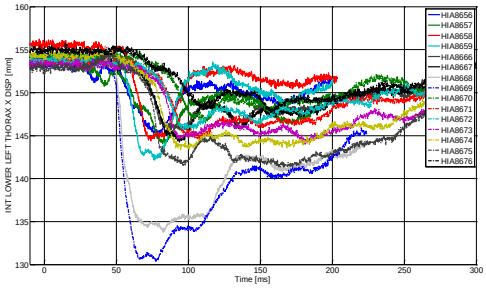



**Figure C-121. INT LOWER LEFT THORAX X DISP**

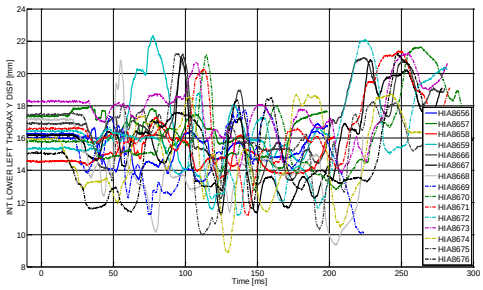



**Figure C-122. INT LOWER LEFT THORAX Y DISP**

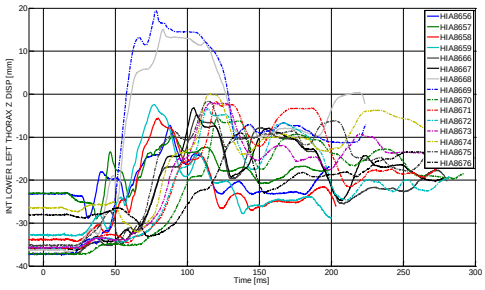



**Figure C-123. INT LOWER LEFT THORAX Z DISP**

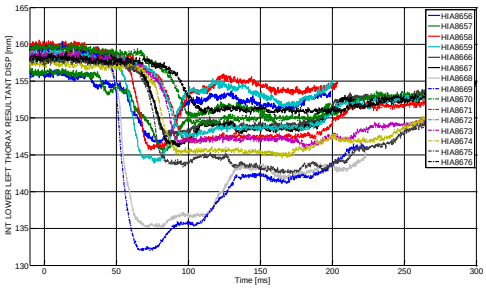



**Figure C-124. INT LOWER LEFT THORAX RESULTANT DISP**

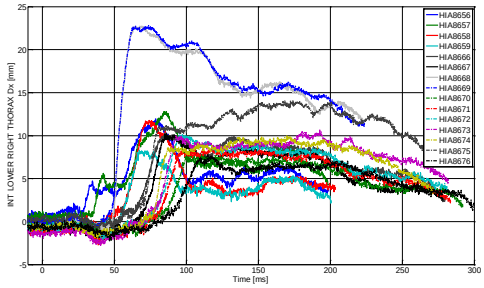



**Figure C-125. INT LOWER RIGHT THORAX Dx**

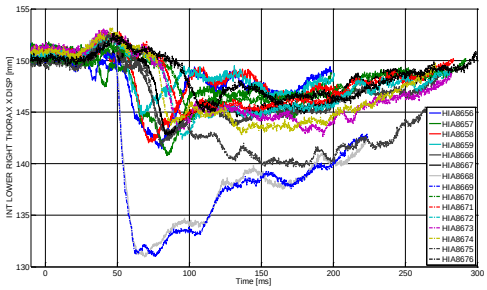



**Figure C-126. INT LOWER RIGHT THORAX X DISP**

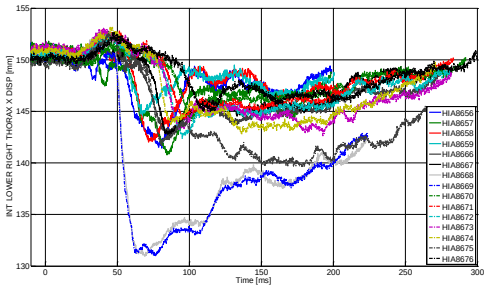



**Figure C-127. INT LOWER RIGHT THORAX X DISP**

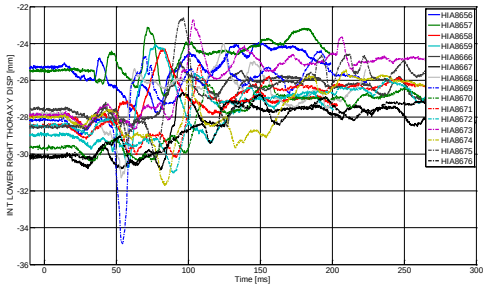



**Figure C-128. INT LOWER RIGHT THORAX Y DISP**

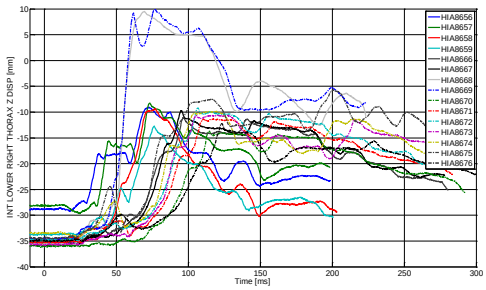



**Figure C-129. INT LOWER RIGHT THORAX Z DISP**

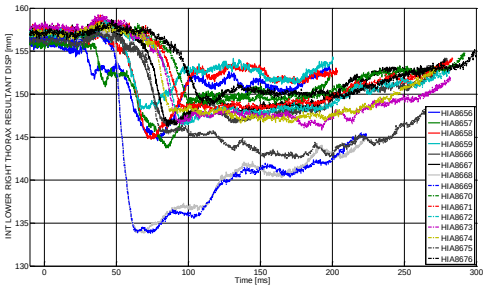



**Figure C-130. INT LOWER RIGHT THORAX RESULTANT DISP**

## D. Aerospace Hybrid III Frontal Tests

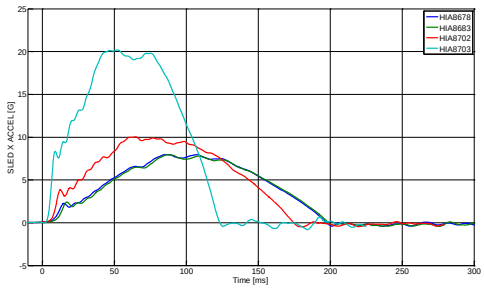



**Figure D-1. SLED X ACCEL**

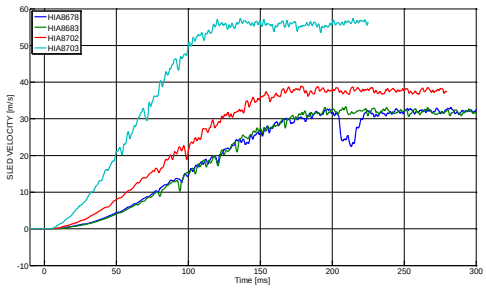



**Figure D-2. SLED VELOCITY**

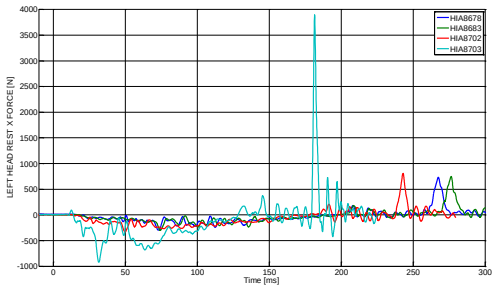



**Figure D-3. LEFT HEAD REST X FORCE**

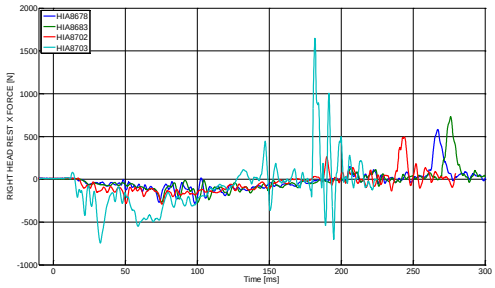



**Figure D-4. RIGHT HEAD REST X FORCE**

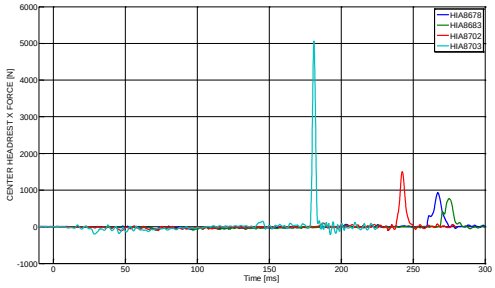



**Figure D-5. CENTER HEADREST X FORCE**

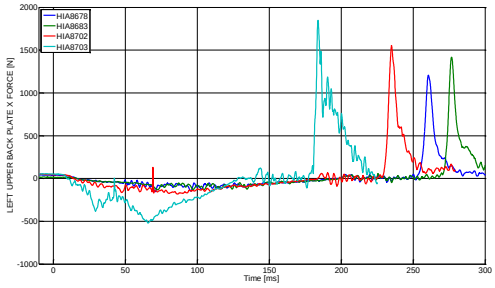



**Figure D-6. LEFT UPPER BACK PLATE X FORCE**

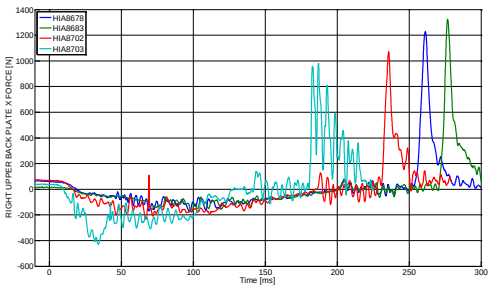



**Figure D-7. RIGHT UPPER BACK PLATE X FORCE**

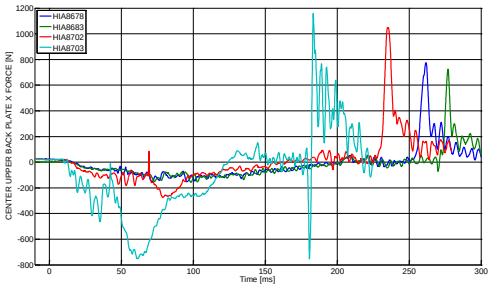



**Figure D-8. CENTER UPPER BACK PLATE X FORCE**

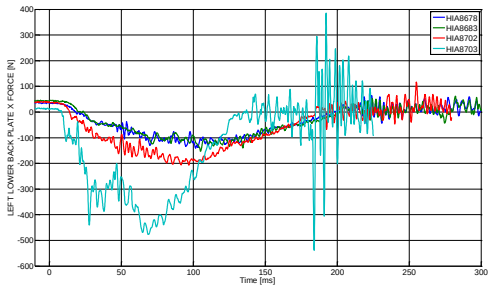



**Figure D-9. LEFT LOWER BACK PLATE X FORCE**

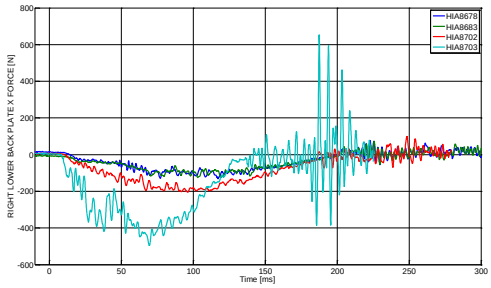



**Figure D-10. RIGHT LOWER BACK PLATE X FORCE**

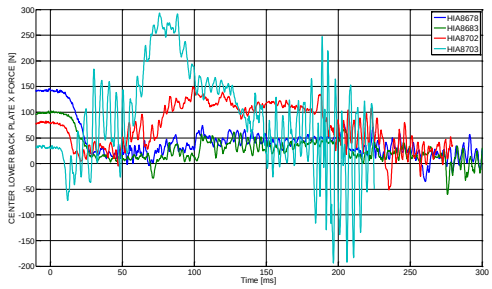



**Figure D-11. CENTER LOWER BACK PLATE X FORCE**

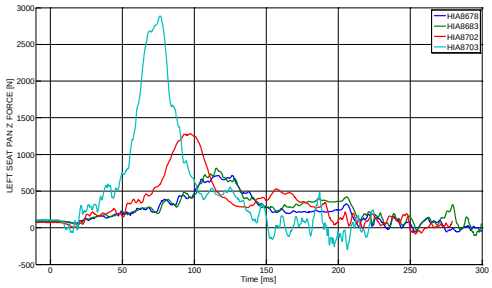



**Figure D-12. LEFT SEAT PAN Z FORCE**

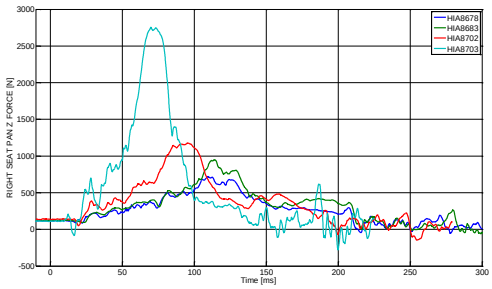



**Figure D-13. RIGHT SEAT PAN Z FORCE**

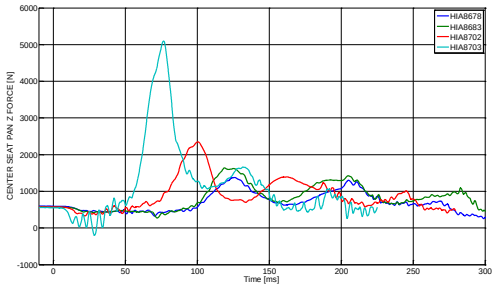



**Figure D-14. CENTER SEAT PAN Z FORCE**

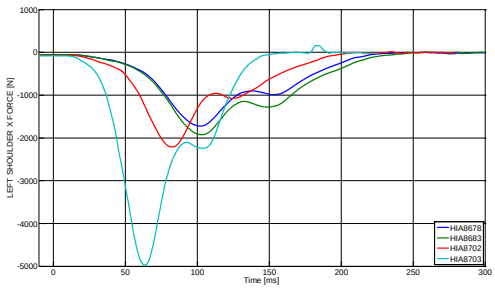



**Figure D-15. LEFT SHOULDER X FORCE**

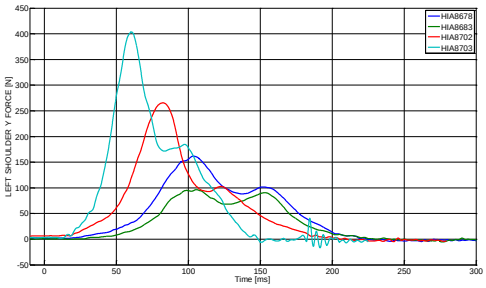



**Figure D-16. LEFT SHOULDER Y FORCE**

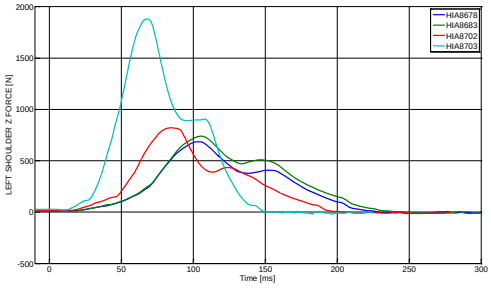



**Figure D-17. LEFT SHOULDER Z FORCE**

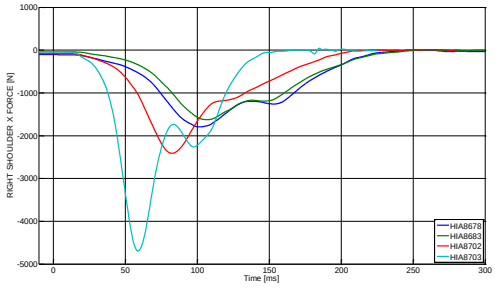



**Figure D-18. RIGHT SHOULDER X FORCE**

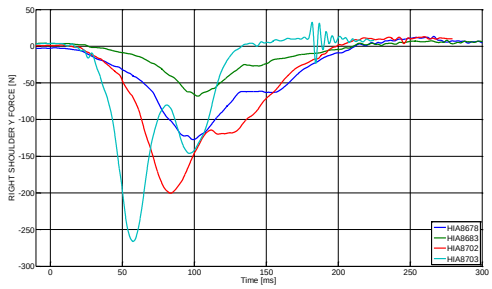



**Figure D-19. RIGHT SHOULDER Y FORCE**

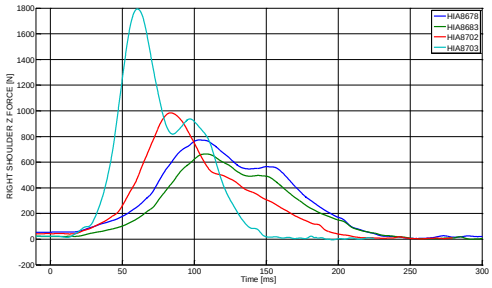



**Figure D-20. RIGHT SHOULDER Z FORCE**

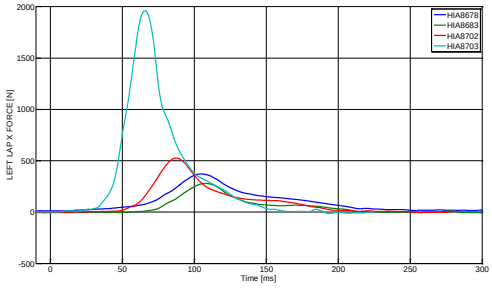



**Figure D-21. LEFT LAP X FORCE**

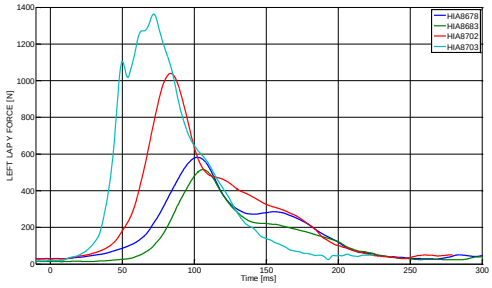



**Figure D-22. LEFT LAP Y FORCE**

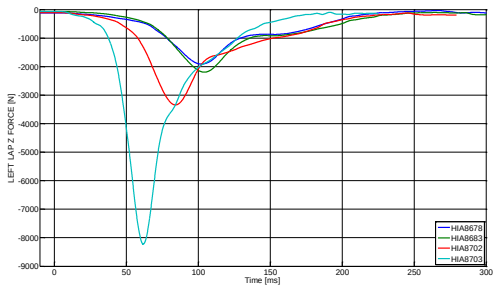



**Figure D-23. LEFT LAP Z FORCE**

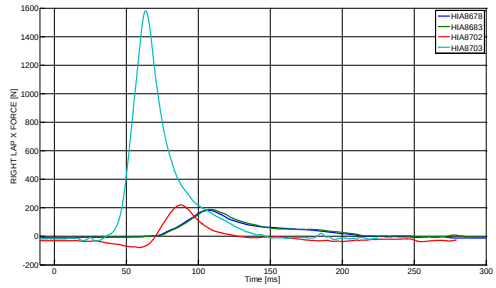



**Figure D-24. RIGHT LAP X FORCE**

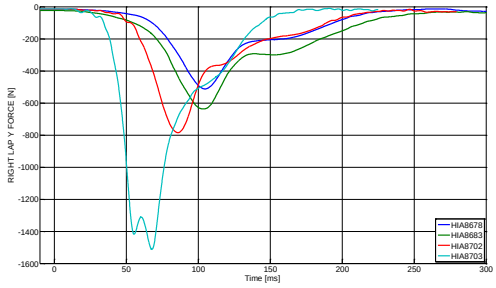



**Figure D-25. RIGHT LAP Y FORCE**

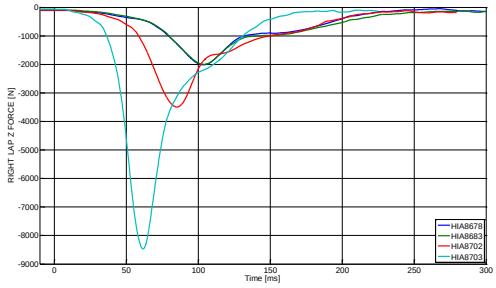



**Figure D-26. RIGHT LAP Z FORCE**

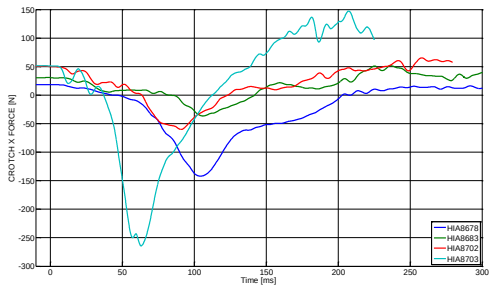



**Figure D-27. CROTCH X FORCE**

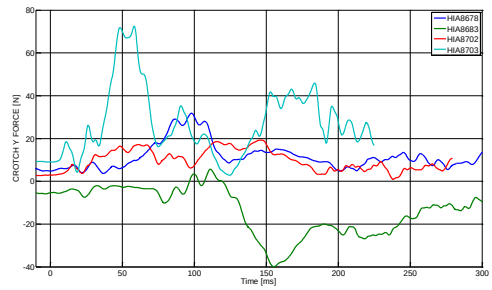



**Figure D-28. CROTCH Y FORCE**

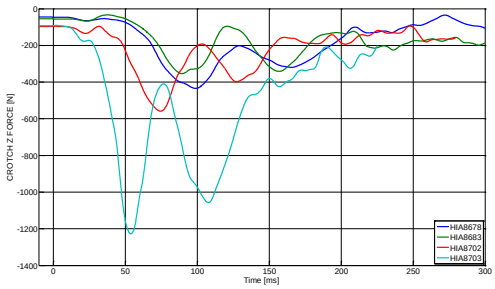



**Figure D-29. CROTCH Z FORCE**

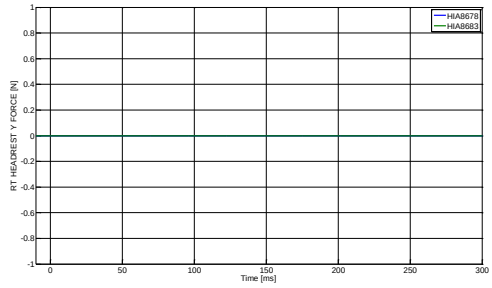



**Figure D-30. RT HEADREST Y FORCE**

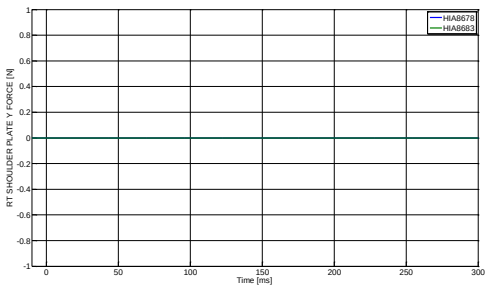



**Figure D-31. RT SHOULDER PLATE Y FORCE**

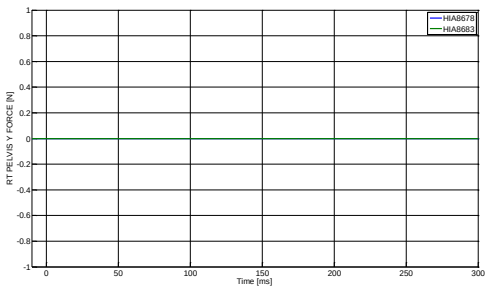



**Figure D-32. RT PELVIS Y FORCE**

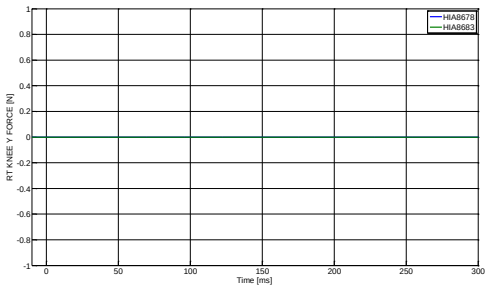



**Figure D-33. RT KNEE Y FORCE**

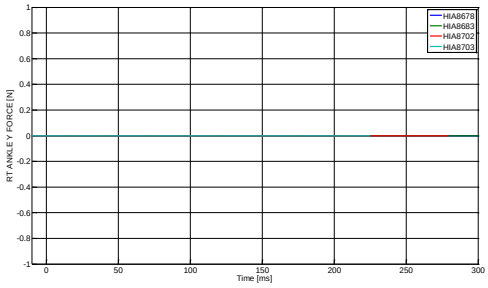



**Figure D-34. RT ANKLE Y FORCE**

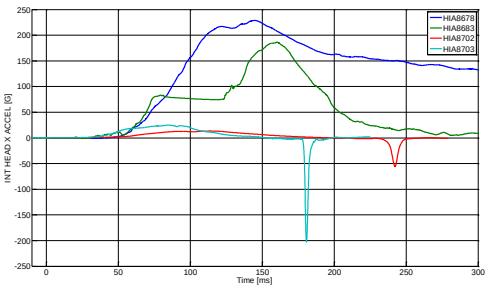



**Figure D-35. INT HEAD X ACCEL**

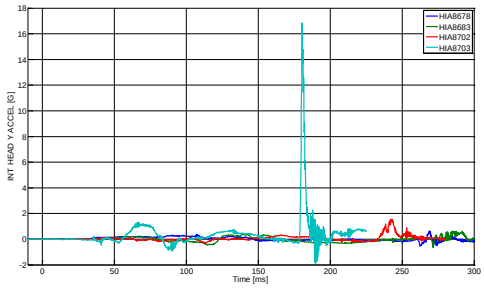



**Figure D-36. INT HEAD Y ACCEL**

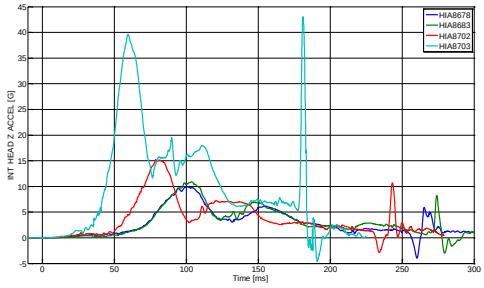



**Figure D-37. INT HEAD Z ACCEL**

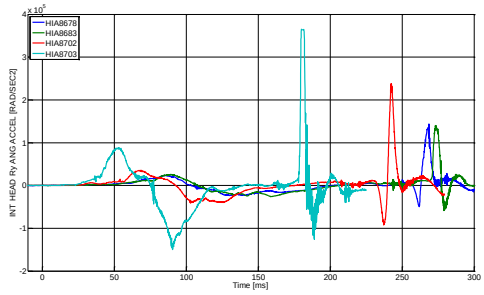



**Figure D-38. INT HEAD Ry ANG ACCEL**

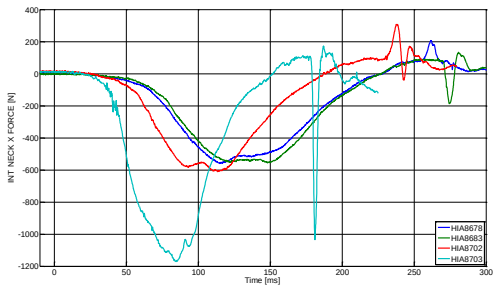



**Figure D-39. INT NECK X FORCE**

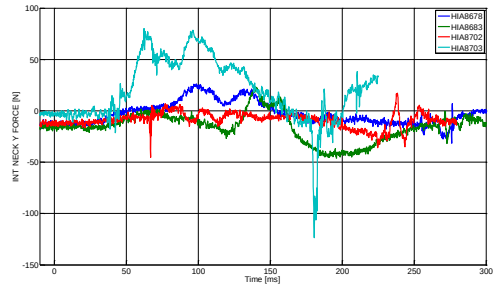



**Figure D-40. INT NECK Y FORCE**

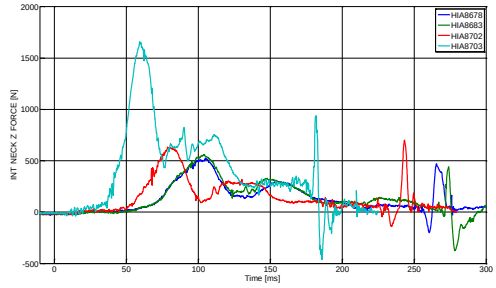



**Figure D-41. INT NECK Z FORCE**

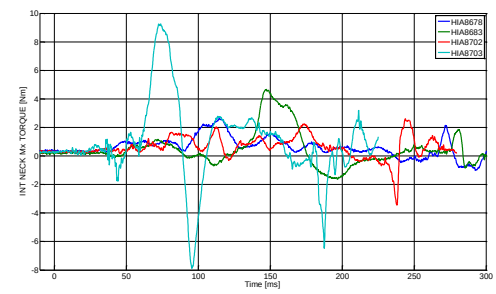



**Figure D-42. INT NECK Mx TORQUE**

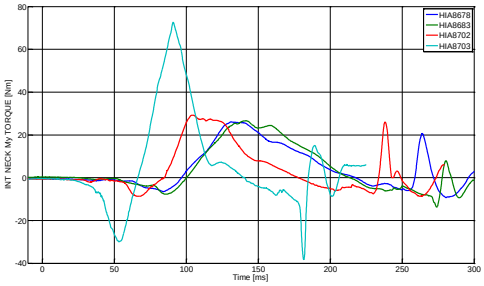



**Figure D-43. INT NECK My TORQUE**

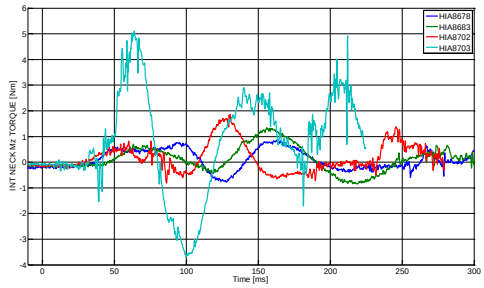



**Figure D-44. INT NECK Mz TORQUE**

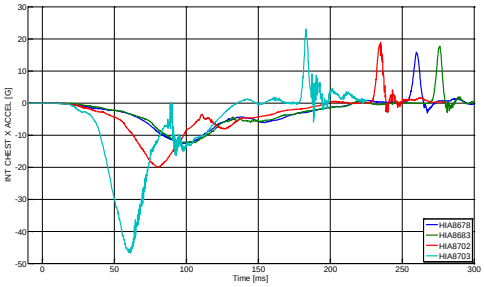



**Figure D-45. INT CHEST X ACCEL**

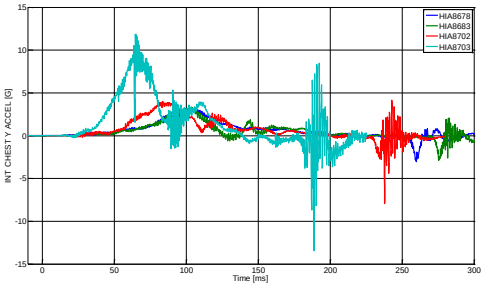



**Figure D-46. INT CHEST Y ACCEL**

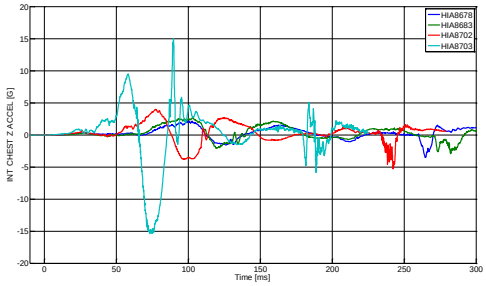



**Figure D-47. INT CHEST Z ACCEL**

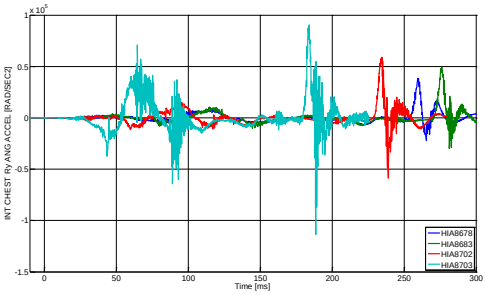



**Figure D-48. INT CHEST Ry ANG ACCEL**

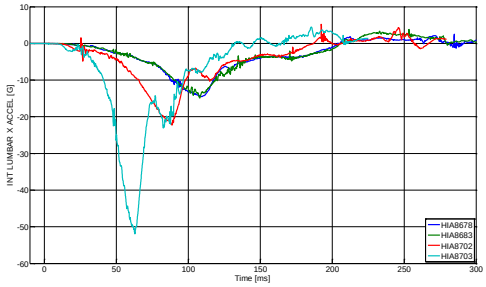



**Figure D-49. INT LUMBAR X ACCEL**

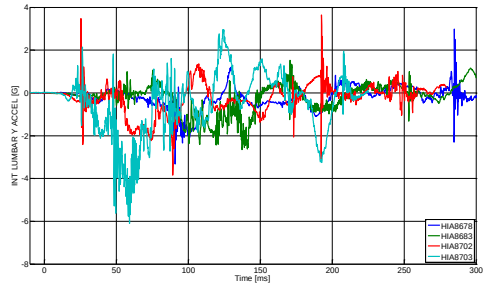



**Figure D-50. INT LUMBAR Y ACCEL**

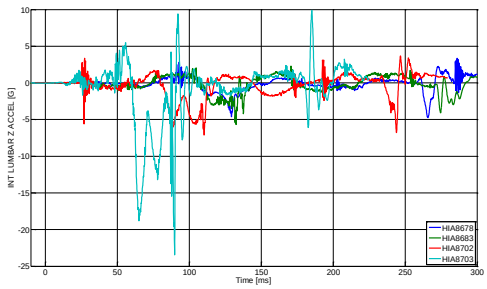



**Figure D-51. INT LUMBAR Z ACCEL**

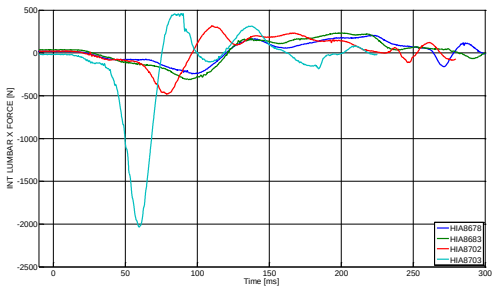



**Figure D-52. INT LUMBAR X FORCE**

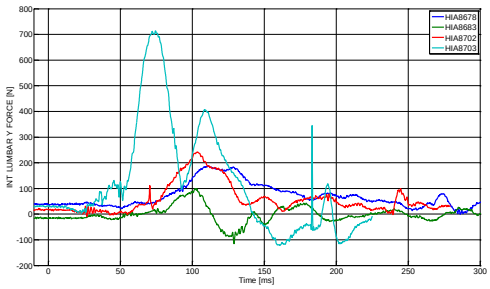



**Figure D-53. INT LUMBAR Y FORCE**

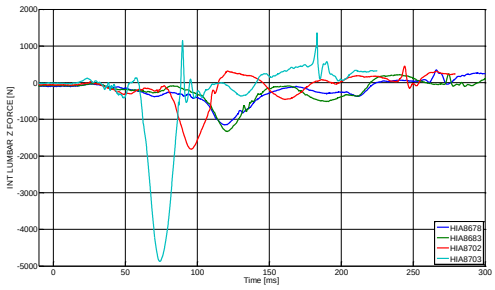



**Figure D-54. INT LUMBAR Z FORCE**

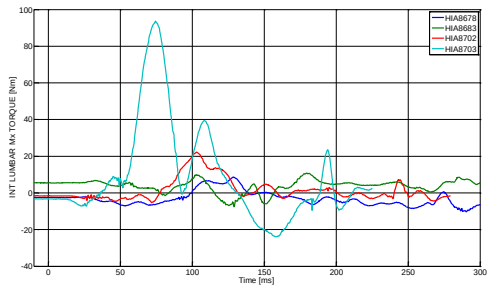



**Figure D-55. INT LUMBAR Mx TORQUE**

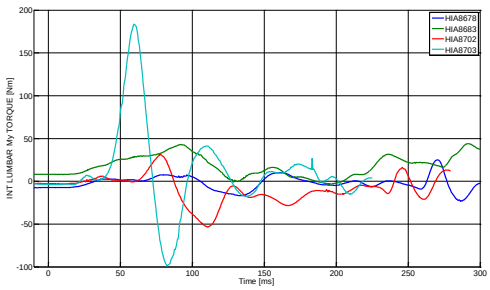



**Figure D-56. INT LUMBAR My TORQUE**

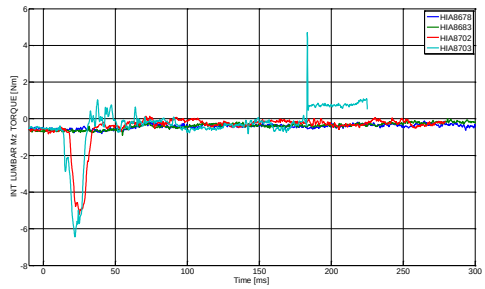



**Figure D-57. INT LUMBAR Mz TORQUE**

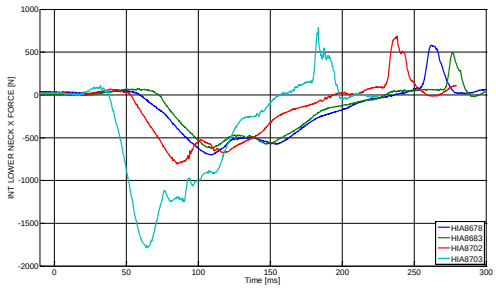



**Figure D-58. INT LOWER NECK X FORCE**

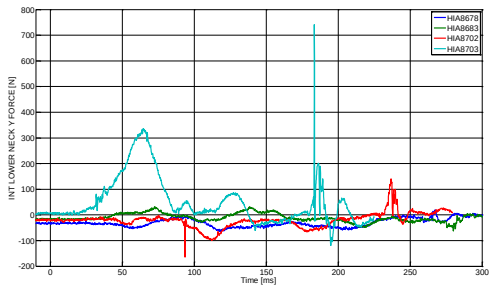



**Figure D-59. INT LOWER NECK Y FORCE**

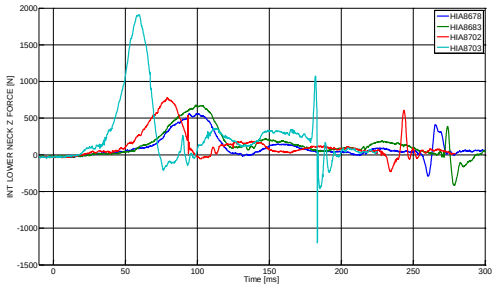



**Figure D-60. INT LOWER NECK Z FORCE**

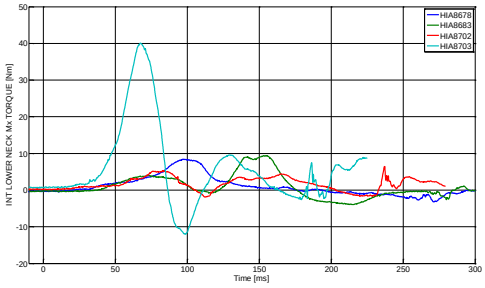



**Figure D-61. INT LOWER NECK Mx TORQUE**

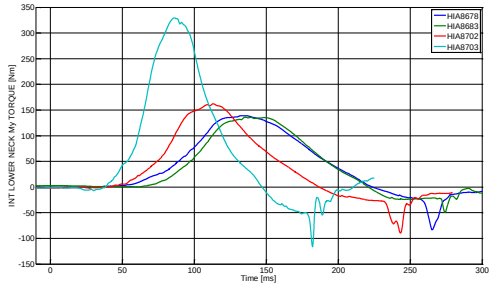



**Figure D-62. INT LOWER NECK My TORQUE**

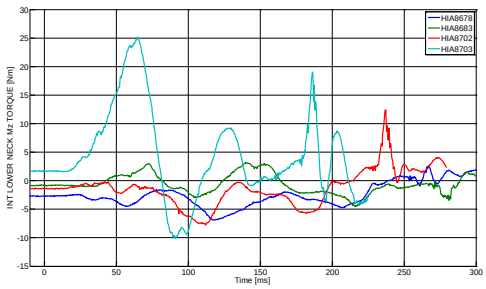



**Figure D-63. INT LOWER NECK Mz TORQUE**

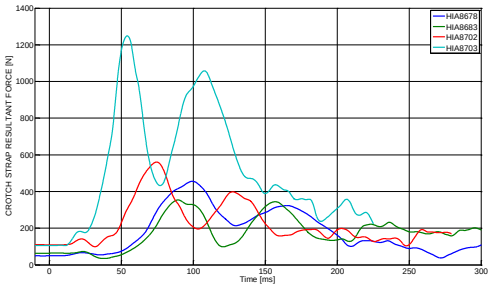



**Figure D-64. CROTCH STRAP RESULTANT FORCE**

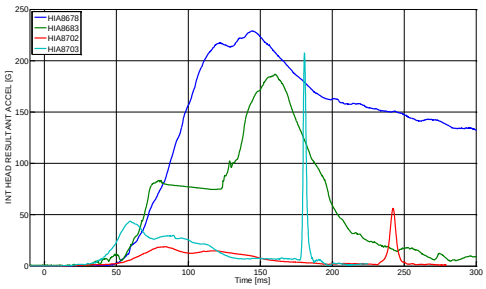



**Figure D-65. INT HEAD RESULTANT ACCEL**

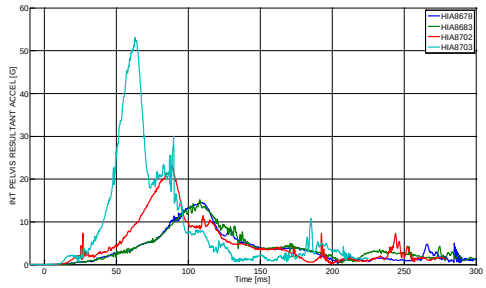



**Figure D-66. INT PELVIS RESULTANT ACCEL**

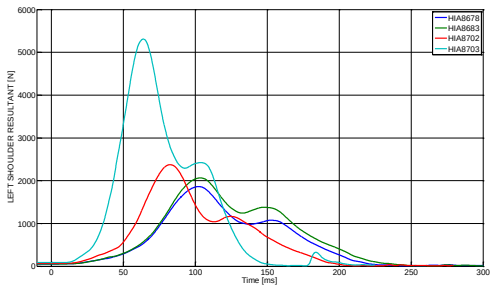



Figure D-67. LEFT SHOULDER RESULTANT

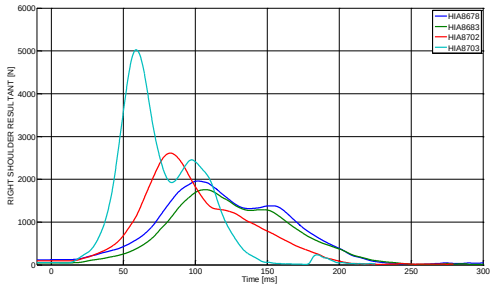



Figure D-68. RIGHT SHOULDER RESULTANT

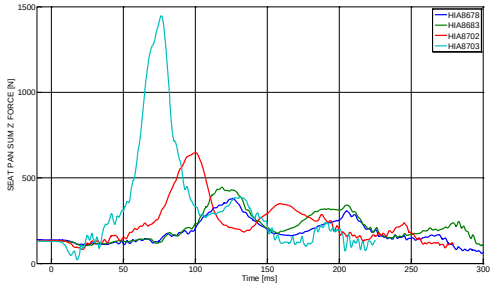



Figure D-69. SEAT PAN SUM Z FORCE

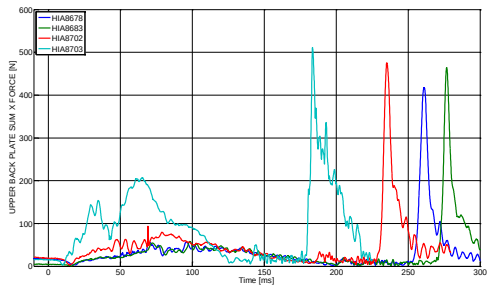



Figure D-70. UPPER BACK PLATE SUM X FORCE

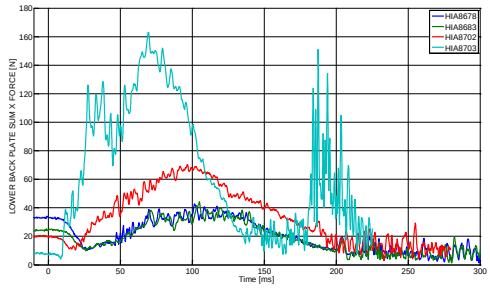



Figure D-71. LOWER BACK PLATE SUM X FORCE

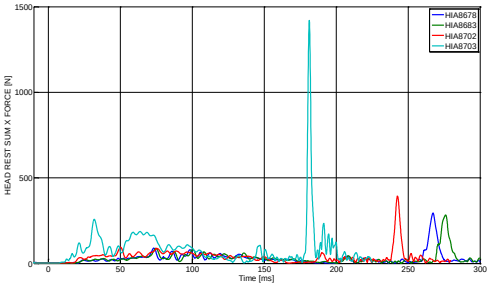



Figure D-72. HEAD REST SUM X FORCE

## E. Aerospace Hybrid III Lateral Tests

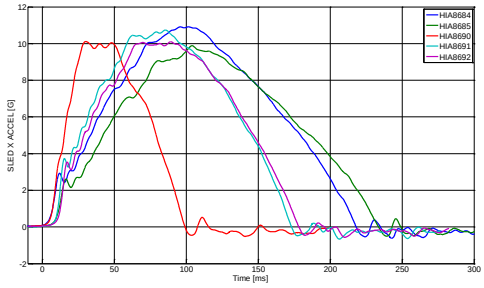



Figure E-1. SLED X ACCEL

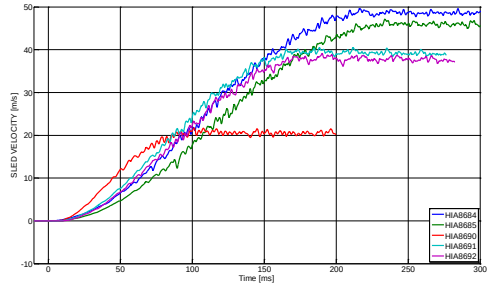



Figure E-2. SLED VELOCITY

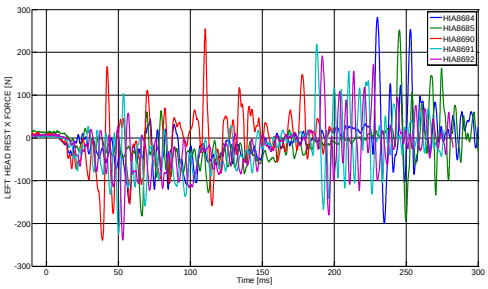



**Figure E-3. LEFT HEAD REST X FORCE**

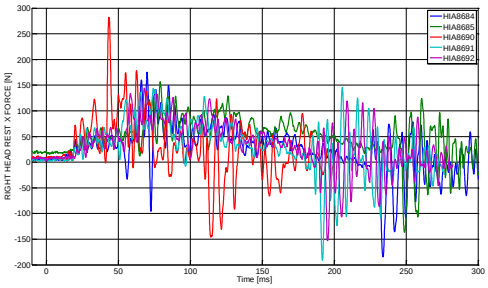



**Figure E-4. RIGHT HEAD REST X FORCE**

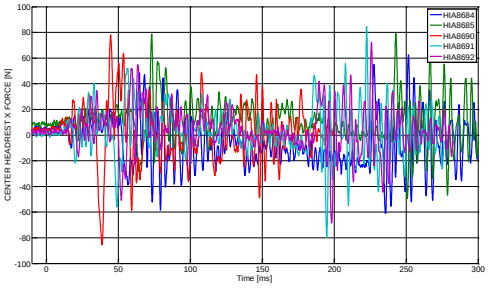



**Figure E-5. CENTER HEADREST X FORCE**

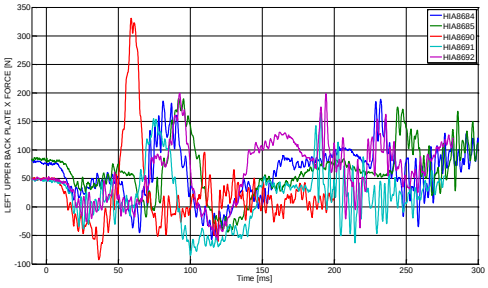



**Figure E-6. LEFT UPPER BACK PLATE X FORCE**

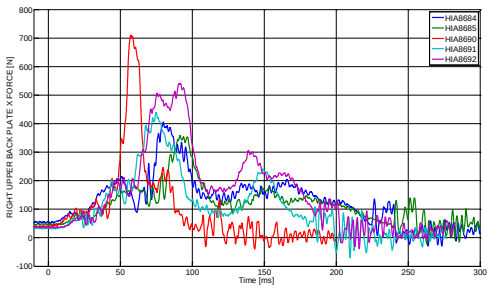



**Figure E-7. RIGHT UPPER BACK PLATE X FORCE**

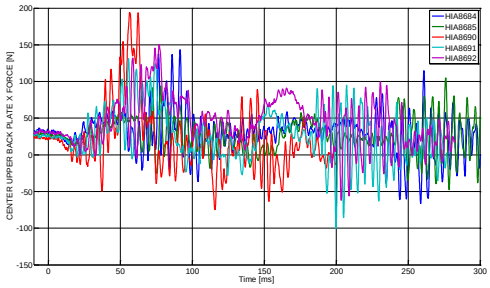



**Figure E-8. CENTER UPPER BACK PLATE X FORCE**

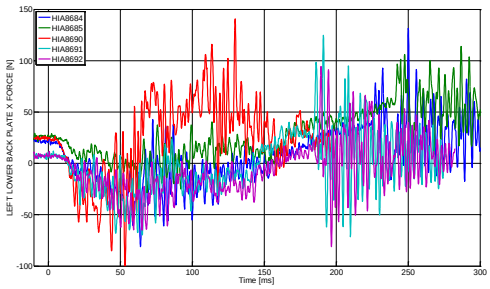



**Figure E-9. LEFT LOWER BACK PLATE X FORCE**

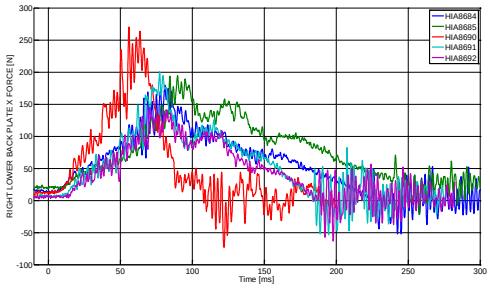



**Figure E-10. RIGHT LOWER BACK PLATE X FORCE**

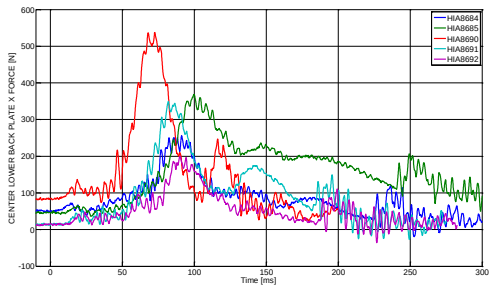



**Figure E-11. CENTER LOWER BACK PLATE X FORCE**

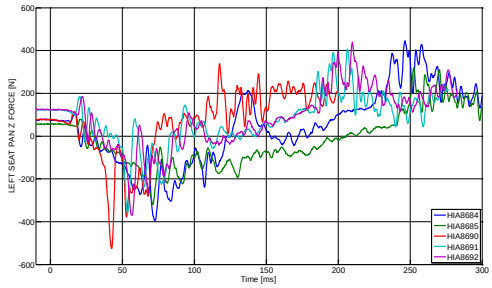



**Figure E-12. LEFT SEAT PAN Z FORCE**

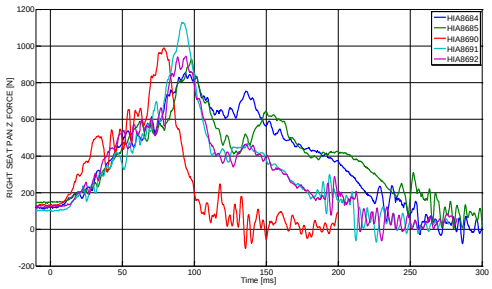



**Figure E-13. RIGHT SEAT PAN Z FORCE**

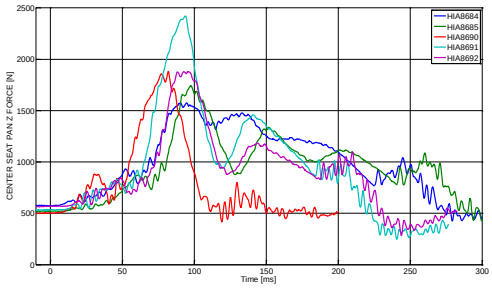



**Figure E-14. CENTER SEAT PAN Z FORCE**

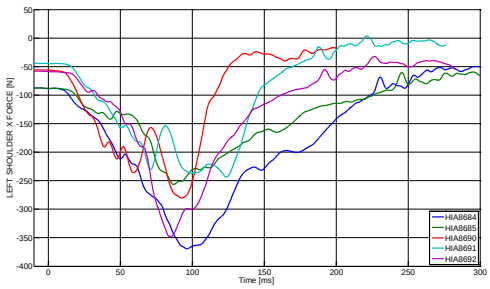



**Figure E-15. LEFT SHOULDER X FORCE**

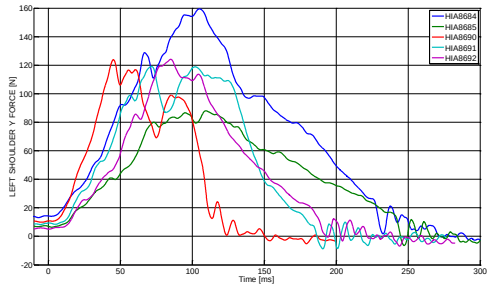



**Figure E-16. LEFT SHOULDER Y FORCE**

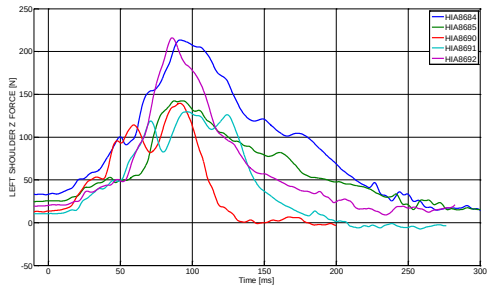



**Figure E-17. LEFT SHOULDER Z FORCE**

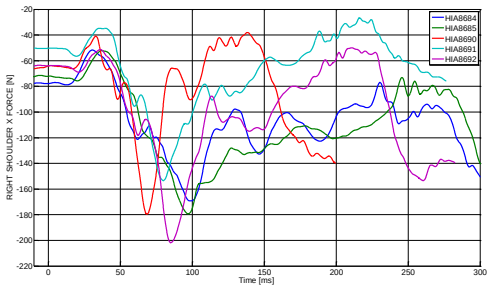



**Figure E-18. RIGHT SHOULDER X FORCE**

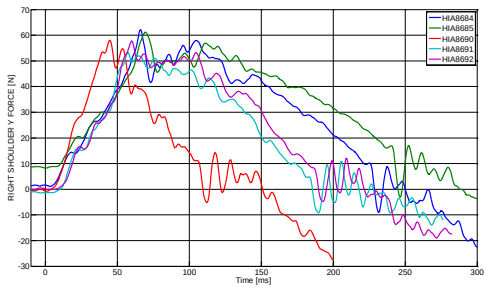



**Figure E-19. RIGHT SHOULDER Y FORCE**

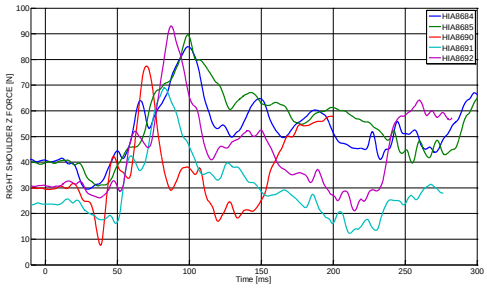



**Figure E-20. RIGHT SHOULDER Z FORCE**

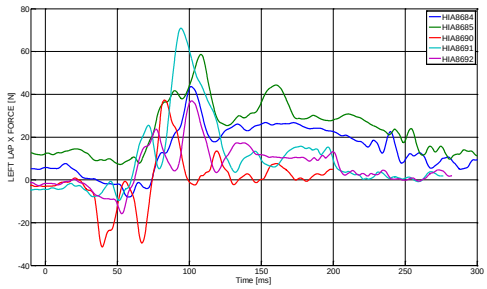



**Figure E-21. LEFT LAP X FORCE**

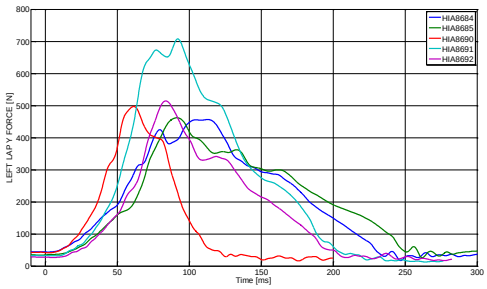



**Figure E-22. LEFT LAP Y FORCE**

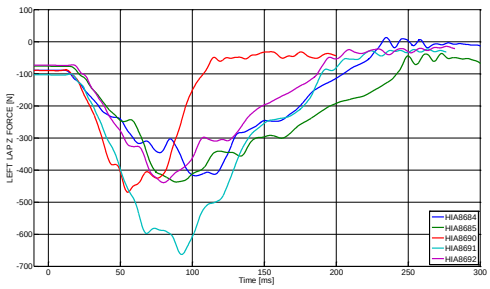



**Figure E-23. LEFT LAP Z FORCE**

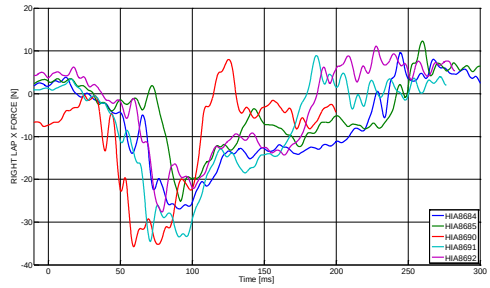



**Figure E-24. RIGHT LAP X FORCE**

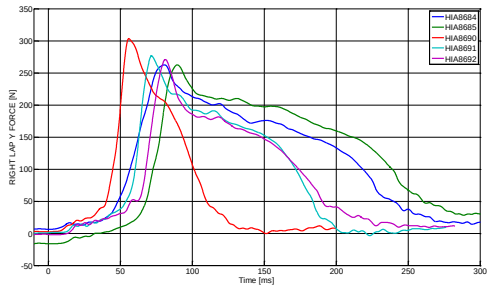



**Figure E-25. RIGHT LAP Y FORCE**

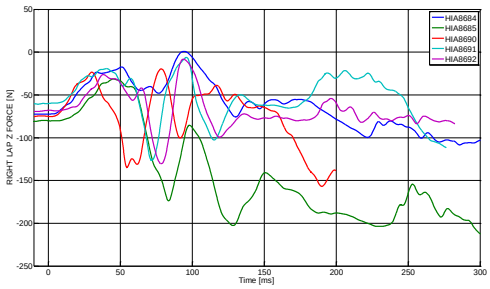



**Figure E-26. RIGHT LAP Z FORCE**

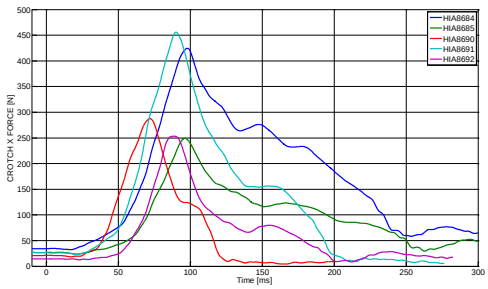



**Figure E-27. CROTCH X FORCE**

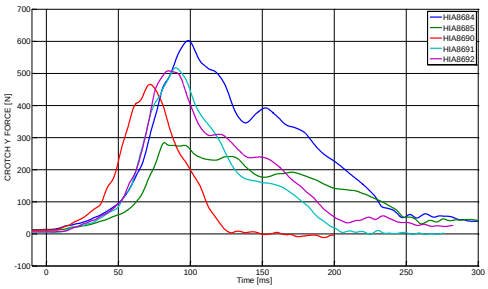



**Figure E-28. CROTCH Y FORCE**

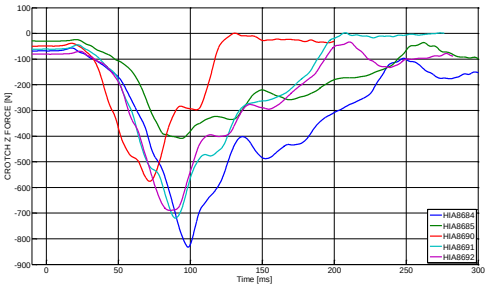



**Figure E-29. CROTCH Z FORCE**

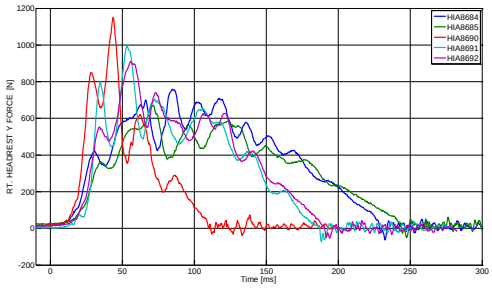



**Figure E-30. RT. HEADREST Y FORCE**

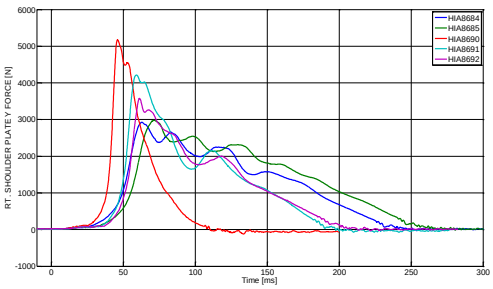



**Figure E-31. RT. SHOULDER PLATE Y FORCE**

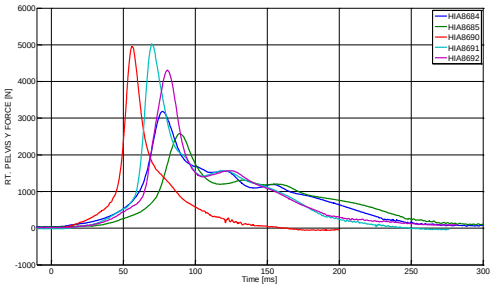



**Figure E-32. RT. PELVIS Y FORCE**

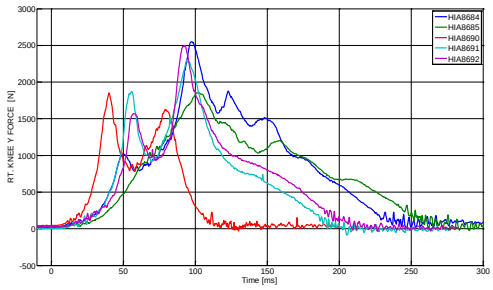



**Figure E-33. RT. KNEE Y FORCE**

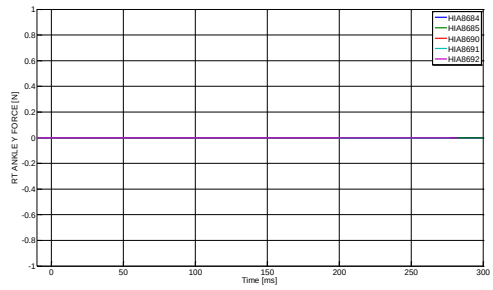



**Figure E-34. RT ANKLE Y FORCE**

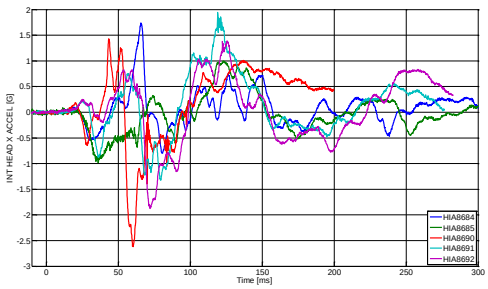



**Figure E-35. INT HEAD X ACCEL**

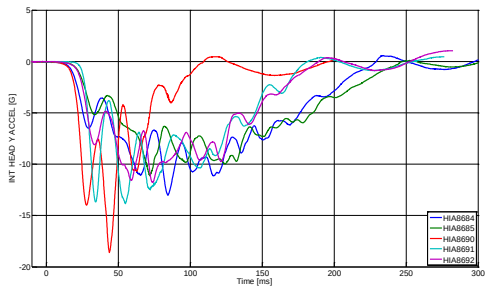



**Figure E-36. INT HEAD Y ACCEL**

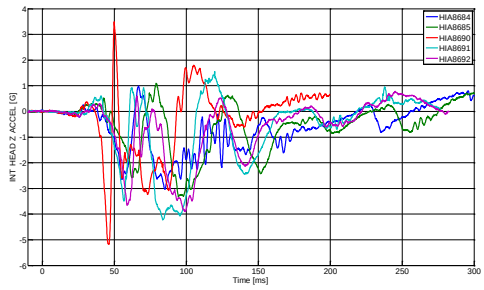



**Figure E-37. INT HEAD Z ACCEL**

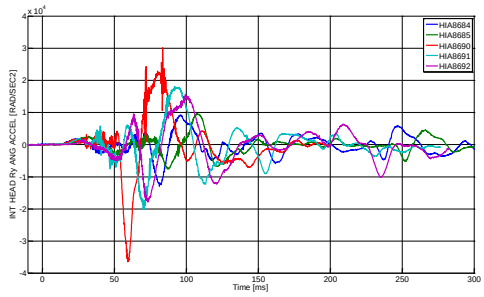



**Figure E-38. INT HEAD Ry ANG ACCEL**

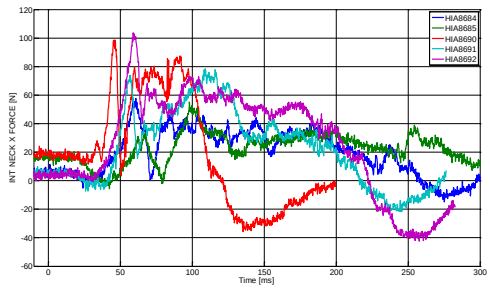



**Figure E-39. INT NECK X FORCE**

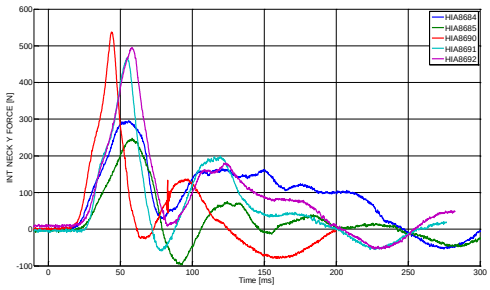



**Figure E-40. INT NECK Y FORCE**

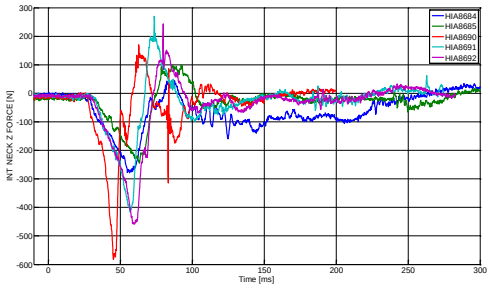



**Figure E-41. INT NECK Z FORCE**

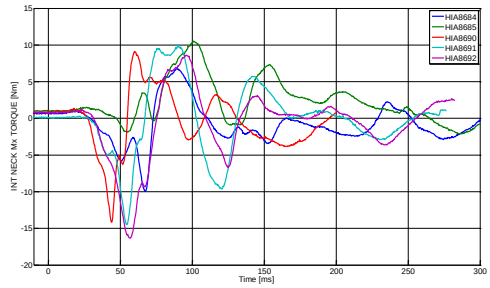



**Figure E-42. INT NECK Mx TORQUE**

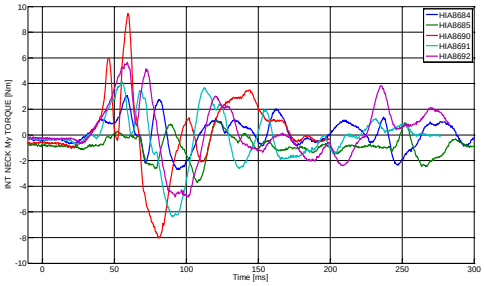



**Figure E-43. INT NECK My TORQUE**

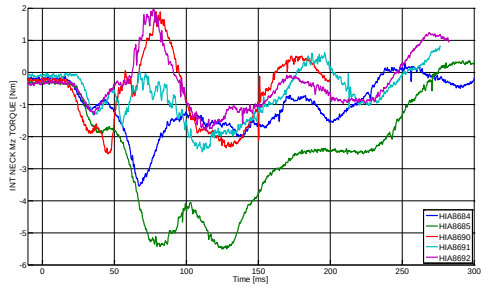



**Figure E-44. INT NECK Mz TORQUE**

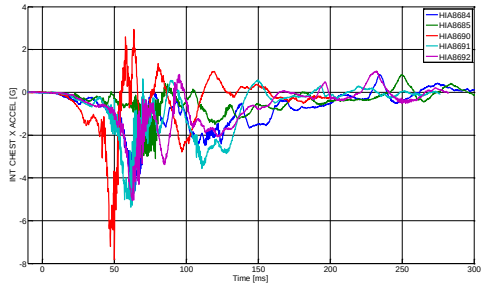



**Figure E-45. INT CHEST X ACCEL**

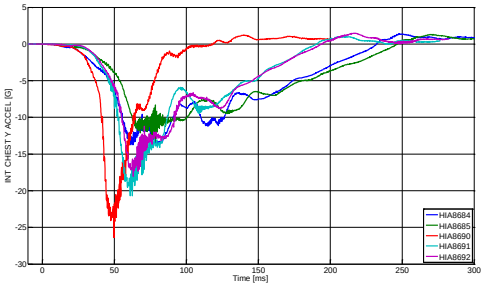



**Figure E-46. INT CHEST Y ACCEL**

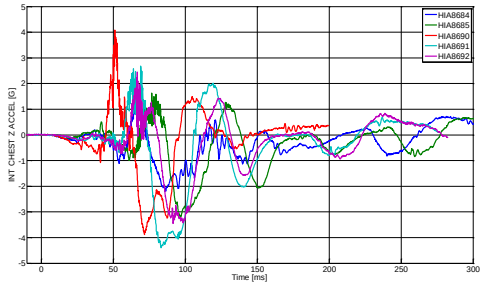



**Figure E-47. INT CHEST Z ACCEL**

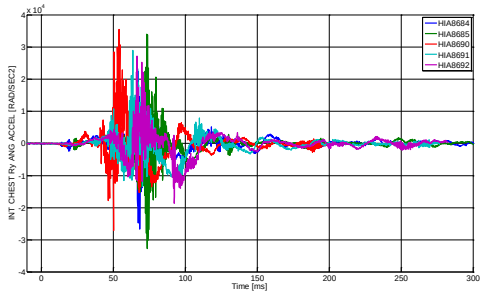



**Figure E-48. INT CHEST Ry ANG ACCEL**

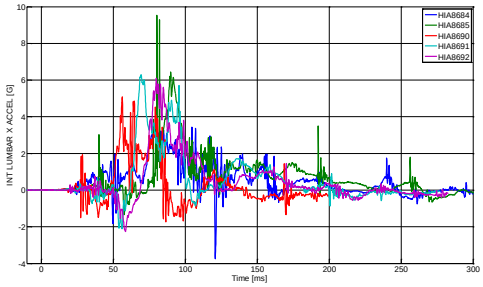



**Figure E-49. INT LUMBAR X ACCEL**

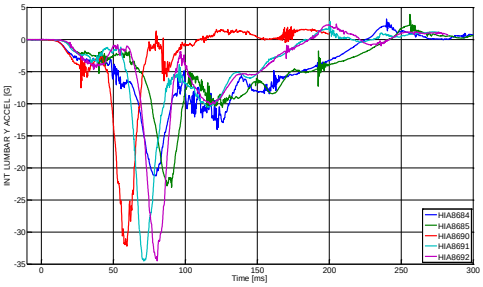



**Figure E-50. INT LUMBAR Y ACCEL**

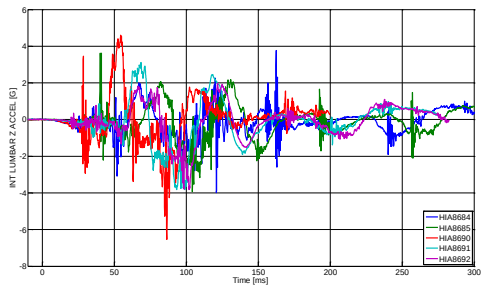



**Figure E-51. INT LUMBAR Z ACCEL**

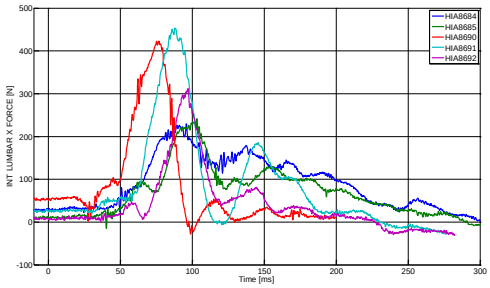



**Figure E-52. INT LUMBAR X FORCE**

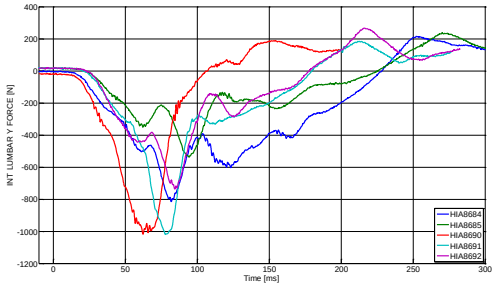



**Figure E-53. INT LUMBAR Y FORCE**

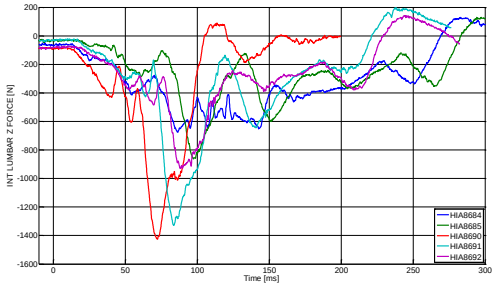



**Figure E-54. INT LUMBAR Z FORCE**

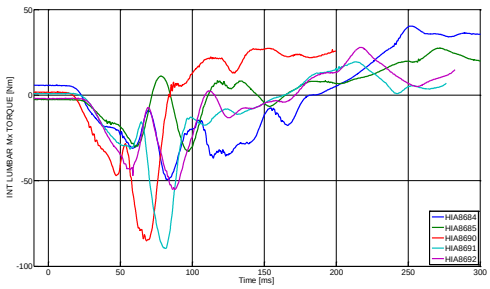



**Figure E-55. INT LUMBAR Mx TORQUE**

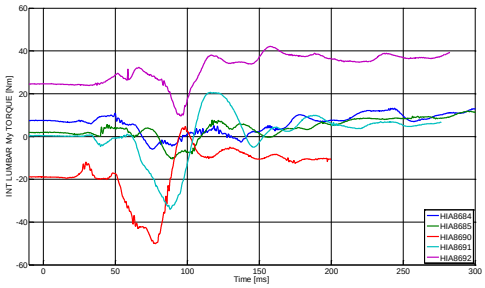



**Figure E-56. INT LUMBAR My TORQUE**

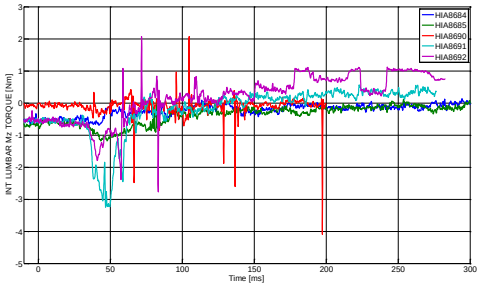



**Figure E-57. INT LUMBAR Mz TORQUE**

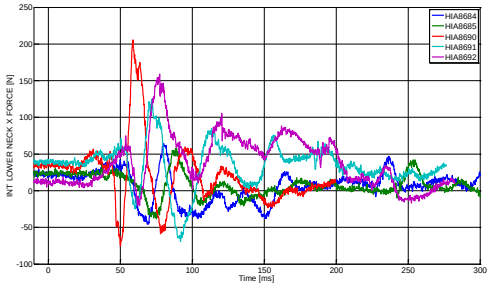



**Figure E-58. INT LOWER NECK X FORCE**

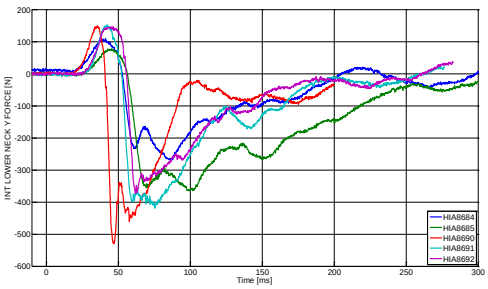



**Figure E-59. INT LOWER NECK Y FORCE**

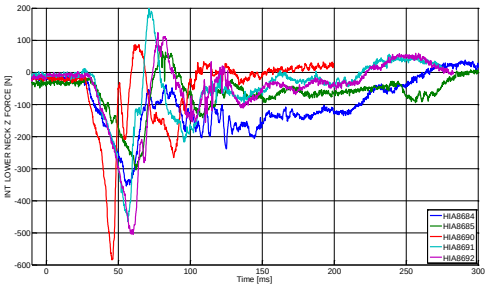



**Figure E-60. INT LOWER NECK Z FORCE**

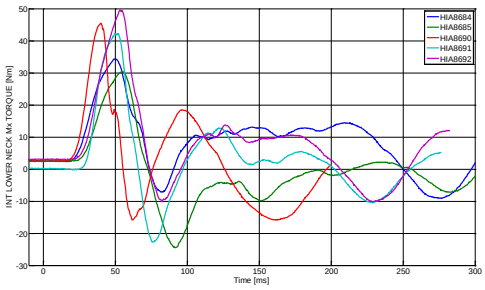



**Figure E-61. INT LOWER NECK Mx TORQUE**

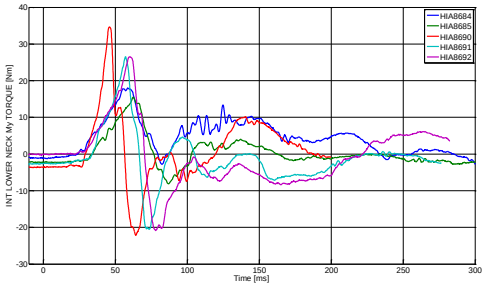



**Figure E-62. INT LOWER NECK My TORQUE**

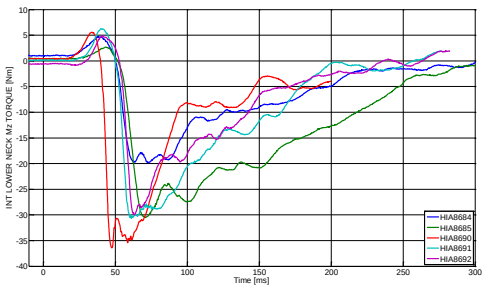



**Figure E-63. INT LOWER NECK Mz TORQUE**

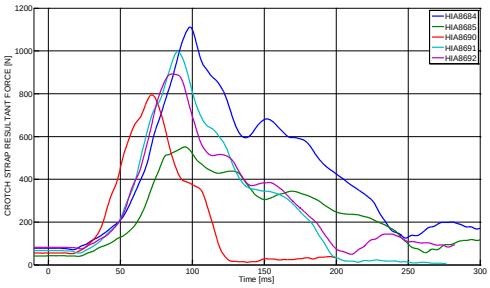



**Figure E-64. CROTCH STRAP RESULTANT FORCE**

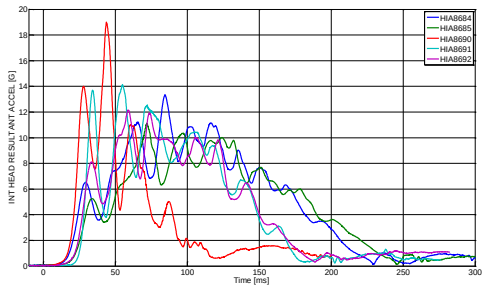



**Figure E-65. INT HEAD RESULTANT ACCEL**

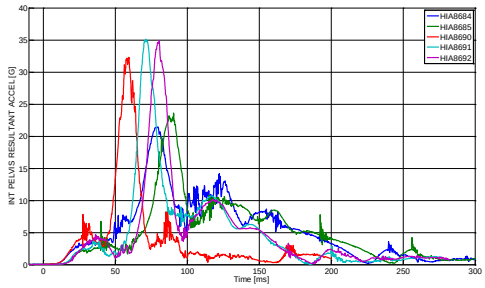



**Figure E-66. INT PELVIS RESULTANT ACCEL**

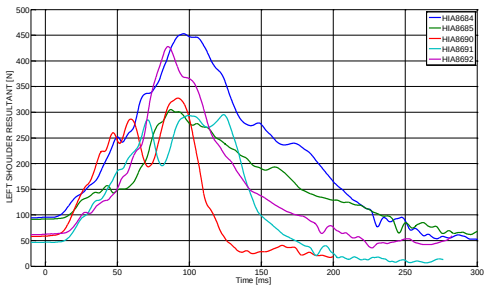



**Figure E-67. LEFT SHOULDER RESULTANT**

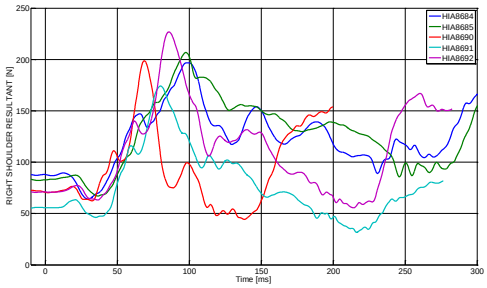



**Figure E-68. RIGHT SHOULDER RESULTANT**

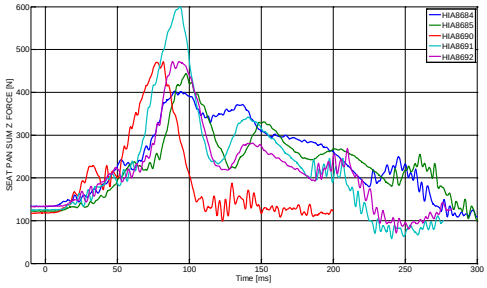



**Figure E-69. SEAT PAN SUM Z FORCE**

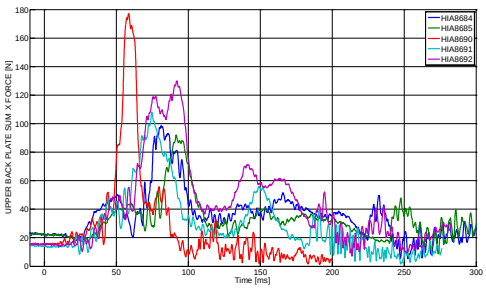



**Figure E-70. UPPER BACK PLATE SUM X FORCE**

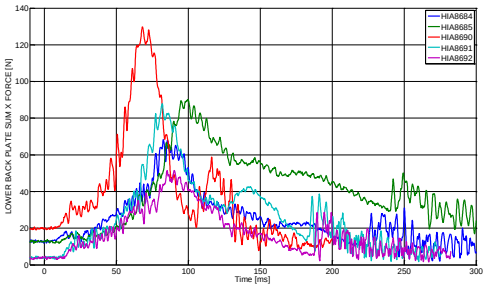



**Figure E-71. LOWER BACK PLATE SUM X FORCE**

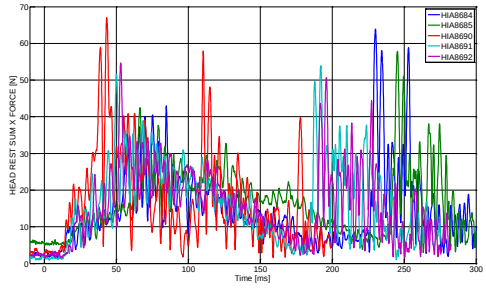



**Figure E-72. HEAD REST SUM X FORCE**

## F. Aerospace Hybrid III Spinal Tests

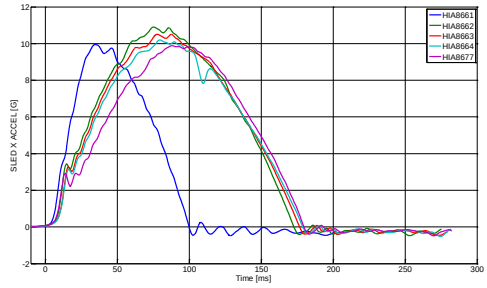



**Figure F-1. SLED X ACCEL**

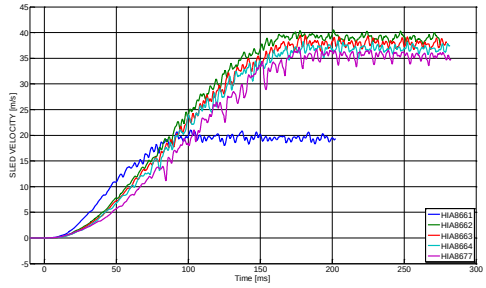



**Figure F-2. SLED VELOCITY**

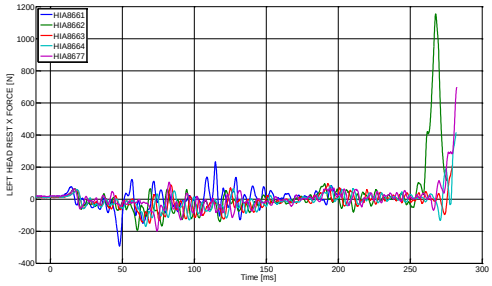



**Figure F-3. LEFT HEAD REST X FORCE**

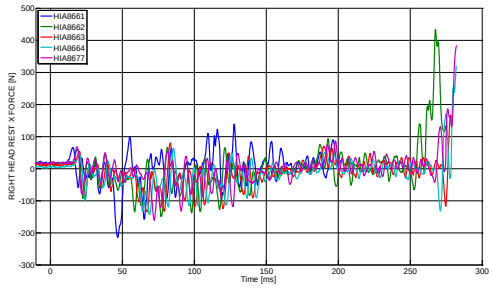



**Figure F-4. RIGHT HEAD REST X FORCE**

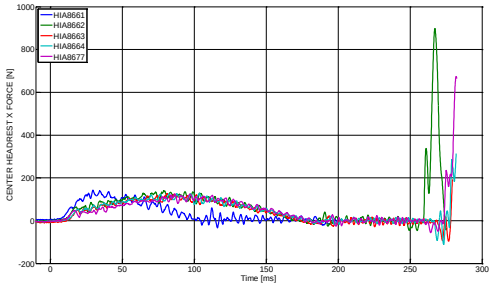



**Figure F-5. CENTER HEADREST X FORCE**

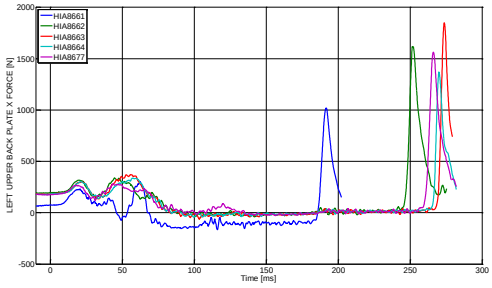



**Figure F-6. LEFT UPPER BACK PLATE X FORCE**

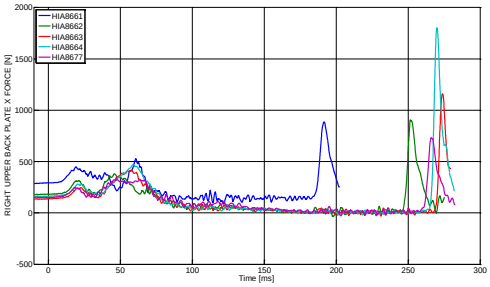



**Figure F-7. RIGHT UPPER BACK PLATE X FORCE**

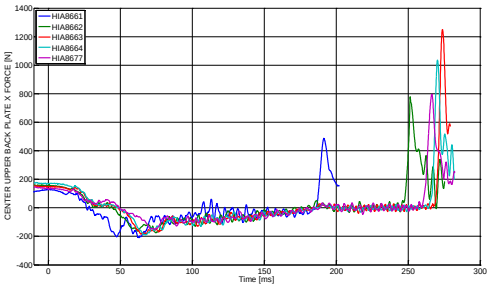



**Figure F-8. CENTER UPPER BACK PLATE X FORCE**

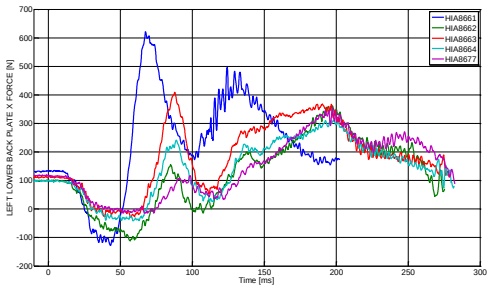



**Figure F-9. LEFT LOWER BACK PLATE X FORCE**

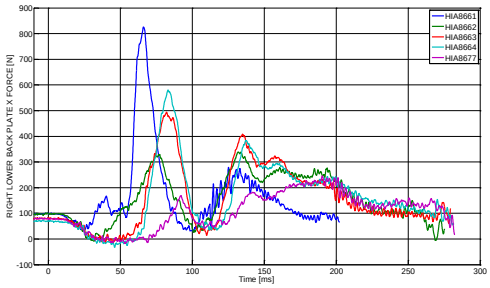



**Figure F-10. RIGHT LOWER BACK PLATE X FORCE**

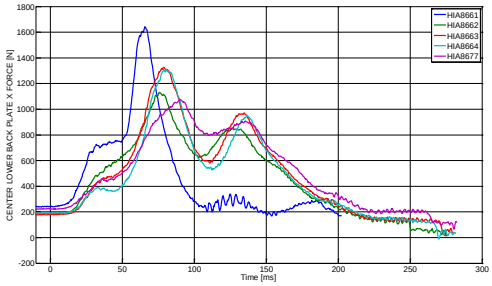



**Figure F-11. CENTER LOWER BACK PLATE X FORCE**

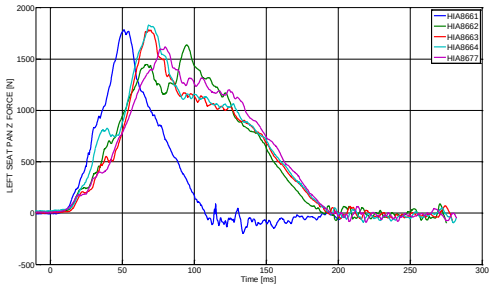



**Figure F-12. LEFT SEAT PAN Z FORCE**

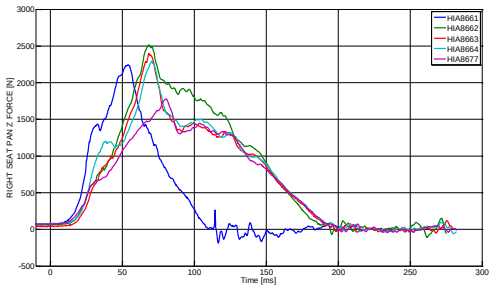



**Figure F-13. RIGHT SEAT PAN Z FORCE**

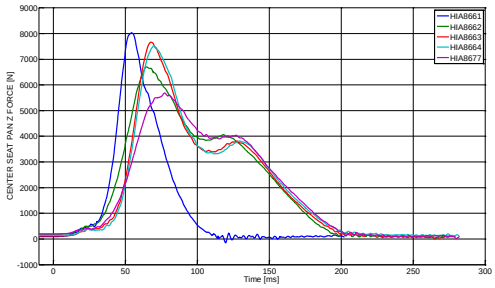



**Figure F-14. CENTER SEAT PAN Z FORCE**

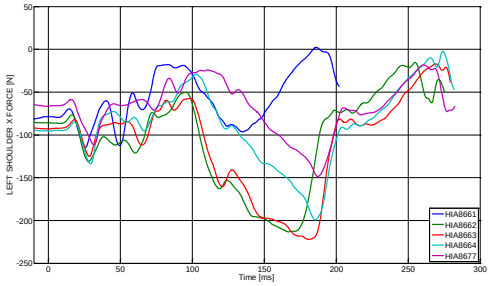



**Figure F-15. LEFT SHOULDER X FORCE**

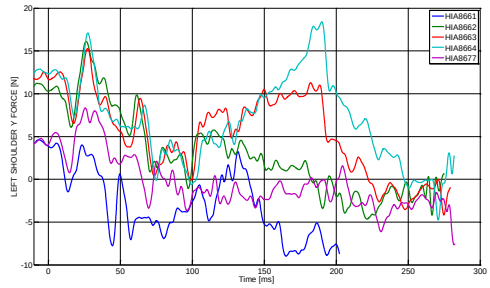



**Figure F-16. LEFT SHOULDER Y FORCE**

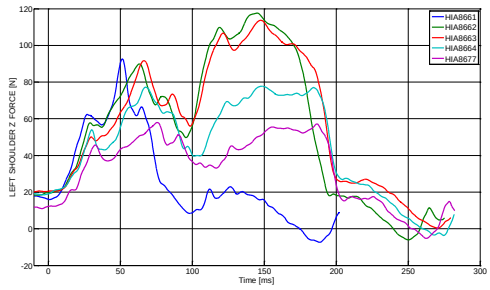



**Figure F-17. LEFT SHOULDER Z FORCE**

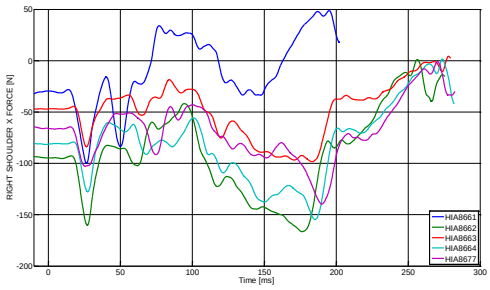



**Figure F-18. RIGHT SHOULDER X FORCE**

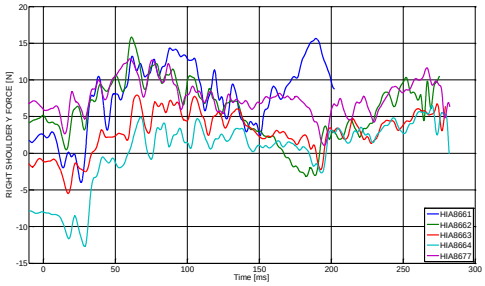



**Figure F-19. RIGHT SHOULDER Y FORCE**

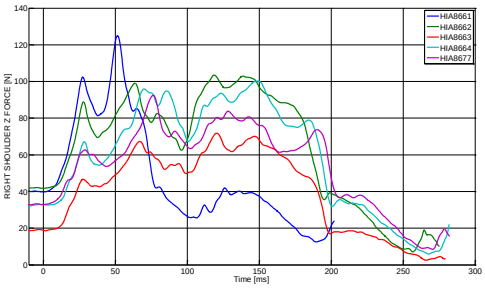



**Figure F-20. RIGHT SHOULDER Z FORCE**

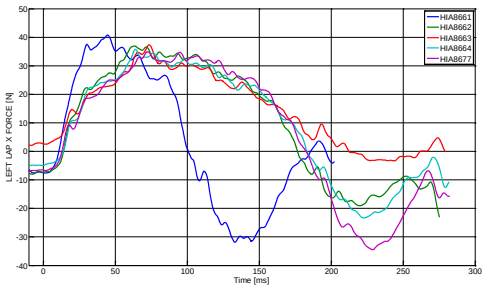



**Figure F-21. LEFT LAP X FORCE**

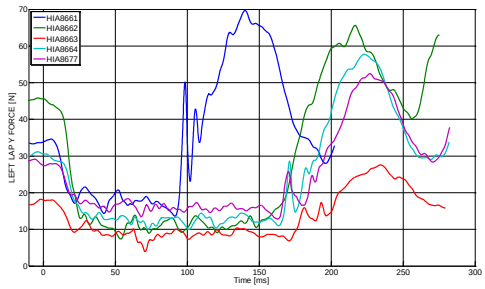



**Figure F-22. LEFT LAP Y FORCE**

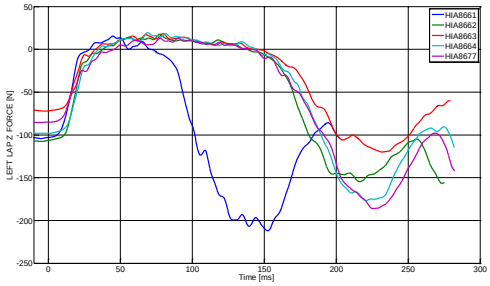



**Figure F-23. LEFT LAP Z FORCE**

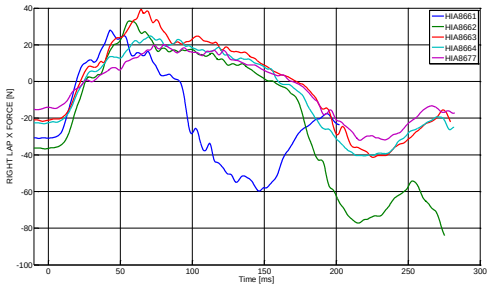



**Figure F-24. RIGHT LAP X FORCE**

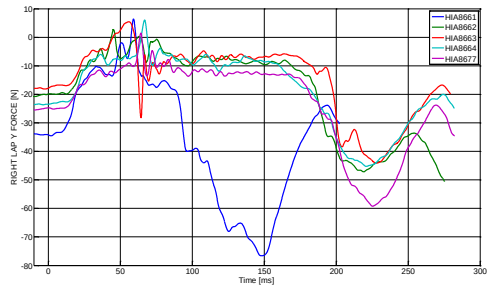



**Figure F-25. RIGHT LAP Y FORCE**

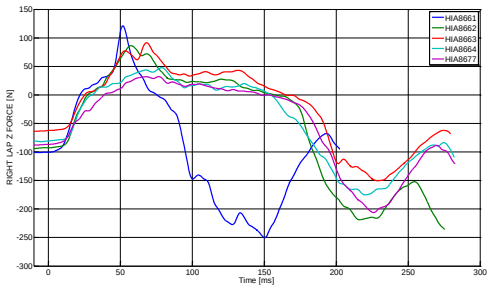



**Figure F-26. RIGHT LAP Z FORCE**

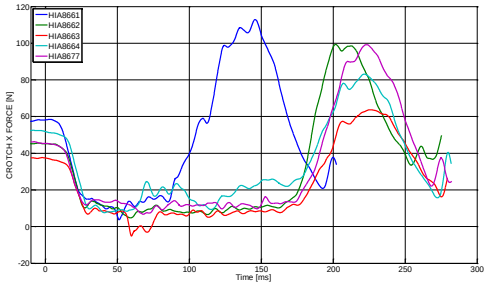



**Figure F-27. CROTCH X FORCE**

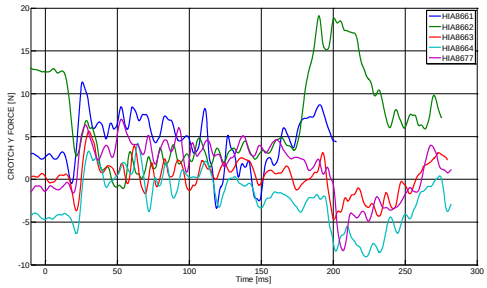



**Figure F-28. CROTCH Y FORCE**

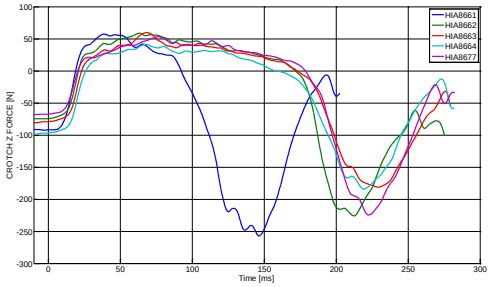



**Figure F-29. CROTCH Z FORCE**

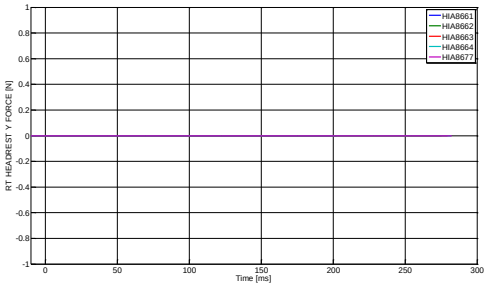



**Figure F-30. RT HEADREST Y FORCE**

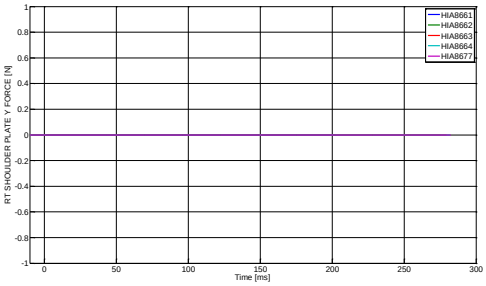



**Figure F-31. RT SHOULDER PLATE Y FORCE**

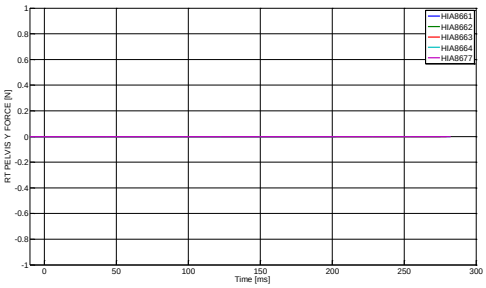



**Figure F-32. RT PELVIS Y FORCE**

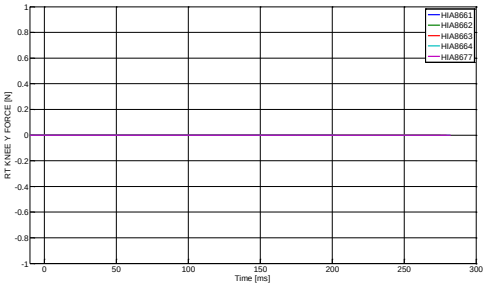



**Figure F-33. RT KNEE Y FORCE**

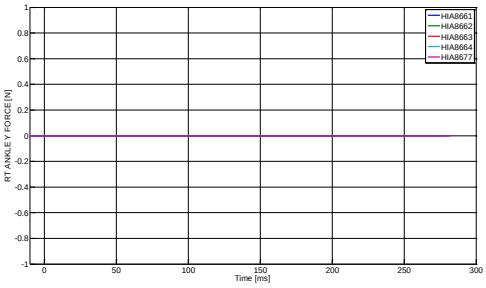



**Figure F-34. RT ANKLE Y FORCE**

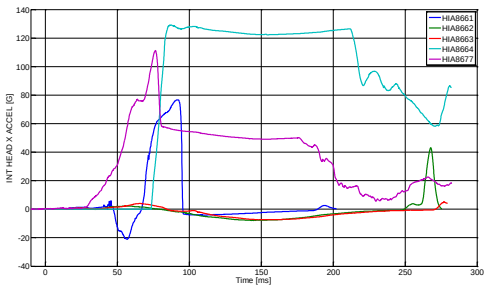



**Figure F-35. INT HEAD X ACCEL**

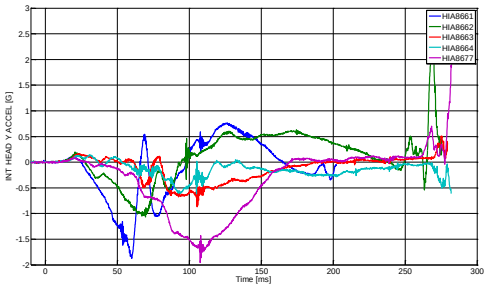



**Figure F-36. INT HEAD Y ACCEL**

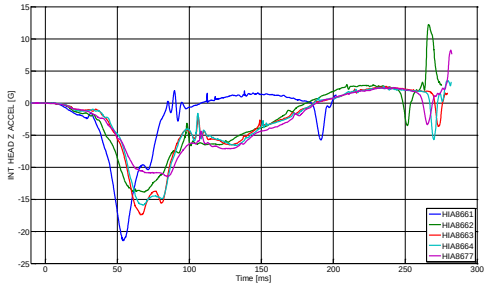



**Figure F-37. INT HEAD Z ACCEL**

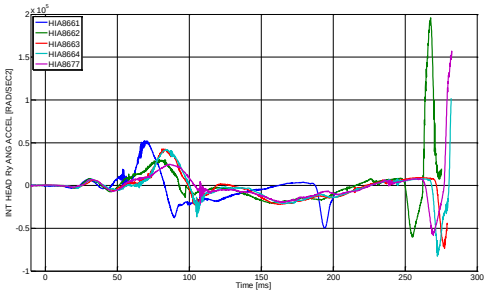



**Figure F-38. INT HEAD Ry ANG ACCEL**

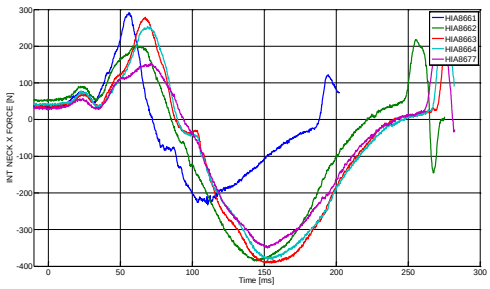



**Figure F-39. INT NECK X FORCE**

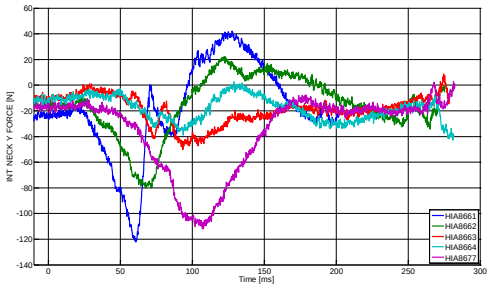



**Figure F-40. INT NECK Y FORCE**

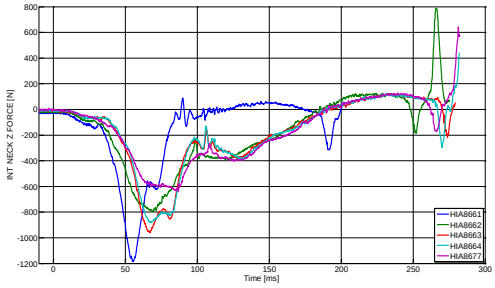



**Figure F-41. INT NECK Z FORCE**

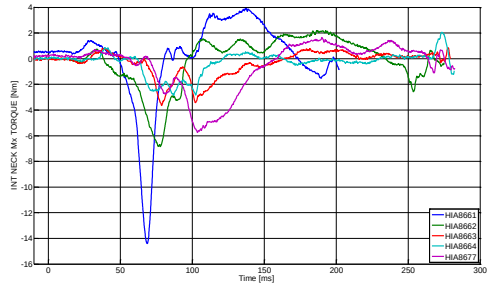



**Figure F-42. INT NECK Mx TORQUE**

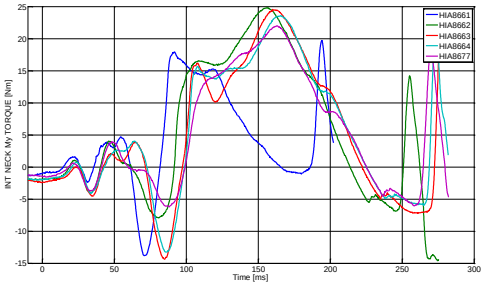



**Figure F-43. INT NECK My TORQUE**

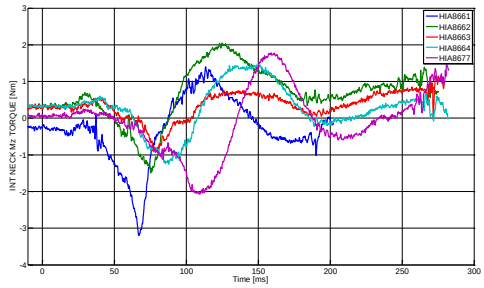



**Figure F-44. INT NECK Mz TORQUE**

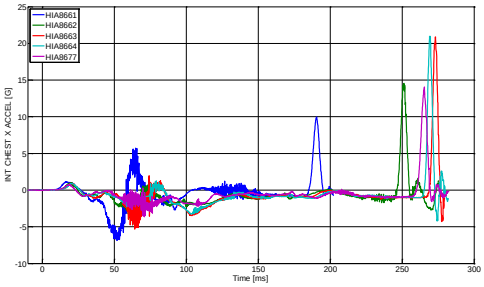



**Figure F-45. INT CHEST X ACCEL**

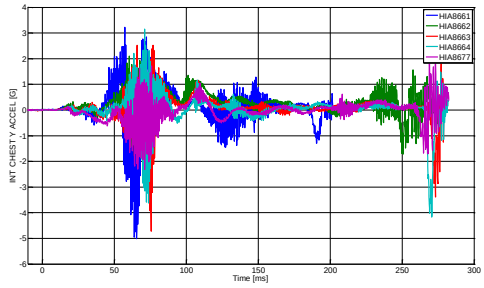



**Figure F-46. INT CHEST Y ACCEL**

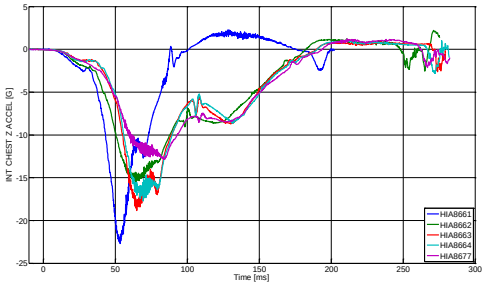



**Figure F-47. INT CHEST Z ACCEL**

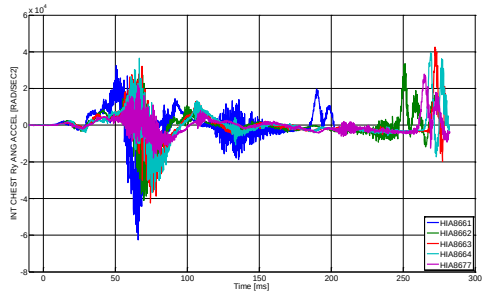



**Figure F-48. INT CHEST Ry ANG ACCEL**

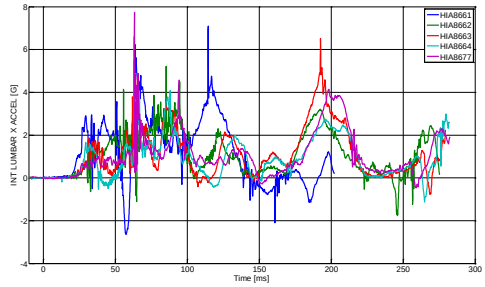



**Figure F-49. INT LUMBAR X ACCEL**

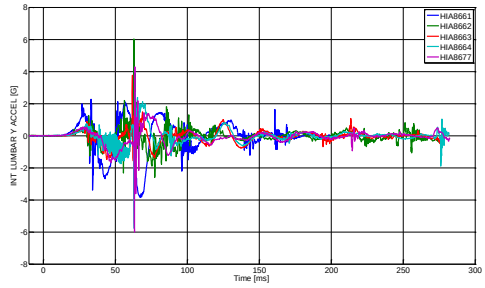
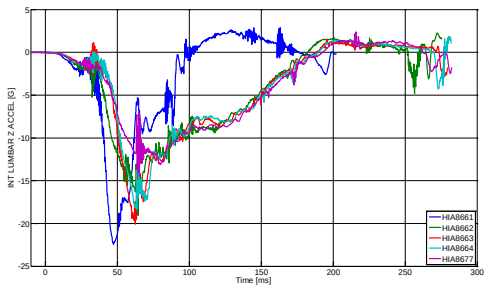



**Figure F-50. INT LUMBAR Y ACCEL**

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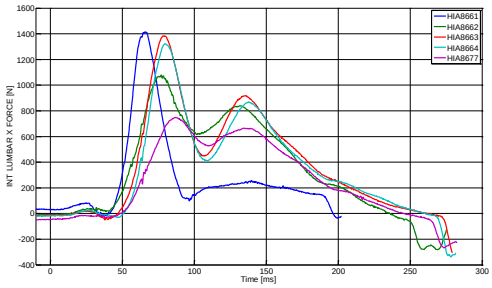


**Figure F-52. INT LUMBAR X FORCE**

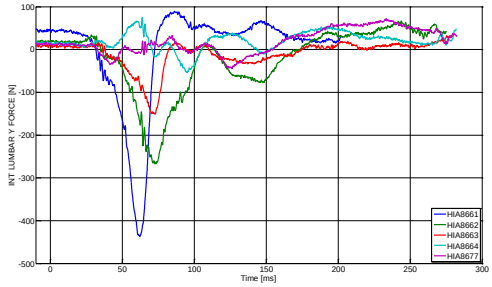


**Figure F-53. INT LUMBAR Y FORCE**

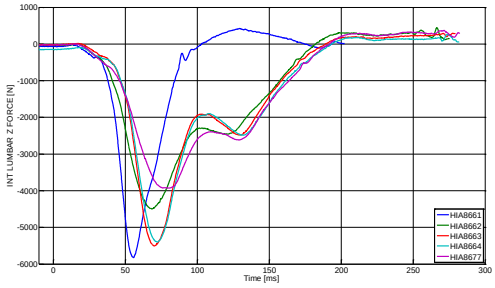


**Figure F-54. INT LUMBAR Z FORCE**

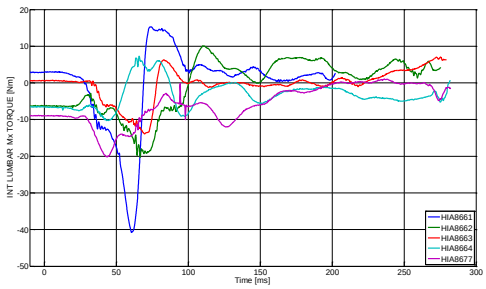


**Figure F-55. INT LUMBAR Mx TORQUE**

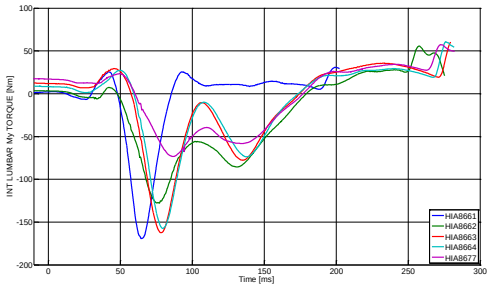


**Figure F-56. INT LUMBAR My TORQUE**

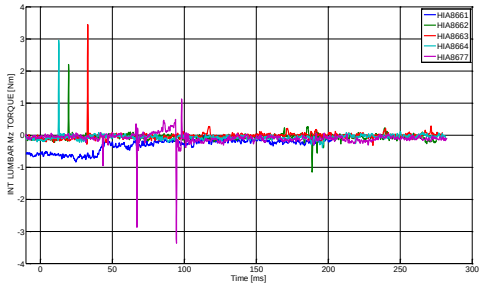


**Figure F-57. INT LUMBAR Mz TORQUE**

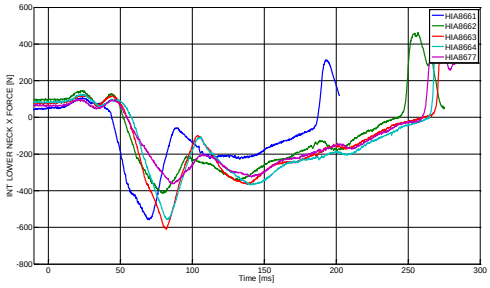


**Figure F-58. INT LOWER NECK X FORCE**

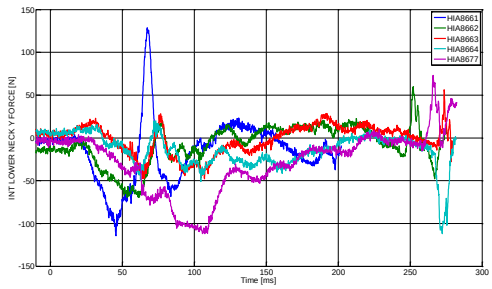


**Figure F-59. INT LOWER NECK Y FORCE**

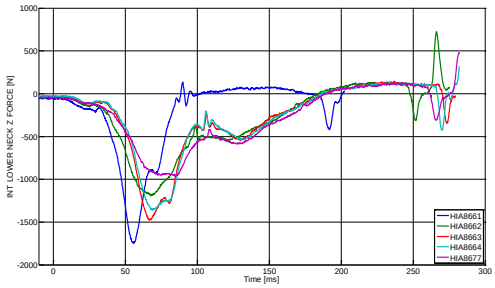


**Figure F-60. INT LOWER NECK Z FORCE**

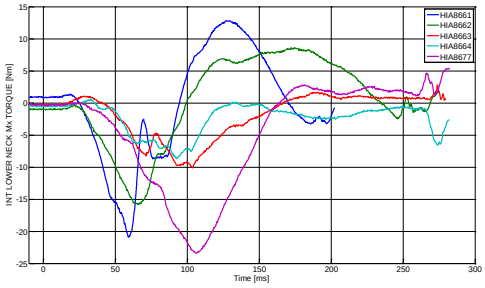


**Figure F-61. INT LOWER NECK Mx TORQUE**

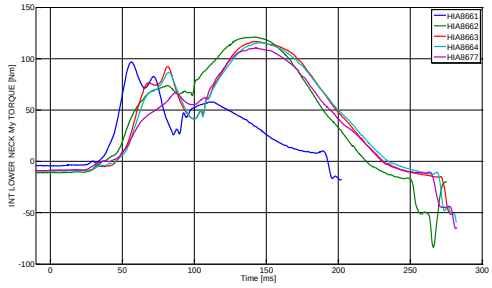


**Figure F-62. INT LOWER NECK My TORQUE**

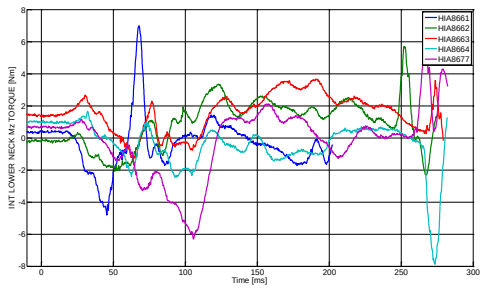


**Figure F-63. INT LOWER NECK Mz TORQUE**

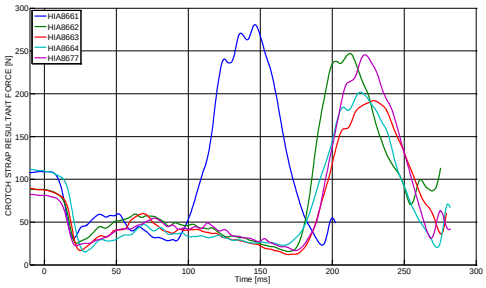


**Figure F-64. CROTCH STRAP RESULTANT FORCE**

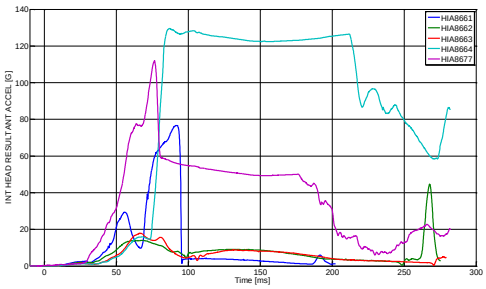


**Figure F-65. INT HEAD RESULTANT ACCEL**

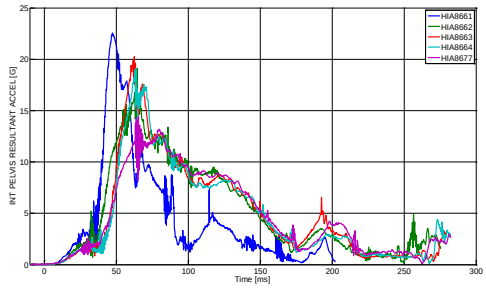


**Figure F-66. INT PELVIS RESULTANT ACCEL**

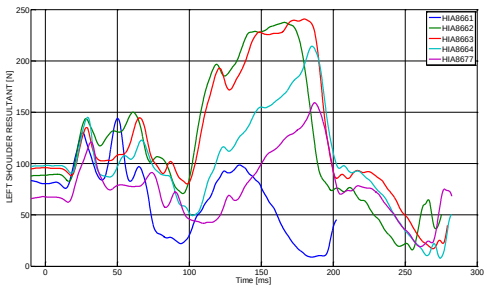


**Figure F-67. LEFT SHOULDER RESULTANT**

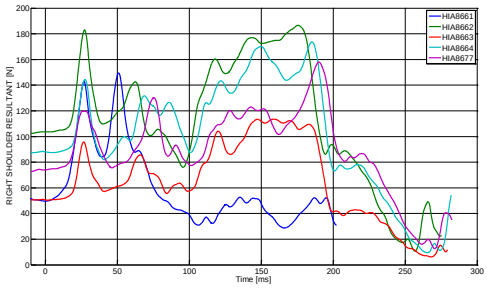


**Figure F-68. RIGHT SHOULDER RESULTANT**

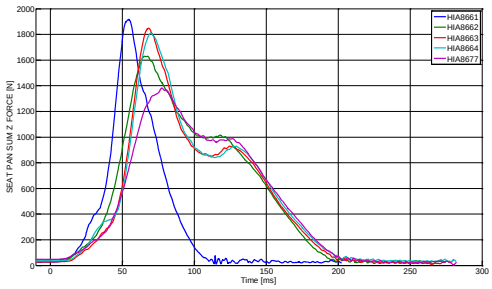


**Figure F-69. SEAT PAN SUM Z FORCE**

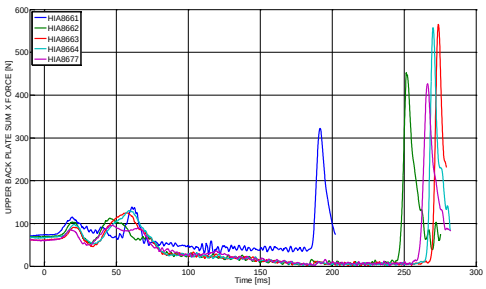


**Figure F-70. UPPER BACK PLATE SUM X FORCE**

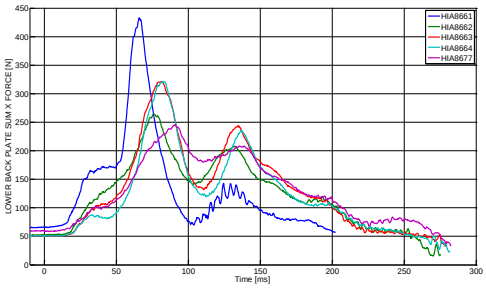


**Figure F-71. LOWER BACK PLATE SUM X FORCE**

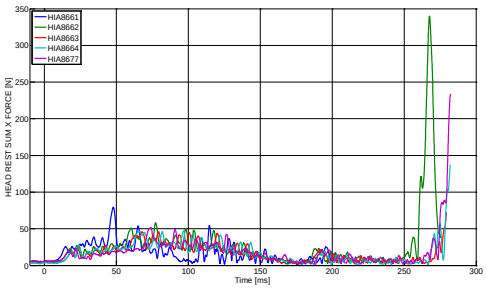


**Figure F-72. HEAD REST SUM X FORCE**

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13. ABSTRACT *(Maximum 200 words)*
NASA is developing the Multi-Purpose Crew Vehicle also known as Orion, as well as working with commercial partners in developing new spacecraft for NASA's use. Because each has unique dynamic loading, and those loads are different than current vehicles in the automotive, commercial aviation, and military industries, new methods are needed to assess crew injury risk. In addition, NASA's injury risk posture is different than most other vehicles. Currently, NASA requirements for new vehicles are based on the Brinkley Dynamic Response Criterion and Hybrid III Anthropomorphic Test Device limits. Because of the limitations to this approach, new methods are desired to mitigate the risk of injury to the crew. After a careful review of the available injury assessment methods [Evidence Book], the Test Device for Human Occupant Restraint (THOR) was chosen as a candidate for further investigation. The testing outlined in this report was conducted to assess the THOR response in various orientations and dynamics for its applicability to the NASA environment. In addition, these data were collected to provide validation data for concurrent development of a Finite Element model of the THOR in cooperation with the National Highway Traffic Safety Administration

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