

## The Evaluation of a Test Device for Human Occupant Restraint (THOR) Under Vertical Loading Conditions: Part 1 – Experimental Setup and Results

Justin Littell Ph.D., Martin Annett  
NASA Langley Research Center  
Hampton Virginia 23681  
[Justin.D.Littell@nasa.gov](mailto:Justin.D.Littell@nasa.gov)  
[Martin.S.Annett@nasa.gov](mailto:Martin.S.Annett@nasa.gov)

### Abstract

A series of 16 vertical tests were conducted on a Test Device for Human Occupant Restraint (THOR) - NT 50<sup>th</sup> percentile Anthropomorphic Test Device (ATD) at NASA Langley Research Center (LaRC). The purpose of the tests conducted at NASA LaRC was threefold. The first was to add vertical response data to the growing test database for THOR-NT development and validation. Second, the THOR-NT analytical computational models currently in development must be validated for the vertical loading environment. The computational models have been calibrated for frontal crash environments with concentration on accurately replicating head/neck, thoracic, and lower extremity responses. Finally, familiarity with the THOR ATD is necessary because NASA is interested in evaluating advanced ATDs for use in future flight and research projects.

The THOR was subjected to vertical loading conditions ranging between 5 and 16 g in magnitude and 40 to 120 milliseconds (msec) in duration. It was also tested under conditions identical to previous tests conducted on the Hybrid II and III ATDs to allow comparisons to be made. Variations in the test setup were also introduced, such as the addition of a footrest in an attempt to offload some of the impact load into the legs. A full data set of the THOR-NT ATD will be presented and discussed.

Results from the tests show that the THOR was largely insensitive to differences in the loading conditions, perhaps due in part to their small magnitudes. THOR responses, when compared to the Hybrid II and III in the lumbar region, demonstrated that the THOR more closely resembled the straight spine Hybrid setup. In the neck region, the THOR behaved more like the Hybrid III. However in both cases, the responses were not identical, indicating that the THOR would show differences in response than the Hybrid II and III ATDs when subjected to identical impact conditions. The addition of a footrest did not significantly affect the THOR response due to the nature of how the loading conditions were applied.

### Introduction

Rotorcraft crashworthiness regulations and standards have been established by the Federal Aviation Administration (FAA) and the Department of Defense (DOD) to limit the likelihood of occupant injury during a crash event. In Title 14 of the Code of Federal Regulations (CFR), Parts 27.562 [1] and 29.562 [2], a set of test conditions are prescribed for

a seated Anthropomorphic Test Device (ATD). The seat is attached to a crash sled and two unique impact scenarios, in terms of velocity and orientation, are specified. MIL-STD-1290A [3] defines seven impact conditions at the vehicle level. Injury criteria such as Eiband [4], Brinkley / Dynamic Response Index [5], and restraint loads can be calculated independent of the type of ATD used.

There are three types of ATDs customarily used in rotorcraft crashworthiness testing and evaluation; the Hybrid II, the Aerospace Hybrid III, and the FAA Hybrid III. All three ATDs include a straight lumbar spine to position the ATD upright compared to the automotive posture. The segmented neck of the Hybrid III is designed to accurately replicate the head and neck flexion/extension kinematics. Injury criteria such as Head Injury Criteria (HIC) [6] and lumbar load limits from the CFRs are evaluated based on the instrumented ATD internal response.

In the mid-1990's, motivated by the advent of new restraint concepts, the National Highway Traffic Safety Administration (NHTSA) initiated a concerted advanced ATD development effort known as the Test Device for Human Occupant Restraint (THOR) [7]. A multi-directional neck was integrated that captured both frontal and lateral responses. Improvements in shoulder, thoracic, abdominal, and pelvic biofidelity were also included. A worldwide consortium of biomechanics and crash test organizations was involved in the evaluation and validation of the THOR, resulting in the release of the THOR Alpha in 2001. Material, instrumentation, and anthropometry improvements led to the revision of the THOR in 2005 known as the THOR-NT [8]. Certification tests for the automotive frontal impact environment were conducted and similar behavior was exhibited compared to THOR Alpha. Starting in 2010, a new phase of modification kits were recommended to improve the THOR-NT response. THOR-NT ATDs with the mod kits are designated the THOR-K [9].

Development of the THOR has been focused primarily on accurately predicting the injury mechanisms associated with automotive frontal impact. There has been limited consideration to assessing the THOR for the omni-directional loading seen in aerospace impacts. For both fixed and rotary wing, loading is predominantly vertical and frontal for crew, and vertical, frontal, and lateral for troop and passengers. Prior to a scheduled THOR-K modification, a THOR-NT was made available by the NHTSA Vehicle Research and Test Center (VRTC) for aerospace testing. The response of the THOR-NT to the 14 CFR 27.562 and 29.562 sled test environments was evaluated by the FAA Civil Aeromedical Institute (CAMI). The THOR-NT was

then provided to NASA Langley Research Center (LaRC) to conduct purely vertical drop tests analogous with Hybrid II and Hybrid III ATD drop tests conducted in 2010 [10]. The results of these THOR-NT drop tests are described herein.

### Test Setup

A 14-ft. vertical drop tower was used for this test series. The THOR-NT ATD (S/N #6) was seated upright in a rigid seat platform and this seat platform was connected to the rails of the drop tower via two sets of guides located on the sides of the platform. The seat platform was raised to a specified height then released. Upon impact, the seat platform crushed various geometrical configurations of stacked 50-psi crushable paper honeycomb or Confor energy absorbing foam materials, which created the input acceleration pulse. The THOR-NT was restrained only by two loose fitting safety straps around the thighs and the mid-abdomen. Seatbelts or other typical occupant restraint mechanisms were not used. Two nominal velocities were used in testing: 12 and 16 feet per second (fps). Figure 1 shows the THOR ATD seated in the seat platform sitting on the paper honeycomb pulse generator.

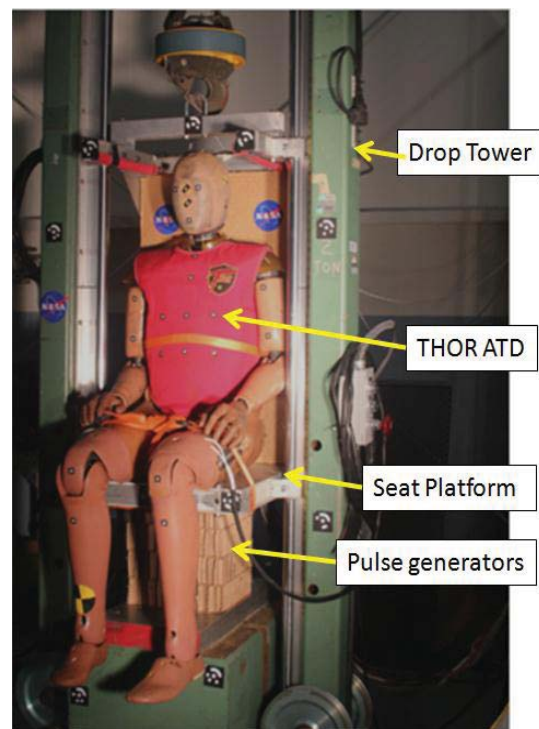


Figure 1 - THOR ATD in test configuration

The input deceleration pulses ranged from 5 to 16 g in magnitude and 40 to 120 milliseconds (msec) in duration, with triangular, trapezoidal and sinusoidal shapes. The nominal test conditions are summarized in Table 1.

The test condition designated as 2010-1 was a repeat of a pulse used for a previous vertical impact test series on the Hybrid II and III family of ATDs [10], and was included such that the responses from the Hybrid family of ATDs and THOR ATD could be compared directly. Pulse 2012-1 and 2012-2 are pulses used to approximate comparable 14 CFR 27.562, 29.562 or MIL-STD-1290 loads. Pulse 2012-3 best matches pulses for the Orion Multipurpose Crew Vehicle predicted landing loads in terms of magnitude and duration. 2012-4 was a generic pulse only used to measure repeatability in the test setup.

*Table 1- Nominal input pulse properties*

<i>Name</i>	<i>Shape</i>	<i>Amplitude (g)</i>	<i>Duration (msec)</i>
2010-1	Trapezoid	10	100
2012-1	Trapezoid	12	80
2012-2	Half-Sine	12	80
2012-3	Half-Sine	16	40
2012-4	Trapezoid	5	120

Data collected from a total of 22 channels consisted of linear accelerations, load, moments and angles from the head center of gravity (CG), chest and pelvis regions in the anterior/posterior (horizontal or X) and spinal (vertical or Z) directions. The sideways (lateral or Y) direction was largely ignored due to the nature of the loading conditions. Two additional accelerometers were placed on the seat platform. The first was aligned with the composite horizontal CG location of the THOR/seat system, while the other was toward the front of the seat and used only as a backup sensor. Laterally, these accelerometers were positioned on the THOR's right side. Data was collected using a TDAS-Pro Data Acquisition System sampling at 10 kHz. Instrumentation locations are summarized in Table 2.

*Table 2 - THOR Sensor data*

<i>THOR Data channel #</i>	<i>Location</i>	<i>Direction</i>	<i>Measurement - Unit</i>
1	Head CG	X	Acceleration - g
2	Head CG	Y	Acceleration - g
3	Head CG	Z	Acceleration - g
6	Occipital Condyle	Y	Rotation - degrees
7	Upper Neck	X	Force --lb.
9	Upper Neck	Z	Force --lb.
11	Upper Neck	Y	Moment - in-lb.
13	Lower Neck	X	Force --lb.
15	Lower Neck	Z	Force --lb.
17	Lower Neck	Y	Moment - in-lb.
19	T1	X	Acceleration - g
21	T1	Z	Acceleration - g
22	Thorax	X	Acceleration - g
35	Spine	X	Force --lb.
36	Spine	Y	Force --lb.
37	Spine	Z	Force --lb.
38	Spine	X	Moment - in-lb.
39	Spine	Y	Moment - in-lb.
40	T12	X	Acceleration - g
42	T12	Z	Acceleration - g
59	Pelvis	X	Acceleration - g
61	Pelvis	Z	Acceleration -g

Photogrammetric imaging was also completed on a subset of the tests, mainly to track the THOR position before and kinematics during the impact event. Photogrammetric imaging data was acquired at a sample rate of 1 kHz. A minimum of three targets were placed on each THOR component, including head, chest, legs and arms. Targets were placed on the projected frontal CG location for the head and chest for kinematic comparisons with the Hybrid ATDs. Figure 2 shows the photogrammetry target locations and IDs on the THOR in the test condition.

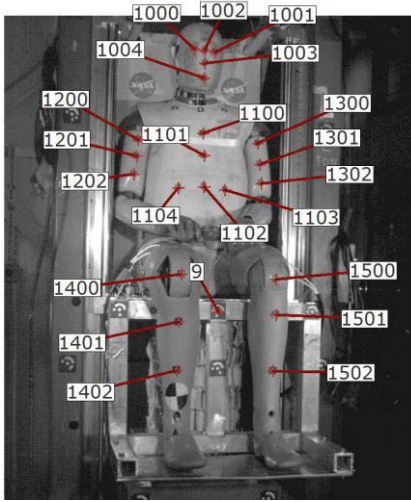


Figure 2- Photogrammetry target locations and IDs

Figure 3 shows the actual measured input deceleration pulse, as measured from the seat platform. The pulse shapes, along with all data presented from the THOR ATD, are low-passed filtered in accordance to guidelines set forth by SAE J211 [11]. Note that the 2010-1 pulse magnitude was nominally 10 g. However, the actual pulse neglecting the first spike, reached a final plateau of approximately 5 g.

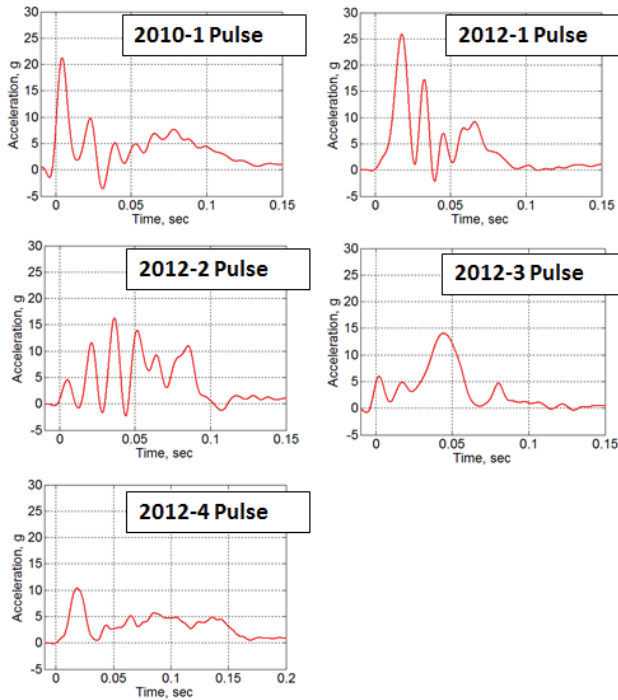


Figure 3 - Actual input pulses

## Results – Data Repeatability

Repeatability of the test setup was examined using the 2012-4 test condition to determine the variability in the input pulse shapes and test setup and their effects in the THOR response. The three 2012-4 seat platform repeat test pulse shapes are shown in Figure 4. The acceleration traces closely match in both their peak values and time histories. Differences in the initial peaks are attributed to high frequency noise in the signal. The curves were integrated to obtain velocity in an attempt to remove the higher frequency noise, and compared again. The variation in the velocity time histories is negligible, indicating that the input pulse into THOR is repeatable.

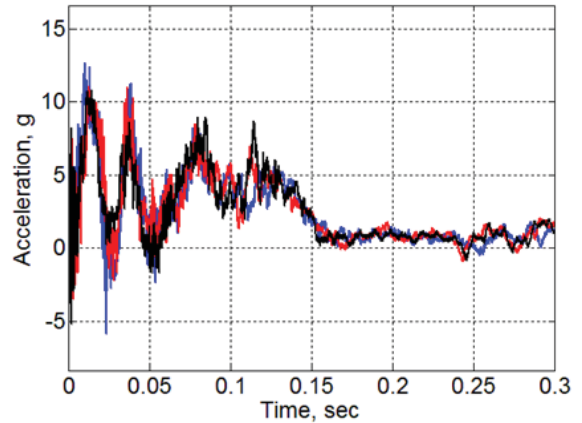


Figure 4- Three repeats of seat platform accelerations for 2012-4 pulse

The vertical acceleration responses from four different locations on the THOR are plotted in Figure 5, while the vertical loads obtained from three discrete locations in the neck and spine are plotted in Figure 6. The acceleration waveforms from pelvis to head are similar in magnitude and duration. The abrupt spike at the end of the head vertical acceleration curve in Figure 5 is likely from the THOR head rebounding against the seat back. The conclusion drawn from the data repeatability test series was that any variation in the THOR response data comes from the THOR ATD itself.

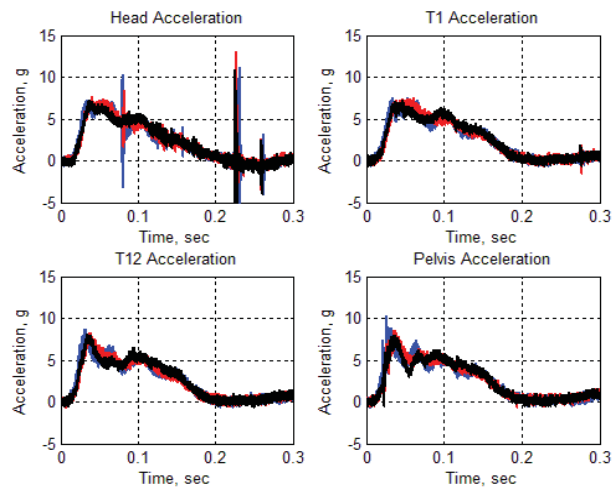


Figure 5 – THOR Vertical acceleration responses for three repeat pulses (2012-4)

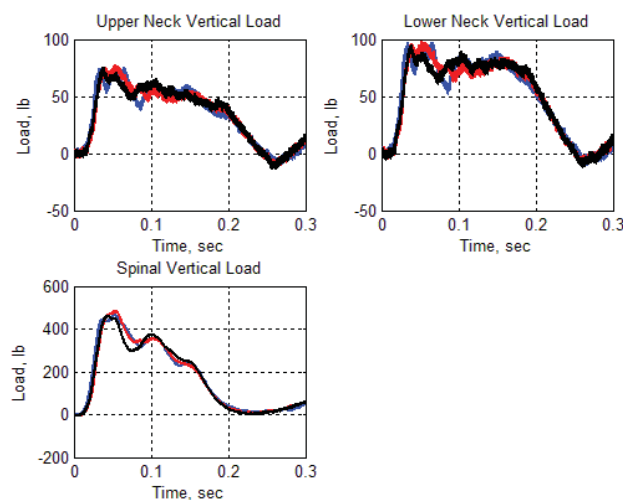


Figure 6 – THOR Vertical load responses for three repeat pulses (2012-4)

### Results – Loading Conditions THOR Response

Figure 7 shows an image sequence for a test using the 2010-1 pulse shape. The upper left picture shows the test 4 msec before initial impact. It was at this moment that the photogrammetry captured the pre-impact position. The upper right picture shows the test 56 msec after impact. THOR torso compression was a maximum at this point. The lower left picture shows the test 164 msec after impact, where the THOR head rotation was at a maximum. The bottom right picture shows the THOR at rest, post impact.

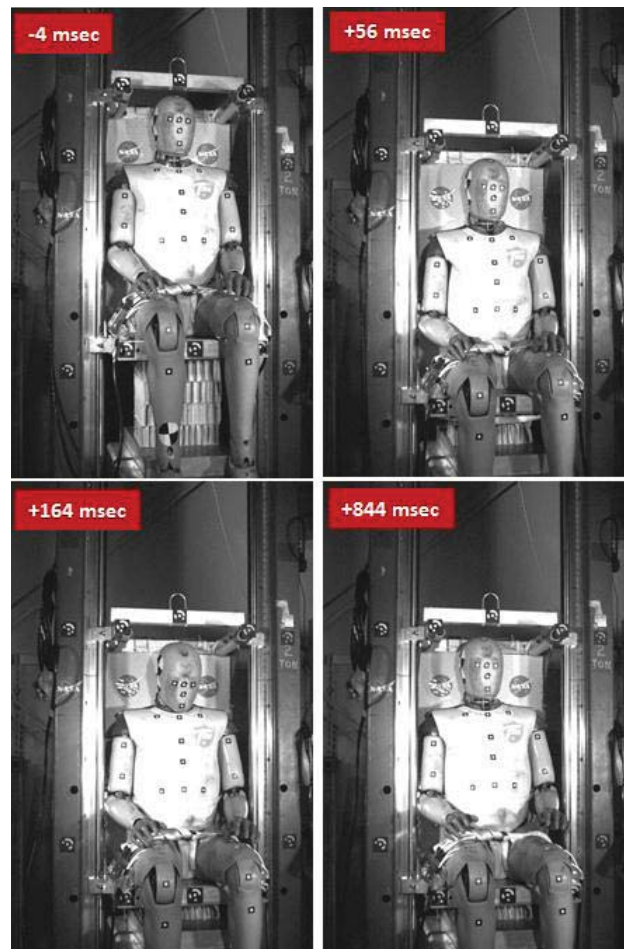


Figure 7 - Image sequence of a typical test

Vertical accelerations for four areas on the THOR are plotted in Figure 8. The acceleration waveforms match the input seat platform pulse. When examining the four vertical acceleration responses starting at the pelvis region and going to the head, there is slight attenuation for the 2012-1 test condition, but relatively unchanged acceleration levels for the 2010-1, 2012-2 and 2012-3 test conditions. The consistency in acceleration levels through the THOR ATD is noteworthy. However, this finding could be different if THOR is subjected to much higher loading conditions. The 2012-3 test condition produces the highest acceleration in the THOR, which is expected since the 2012-3 condition was the most severe of the four.

The acceleration waveform shape from the 2010-1 test condition is much different than the response from the other three test conditions. The 2010-1 response has a defined plateau region while three of

the four pulses were more triangular in shape. The 2010-1 response also has a slightly higher onset rate; however, the onset rate is generally unchanged due to the common materials being used for the input pulse generation.

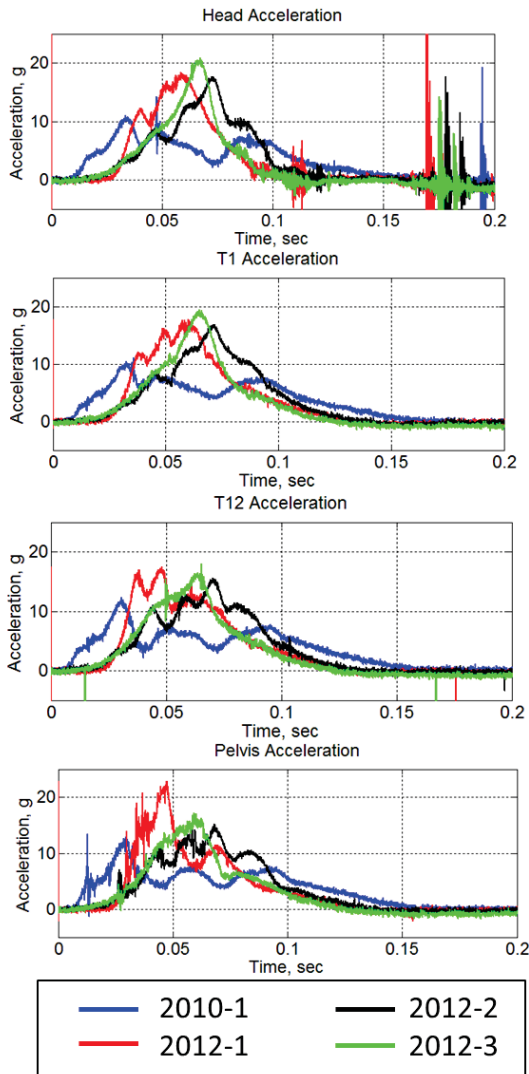


Figure 8 - Vertical accelerations for four different input pulses

The vertical neck and spinal loads shown in Figure 9 track the acceleration trends. On average, the 2012-3 test condition generated the highest load. The THOR load reaches a maximum of approximately 1,100 lb. in the spine, while maximum values of 300 and 200 lb. are seen in the lower neck and upper neck, respectively. The 2010-1 test condition again generated a plateau shaped THOR response. The maximum load in the spine is approximately 500 lb.,

and this load levels off at approximately 400 lb. The loads in the neck are much lower, reaching maximums of 100 lb. for the lower neck and between 50 and 100 lb. for the upper neck.

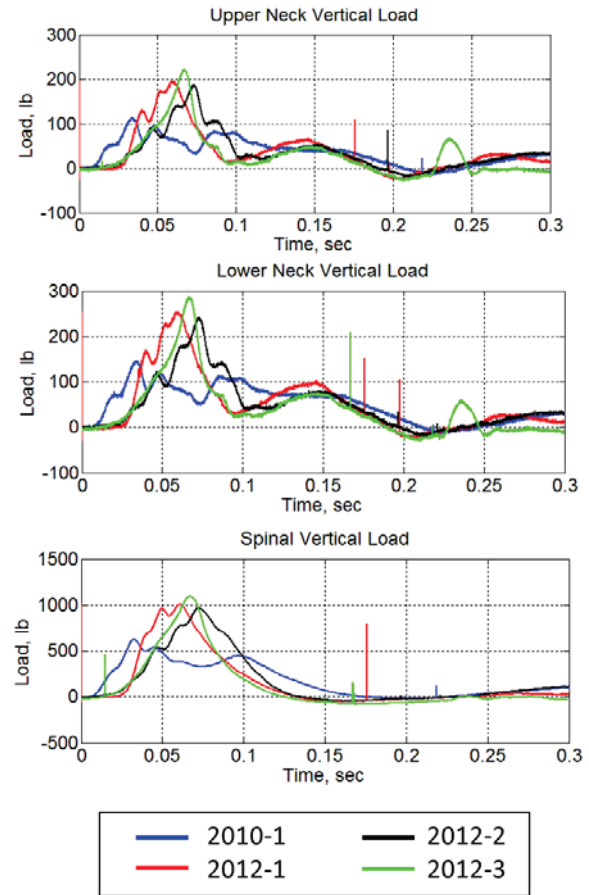


Figure 9 - Vertical loads for four different input pulses

Measured horizontal loads on the THOR, as seen in Figure 10, are small and not indicative of large forward motion. These loads develop primarily from the horizontal THOR motion during impact, either from the large rotations of the upper body and head, or, to a lesser extent, a small horizontal offset between the drop tower guide rails and the position of the composite THOR and seat platform CG. The major response is from the upper neck, which is due to the head rotational motion. The response curves from the four test conditions generally follow the same waveform trend.

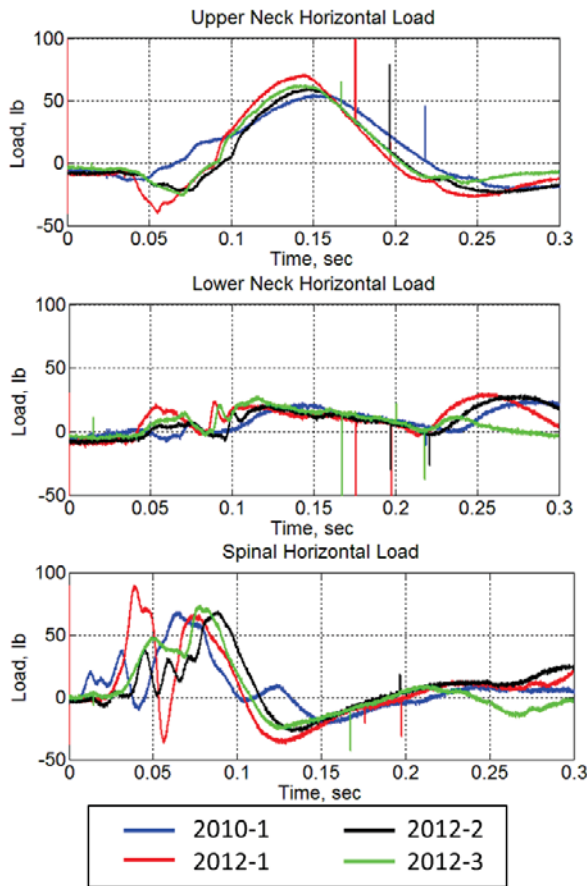


Figure 10 - Horizontal loads for four different input pulses

The rotational moment responses are plotted in Figure 11 and closely follow the horizontal motion response. Of the three rotational moments measured, the spinal response is much higher than either of the neck responses. In contrast to the spinal moment, the shape and peak values of the response curves at both the lower and upper neck are very similar. Moment results consistently reach maximums of approximately 200 in-lb. for the lower neck and 50 in-lb. for the upper neck. These results suggest that the exact shape and amplitude of the input pulse has little effect on the THOR head and neck response for predominant vertical loading.

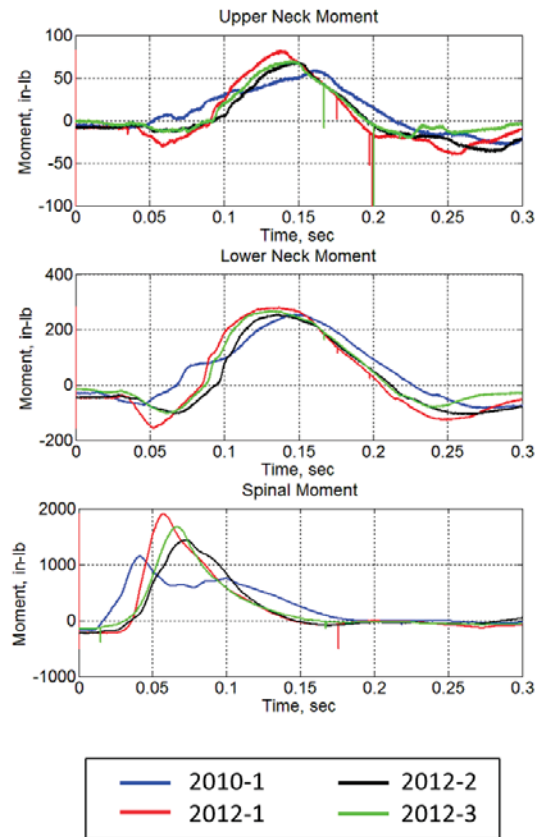


Figure 11 - Rotational (y) moments for four different input pulses

The photogrammetry data was examined to determine whether the THOR kinematics are affected by the different test conditions. The head CG vertical displacement plotted in Figure 12 is first examined. The head vertical displacement can be partially representative of the total THOR vertical compression during the impact; however, it should be noted that the head rotation will also affect the vertical displacement result. The four test conditions showed similar rates of head displacement ranging between 4.34 in. for the 2012-2 test condition to 4.95 in. for the 2012-2 test condition.

The head displacement data illustrates that the motion of the head lags behind the acceleration of the head. By re-examining Figure 8, the maximum values in the acceleration curves occur approximately 50 msec after impact. The acceleration reaches a state of rest between 150 msec and 200 msec after the impact. The displacement data, however, shows head motion during the first 50 msec after impact. The head displacement reaches a maximum value between 100

and 150 msec and begins to rebound more than 200 msec after impact.

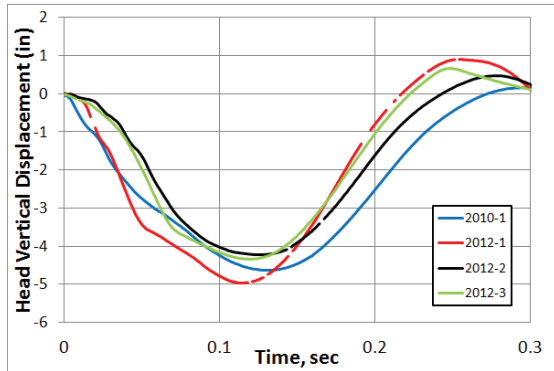


Figure 12 - Head CG vertical displacement for four different input pulses

Horizontal head displacement is next examined in Figure 13. The THOR head horizontal displacement results follow two distinct trends: a higher plateau and a lower plateau. The 2010-1 and 2012-3 test conditions follow the lower plateau, reaching a maximum value of 3.15 in. The 2012-1 and 2012-2 test conditions follow the upper plateau which reaches a maximized value of 4.97 in. The initial peak displacement occurs at approximately 200 msec, which is very late in the time history. The horizontal motion from the THOR ATD is not consistent with the magnitude of the vertical loading for the various cases, suggesting that other late time factors such as the abdomen safety strap or initial head position influence the horizontal displacement. The time durations for both of the plateaus are approximately the same at 600 msec.

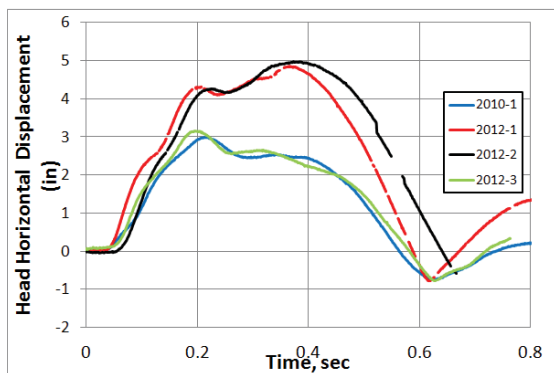


Figure 13 - Head CG horizontal displacement for four different input pulses

Finally, chest vertical displacements are compared in Figure 14. The chest displacement measurements follow trends seen in both the head moment response and pelvic load response. The 2010-1 test condition generates a THOR response with a defined plateau region, while the other conditions generate triangular shaped responses. However, the triangular curve shapes are much less distinct than those seen in the pelvic / lower spinal region. The trends in the chest displacement however do not follow the peak trends seen in the head motion. A maximum chest response of 4.31 in. was measured from the 2012-1 test condition. The 2010-1 test condition generates the highest head displacement but the lowest chest displacement of 3.01 in. This additional chest displacement data confirms that the total head displacement data is a combination of THOR compression and head rotation. Thus, the chest data may be a better indicator of total ATD compression in some test cases.

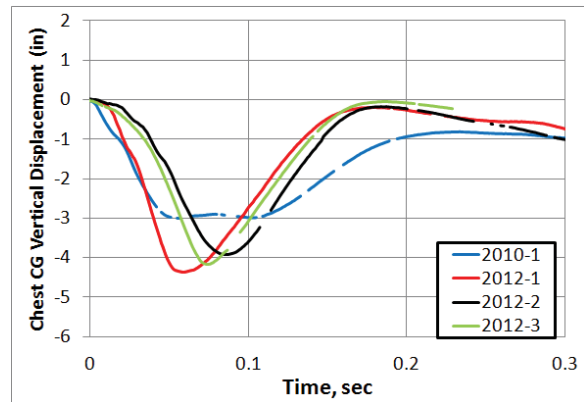


Figure 14 - Chest CG vertical displacement for four different input pulses

### Results – THOR comparisons to Hybrid ATDs

The THOR data generated by using the test condition labeled 2010-1 is next compared to the previously generated data obtained from similarly conducted tests with the Hybrid series of ATDs. It must be noted that interpretation and comparison of the data between different ATDs was not exact given the difference in physical placement of the measurement sensors. One example is presented by examining and comparing the CG and corresponding head accelerometer measurement sensor locations between the Hybrid II and Hybrid III. The Hybrid II head



accelerometer location is approximately 0.969 in. above the center point of the neck attachment, centered laterally in the head cavity, and vertically in-line with the nose. The Hybrid III ATD head accelerometer location is positioned forward of the neck positioning joint and higher in the head cavity, with the CG vertical projection being approximately at eye level. Additionally, the THOR-NT head CG location is different from both of the Hybrid CG's.

With these caveats noted, the head vertical accelerations are first compared in Figure 15. The general shape and peak values for each of the ATDs are approximately the same. Each ATD displays a generalized plateau shape with sinusoidal peaks and valleys representing the layer crushing of the stacked paper honeycomb. The major difference between the curves is the onset rate of the THOR lags the onset rate of the Hybrid ATDs. The THOR maximum value is 11.4 g at 30 msec after impact, whereas the generalized Hybrid maximums are between 8 and 10 g, and occur between 12 and 20 msec after impact. The tail end of the plateau region after the 100-msec mark agrees well between the THOR and Hybrid III ATDs.

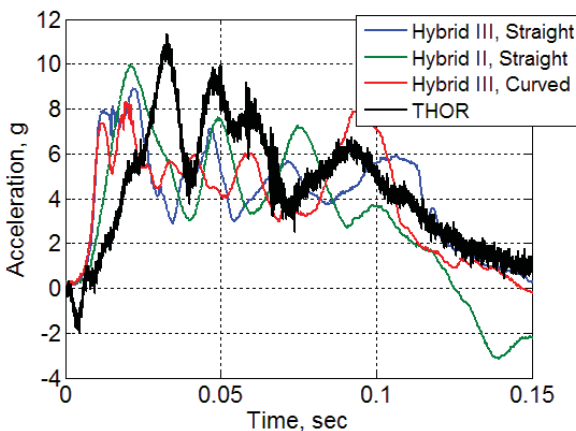


Figure 15 - THOR - Hybrid comparison - Head vertical acceleration

The vertical pelvic acceleration results are plotted in Figure 16. Upon examination, the vertical acceleration results of the pelvis exhibit similar behavior to the head acceleration results. All of the responses resemble a plateau shape with the exception of having a large short duration peak at the initial onset. However, in the pelvis acceleration, the

Hybrid II more closely matches the Hybrid III and THOR during the tail end of the plateau after 100 msec. The entire response lasts for approximately 150 msec. The vertical acceleration in the THOR again lags the acceleration in the Hybrid ATDs, which is due to a slower onset rate. The differences in the onset rate seen in both the head and pelvis regions suggests that the THOR pelvis is made of a softer material or is geometrically different than from the Hybrid ATDs. The maximum values, however, are similar and range between 13.4 to 16.6 g for the Hybrid ATDs and 14.7 g for the THOR.

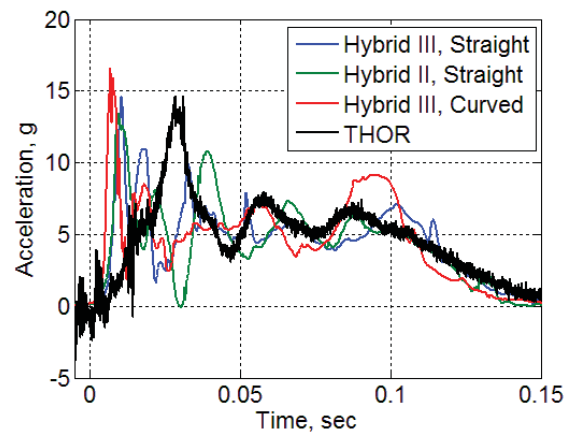


Figure 16 - THOR - Hybrid comparison - Pelvis vertical acceleration

Finally, lumbar load values are examined and plotted in Figure 17. The lumbar load response curves parallel the trends of the pelvic accelerations, showing a plateau shaped response with an initial peak. However, unlike the pelvic accelerations which exhibit almost identical response durations, the total duration of the loading is between 100 and 150 msec for the Hybrid ATDs and approaches 200 msec for the THOR.

The THOR has a maximum lumbar load of 673 lb. which occurs at 37 msec after impact. The next highest load occurs in the Hybrid III with a straight spine configuration. The maximum load is 591 lb. and occurs 20 msec after impact. These differences can be seen in Figure 17. All ATDs having the straight spine configuration are at or slightly above the 600-lb. maximum load mark; whereas the maximum load for the Hybrid III with curved spine configuration is slightly above 400 lb. Some of the

scatter in the data could be due to ATD test positioning; however, the majority of the difference can be attributed to the orientation of each ATD's load cell with respect to the vertical axis. Three of the ATDs tested; the Hybrid II, Hybrid III in a straight spine configuration and the THOR, all have straight spinal columns with the load cell positioned parallel to the vertical direction. The Hybrid III in a curved spine configuration however contains a load cell with a measurement axis positioned 22 degrees off-axis from the vertical direction. Therefore, it is expected that the loads measured from the curved spine load cell would be lower than those measured from the straight spine.

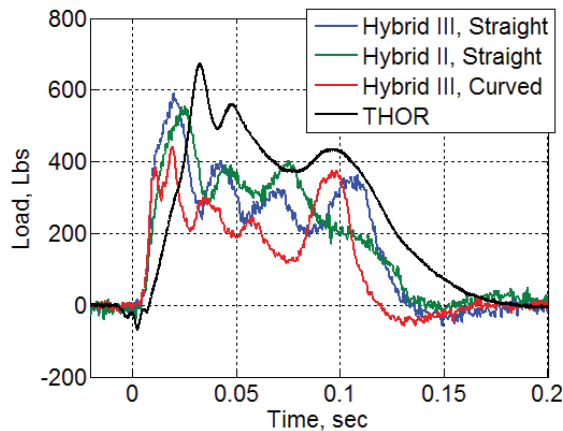


Figure 17 - THOR - Hybrid comparison - Lumbar load

Kinematic motion is next compared between the four configurations of ATD. Figure 18 shows the head CG vertical motion. The THOR head motion is bounded on either side by the head motion of the Hybrid ATDs, but trends closer to the curves of the Hybrid III. The data suggests the THOR more closely resembles the Hybrid III ATD, which is expected since the head displacement is highly dependent on the neck motion, and the THOR and Hybrid III neck articulation is similar. The data also suggests that updates in design when going from the older Hybrid II to the newer Hybrid III neck severely decrease the head motion. For the tests conducted in this test series, this reduction is approximately 3 in.

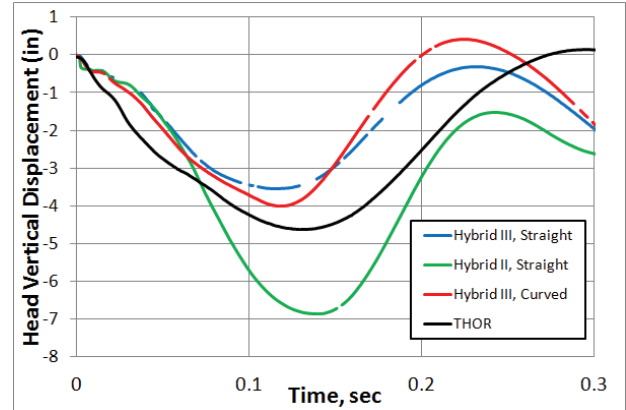


Figure 18 - THOR - Hybrid comparison - Head CG vertical displacement

Similarly, the angle of the head with respect to the vertical direction is plotted in Figure 19. The inherent design of each ATD constrains the head to a forward lean, which gives a positive head angle offset at 0-msec when examining the data. One conclusion that can be drawn is that the ATDs in the straight spine configuration (Hybrid III in straight configuration, Hybrid II and THOR) all show the head angle at an approximate 7-degree forward lean, while the ATD with a curved spine configuration (Hybrid III in curved spine configuration) gives the head angle at a much larger 11.8-degree lean. The much larger offset angle is due to the curved spine causing the ATD to “slouch” more than the ATDs with straight spines.

The THOR and Hybrid III time histories of the head angle respond similarly when subjected to the test condition, and, in addition, both the THOR and Hybrid III respond differently than the Hybrid II. The Hybrid II ATD head and neck responses are the largest of the ATDs tested, suggesting that the neck on the Hybrid II is much more compliant than that of the Hybrid III and THOR.

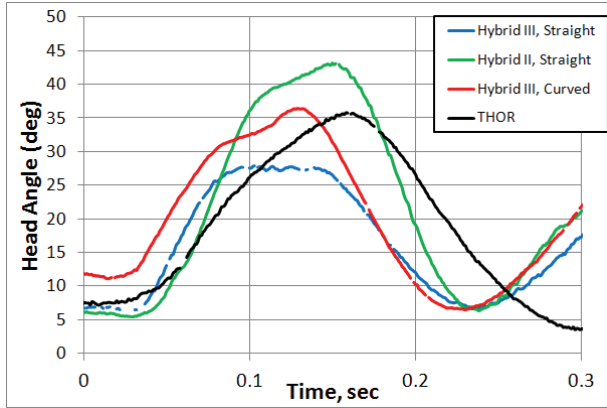


Figure 19 - THOR - Hybrid comparison - Head angle

Chest displacements are next examined in Figure 20. Unlike the head motion results where the THOR and Hybrid III follow similar trends, the THOR shows the maximum chest vertical motion, while the Hybrid III show a minimum. Together, these two responses bound the Hybrid II motion. The THOR chest has been completely redesigned from the chest of either the Hybrid II or III, and it would be expected that the motion would be different. However, another possibility for the large difference is that the THOR torso region is covered with a cloth vest. The motion of this vest may not be fully representative of the underlying motion internal to the THOR chest cavity. Care must be taken when interpreting the chest results.

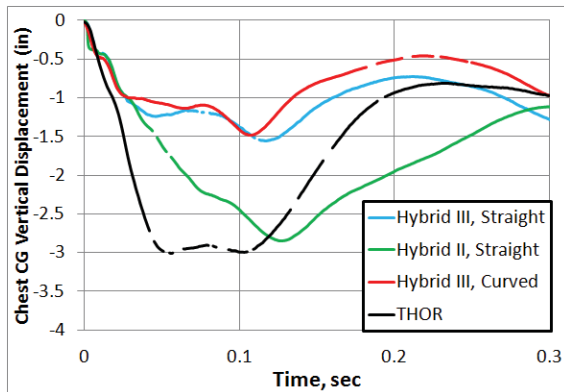


Figure 20 - THOR - Hybrid comparison - Chest CG vertical displacement

### Results - Injury Metric Comparison

Two common injury metrics are used to generate further comparisons between the Hybrid and THOR ATDs. The first examined is the Head Injury Criteria

(HIC), which is a common injury criteria used in determining injury to the head in both automotive crash testing and also aircraft and rotorcraft crashworthiness. The HIC uses an integrated form of the resultant acceleration obtained from the ATD's head in equation (1) below.

$$HIC = \max \left[ \frac{1}{t_2 - t_1} * \int_{t_1}^{t_2} a(t) * dt \right]^{2.5} * (t_2 - t_1) \quad (1)$$

The times  $t_2$  and  $t_1$  define the boundaries of the moving window over the time history of the resultant head acceleration data. The HIC is primarily designed to combine a maximum acceleration value and its duration into a single number over a time interval, with the maximum HIC value recorded over multiple windows. Guidelines established by Federal Motor Vehicle Standard (FMVSS 208) [6] and the National Highway Transportation Safety Association [12] suggest that HIC values be less than the limits of 1000 and 700 for time intervals of 36 msec and 15 msec, respectively.

Table 3 - HIC Values

ATD Type	HIC 15 Value	HIC 36 Value
Hybrid II	2.5	4.1
Hybrid III, Straight Spine	2.1	3.1
Hybrid III, Curved Spine	2.3	3.9
THOR-NT	2.3	4.8

Table 3 shows the HIC values for all of the tests for both time intervals are extremely low. The highest value of HIC 15 occurs in the Hybrid II ATD with a value of 2.5, which was 0.35% of the limit. The highest value of HIC 36 occurs in the THOR. The value is 4.8 which is 0.48% of the limit. These resultant HIC values are grouped extremely close together which shows for this set of loading conditions, the likelihood of injury to the head is extremely low. The low results are partially expected, since HIC values approach the limits when high spikes in the acceleration response are seen. The high spikes are typically the result of a head blunt impact, which was not present in this test series.

Lumbar load values are next compared between the Hybrid and THOR ATDs, and are shown in Table 4. The lumbar load value limits defined within 14 CFR 27.562 state that a 50<sup>th</sup> percentile male ATD cannot experience loads greater than 1,500 lb. in compression as measured from a load cell in the lumbar region. As an aside, the recommended military lumbar load tolerance level for a 50<sup>th</sup> percentile male is 2,065 lb. [13]. Table 4 summarizes the lumbar load values measured.

*Table 4 – Drop test Lumbar load values*

<i>ATD Type</i>	<i>Maximum Lumbar Load (lb.)</i>	<i>% of 14CFR 27.562 guideline</i>
Hybrid II	554	36.9%
Hybrid III, Straight Spine	591	39.4%
Hybrid III, Curved Spine	441	29.4%
THOR-NT	675	45.0%

The highest lumbar load value was measured in the THOR, while the lowest lumbar load value was measured on the Hybrid III in the curved spine configuration. The difference between these two numbers is almost 35%, but all ATDs pass when evaluating the criteria.

The lumbar load data presented reiterates that care must be taken when choosing an acceptable ATD when evaluating a lumbar loading criteria. If each of the ATDs were retested and subjected to significantly higher loading magnitudes, potential for discrepancies for the pass/fail criteria could be present.

**Results – Footrest Investigations**

A footrest was added to the platform and shoes were placed on the THOR for the final investigations of this test series. The updated test setup is depicted in Figure 21. The purpose of these additions was to study the offloading effects on the THOR response due to the presence of a lower surface contact.



*Figure 21- THOR test setup with footrest*

It is assumed that the footrest would offload the lumbar and torso loading of the THOR, as additional load would be taken by the lower limbs. For the comparative study, the THOR ATD was subjected to each of the previously used loading conditions (2010-1, 2012-1, 2012-2, 2012-3) both with and without the footrest. In the following plots, the black curves are the tests conducted with the addition of the footrest, while the colored curves are the baseline tests. The coloring scheme follows the color scheme shown in Figure 8 through Figure 13. Head vertical accelerations are first plotted in Figure 22.

The addition of the footrest affects the head response from each loading condition differently. In the 2010-1 test condition, the addition of the footrest adds a tail to the falling edge of the plateau. The footrest adds a second peak to the onset of the 2012-1 test condition, it flattens out the peak of the 2012-2 test condition, and it increases the maximum acceleration for the 2012-3 test condition.

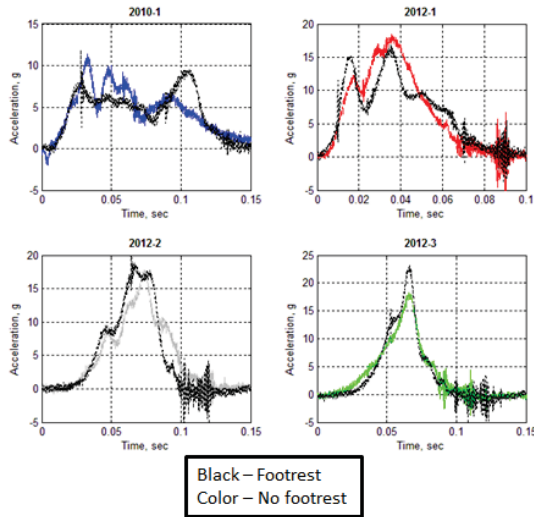


Figure 22 - Head vertical accelerations for four different input pulses

The lumbar region load responses are shown in Figure 23. The 2012-1 acceleration response mimics the lumbar load response with the addition of the footrest, where one larger peak is divided into two smaller peaks. The two peaks occur from two separate impacts, presumably between the THOR pelvis and the seat bottom and between the THOR legs and footrest. For the 2012-2 and 2012-3 test conditions, the addition of the footrest did not change the shape of the curve, but increased the magnitude.

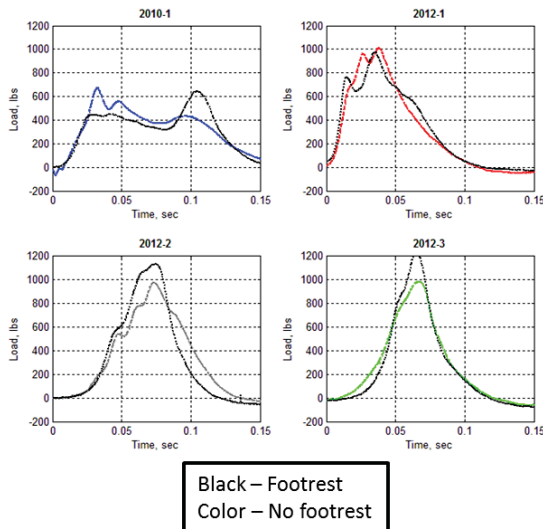


Figure 23 - Lumbar loads for four different input pulses

The lower neck y-moments both magnitudes and durations are unaffected by the addition of the footrest. Figure 24 shows the response curves.

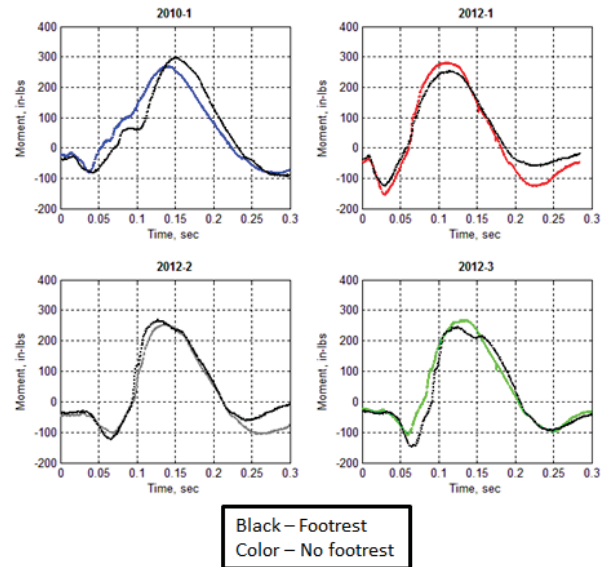


Figure 24 - Lower neck moment for four different input pulses

The results in the head and lumbar regions are explained by further examining the seat platform impact accelerations. The changes in the THOR head and pelvis response curves are paralleled with the acceleration changes in the response of the seat platform. For the 2010-1 curve, the seat platform response shows an added tail to the downward slope of the plateau, whereas in the 2012-1 curve divides the single peak value into two separate peaks. The seat platform results for the 2012-2 and 2012-3 pulses also exhibit higher accelerations.

The conclusion drawn from these findings is that the offloading was negated because the primary load path was still achieved through the primary impact between the seat platform and the energy absorbing material.

### Summary

The THOR-NT is an advanced biofidelic ATD developed for the NHTSA in the early 2000s. The purpose of developing and building the THOR ATD was to design an omnidirectional (frontal, lateral, rear

and vertical) ATD as a replacement for the legacy single-axis use ATDs, mainly consisting of a mix of Hybrid II and Hybrid III ATD and Side Impact Dummies (SIDs). Several tests were conducted at NASA LaRC in which the THOR ATD was subjected to a number of low level but significantly different input pulses in a vertical loading condition. The purpose of these tests was to generate data for FEM calibrations and to add to the growing test database of THOR data. It is hoped that, with enough validation, the THOR ATD could be a suitable replacement for the older ATDs.

The four input pulse shapes played a role in the THOR response. The trapezoidal shaped input pulse (2010-1) generated the most trapezoidal response from the THOR. The THOR responses resemble a more triangular shape for the other three input pulses and peak at approximately 20 g. The spinal loads were between 100 and 300 lb. for the upper spine and around 500 to 1,000 lb. for the lower spine. The 2010-1 input pulse consistently saw the lowest response from the THOR.

In general, the THOR-NT resembles the Hybrid III ATD more closely than the Hybrid II in most instances. One noticeable difference is the onset rate of acceleration. The neck of the THOR more closely resembles the Hybrid III neck, but the pelvic region more closely resembles ATDs with a straight spine. All of the tested configurations of the Hybrid II, Hybrid III and THOR passed all of the injury criteria examined. The lumbar load and head accelerations were in the very low regimes and did not approach the various limits imposed. However, retesting the THOR and comparing to the Hybrid ATDs at a higher loading condition will amplify the small differences seen in the results.

The effect of adding a footrest changes the input accelerations while doing very little to offload some of the response carried through the pelvic region. This result is an artifact of the specific test setup, and not an artifact of the THOR-NT itself. To subject the THOR to a valid offloading comparison, the footrest must also be subjected to an impact surface.

The THOR ATD is still a developmental tool currently undergoing extensive testing across different automotive and aerospace organizations.

There is great potential for using the THOR ATD for evaluating occupant responses where vertical loading is prevalent. More vertically oriented test data is recommended before instituting certification guidelines for FAA and NASA applications.

### **Acknowledgements**

The authors extend their appreciation to Joseph Pelletiere of the FAA and Dan Parent and Joe McFadden at NHTSA for facilitating the acquisition of the THOR-NT ATD. We would also like to thank Rick DeWeese and Ronnie Minnick of the FAA, and Langley Aerospace Research Summer Scholars (LARSS) student Victor Luquin for their technical assistance in conducting these tests.

### **References**

1. Code of Federal Regulations, Federal Aviation Regulations for Aviation Maintenance Technicians FAR AMT, Part 27 Airworthiness Standard: Normal Category Rotorcraft, 27.562 – Emergency Landing Dynamics.
2. Code of Federal Regulations, Federal Aviation Regulations for Aviation Maintenance Technicians FAR AMT, Part 27 Airworthiness Standard: Transport Category Rotorcraft, 27.562 – Emergency Landing Dynamics.
3. Military Standard, MIL-STD-1290A (AV), Light Fixed- and Rotary-Wing Aircraft Crash Resistance, Department of Defense, Washington DC, 20301, 26 September 1988.
4. Eiband, A.M. “Human Tolerance to Rapidly Applied Accelerations: A summary of the Literature,” NASA Memorandum 5-19-59E. 1959.
5. Brinkley, J.W., Specker, L.J., and Mosher, S.E., “Development of Acceleration Exposure Limits for Advanced Escape Systems.” NATO AGARD Proceedings, AGARD-CP-472, February 1990.
6. U.S. Department of Transportation. “Federal Motor Vehicle Safety Party 571. Standard 208 – Occupant Crash Protection.” [www.fmcsa.dot.gov](http://www.fmcsa.dot.gov)
7. Haffner, M., et al, “Foundations and Elements of the NHTSA THOR Alpha ATD Design,” The

17<sup>th</sup> International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, June 4-7, 2001.

8. Shams, T., et al, "Development of THOR NT: Enhancement of THOR ALPHA-The NHTSA Advanced Frontal Dummy," The 19<sup>th</sup> International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington D.C., June 6-9, 2005.
9. Ridella, S. A., and Parent, D. P., "Modifications to Improve the Durability, Usability, and Biofidelity of the THOR-NT Dummy," The 22<sup>nd</sup> International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, D.C., June 2011.
10. Polanco, M.A., and Littell, J.D., "Vertical Drop Testing and Simulation of Anthropomorphic Test Devices," Proceedings of the American Helicopter Society 67<sup>th</sup> Annual Forum, Virginia Beach, VA, May 3-5, 2011.
11. Society of Automotive Engineers. "Surface Vehicle Recommended Practice: Instrumentation for Impact Test-Part 1-Electroic Instrumentation." SAE J211-1, July 2007.
12. Kleinberger, M. et al. Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems. NHTSA report. 1998.
13. Richards, M., Podob, R., "Development of an Advanced Energy Absorber," Proceedings of the American Helicopter Society 54<sup>th</sup> Annual Forum, Washington, D.C., May 20-22, 1998.