OOP AIR BAG TESTS WITH THE FIFTH PERCENTILE FEMALE THOR AND HYBRID III DUMMIES

Peter G. Martin
Matthew Craig
Stephen Ridella
National Highway Traffic Safety Administration
U.S. Department of Transportation
Washington, D.C., USA

Paul Rigby
Philemon Chan
L-3/Jaycor
San Diego, CA, USA

Paper Number 09-0546

ABSTRACT

The THOR-05F is a new anthropomorphic test device with many notable features, including a biofidelic neck design with built-in lordosis that segregates load paths within the cervical spine. Static air bag deployment tests were carried out with the dummy positioned in the NHTSA-1 (chin on module) driver Out-Of-Position (OOP) configuration. A set of late-model two-stage air bag modules were used in a total of forty tests, including reference tests conducted with the 5th percentile female Hybrid III dummy. All of the modules were driver-side units, and each was contained within its own steering wheel assembly. Half of the modules were configured to deploy more aggressively. All bags were observed to deploy asymmetrically, resulting in a substantial twist of the head about the z-axis of the THOR-05F neck, and a high corresponding Mz upper neck moment. The THOR-05F demonstrated its ability to discriminate air bag aggressiveness, especially in its upper neck tension measurements which was the most predominant upper neck load. Compared to Hybrid III, the THOR-05F neck showed less tendency to go into extension. The upper neck moment (My) and shear (Fx) were much lower in magnitude than those of the Hybrid III 5th. Head accelerations were similar to those produced by the Hybrid III 5th.

INTRODUCTION

The THOR 5th percentile female dummy is a new anthropomorphic test device (ATD) with many notable features, including a biofidelic neck design with built-in curvature that segregates load paths within the cervical spine. This ATD is very similar to the THOR-NT 50th percentile male archetype which has seen wide interest since its release in 2003. Both dummies were developed by NHTSA for advancing the study of biomechanical phenomena and the development of new injury criteria supported by other efforts in human volunteer tests, cadaver tests and modeling. The new fifth percentile female has been called informally THOR-05F during the development process.

Figure 1. Fifth percentile female THOR-05F ATD.

The development of the THOR-05F was initially presented at international conferences in 2003. A paper was presented at the ESV conference, titled "Design requirements for a fifth percentile female version of the THOR ATD" which discussed the scaled biomechanical corridors that were developed for evaluating the biofidelity of the new dummy [Shams, 2003]. This was followed by a paper at the 2003 Stapp Conference titled, "Design and development of a THOR based small female crash test dummy" that summarized the development work and the initial biofidelity testing [MacDonald, 2003].

The THOR-05F dummy was designed using the anthropometric data developed for the 5th percentile female [Robbins, 1983] and biomechanical requirements derived from scaling the responses of the 50th male [Shams, 2003]. While many of the mechanical components of the THOR-NT 50th male were scaled according to the appropriate anthropometric data, a number of improved design features have been introduced in the THOR-05F.

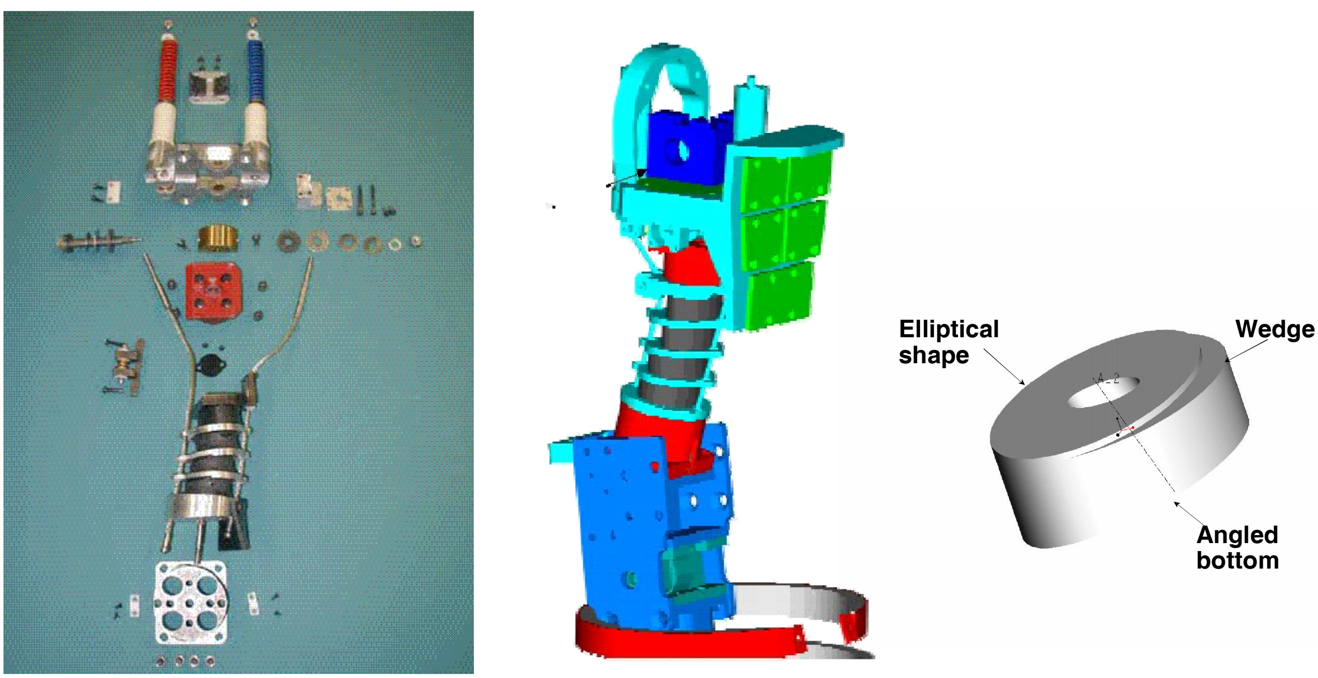
THOR neck technology – Multiple load paths

The study herein focuses on the performance of air bags as measured within the THOR-05F's head/neck complex. As with the 50th percentile male THOR-NT, the neck has distinct sub-assemblies reflecting a design premise that human necks are loaded along multiple paths, and that loads are borne by both ligamentous tissues and musculature. Loads that pass through a human neck are presumed to include those borne by "external" musculature only (represented in THOR by the two cable sub-assemblies), and those borne by both "internal" muscles and ligaments (represented in THOR by the molded neck sub-assembly and the pin joint/nodding block sub-assembly).

The THOR design philosophy also presumes that human neck injuries occur when ligamentous tissues become overloaded. Hence, a THOR injury criterion will be based on its upper neck load cell alone, which is mounted to the neck rather than in the head (as with the Hybrid III). Forces measured in the load cells attached to THOR's anterior and posterior cables represent "external" non-injurious loads borne by musculature alone (and not ligamentous tissues). These load cell measures are contemplated as reference measures only, and may not be directly linked to an injury criterion.

THOR-05F Beta neck construction.

Unlike the THOR-NT 50th male, the THOR-05F incorporates the "Beta neck" design (Fig. 2). This neck features built-in lordosis and is more anthropometrically correct than the standard THOR-NT neck. The Beta neck concept was originally developed for the 50th male version of THOR [Huang, 2003]. Due to cost considerations, the prototype was constructed by gluing (rather than molding) the rubber pucks to the aluminum plates. But failures due to debonding prevented the Beta neck design from ever being verified for inclusion with the release of the standard THOR-NT.



a. THOR-05F Beta neck components

b. THOR-05F Head/neck system on spine.

c. Beta neck's wedge-shaped rubber puck (one of four).

Figure 2. THOR-05F Beta neck system and components.

Thus, further development of the basic Beta neck has been carried out in conjunction with the experimental THOR-05F. By using standard scaling techniques, a new, smaller Beta neck was designed for the THOR-05F. To overcome the debonding problem, the new neck has been injection molded. In addition to the core design concept of multiple load paths that is represented in the standard THOR-NT neck, the Beta neck includes the following principal design features.

Four Pucks and Offset Geometry. The four-puck neck agrees with the length between the human occipital condyles and the first thoracic vertebra (OC-T1 length) derived from volunteer tests and the T1 is located at a well-defined rigid position. As a result, the new neck is offset from the top to the bottom. The gradual offset design is different from the THOR-NT and Hybrid III one-step change, and the Beta neck resembles the curvature of the human neck structure.

Elliptical Puck Shape. The shape of the pucks in the neck is elliptical. In order to have different responses in flexion and extension, the two bottom pucks are wedge shaped (Fig. 2c). The wedged pucks result in higher stiffness in extension at larger bending angles than in flexion. The current material for the puck is Neoprene with 75A durometer.

Cam/Rubber Mechanism for the OC Joint. The head-to-neck joint in the dummy is meant to mimic the neck segment between the OC and the second cervical vertebra in the human. A metal cam/rubber mechanism is used for the design of the OC joint in the 5th percentile female neck. The rubber shape is used to control the characteristics of OC to provide a more biofidelic moment-angle property at the OC joint.

Central Compliant Rubber Bushing. The main purpose of this design is to allow the neck to extend in the longitudinal direction (z-axis), in much the same way a human neck will react during impact. The rubber bushing is located within the lower neck load cell. The central cable will push to compress the rubber during motion and develop the z-axis extension.

This paper presents results of laboratory tests with the THOR-05F using driver-side air bags which reveal unique characteristics of the THOR-05F response. When exposed to a static air bag deployment in the NHTSA-1 OOP position, the THOR-05F provides new insights into cervical spine loading. The THOR-05F also provides a new perspective on discriminating air bag aggressiveness.

As the THOR-05F is a relatively new dummy, this paper also serves to provide an evaluation of the dummy's functionality, durability, and repeatability under well controlled conditions. The focus of the evaluation is on the all-new Beta neck. For reference, the responses of the THOR-05F dummy are compared to those of Hybrid III 5th percentile female under the same air bag deployment conditions.

METHODS

All tests were carried out with the dummy positioned in the NHTSA-1 (chin on module) driver OOP position. A set of late-model two-stage air bag modules installed within a steering wheel assembly were used in a total of forty tests, including reference tests conducted with the 5th percentile female Hybrid III dummy. All steering wheels/air bag modules were obtained directly from an air bag supplier and were not adulterated in any way after receipt. All of the modules were driver-side units, and each was contained within its own steering wheel assembly. All bags contained two 15-cm tethers. Half of the modules were configured by the supplier to deploy more aggressively (described below as "normal" and "aggressive") and the stage-two firing times were experimentally varied.

Air bag Modules – Normal and Modified. Two types of driver air bags were used under two deployment conditions. The first type was an actual fleet air bag for a late model sedan (i.e., "Normal" bag) with a reverse-rolled cushion at the six and twelve o'clock positions. The second type was a modification of the first (i.e., "Modified" bag). It was folded using an accordion pattern at the six and twelve o'clock positions in lieu of the reverse rolls of the "Normal" bag. Generally, an accordion fold is easier to unravel and inflate, producing a more aggressive thrust. The different bag folding patterns are also shown in Fig. 3.

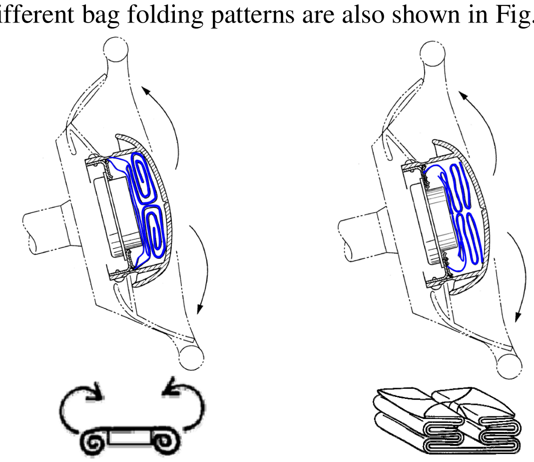


Figure 3. Air bag fold patterns: (Left) "Normal" reverse roll bag; (Right) "Modified" accordion bag.

Also, the gas diffuser/deflector was removed from the second type to provide a more aggressive deployment. A diffuser/deflector is a small, tethered patch of cloth covering the inflator which fills with gas like a parachute and diffuses the gas (Fig. 4).

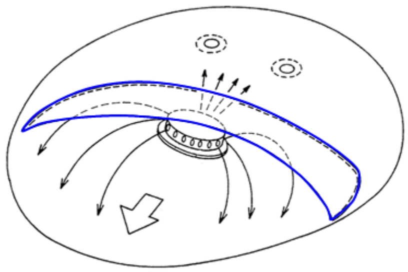


Figure 4. Typical gas diffuser within an air bag.

The second type of bag was supplied for the experimental purposes herein. While accordion folds are used widely in production, and not all production bags have diffusers, it is not known whether the particular "modified" bag employed herein is used in any fleet vehicles.

<u>NHTSA-1 Setup: Benign vs. Aggressive.</u> All forty tests were carried out with the dummy positioned in the standard NHTSA-1 position (chin on module) in accordance with the seating procedure of Federal Motor Vehicle Safety Standard (FMVSS) No. 208, "Occupant crash protection," (Part 571.208). The position of the dummy was accurately controlled using fixed position markers on the seat and the adjustable neck positioning arm for each test. The transducers used in THOR-05F and Hybrid III included accelerometers, load cells, displacement string potentiometers, and rotary potentiometers.

All signals were recorded using a digital data acquisition system with a sampling rate of 10 kHz. A high-speed digital camera recorded the air bag-dummy interaction at 1000 frames per second. Signal conditioning, filtering, and recording techniques complied with the SAE J211 standard [1995].

Two variations of the steering wheel module were imposed in order to produce a "benign" deployment and an "aggressive" deployment. For the benign setup, the two air bag stages were initiated 30 msec apart and the steering wheel angle was set at 68° from horizontal. For the aggressive setup, air bag stages were initiated simultaneously, which provided a more aggressive deployment than sequential firing. Moreover, the steering wheel angle was set at 60° from horizontal. This promoted more of an upward deployment than the 68° setup. As such, it tended to produce higher ATD neck forces and moments.

The choice of steering wheel angle is representative of typical passenger cars in the U.S. fleet. The 68° angle is typical of a production sedan such as that in which the modules tested herein are intended to be installed. The 60° angle is not uncommon in larger vehicles like pickup trucks and SUVs.

Additionally, a shield was installed behind steering wheel to prevent the air bag from slipping under and behind the steering wheel rim during inflation, which reduces repeatability. The shield fit behind the steering wheel so as to not interfere with the air bag deployment.

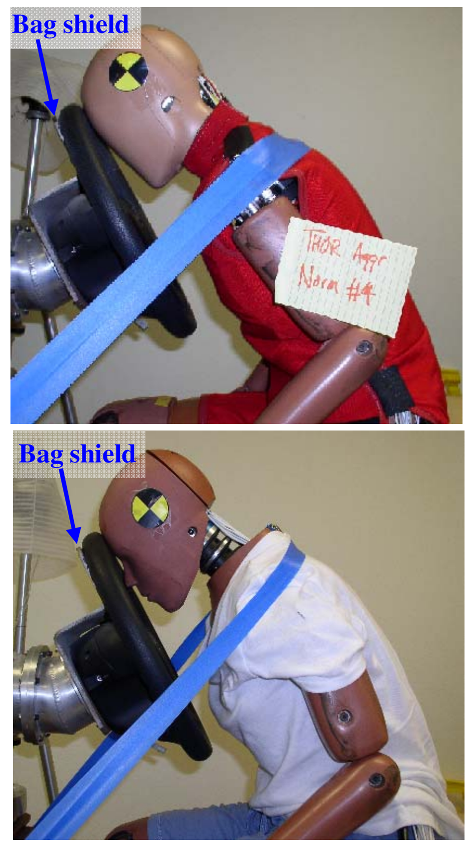


Figure 5. THOR-05F (top) and Hybrid III (bottom) in the NHTSA-1 Aggressive Setup (steering wheel angled upward).

<u>Test Matrix</u>. A series of forty full-deployment air bag impact tests were carried out. Two ATD units were used: the prototype THOR-05F and a Hybrid III 5th percentile female. Both units passed through standard dummy certification tests (head drop, head/neck pendulum swings, chest impacts) just prior to the air bag series. The forty tests were carried out on an "on again, off again" basis that extended over 40 weeks. Tests were typically run in batches of three to five tests per batch. During the "on again"

periods, a one-hour test-to-test delay was imposed to allow full dummy recovery. No re-certifications or part replacements occurred at any time during the 40-week period.

Five repeat tests were performed for each test condition, as indicated in Table l. Head/neck load time-history data comparison was performed for each air bag model. Air bag inflation repeatability and variability for each model was confirmed and analyzed using the high-speed video recordings. Data analysis focused primarily on trend comparisons in the head/neck region. Data for five repeat tests for each case were averaged for time-history trend comparison. Values of Head Injury Criterion based on the 15-ms time interval (HIC_{15}) were also computed.

Table 1. Test matrix

Setup Position	Normal Air bag		Modified Air bag	
	THOR-05F	Hybrid III	THOR-05F	Hybrid III
Benign	5	5	5	5
Aggressive	5	5	5	5

Comparing THOR-05F with Hybrid III. As stated earlier, the THOR-05F has a unique neck construction in which muscles and osteoligamentous structures are represented by separate mechanical components (Fig. 2). The primary structural component of the THOR-05F neck is the segmented molded rubber column which is designed based on the responses of the human cervical spine. A six-axis load cell is placed at the top of this component to directly measure the loads at the head/neck pin joint, which represents human occipital condyles. In the results presented herein, all upper neck loads refer to the OC pin joint location. Cable elements representing the anterior and posterior neck musculature also bear loads. Cross-sectional loads refer to loads including the front and rear cable loads with respect to the head coordinate system.

The Hybrid III does not account for separate load paths; its neck load cell measurements correspond to “cross-sectional” neck loads. Unlike the THOR-05F, the Hybrid III upper head/neck load cell is installed in the head above the OC pin joint and measures the load in the head coordinate system. The upper head/neck moment, My, measured by the upper head/neck load cell is translated to the OC level by subtracting the moment obtained by multiplying the shear force Fx by the height of the load cell above the OC from the moment data measured by the load cell.

To facilitate comparison with the Hybrid III, the THOR-05F instrumentation allows one to compute its “cross-sectional load” by accounting for the cable loads. The dummy also has a rotary potentiometer that measures rotation of the head with respect to the neck. Using data from this potentiometer, one may translate THOR-05F’s cross-sectional neck loads to the head coordinate system for direct comparison with the Hybrid III.

RESULTS

All THOR-05F neck results presented hereafter are “ligamentous” loads of the upper neck at the level of the head/neck pin joint (representing the human occipital condyles) unless otherwise specified. As such, these loads are derived from the upper neck load cell only, and do not include the contributions of the front and rear cables. Furthermore, since the upper neck load cell is mounted atop the neck and beneath the head/neck pin joint, the THOR-05F neck load vectors correspond to a local upper neck coordinate system. This is the way the neck data are expected to be used for injury assessment.

For the Hybrid III, the upper neck load cell is contained within the head and is mounted on the head instrument plane. Thus, all Hybrid III loads reported herein represent the total cross-sectional loads and the load vectors correspond to a local upper neck coordinate system. The Hybrid III head rotates very little with respect to the neck due to the engagement of its nodding blocks. On the other hand, the THOR-05F head/neck pin joint offers much less resistance so that the head may rotate as much as +/- 40 degrees before its nodding blocks engage fully. Thus, the directions of the upper neck load cell force vectors of the THOR-05F and Hybrid III can vary substantially.

Repeatability and variability. The dummy response in tests with the normal air bags proved to be more repeatable than in tests with the modified bags for both the THOR-05F and Hybrid III. Figure 6 shows the averages of the THOR-05F and Hybrid III upper neck tension (Fz) and upper neck flexion/extension moment (My) for the benign setups (Figs. 6a and b) and the aggressive setups (Figs. 6c and d). The shaded areas represent one standard deviation about the mean. The Fz and My measures, which are typically used to define injury risk, are used for comparison herein. However, the other ATD channels, including head acceleration measurements, indicate the similar findings.

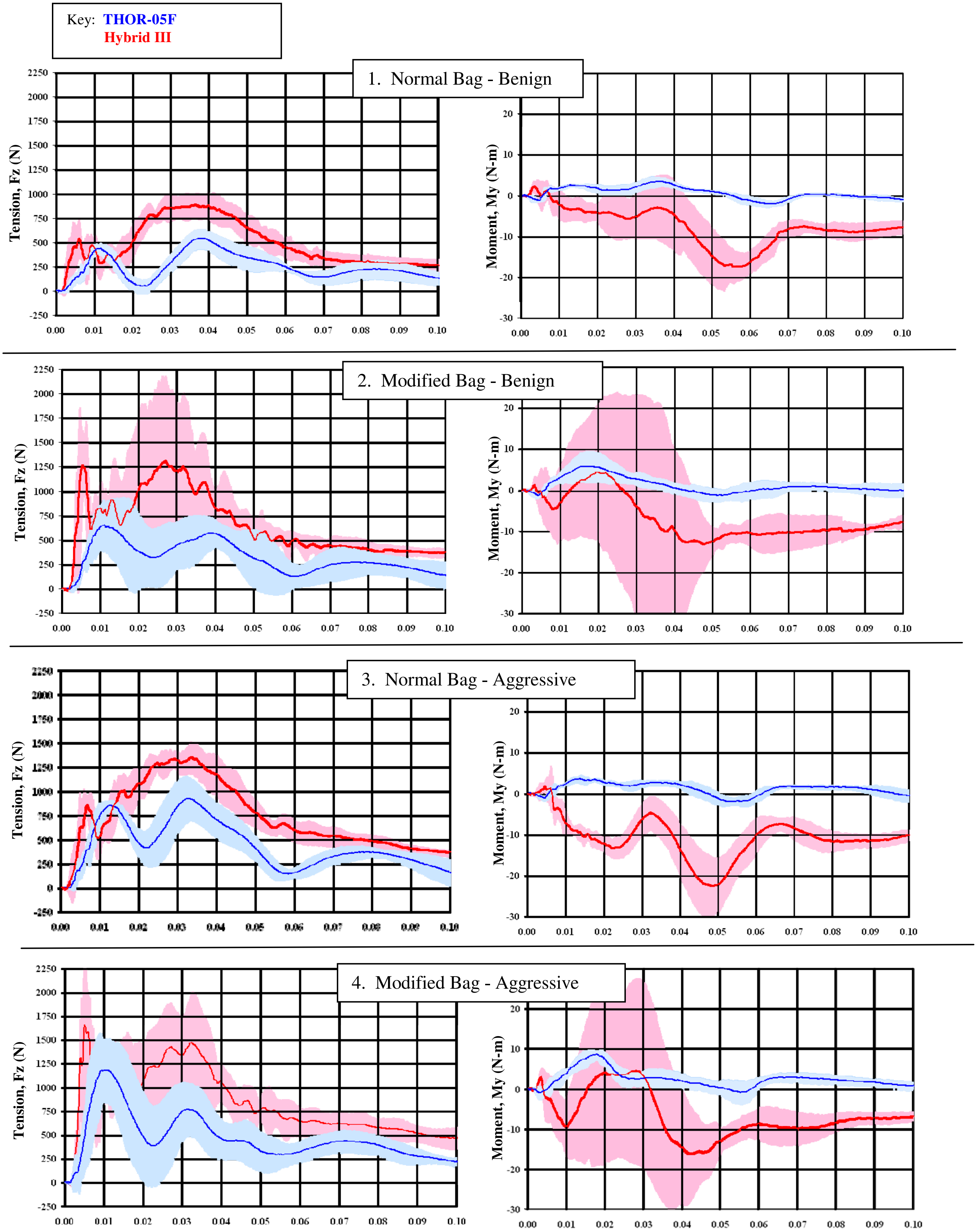


Figure 6. THOR-05F and Hybrid III time-histories (sec). Average upper neck tension (Fz) and flexion/extension moment (My) for the four test conditions. The shaded areas represent +/- 1 standard deviation.

All plots in Fig. 6 indicate a tighter shaded area – and greater repeatability – for the normal bags. When comparing the tests run under the benign vs. aggressive setups, the relative repeatability appears to be about the same for each dummy. As shown in Fig. 6, the repeatability of the Hybrid III upper neck is on a par with the THOR. An assessment of repeatability is discussed in the next section.

<u>THOR-05F and Hybrid III comparison</u>. Consider the THOR-05F vs. the Hybrid III in the "Normal Bag/Aggressive Setup" condition. This condition is the best of the four to compare the two, because it involves a relatively repeatable air bag with a strong deployment with relatively high measurements. Upper neck tension Fz, shear Fx, and moment My are compared since they represent the primary measurements of the current NHTSA injury criteria (Fig. 7).

In both the THOR-05F and Hybrid III, upper neck Fz force is generally positive, indicating that the neck is in tension for both dummies (Fig. 6). This tensile force is a combined effect of the external air bag load and the centrifugal rearward rotation of the head. However, the Hybrid III recorded a much stronger upper neck extension (negative My) and a higher upper neck shear force (negative Fx) than THOR-05F (Fig. 7). Other dissimilarities are discussed below.

For the THOR-05F, the upper neck load data shown in the figures above all indicate a fairly consistent response typified by the relatively repeatable "Normal Bag/Aggressive Setup" condition. In general, the neck tension (Fz) was the predominant load, with very low moment (My) and shear (Fx). The low My is attributable to the THOR-05F head/neck junction where the pin joint offers little resistance (and sustains low moments) to relative head-to-neck rotation of up to 30 deg. Even so, the potentiometer that captured this rotation indicated that the rotation was never greater than 10 degrees in any of the tests.

What little upper neck moment and shear that was present in the THOR-05F indicates that the air bag pushed the chin backwards and downwards, which generated a negative upper head/neck shear force (negative Fx) and positive flexion moment (positive My) at about 20 ms. The THOR-05F neck did not go into extension until well after bag separation.

The general response of the Hybrid III differs from the THOR-05F. Under the "Normal Bag/Aggressive Setup" condition, high-speed video data showed the air bag became trapped under the Hybrid III chin and pushed it upwards. The neck was shown to be in extension with a slight bend to the neck column as the dummy separated from the bag. This condition produced the negative My (extension) moments apparent in the data. It also generated a corresponding negative upper neck shear Fx due to the bag being lodged between the chin and the neck. This was consistent for all five tests.

For the "Modified Bag/Aggressive Setup" condition, however, the above condition was only apparent in one of the five Hybrid III repeat tests. Other repeat tests resulted in a response closer to that of the THOR-05F in which the neck was initially placed into flexion.

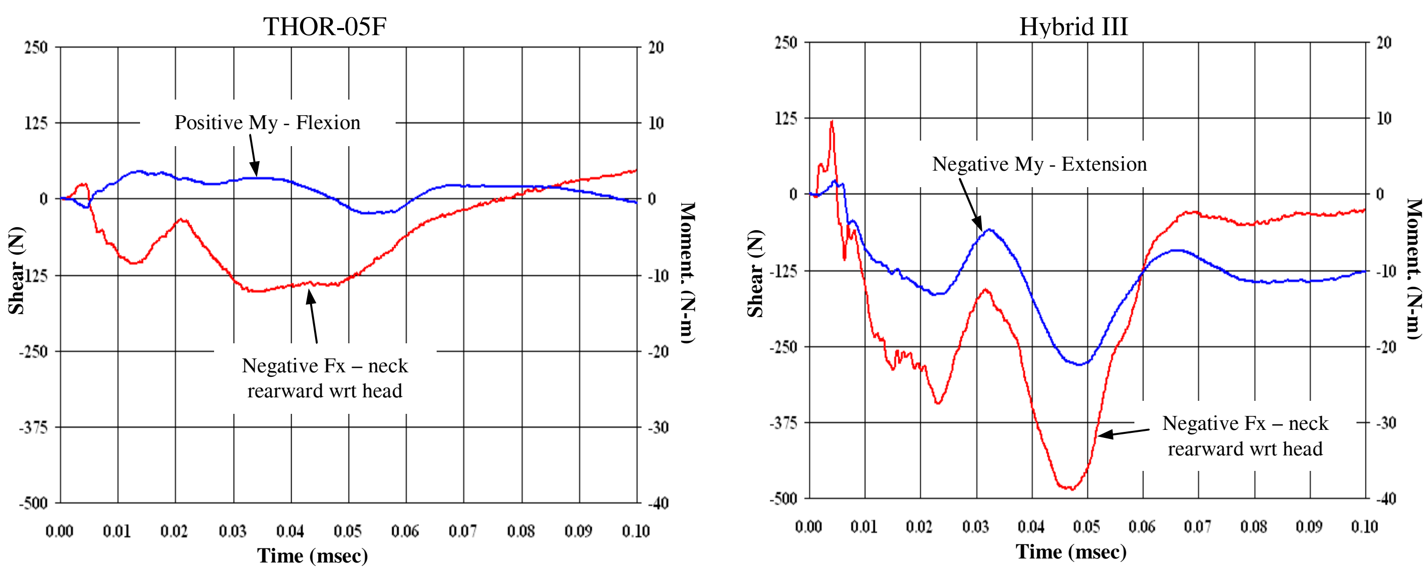


Fig. 7. Average upper neck shear (Fx) and flexion/extension (My) comparison for THOR-05F (left) and Hybrid III (right), normal bag, aggressive setup.

Injury metrics for various air bags. Table 2 provides the critical injury assessment values for human spine tolerance of a fifth percentile female and corresponding injury reference values for the Hybrid III. For the human, compression force, flexion moment, and extension moment were derived from tests on female post-mortem human subjects [Nightingale 1997; Nightingale, 2002]. Tensile force was derived from the male failure values reported by Chancey [2003] and scaled by 0.63 per the "equal stress, equal velocity" model scaling convention for geometrically similar models.

Table 2. 5th percentile female: critical values for upper neck, M_Y and F_Z.

	Human	HIII
Compression, F_C (N)	2020	2520
Tension, F_T (N)	1580	2620
Flexion, M_F (Nm)	29	155
Extension, M_E (Nm)	52	67

While the THOR-05F is designed to mimic the human neck, it is probably stiffer than the human spine. Though the increased stiffness has not been quantified, it is likely that some adjustment of the human cervical spine tolerance values will be necessary before they can be used as injury reference values in the THOR-05F. Thus, the human threshold values as presented herein are to be used for reference only.

Of the four test conditions with the THOR-05F, the "Modified Bag/Aggressive Setup" condition is the only one where the critical value for neck tension given in Table 2 was exceeded. The axial tension force Fz exceeded the human critical value of 1580 N shown in Table 2 in one of the five repeat tests. This air bag also produced the highest inflation pressure in tank test reports provided by the air bag supplier. Compared to the others, this setup also produced the largest upper neck moment which was dominated by extension throughout the entire bag-dummy interaction process (Fig. 6).

Values of HIC_{15} were also computed for each test. All forty air bag tests (both dummies, all test conditions) produced HIC_{15} values well below the threshold value of 700. As with the upper neck measurements, the "Modified Bag/Aggressive Setup" produced the highest HIC_{15} values (Fig. 8).

Air bag discrimination. Both the THOR-05F and the Hybrid III identified the "Modified Bag/Aggressive Setup" as the most threatening condition and the "Normal Bag/Benign Setup" as the least threatening condition. This finding was expected, as these two setup conditions and modifications to the bags were put in place in an attempt to facilitate this outcome. So, it is reassuring that the outcome was confirmed by both dummies. Though both the THOR-05F and Hybrid III found the "Modified Bag/Aggressive Setup" to be most threatening, the distinction for the Hybrid III was not as clear cut, where the highest two average Nij bars in Fig. 8 are almost even.

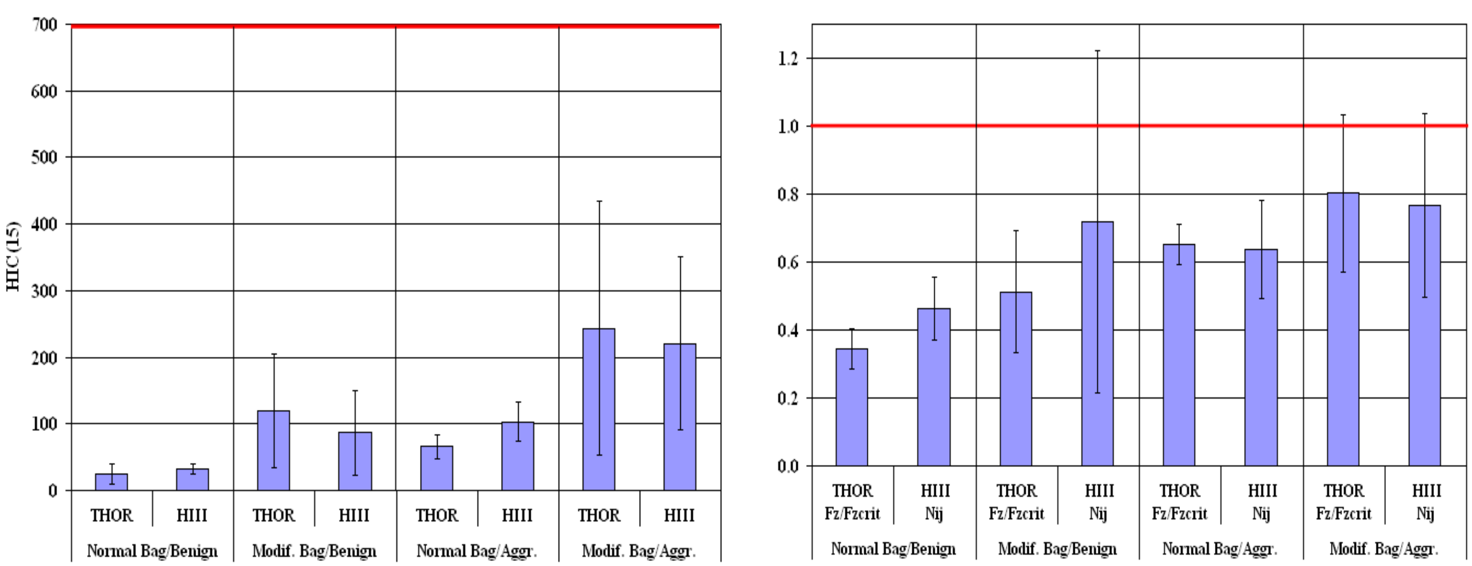


Figure 8. Average of Head Injury Criteria (HIC15) (left) and upper neck measurements (right) for the four test conditions. Error bars represent one standard deviation.

The distinction between "Normal Bag/Aggressive Setup" vs. "Modified Bag/Benign Setup" as the 2nd- or 3rd-most threatening is less apparent. It depends on which dummy and which injury metric is used. Using neck tension Fz as an arbitrator, the THOR-05F identified "Normal Bag/Aggressive Setup" as the more threatening of the two, but when HIC is used "Modified Bag/Benign Setup" is more threatening. The Hybrid III indicated the exact opposite conditions as the most threatening when Nij and HIC are considered. However, the high variability associated with the modified bag renders this comparison non-conclusive, as can be shown in Fig. 8 where the error bars associated with "Modified Bag/Benign Setup" are extremely large.

<u>Deployment asymmetry</u>. An asymmetric air bag deployment was observed in all forty deployments. Asymmetry was also observed in a series of deployments with no dummy present. These deployments were carried out to assure that the asymmetry was due to the air bag module alone and not an artifact of dummy positioning (Fig. 9).

As shown earlier, both versions of the air bags were tucked within the module using pleats on the right and left sides and folded (accordioned or reversed rolled) top and bottom. As the bag escaped from the module, the upper fold was observed to unravel and inflate well before the lower fold. This condition was observed for both normal and modified bags, and for both the simultaneous and sequential firings. The asymmetry, however, was more prominent in the modified bags.

When a dummy was present, the asymmetrical deployment of the first fold tended to produce a lateral thrust to the dummy resulting in a significant y-acceleration to the head with an Fy-force and Mx-moment at the upper neck. By the time the dummy was moving away from the bag, the second fold was just beginning to unravel and inflate. This "second punch" effectively spun the head about the neck z-axis by more than 90° producing an appreciable upper neck Mz moment (Fig. 10).

The THOR-05F and Hybrid III showed similar behavior in this regard. However, differences in overall body kinematics between the THOR-05F and the Hybrid III were revealed in the high-speed video. The THOR-05F exhibited much greater lateral head rotation and overall lateral body movement (Fig. 11).

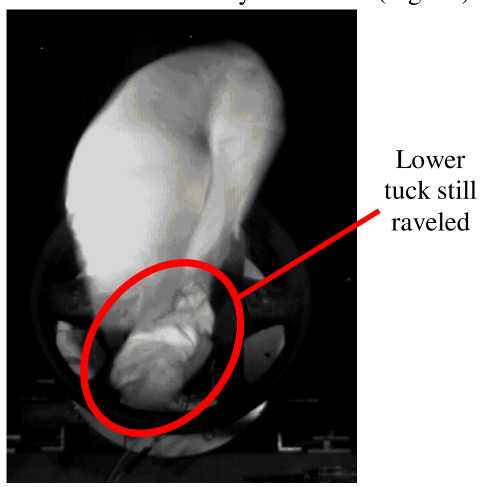
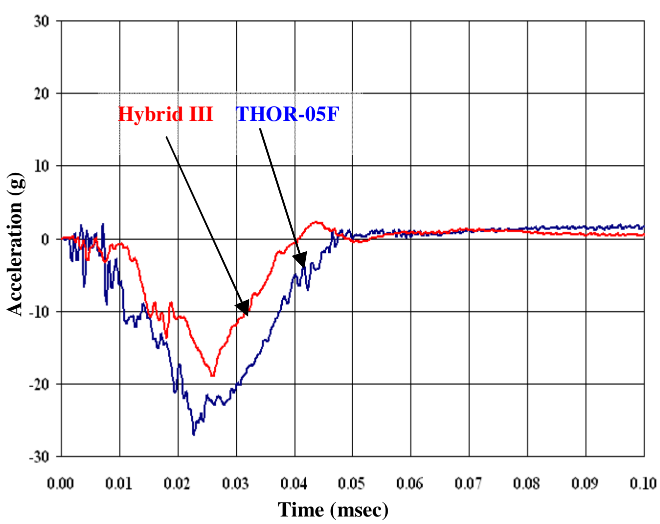
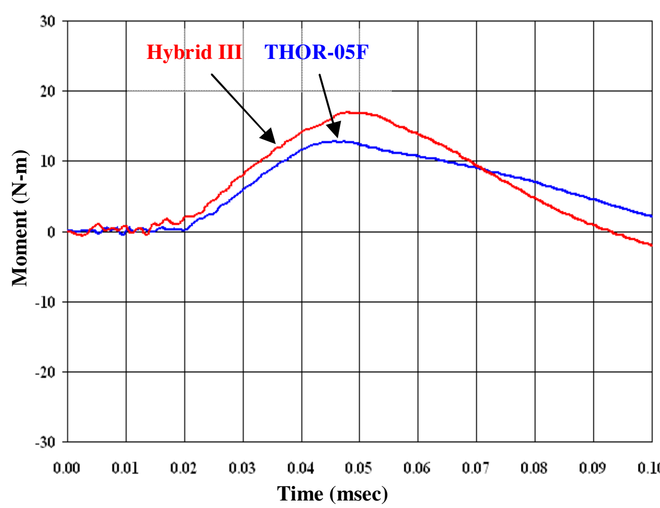


Figure 9. Asymmetric air bag deployment. Left side unravels and inflates before right.

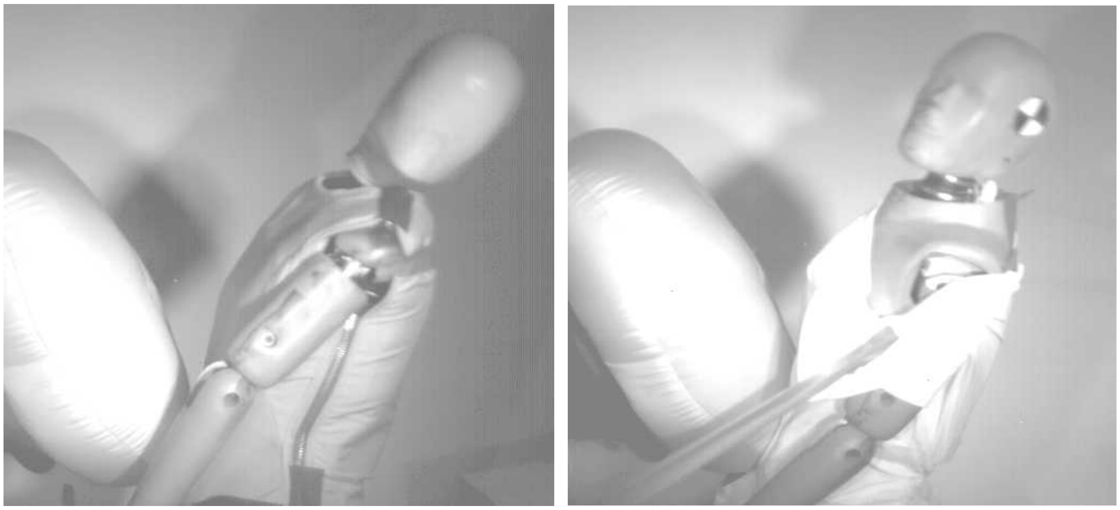


a. Head CG-y Acceleration



b. Upper Neck Mz moment

Figure 10. THOR-05F vs. Hybrid III for "Modified Bag/Aggressive Setup" condition: Average head CG-y acceleration (left) and upper neck moment (right).



a. THOR-05F　　b. Hybrid III

Figure 11. THOR-05F vs. Hybrid III for “Modified Bag/Aggressive Setup” condition: head position at bag separation.

Cross-sectional vs “Ligamentous” comparison. For the THOR-05F, the total cross-sectional Fz is about 10% higher than the OC Fz, which means the front and rear neck cables have only a small contribution to the upper neck tension force. This also means that most of the load is borne by the “ligamentous” spine, which is significant from an injury assessment standpoint. The cable loads have more of a contribution to the total cross-sectional My moment, given the relatively low upper neck load cell moment, but the overall moment is still relatively low (only about 10 Nm maximum). This trend is consistent for all test conditions. This further confirms the intended capability of the THOR-05F neck design to distinguish the musculature from the ligamentous load by transferring load around the neck column via the cables.

Durability and functionality. There were no reports of durability or functionality problems with the THOR-05F during the 40-week test interval.

DISCUSSION

The present study herein has shown that the head/neck complex of the THOR-05F dummy is capable of capturing the detailed air bag load effects due to the variability of bag inflation on the occupant head and neck in OOP conditions. The test data obtained confirmed the expected performance of the THOR-05F head/neck complex design.

From an overall air bag assessment standpoint, both the THOR-05F and the Hybrid III identified the same test conditions as being the most threatening and the least threatening to the risk of an upper neck injury (where the most threatening condition produced responses near or above given injury risk assessment values). Both dummies indicated that the head injury risk was well below the HIC_{15}=700 reference value for all test conditions. Both dummies also identified the asymmetry of the deployments, and both recognized the “modified” bags to be less repeatable.

There were, however, some differences in responses between the two dummies. In the THOR-05F, neck tension was the predominant upper neck load. The upper neck moment and shear were much lower in magnitude than that of the Hybrid III. Compared to the Hybrid III, the THOR-05F neck had less tendency to go into extension. Hybrid III neck measurements also exhibited a sharp initial spike – most likely due to the relatively rigid head-to-neck coupling – that was not present in the THOR-05F signals.

Repeatability/Asymmetry. The tests herein indicate that both the asymmetry of the air bag deployments and the removal of the gas diffuser contributed to dummy response variability. This precludes a full assessment of THOR-05F repeatability. A valid repeatability assessment requires well-controlled air bag inflation and symmetric deployment. Such an assessment was performed previously on the 50th male THOR-NT using fleet air bags that deployed symmetrically and were folded in a conventional accordion pattern. These tests produced highly repeatable bag inflation and dummy responses [Li, 2007]. Such tests are necessary to fully assess the repeatability of the THOR-05F.

On the other hand, all Hybrid III tests under the “Normal Bag/Benign Setup” (the condition most similar to an actual NHTSA vehicle compliance test) resulted in injury metrics well below injury thresholds. Therefore, it is likely that the range of the "Normal" fleet bag inflation variability is within the manufacturer's acceptable limits. (Note: the steering wheel-mounted bag blocker utilized herein – while providing a more aggressive deployment – probably produced more repeatable results than would actual fleet tests with no blocker since variability associated with the bag lodging behind the steering wheel rim was avoided.)

Assuming that the THOR-05F can be shown to be repeatable under truly identical test conditions, the variability of the test data herein may serve well in the assessment of air bag risk. For a given neck measurement under a given test condition, both the THOR-05F and the Hybrid III show some amount of variation. But the magnitude of the measure – and the amount of variation – depends on the dummy. Therefore, the acceptable limits that an air bag manufacturer places on inflation could depend on which dummy is used to develop the bag.

Caveats and Limitations. The experimental tests were carried out on a single air bag design and a modification of that design. All bags had similar capacities. Repeat tests for each test condition were limited to five. In addition, only driver air bags were tested and only at one OOP position. Nonetheless, the general observations made above on the THOR-05F upper neck Fz predominance, low My, and no extension are all consistent with prior OOP tests conducted with the 50th male THOR-NT using different air bags. Thus, the observations are true to form with the general THOR neck technology, and not an artifact of the particular air bags and test setups described herein.

The forty tests performed herein are not standard regulatory tests but rather scientific studies for the evaluation of the THOR-05F dummy. Moreover, the use of a non-standard steering wheel bag blocker is not representative of a production vehicle.

Nonetheless, the tests where the 1st and 2nd stages were fired sequentially with a 30 ms time lag represents a possible "low-level" deployment scenario that may exist in production vehicles. Additionally, the tests herein where both stages were fired simultaneously are representative of a possible "high-level" deployment that may also be seen in production vehicles.

Future Work. Previous work has been performed on the 50th percentile male THOR-NT showing favorable biofidelity of the head/neck complex. These tests include a comparison of THOR-NT loads against muscle and occipital condyle loads measured in tests run by the Medical College of Wisconsin (MCW) using post mortem human subjects [Pintar, 2005]. A favorable comparison of the THOR-NT neck response against a human model was also demonstrated by Duke University [Dibb, 2006]. Similar biofidelity evaluations have not yet been carried out on the new THOR-05F's Beta neck.

It should be noted that there are no injury criteria defined for the THOR-05F dummy, nor are there standard OOP positions defined for using the THOR-05F dummy. The present work was intended to understand air bag load paths to the neck in OOP conditions so that well-defined OOP positions for the THOR-05F dummy can be established and injury criteria may be developed in the future. This should probably include a lateral bending criteria.

SUMMARY

• Neck tension in the THOR-05F was the most critical load, with most passing through the ligamentous spine and very little load borne by musculature. This result contributes to the understanding of how injurious air bag load paths are imparted to the neck of humans in OOP conditions.

• Compared to Hybrid III, the THOR-05F neck shows less tendency to go into extension. The upper neck moment (My) and shear (Fx) were much lower in magnitude than those of the Hybrid III. Head accelerations were similar to those produced by the Hybrid III 5th.

• The THOR-05F demonstrated its ability to discriminate air bag aggressiveness, especially in its upper neck tension measurements.

• The THOR-05F response to the asymmetric deployments resulted in a substantial twist of the head about the z-axis of the neck, and a high corresponding Mz upper neck moment. This indicates that an ATD biofidelity requirement and an injury criterion may need to be investigated to assess the threat of injury for such a response.

• The THOR-05F produced relatively repeatable measurements and proved to be durable. It performed smoothly throughout the test series and was generally user-friendly.

• The THOR-05F's distinct neck assembly provides a new perspective on loading of the cervical spine and application of injury tolerances. It also prompts a new requirement for neck injury reference values specific to the THOR-05F.

DATA AVAILABILITY

All reports and data, including time-history traces, videos, and still photos from the tests described herein may be downloaded by accessing NHTSA's online Biomechanics Database at: http://www-nrd.nhtsa.dot.gov/database/nrd-51/bio_db.html. Reports include descriptions of the test set-ups and instrumentation. Data channels collected on both dummies, but not reported herein, include linear and angular head acceleration, chest deflection, and chest acceleration. Additionally, the THOR-05F recorded lower neck loads and upper spine acceleration.

ACKNOWLEDGEMENTS

This research effort was sponsored by the National Highway Traffic Safety Administration (NHTSA) through a Joint Cooperative Research Agreement with the US Army Medical Research and Materiel Command under contract W81XWH-06-C-0051.

REFERENCES

1. Robbins, D. (1993), "Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropometric Dummy Family.," Volumes 1 & 2. DOT-HS-806-716, 717, National Highway Traffic Safety Administration, Washington DC.

2. SAE J211 (1995) "Instrumentation for Impact Test," SAE Surface Vehicle Recommended Practice, Society of Automotive Engineers, Warrendale, PA, March 1995.

3. Nightingale, R.W., McElhaney, J.H., Camacho, D.L., Winkelstein, B.A., Myers, B.S.(1997), "The dynamic responses of the cervical spine: the role of buckling end conditions and tolerance in compressive impacts," 41st Stapp Car Crash Conference Proceedings, 451-471

4. Nightingale, R.W., Winkelstein, B.A., Knaub, K.E., Myers, B.S. (2002), "Comparative bending strengths and structural properties of the upper and lower cervical spine," Journal of Biomechanics 35 (6), 725-732.

5. Chancey, V.C., Nightingale, R.W., Van Ee, C.A., Knaub, K.E., Myers, B.S. (2003), "Improved estimation of human neck tensile tolerance: reducing the range of reported tolerance using anthropometrically correct muscles and optimizing physiologic initial conditions, " Stapp Car Crash Journal 47, 135-154.

6. Shams, T., Huang, T., Rangarajan, N., Haffner, M. (2003), "Design requirements of a fifth percentile female version of the THOR ATD," Paper Number 421, 18th International Technical Conference on Enhanced Safety of Vehicles, U.S. DOT.

7. Huang, T.J, Shams, T., Rangarajan, N., Haffner, M., Eppinger, R. (2003), Development of an advanced 50th percentile male head/neck system for application to crash test dummies," Paper Number 425, 18th International Technical Conference on Enhanced Safety of Vehicles, U.S. DOT.

8. J. McDonald, T. Shams, N. Rangarajan, D. Beach, T. Huang, J. Freemire, M. Artis, Y. Wang , M. Haffner (2003), "Design and development of a THOR based small female crash test dummy," Stapp Car Crash Journal, V47.

9. Pintar, FA, Yoganandan N, and Baisden J. (2005) "Characterizing occipital condyle loads under high-speed head rotation," Stapp Car Crash Journal, V49:33-47.

10. Dibb, A.T., Nightingale, R.W., Chancey, V.C., Fronheiser, L.E., Tran, L., Ottaviano, D., Myers, B.S., (2006) "Comparative Structural Neck Response of the THOR-NT, Hybrid-III, and Human in Combined Tension-Bending and Pure Bending," Stapp Car Crash Journal, 50:567-581.

11. Lu, Z, Chan, P. C., Martin, P.G., Ridella S. (2007), "OOP air bag tests using the THOR-NT", Paper Number 07-0293, 21st International Technical Conference on the Enhanced Safety of Vehicles, U.S. DOT.

12. National Highway Traffic Safety Administration, U.S. Department of Transportation, Motor Vehicle Safety Standard No. 571.208.