OOP Air Bag Tests using the THOR-NT

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ABSTRACT

An experimental study of driver side air bag loads for out-of-position (OOP) occupants at the ISO-1 (chin on bag) position was performed using the 50th percentile THOR-NT dummy. The main objective was to observe the response of the dummy under exposures to various types of air bags. Dummy sensitivity to the air bags was evaluated in terms of upper neck loads and head acceleration. Five types of late-model fleet air bag modules were used in a total of ten tests (two repeat tests per air bag). Sealed tank tests were also performed to characterize the five different air bag inflators. For one bag, the THOR-NT produced very repeatable measurements. For other bag types, the THOR-NT exposed the variability of the air bags, especially in its upper neck moment measurements. The high-speed videos confirmed the inflation variability of those air bags. The THOR-NT was able to segregate the moment at the head/neck pin joint (representing human occipital condyles) from the total head/neck cross-sectional moment. The THOR-NT performed smoothly throughout the test and was generally user-friendly. A limitation is recognized that only two air bags for each model were used for repeat tests.

INTRODUCTION

The THOR (Test device for Human Occupant Restraint) dummy is an anthropomorphic test device (ATD) developed 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 [1-3]. The notable new features of THOR include a neck design that segregates load paths within the cervical spine, and the use of multiple potentiometers for measuring chest and abdomen deformations at distributed locations. The current THOR version, denoted as THOR-NT, has an improved design to overcome the limitations of the previous version.

The study herein focuses on the performance of air bags as measured within the THOR-NT head/neck complex. As shown in Figure 1, the THOR-NT distinct neck subassemblies reflect 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-NT by the two cable subassemblies), and those borne by both "internal" muscles and ligaments (represented in THOR-NT by the molded neck subassembly and the pin joint/nodding block subassembly).

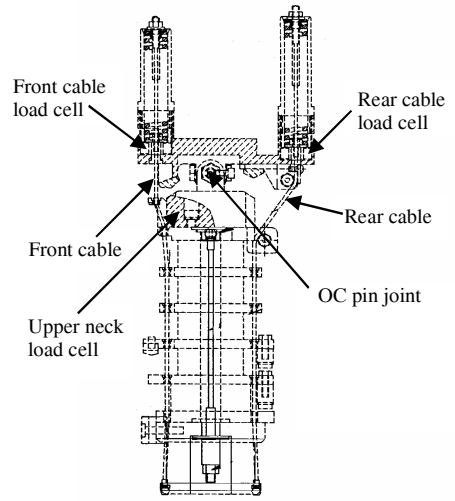


Figure 1. THOR-NT neck structure.

The THOR-NT design philosophy also presumes that human neck injuries occur when ligamentous tissues become overloaded. Hence, a THOR-NT injury crite-

rion will be based on measurements in its upper neck load cell alone, which is mounted on the neck rather than in the head (Fig. 1). Forces measured in the load cells attached to THOR-NT anterior and posterior cables represent "external" noninjurious 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.

Other previous work has been performed showing favorable biofidelity evaluation of the head/neck complex of THOR-NT. These tests include a comparison of THOR-NT loads against muscle and occipital condyle (OC) loads measured in tests run by the Medical College of Wisconsin (MCW) using post mortem human subjects [4]. A favorable comparison of the THOR-NT neck response against a human model was also demonstrated by Duke University [5].

Previous tests by L-3/Jaycor using the Air bag Test Simulator (ATS) with a previous version of THOR-NT has shown highly repeatable head/neck responses to well-controlled air bag deployments in out-of-position (OOP) conditions [6-8]. The ATS is a device developed by L-3/Jaycor that deploys air bags in a very repeatable fashion and with the same deployment characteristics as an actual production air bag module [9]. Using the ATS, the air bags were pneumatically inflated and two air bags with conventional folding were used with tests conducted at the ISO-1 (chin on bag) and ISO-2 (chin on upper steering wheel rim) positions [10]. At least five repeat tests were conducted at the same condition, respectively, for both the 50th percentile Hybrid-III and THOR dummies, for data comparison. Data showed that the THOR neck design could carry loads through the cable elements and the head/neck pin joint akin to the way loads are transferred through and around the occipital condyles of a human neck.

This paper presents results from testing the THOR-NT using fleet driver side air bag modules in the laboratory. As the THOR-NT is a relatively new dummy, this paper also serves to provide an evaluation of the dummy itself under well controlled conditions. The tests conducted do not represent standard regulatory tests since there is no standard OOP position or injury metrics established for THOR-NT.

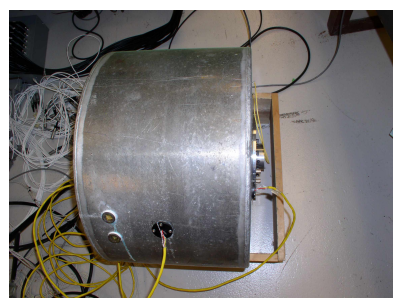
METHODS

Five models of fleet driver side air bags were used, which are labeled as Bag A, B, C, D, and E, respectively (Table 1). Other than Bag E that has a single-stage inflator, the other four models have dual-stage inflators (Table 1).

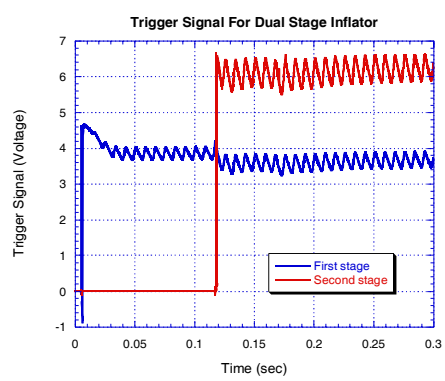
Table 1. Five driver side air bag modules.

Bag	Model	Position	Stage
A	compact	driver	dual
B	SUV	driver	dual
C	sedan	driver	dual
D	sedan	driver	dual
E	light truck	driver	single

The air bag inflators were characterized using the SAE standard sealed tank test as specified in SAE J2238 [11]. The inflator was separated from the air bag unit, connected to the tank, and electrically discharged. The tank gas pressure and temperature histories were recorded. Pressure and temperature gauges were mounted on the top, side and bottom of the tank (Fig. 2a). To characterize both stages of a dual-stage inflator in a single tank test, the second stage was triggered about 0.12 sec after the first stage (Fig. 2b). This 0.12-sec trigger delay for the second stage was only used for the tank tests to characterize the dual inflators in a single test.



(a) Sealed tank and instrumentation



(b) Trigger signal for dual stage inflator

Figure 2. Sealed tank test setup.

For the OOP air bag impact tests, the 50th percentile male THOR-NT dummy was placed in the adjustable seat fixture of the ATS platform (Fig. 3). The dummy was placed at the ISO-1 position (Fig. 3). 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-NT 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 [12]. A complete new air bag module with the original steering wheel was used for each test.

Figure 3. THOR-NT test setup at ISO-1 position.

Stage-by-stage comparison. OOP tests using the 50th percentile male Hybrid-III dummy were first performed to examine the effects of full deployment vs. first stage only using Bag A. The Hybrid-III dummy was also placed at the ISO-1 position. Two tests were performed separately using deployments from the 1st stage inflator and from both stages. For the full deployment test, both stages were triggered simultaneously. Based on the results observed, it was decided to conduct all THOR-NT dummy tests using deployments from both stages for all the dual-stage air bag modules.

Full-stage air bag tests. Full-deployment air bag impact tests were carried out for all five models for the THOR-NT dummy. For dual-stage models, both stages were triggered simultaneously for each test. Two repeat tests were performed for each air bag model. Head/neck load time-history data comparison was performed for each air bag model. Air bag inflation repeatability or variability for each model was confirmed and analyzed using the high-speed video recordings. Values of Head Injury Criterion based on the 15-ms time interval (HIC_{15}) were computed for comparison.

As stated earlier, the THOR-NT has a unique neck construction in which muscles and osteoligamentous structures are represented by separate mechanical components (Fig. 1). The primary structural component of the THOR-NT 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 neck loads (or upper head/neck loads) refer to the OC pin joint location (Fig. 1). Cross-sectional loads refer to loads including the front and rear cable loads with respect to the head coordinate system.

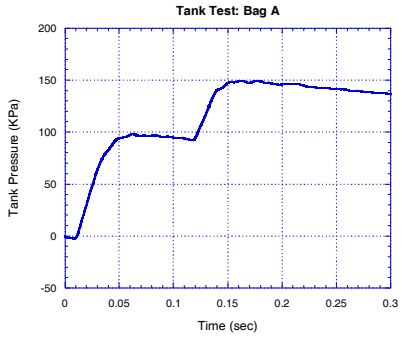
The THOR-NT instrumentation allows one to compute its "cross-sectional load" by accounting for the cable loads. The dummy has a rotary potentiometer that measures rotation of the head with respect to the neck. Using data from this potentiometer, one may translate THOR-NT's cross-sectional neck loads to the head coordinate system using the THORTEST program [13]. In the results herein, cross-sectional loads are always given in the head coordinate system. The THOR-NT neck load data can also be presented in the neck coordinate system as will be indicated.

RESULTS

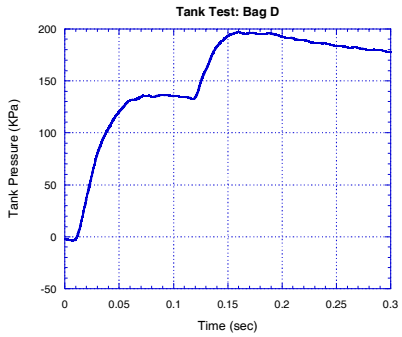
Comparison of single and dual-stage inflations. The sealed tank test data for each inflator are shown in Table 2, with the two pressure values indicating the outputs from the first and both stages, respectively, for Bags A-D, while only one value is shown for Bag E with single-stage inflator. For a dual-stage inflator, the tank pressure history shows that the combustion of the first stage usually completes in 50 ms and a fairly stable tank pressure level is sustained for a long time until the second stage is ignited (Fig. 4). For dual-stage inflators, the first stage generally contains the larger portion of the total energy with the second stage contributing about 6-30% of the total energy output (Table 2; Fig. 4). The tank test data justify the use of 0.12-sec trigger delay to collect dual-stage data without sacrificing additional inflators.

Table 2. Tank test results

Bag	Model	Stage	Pressure, KPa
A	compact	dual	100/150
B	SUV	dual-	125/140
C	sedan	dual	165/175
D	sedan	dual	140/190
E	light truck	single	160



(a) Bag A



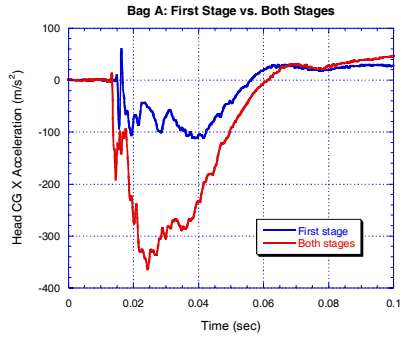
(b) Bag D

Figure 4. Sealed tank test pressure data.

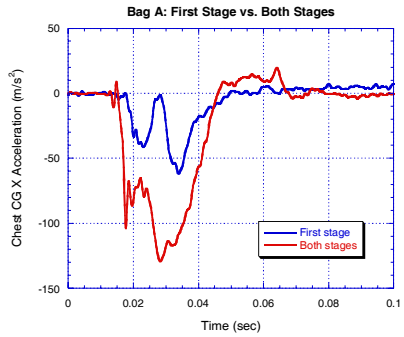
Tests conducted using Bag A and the Hybrid-III dummy showed air bag loads from the 1st stage and both stages resulted in significant differences in the dummy response (Fig. 5). Inflation from both stages deploying simultaneously delivers a much stronger load to the dummy than that just from the 1st stage (Fig. 5). The results are consistent with the tank data showing the tank pressure increasing from 100 to 150 KPa when the 2nd stage is triggered (Fig. 4a and Table 2). To achieve the maximum impact load for dummy evaluation, the remaining tests with the THOR-NT were conducted by deploying both stages simultaneously for all dual-stage modules.

<u>Data repeatability and variability.</u> It was found that the bag inflation variation was a dominant factor affecting the data repeatability of the air bag impact test results (Figs. 6-10). Bag A produced data with excellent repeatability as observed from the two tests for the THOR-NT dummy (Fig. 6). However, the other four types of bags produced significant variability in dummy metrics (Figs. 7-10).

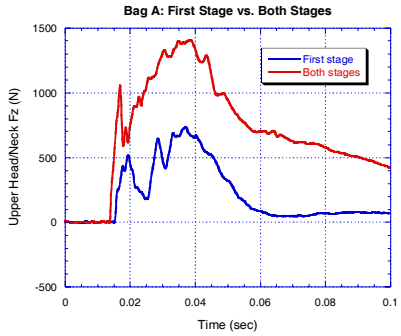
For illustration, large inflation variability was observed for Bag C deploying against the THOR-NT dummy (Fig. 7). The upper head/neck load data shown in Figure 7 are in the head coordinates. For test 1, the air bag pushed the chin backwards, which



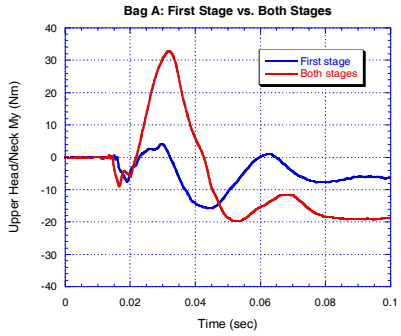
(a) Head CG X-acceleration



(b) Chest CG X-acceleration



(c) Upper head/neck Fz

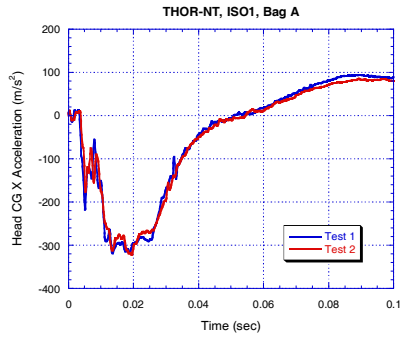


(d) Upper head/neck My

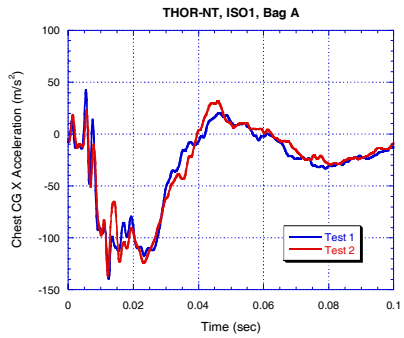
Figure 5. Hybrid-III responses to first stage and full deployments for Bag A.

generated large positive upper head/neck shear Fx and moment My (flexion) at 20 ms (Figs. 7a-b). For test 2, the air bag was trapped under the chin and pushed it upwards, which generated large negative Fx

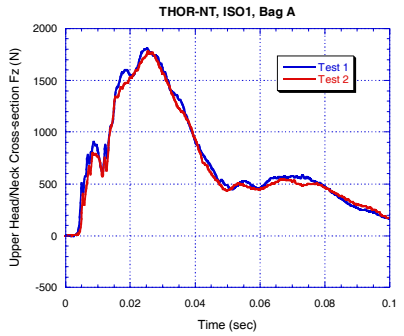
and My (extension) at 40 ms (Figs. 7a-b). The air bag also slipped behind the steering wheel for test 2, which did not happen in test 1 (Fig. 8a vs. 8b).



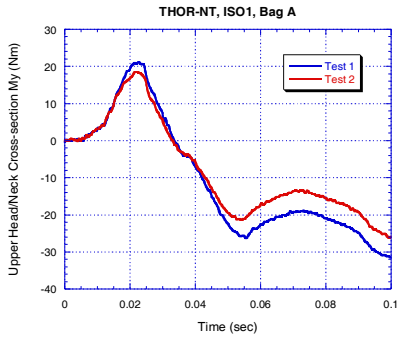
(a) Head CG X-acceleration



(b) Chest CG X-acceleration

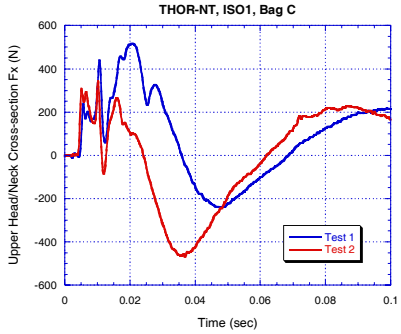


(c) Upper head/neck Fz

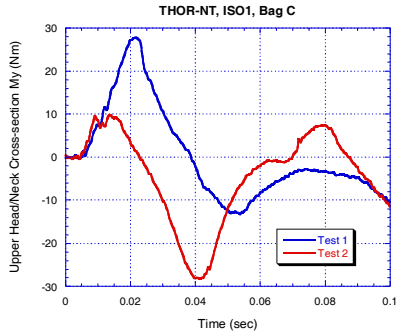


(d) Upper head/neck My

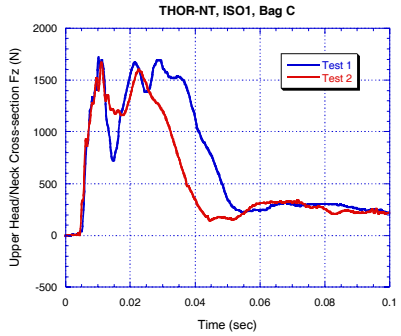
Figure 6. Excellent data repeatability observed for bag A.



(a) Upper head/neck Fx

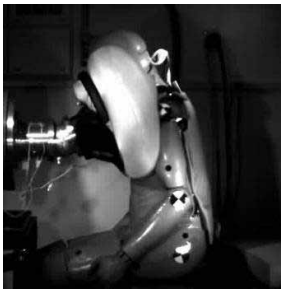


(b) Upper head/neck My

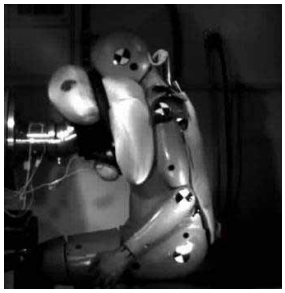


(c) Upper head/neck Fz

Figure 7. Head/neck load data comparison for Bag C (head coordinates).

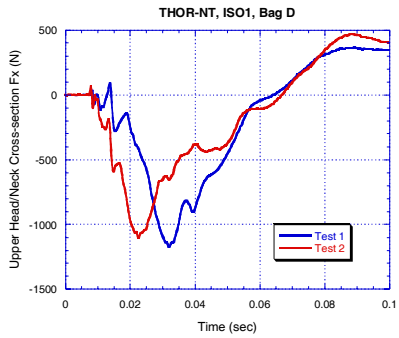


(a) Test 1

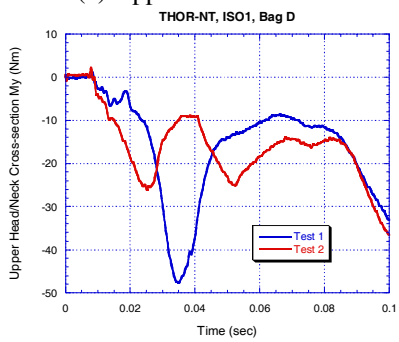


(b) Test 2

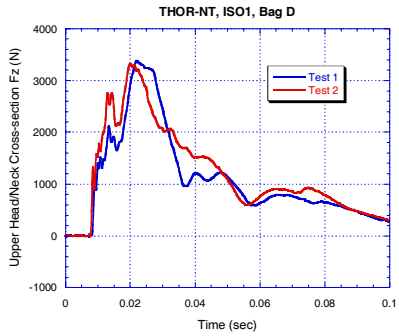
Figure 8. Inflation variability for Bag C deployed against THOR-NT.



(a) Upper head/neck Fx

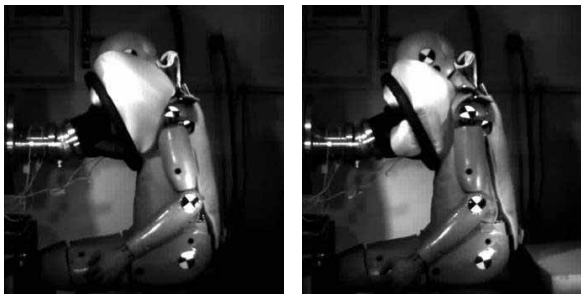


(b) Upper head/neck My



(c) Upper head/neck Fz

Figure 9. Head/neck load data comparison for Bag D (head coordinates).



(a) Test 1 (b) Test 2

Figure 10. Inflation variability observed for Bag D deployed against THOR-NT.

Inflation variability was also observed for tests using other air bags. For Bag D, high-speed video data showed the air bag was trapped under the dummy chin and pushed it upwards, which generated large negative My (extension) for test 1 at 35 ms (Figs. 9b and 10a). This neck trapping situation was less severe for test 2 as indicated by the much smaller negative My (Fig. 9b). In addition, the air bag slipped behind the steering wheel more for test 2 than for test 1 as shown by the high-speed video data (Figs. 10a vs. 10b). This partially explains why test 2 delivered a softer load on the neck than test 1 (Fig. 9b).

The inherent bag inflation variability manifested itself mostly in upper head/neck Fx and My. The head/neck axial force Fz was fairly consistent (Figs. 7c and 9c). The Fz forces are positive most of the time (Figs. 6c, 7c and 9c), which means the neck pulls the head downwards in tension. This tensile upper head/neck Fz is a combined effect of the external air bag load and the centrifugal rearward rotation of the head.

Injury metrics for various air bags. For the head, a HIC_{15} = 700 injury reference value may be used to assess injury risk. All five air bags produced HIC_{15} values of less than 200 and significantly below this threshold, although Bag D produced the highest HIC_{15} values (Fig. 11). This seems to be consistent with the tank pressure data showing Bag D generating the highest dual-stage pressure (190 KPa) among the five models (Table 2).

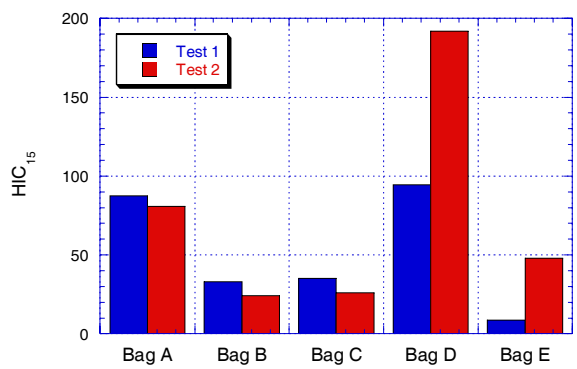


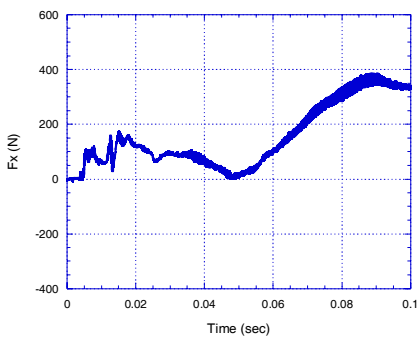
Figure 11. HIC_{15} data comparison.

Table 3 provides the critical injury assessment values for human spine tolerance [5]. While the THOR-NT is designed to mimic the human neck, it is stiffer than the human spine; thus 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-NT. Nonetheless, the human threshold values may be used for experimental purposes.

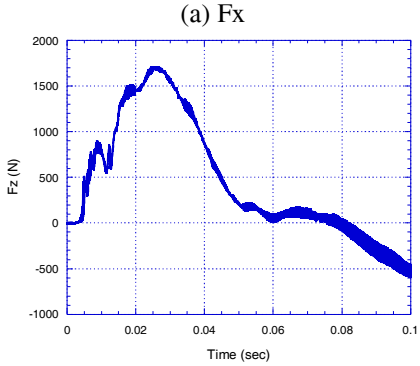
Table 3. Critical Values for Neck, M_Y and F_Z

	Human
Compression, F_C (N)	3640
Tension, F_T (N)	2520
Flexion, M_F (Nm)	48
Extension, M_E (Nm)	72

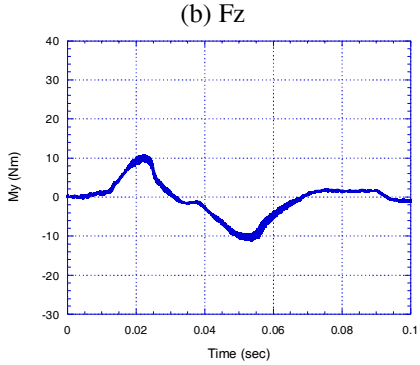
The neck load data for all five bags are shown from Figures 12-16. These "OC" neck loads as shown are in the neck coordinate system as measured by the upper neck load cell excluding the cable effects, with the moment, My, moved up to the level of the head/ neck pin joint (the load cell is located 2.54 cm below the joint). The THOR-NT data are presented as such consistent with the way the neck data are expected to be used for injury assessment. Furthermore, the range of variability for each data metric is indicated by the shaded region bounded by the time-history data recorded from the two repeat tests for each bag.



(a) Fx

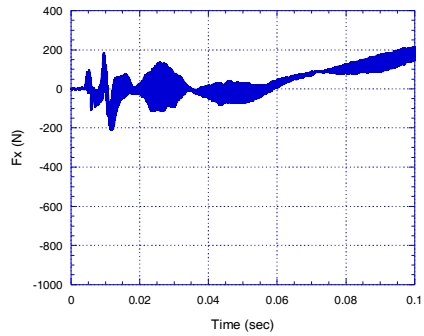


(b) Fz

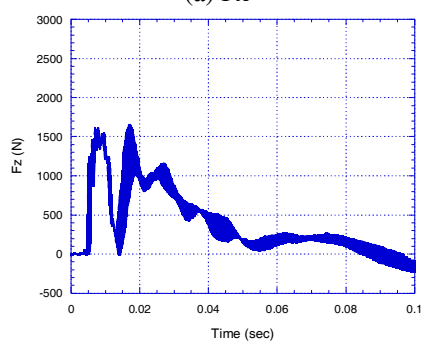


(c) My

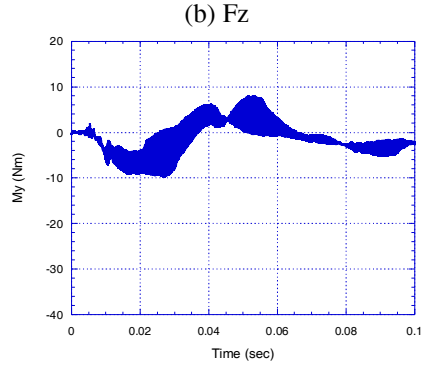
Figure 12. Neck load for Bag A (neck coordinates).



(a) Fx



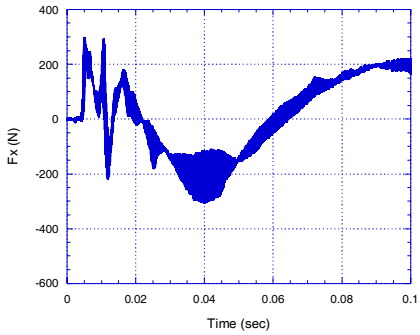
(b) Fz



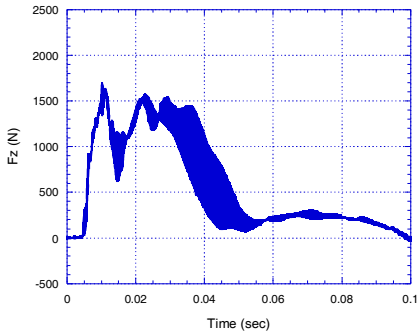
(c) My

Figure 13. Neck load for Bag B (neck coordinates).

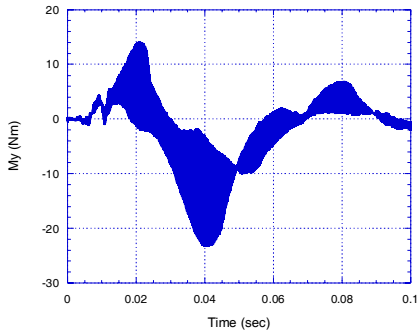
The data comparison shown from Figures 12-16 indicates some clear trends even though only two tests were performed for each bag. The data spread for Fz is much smaller than that for Fx and My. The shear force Fx shows consistency with My, with both generally staying positive or negative simultaneously, for flexion or extension, respectively. Other than for Bag D, the neck moment cycled from flexion to extension or vice-versa smoothly within the safe critical values indicated in Table 3 (Figs. 12-16).



(a) Fx

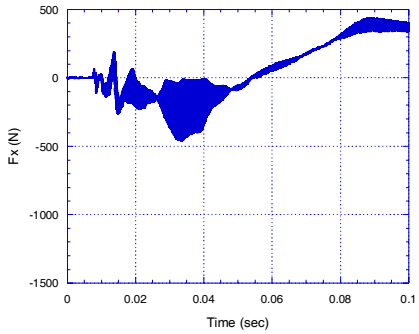


(b) Fz

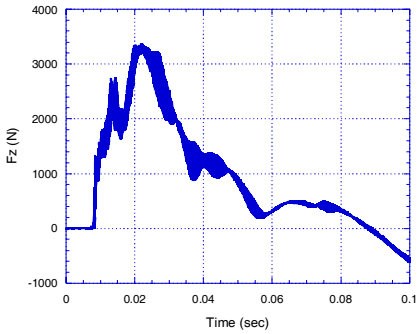


(c) My

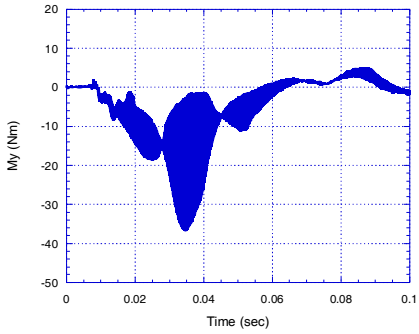
Figure 14. Neck load for Bag C (neck coordinates).



(a) Fx



(b) Fz



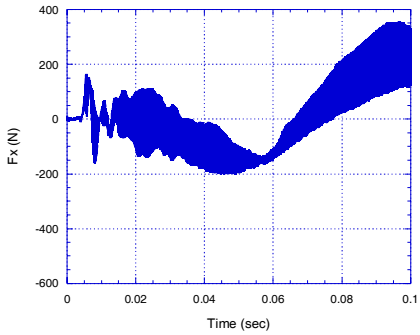
(c) My

Figure 15. Neck load for Bag D (neck coordinates).

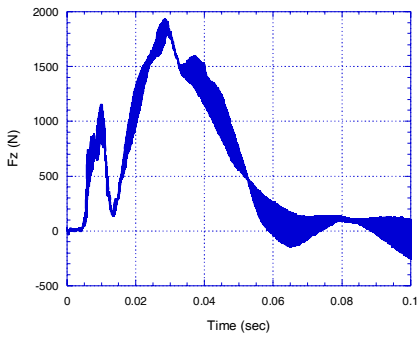
Of the five types of air bags tested with the THOR-NT, Bag D exceeded the critical value for neck tension given in Table 3. For Bag D, the axial tension force Fz recorded by THOR-NT reached 3300 N (Fig. 15b), which exceeded the human critical value of 2520 N shown in Table 3. This air bag also produced the highest inflation pressure in the tank test (Table 2). Compared to the other bags, Bag D also produced the largest extension moment reaching -38 Nm and the neck moment was dominated by extension throughout the entire bag-dummy interaction process (Fig. 15c).

Cross-sectional vs OC My comparison. With the exception of Bag A, each air bag had inflation variability that certainly contributed to the differences in dummy responses for a given air bag type. Nonetheless, there were some consistent trends that can be illustrated comparing the OC neck moment against the cross-sectional neck moment calculated by including the cable load effects.

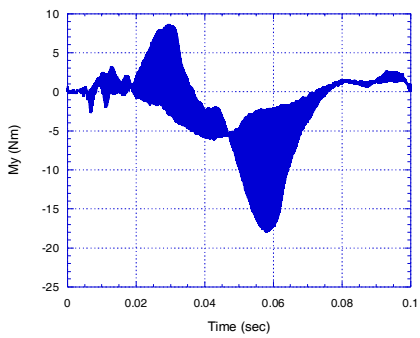
As shown in Figure 17 using data from Bag A and Bag D, the OC moment at the pin joint recorded by THOR-NT is considerably smaller than the total cross-sectional moment (Fig. 17). This trend is consistent for all five air bags tested. This further confirms the intended capability of the THOR-NT neck design to distinguish the musculature from the ligamentous load.



(a) Fx

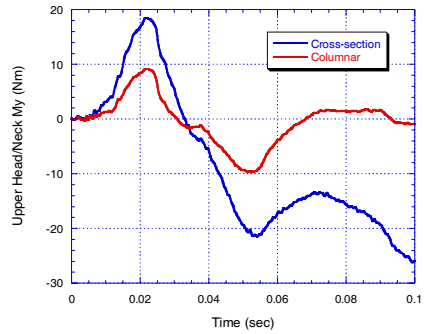


(b) Fz

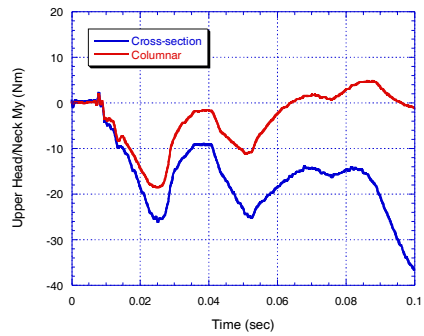


(c) My

Figure 16. Neck load for Bag E (neck coordinates).



(a) Bag A



(b) Bag D

Figure 17. Upper head/neck moment comparison.

DISCUSSION

The present study has shown that the head/neck complex of the THOR-NT 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 variability of the early inflation behavior of the fleet air bag modules tested was confirmed by the high-speed video data. Nevertheless, all HIC_{15} values calculated from the tests are well below the injury threshold. Our previous studies for the THOR and Hybrid-III dummies have shown that highly repeatable dummy responses can be obtained if the inflation and bag folding can be tightly controlled for each test in the laboratory [6-8]. Other studies have also demonstrated the importance of dummy position control [14]. The dummy position was well controlled for the present work. On the other hand, the variability of the pyrotechnics and bag folding in the fleet air bag modules is something that may not be as easily controlled by the scientific researcher in laboratory tests.

Data variability can be an important issue for scientific research and dummy evaluation. It is likely that the range of bag inflation variability is within the manufacturer's expectation, and in terms of standard safety evaluation, it may not result in any significant differences in injury metrics such as that demonstrated by the HIC_{15} values that are all well below the injury threshold. One way to circumvent data variability is to tightly control the inflation process. However, it is probably a reality that some fleet air bags will not inflate with high repeatability as the present work has demonstrated. When these bags are used for research, it is desirable that a significant number of repeat tests are performed with the statistical variation of the results quantified.

By its design nature, the THOR-NT neck separates the musculature load from the spinal ligamentous load on the neck, which results in a lower OC moment than the total cross-sectional value. The test data obtained confirmed the expected performance of the THOR-NT head/neck complex design.

The tests performed are not standard regulatory tests but rather scientific studies for the evaluation of the THOR-NT dummy. It should also be noted that there are no injury criteria defined for the THOR-NT dummy, nor are there standard OOP positions defined for using the THOR-NT dummy. Part of the purpose for the present work is to collect scientific data to understand the attributes to the variability in the dummy responses so that well-defined OOP positions for the THOR-NT dummy can be established in the future. In addition, injury criteria for the THOR-NT will still need to be established and the present work contributes to the understanding of air bag load paths to the neck in OOP conditions.

A limitation of the present work is that the number of repeat tests for each case is small. In addition, a limited range of driver side air bags was tested and only at one OOP position.

CONCLUSIONS

Comparative tests have been carried out successfully for five late model driver side air bag models using THOR-NT in the ISO-1 position. The major findings are that the inflation variation in four of the five air bags was the cause of highly variable neck moment responses in the THOR-NT. Neck tension, on the other hand, was not influenced nearly as much by the inflation variation. However, neck tension appears to be the most critical load and almost all of the tension is passed through the ligamentous spine, with very little load borne by musculature. Neck tension was shown to approach the human threshold value for one of the bags. The THOR-NT dummy has shown good usability for the test effort and was successful in capturing the effects of inflation variability on head/neck responses.

ACKNOWLEDGEMENTS

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REFERENCES

1. Haffner, M., Eppinger, R., Rangarajan, N., Shams, T., Artis, M., and Deach, D., (2001) “Foundations and Elements of the NHTSA THOR Alpha ATD Design,” Paper #458, 17th International Technical Conference on the Enhanced Safety of Vehicles, HS 809 220 (U.S. DOT, 2001).

2. Kent, R., Lessley, D., Shaw, G., and Crandall, J., (2003) “The Utility of Hybrid-III and THOR Chest Deflection for Discriminating Between Standard and Force-Limiting Belt Systems,” SAE Paper 2003-22-0013, in the 47th Stapp Car Crash Conference Proceedings.

3. Xu, L., Jensen, J., Byrnes, K., Kim, A., Agaram, V., Davis, K.L., Hultman, R.W., Kostyniuk, G., Marshall, M.E., Mertz, H., Nusholtz, G., Rouhana, S. and Scherer, R., (2000) “Comparative Performance Evaluation of THOR and Hybrid-III,” SAE Paper 2000-01-0161, SAE 2000 World Congress, Detroit, Michigan, March 6-9, 2000.

4. Pintar, FA, Yoganandan N, and Baisden J. (2005) “Characterizing occipital condyle loads under high-speed head rotation,” SAE paper 2005-22-0002, in the 49th Stapp Car Crash Journal, 49:33-47.

5. 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.

6. Chan, P. C. and Lu, Z. (2003) “Evaluation of Hybrid-III and THOR Dummy Head/neck Responses to Airbag Load at Close Proximity,” 2003 IRCOBI Conference, Lisbon, 2003.

7. Chan, P. C. and Lu, Z. (2004) “Laboratory Study of Hybrid-III and THOR Dummy Head/neck Responses to Airbag Load at Close Proximity,” SAE Paper 2004-01-0320, 2004.

8. Lu, Z. and Chan, P. C. (2004) "Out-of-Position Airbag Load Sensitivity Study,” SAE 2004 Transactions Journal of Passenger Cars: Mechanical Systems, 2004-01-0847, pp. 507-520, 2004.

9. Bandak, F., Chan, P. C., Ho, K. H., and Lu, Z. (2002) “An Experimental Air Bag Test System for the Study of Air Bag Deployment Loads.” Int. J. Crashworthiness, 7(2), pp.1-12.

10. National Highway Traffic Safety Administration, U.S. Department of Transportation, Motor Vehicle Safety Standard No. 208, Notice of Proposed Rule Making.

11. SAE J2238 (1995) “Airbag Inflator Ballistic Tank Test Procedure,” SAE Surface Vehicle Recommended Practice, March 1995.

12. SAE J211 (1995) “Instrumentation for Impact Test,” SAE Surface Vehicle Recommended Practice, March 1995.

13. User Manual,“THOR Instrumentation Data Processing Program”, November 2001, GESAC-01-06.

14. Bass, C. R., Crandall, J. R., Bolton, R. R., Pilkey, W. D., Khaewpong N., and Sun, E. (1999). “Deployment of Air Bags into the Thorax of an Out-of-Position Dummy,” SAE Paper 1999-01-0764, Air Bag Technology 1999, SAE SP-1411.