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Development of a Thor-based Advanced Head/Neck Assembly for Retrofit to the 50th Percentile Male Hybrid III ATD

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M. Haffner and R. Eppinger

ABSTRACT

This paper presents the development of an advanced head/neck assembly based on Thor, a 50th percentile male dummy developed by GESAC under the NHTSA funding. The main goal of this study is to develop a mechanical neck system which is capable of duplicating the responses of a human neck in kinematics and dynamics during multi-direction impacts. Besides this main objective, the new head/neck complex is expected to retrofit to the conventional dummies, not only Thor but also Hybrid III. An overview of this new biofidelic neck design is presented. Simulations using a lumped-mass model were used for design and validation purposes and the outcomes are discussed as well. In addition, preliminary evaluation of this new design, using static and dynamic testing, was performed and the results are presented and discussed in this paper.

INTRODUCTION

The use of Anthropomorphic Test Devices (ATD) or crash test dummies is a practical way to evaluate the safety of motor vehicles in a crash environment. Injuries to the human head-neck complex often occur in vehicle crash accidents and may lead to serious to fatal consequences. Therefore, there is a need to develop a more biofidelic mechanical head/neck system, which can be implemented into current crash dummies. Over the years, different neck designs have been developed with various degrees of success. A neck developed by Mertz et al. (1973) is used in the current Hybrid III dummy, and meets the standard Mertz corridors, which correlate the moments around the occipital condyle joint with head angle relative to T1 (Mertz et al., 1973; Patrick and Chou, 1976). However, this neck did not have good agreement with respect to head kinematics when compared to results from volunteers' tests conducted at the Naval Boidynamics Laboratory (NBDL) (Ewing et al., 1975). The NHTSA has been performing and funding research on mechanical neck systems for several years. In 1985, the Vehicle Research and Test Center

(VRTC) of NHTSA made an initial effort on a new concept for a Head/neck simulator and presented the results at the 12th ESV (Mendis et al., 1989). One of their main improvements was to use a spring/cable exterior to the neck to simulate the human neck ligaments' effect during impact. The spring/cable design was meant to obtain the proper excursions and lag which were seen in the NBDL volunteers' experiments. After this initial effort, the VRTC researchers developed several prototype neck design during follow-up work. Based on the performance criteria for biofidelic dummy necks formalized by Klinich et al. (1995), the BNN-3 was constructed by the VRTC and had promising results relative to those criteria. However, this design was not suitable for inclusion in a test dummy.

In 1996, GESAC was funded by NHTSA to adapt this design and develop a head/neck system which could be integrated into the NHTSA advanced frontal dummy, Thor (White et al., 1996). This neck was evaluated by several research institutes such as TNO, UPM and JARI (Hoofman et al., 1998) and the results indicated that the neck substantially satisfied the frontal and lateral flexion requirements. However, additional improvement of the neck was still needed. For example, new neck experiments on volunteers have been conducted by several researchers in recent years (Ono et al., 1999; Davidsson, 1999) and newly updated corridors were developed according to these data. Another area was in improving the antropometry of the Thor neck. In the current Thor neck, the location of the C7/T1 joint is not clearly delineated and it was thought that a properly defined T1 would help in the definition of any injury assessment using Thor. In addition, there appeared a need to replace the conventional HIII dummy neck with that of Thor. A similar retrofit has been done for the Hybrid III lower extremity by using the newly design Thor-Lx (Shams et al., 1999). In order to meet these new design criteria, and the need to retrofit to the HIII, modifications to the current Thor neck are required. In this paper, the modifications to the design of the Thor neck for these purposes are discussed, which includes design requirements, simulations, design, and preliminary tests.

DESIGN REQUIREMENTS

There are three major design requirements for this new neck, which are anthropometry, geometry constraints for retrofit to HIII ATD, and human neck responses in kinematics and dynamics. Since this mechanical neck is used to represent a human, the new neck needs to generally match the AATD anthropomorphic landmarks such as A-O junction and T1. In addition, we expect to retrofit this neck to HIII; therefore, the current constraints in the Hybrid III head/neck complex have to be considered. Those constraints include the length of neck, a large horizontal offset from the neck base to the occipital condyle joint, and the location of the pitch change relative to the thoracic spine. Except for these structural requirements, the other important criterion is to match the dynamic and kinematic responses of this mechanical neck to the human responses. The main sources of human head/neck response requirements for our mechanical neck are listed in Table 1. The corridors define the trajectories of the head during dynamic impacts. We will plot these corridors with our simulation results in the discussion of our preliminary simulations. In addition, the Mertz corridors (Mertz et al., 1973; Patrick and Chou, 1976) have been utilized as secondary requirements as well.

Table 1. **SOURCES OF REQUIREMENTS OF HUMAN HEAD/NECK RESPONSES**

		Sled Pulse	Tested by	Reference
Sled HyGe Test	Flexion	15g	NBDL	Thunnisen et al.(1995)
	Extension	4g~5g 3g~4g	JARI Chalmers University	Ono et al.(1999) Davidsson (1999)
	Lateral	7g	NBDL	Wismans and Spenny (1983)
Strap Test	Out of Position	-	JARI and MCW	Ono et al. (2000)

THOR BETA NECK / HIII NECK RETROFIT

Based on these requirements described in the previous section, a new neck was designed and fabricated. This neck is called the Thor-Beta neck and shown in the Figure 1.

Figure 1. Thor-Beta Neck.

This new design includes several new features, which are listed as follows

(1) 4 pucks

As we discussed in the previous section, the distance from the OC joint to T1 is a significant anthropometric dimension for the dummy neck design. By using the 4-puck design, the new neck agrees with the OC-T1 length derived from NBDL tests and the T1 is located at a well defined rigid position. (Figure 2)

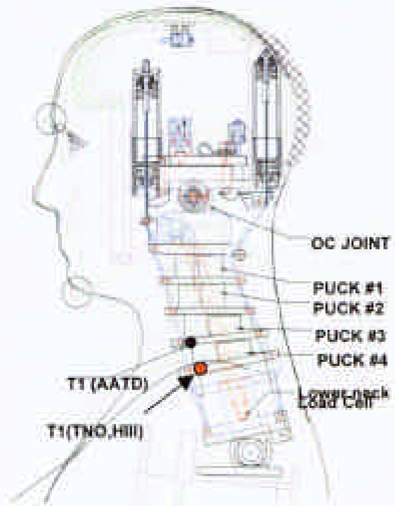

Figure 2. Thor-Beta Neck overlaying AATD

(2) Offset geometry

One of our objectives for this new neck is to retrofit with the Hybrid III dummy. Therefore, the new neck has to satisfy the design constraints in the current Hybrid III head-neck structure, which we described in the Design Requirements section. In order to do so, we modified the new shape with small angles in the bottom two of the four pucks (puck#3 and #4 in Figure 2). As a result, the new neck is offset from the top to the bottom. The gradual offset design is different from the Hybrid III one -step change, and the Beta neck is similar in curvature to a human neck structure.

(3) New puck shape to simulate extension stop

For the human neck, the responses in flexion and extension are different. In the original design, we used the neck extension stops to simulate this difference. The stop produces a relatively concentrated load, and a sharp transition in force and moment. In order to improve the smoothness of the response, the new design replaces the stop by using a puck with a wedge which is shown in Figure 3.

Figure 3. Puck with wedge

The kinematics for this new puck can be depicted in Figure 4. Because the wedge, the stiffness at larger bending angles in extension should be greater than in flexion.

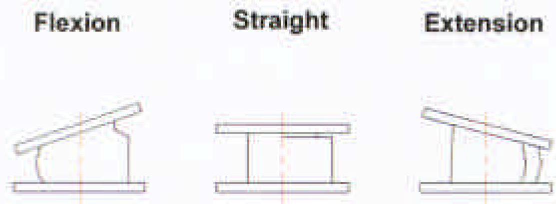

Figure 4: Kinematics of the new puck with wedge

(4) New spring with rubber tube insert.

In the original Thor neck spring-cable design, the end of the cable is connected to a compression spring which is located inside the head. Since this is a pure compression spring, the loading will increase rapidly after bottoming of the spring. This sharp increase in load is not biofidelic and may also damage the cable and create durability problems. A simple way to solve this problem is to reduce the stiffness and add a rubber tube within the spring (Figure 5). The combination of rubber and spring will reduce the sharp bottoming effect, make the response more biofidelic, and also possibly prevent possible cable damage.

Apart from the above new features, two more modifications are planned to be included in our new design. They are an additional compressive element in the center cable and modification for the stop on the Head/Neck A-O junction. With the new modifications, the neck is expected to respond with greater biofidelity.

Figure 5. Spring with rubber insert

SIMULATIONS

In order to validate our new design, simulations using DYNAMAN (Shams et al., 1992) were performed based on the new design. These simulations of 15g frontal flexion, 7g lateral flexion, and 3g~5g rear extension tests are based on the sources described in Table 1. The results for the simulations are shown in Figure 6, 7, 8, and 9, respectively.

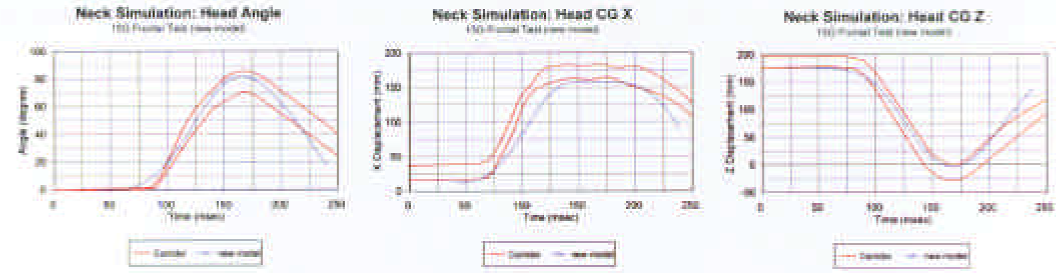

Figure 6. Results for 15g frontal flexion simulation

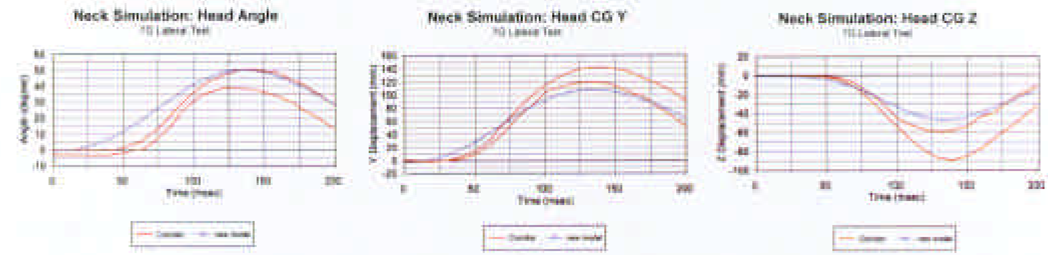

Figure 7. Results for 7g lateral simulation

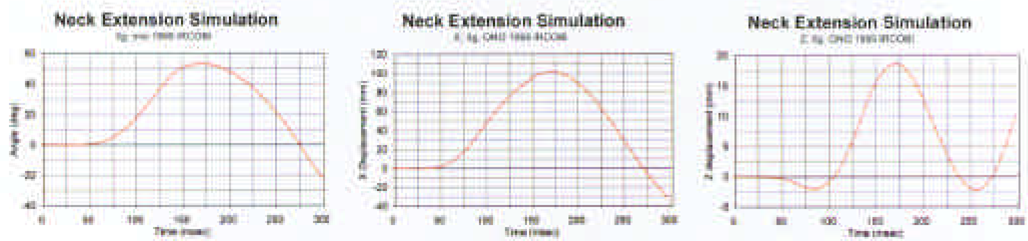

Figure 8. Results for 4g~5g extension simulation (Ono et al., 1999)

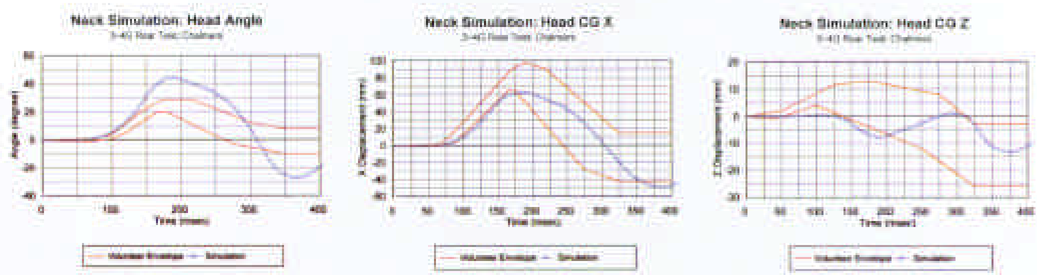

Figure 9. Results for 3g~4g extension simulation (Davidsson, 1999)

For 15g flexion simulations, the head angle is inside the corridor and both of the head displacements (X and Z) are at the lower boundary of the corridors. For 7g lateral simulation, the head angle is in the upper boundary of corridors but the Head X and Z displacements are short of corridors. At this time, we didn't overlay the JARI volunteer extension testing results with our simulation. However, we can compare the outcome by observing the maximum value. According to Ono et al. (1999), the maximum head angle for the JARI test is around 35-50 degree. On the other hand, the result from our simulation is around 55 degree. That is close to the upper boundary of Ono's tests. For Chalmers' extension tests, results from simulation have a match on the X and Z displacements, but the simulation head angle is larger than volunteers. The reason probably is that we didn't have appropriate properties for the headrest used in Chalmers' tests. In conclusion, the results from these three types of simulations have generally good agreements in comparison with corridors.

In addition, we performed a preliminary simulation for the strap neck tests (out of position) which were similar to JARI volunteer's tests conducted by Ono et al. (2000). Both results from our simulation and JARI volunteer strap test are compared in Table 2.

Table 2: **COMPARISON FOR BOTH RESULTS FROM SIMULATIONS AND ONO TESTS**

	Angle (degree)		Moment (N-m)		Shear Force (N)		Axial Force (N)	
	Ono	Sim	Ono	Sim	Ono	Sim	Ono	Sim
Chin upward	10~20 (200ms)	11 (130ms)	-3 (45ms)	-1 ~1 (20~100ms)	-30~30 (60~140ms)	-20~30 (28~130ms)	130 (50ms)	150 (25ms)
Chin rearward	-5~5 (50~150ms)	-3~7 (35~130ms)	6 (40ms)	3~ -2.5 (40~60ms)	60 (40ms)	170 (40ms)	30 (40ms)	120 (40ms)
Forehead	15~20 (200ms)	18 (125ms)	*	-2.1 (80ms)	30 (25ms)	60 (100ms)	30 (25ms)	50 (200ms)

* need to review

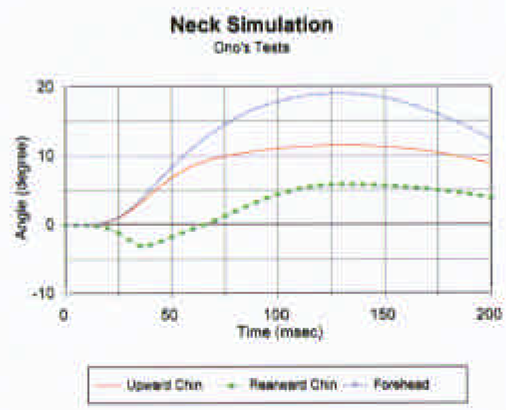

Figure 10. Head kinematics for three simulations

The results from the simulations look encouraging. Especially for the kinematics, the head motion from simulations is similar to the volunteer strap tests (Figure 10). The results are summarized as follows:

(1) Upward at Chin:
Kinematics: Extension occurred during the entire period; Our peak angle (11.5 degree) was close to the volunteer but the unloading part was faster than volunteer (typically the rubber sees less hysteresis than the human)

Force & Moment: We have good agreement for both shear and axial forces (Fx, Fz); For the moment, although the number was close, it is hard to compare with because it was small (peak for the volunteer's test around 3 N-m).

(2) Rearward at Chin:
Kinematics: The head rotated in flexion first; then turn in extension; That was similar to the volunteers' results (we have both flexion and extension)
Force & Moment: Both forces were higher than volunteer but the shape was close. For the moment, we have a good agreement, but it's still hard to compare with because of the small number.

(3) Rearward at Forehead:
Kinematics: Extension during the entire period; The peak (19 degree) was also close to volunteers' results, but the unloading part was early.
Force & Moment: Detailed results from volunteers at this series of tests were not available; therefore, we didn't do any comparison here.

These are preliminary simulations, but they indicate that this neck should qualitatively match the output seen from volunteers.

PRELIMINARY TESTS

In order to verify our new neck, static bending and dynamic pendulum tests were performed.

(1) Static Bending Tests

The static flexion, extension, and lateral bending tests were performed to verify our new design. In the static tests, we tested the Thor-Beta / HIII retrofit neck without front and rear cable installation. The basic setup is to fix the bottom of neck (lower neck load cell) and pull a cable connected to the top of neck (at the hole for the O.C. pin) to bend the neck. A tilt sensor was installed on the top of the neck to measure the bending angle. The neck in these tests was bent around 45 degree in flexion and extension, and 35 degree in the lateral direction. The results from the new neck tests in flexion, extension, and the lateral directions are shown in Figure 11. Moment vs. bending angle is presented for these graphs.

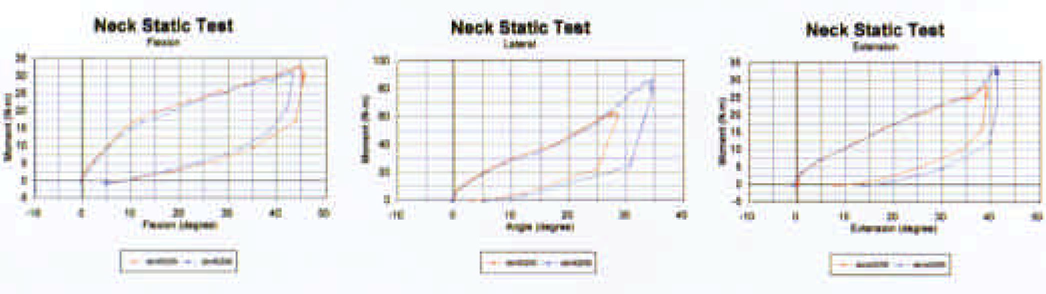

Figure 11. Moment vs. Angle in flexion for the Thor-Beta neck static bending tests

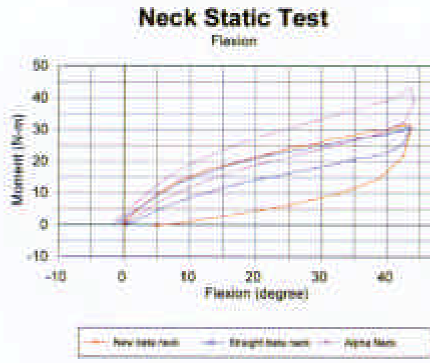

Figure 12. Moment vs. Angle in flexion for the new Thor-Beta ,straight 4-puck, and Alpha necks

In the graphs above (Figure 12), the stiffness of the Beta neck in flexion and extension was seen to be softer than the current Thor neck and the stiffness in the lateral direction was similar for both necks. That was because we modified the size of the puck along the x-semi axis so that the total stiffness reduction should be around 35% (proportional to cube of the semi-axis length). In addition, there is a small difference for the results in flexion and extension. As we can see in Figure 11, the moment in extension at 40-degree bending is about 5% greater than in flexion. This also proves the effect of wedge design in the puck. Although the y semi-axis didn't change, we expected a 5% increase in the lateral direction due to the x semi-axis change. The overall results seem reasonable.

(2) Dynamic Pendulum Test

The pendulum test was chosen to verify the new neck dynamic responses. The tests in flexion, extension, and lateral flexion were performed in our preliminary studies for this new neck. In these tests, we dropped the head-neck assembly from a specified angle into a contact plate which is covered by foam (50.8 mm sponge rubber). The drop angles, 30 and 45 degrees, were chosen in flexion and extension. In the lateral direction, 45 and 60 degrees were chosen as the drop angle. 5-puck (alpha; current), 4-puck (beta-straight), and 4-puck (beta-current) necks without front and rear cables were tested in our preliminary studies. Accelerometers were installed on the pendulum and at the head CG to measure the pendulum deceleration and head acceleration, respectively. In addition, a potentiometer was used on the pendulum arm to measure the rotation of pendulum. By differentiating the reading from this potentiometer, the impact velocity can be obtained. The kinematics of the head is one of the important variables from the pendulum tests, which we would like to use for comparison. Since a high-speed camera was not available during these tests, moment, we used the head acceleration as an alternate method to verify the new neck kinematics.

For the flexion tests, results from Alpha and current Beta necks at the 30-degree dropping tests (2.0 m/s impact velocity) are similar. The initial peak values of head CG acceleration in the X and Z direction are listed in Table 3. For the 45-degree drop tests (3.2 m/s) in flexion, the peak values of acceleration were similar for the two necks especially for the first peak. The test results in extension for these three necks are also listed in Table 3. In both 30-degree and 45-degree drop tests, the peak accelerations of Thor-Beta neck were less than the Alpha neck according to these data. These results suggest that the Beta neck might be stiffer in extension. In addition, the Beta neck seems to have a clear response in acceleration than the Alpha neck especially in the 45-degree dropping case. The reason probably is the removal of the rear stop for the Beta neck. For the timing, the results for both flexion and extension matched fairly well.

Table 3. COMPARISON FOR PEAK ACCELERATION RESULTS FOR ALPHA AND BETA NECKS IN PENDULUM FLEXION AND EXTENSION TESTS

	Flexion				Extension			
	2.0 m/s (30 Degree Drop)		3.2 m/s (45 Degree Drop)		2.0 m/s (30 Degree Drop)		3.2 m/s (45 Degree Drop)	
	X	Z	X	Z	X	Z	X	Z
Alpha	7.7g (100ms)	6.8g (90ms)	13.2g (65ms)	20.0g (50ms)	-8.2g (98ms)	8.8g (90ms)	-18g (58ms)	26.4g (50ms)
Beta	8.4g (99ms)	8.7g (90ms)	18.0g (54ms)	23.4g (49ms)	-5.3g (94ms)	5.2g (88ms)	-9.0g (52ms)	21.8g (55ms)

The head CG accelerations for the three necks, during lateral pendulum tests, are very similar and their time-history graphs in the Y and Z direction are shown in Figure 13 to 16. These graphs also show a good agreement for these three necks. One visual difference between the two necks according to these graphs was the response frequency. That was caused probably by the length of the new neck because the new neck is shorter than the current one. Since the Thor neck didn't have ligament cables in the lateral direction, the lateral experiments here were very close to the actual neck pendulum tests. The lateral testing results were encouraging. According to the three direction dynamic pendulum tests, it was felt the design changes were moving in the right direction for modifying the neck column.

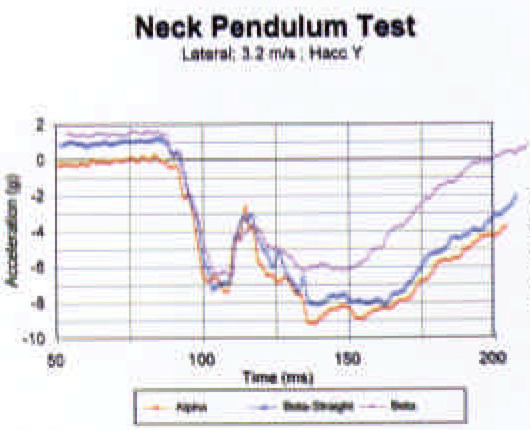

Figure 13. Head CG Y acceleration at the 45 degree lateral pendulum test

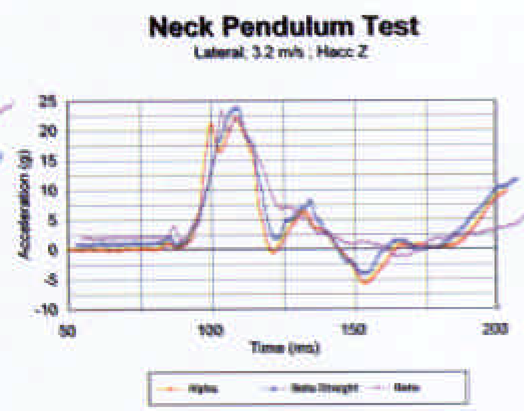

Figure 14. Head CG Z acceleration at the 45 degree lateral pendulum test

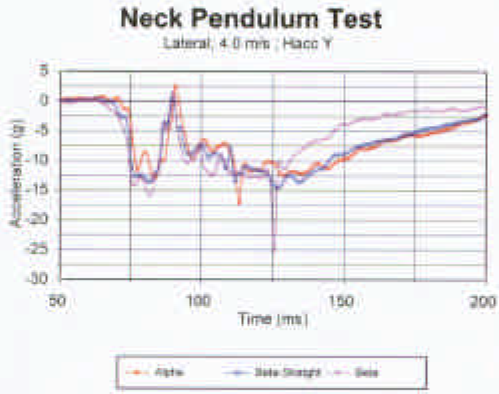

Figure 15. Head CG Y acceleration at the 60 degree lateral pendulum test

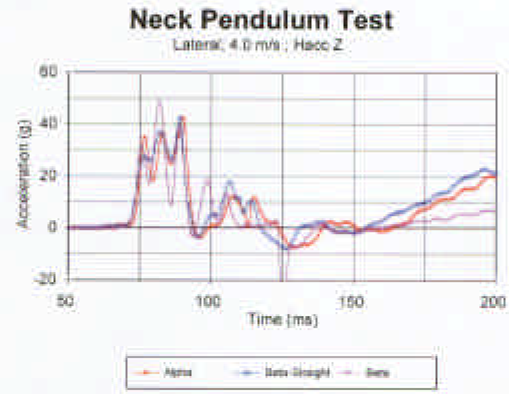

Figure 16. Head CG Z acceleration at the 60 degree lateral pendulum test

CONCLUSIONS AND FUTURE WORK

A new head-neck system for Thor and Hybrid III has been fabricated. According to our simulations, the new neck has a good agreement in kinematics in all three directions in comparison with the corridors. In addition, the dynamic pendulum tests suggest that the new neck has a good test durability and a fair agreement, with respect to acceleration response, in comparison with the Thor-Alpha neck. Although the overall results were encouraging, additional improvement and validation for the new neck are still needed. We plan to add a compressible element to the central cable to help in achieving appropriate X displacement of Head CG and modifying the Head/Neck stops at the A-O joint. Testing of the neck on a standard HyGe sled will help in the validation testing of the new neck. Finally, sled tests of the complete Hybrid III with the new, retrofit neck will be carried out and head kinematics compared with that of a standard Hybrid III neck.

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DISCUSSION

PAPER: **Development of THOR-based Advanced Head/Neck Assembly for Retrofit to the 50th Percentile Male Hybrid III ATD**

PRESENTER: ***T.J. Huang, GESAC***

QUESTION: *Guy Nusholtz*

It was difficult for me to see what type of comparisons you did. Did you make a comparison between the THOR with the THOR neck and the Hybrid III?

A: Not yet.

Q: *Joel Volsar, GM consultant*

The noise that I saw in the data was extremely spiky. I have a hard time seeing that's an advanced neck, I think we're going in the wrong direction. Any time you have springs and cables and springs and metal to metal or whatever it is not acceptable for use in the industry.

A: We understood that one.

Q: Okay.

A: We already resolved that problem but at this time I didn't bring it up because it was used like the old design. This one was the old design head, but the new design head is metal to metal contact we work with.

Q: I fail to see the advantage of really adding all the added mechanisms. I don't see the advantages at this point. We need to see that in the future.

A: We will.