DEVELOPMENT OF THOR NT: ENHANCEMENT OF THOR ALPHA-THE NHTSA ADVANCED FRONTAL DUMMY

T. Shams, N. Rangarajan, J. McDonald, Y. Wang, G. Platten, C. Spade, P. Pope
GESAC, Inc.
United States
M. Haffner
HCS
United States
Paper Number 05-0455

ABSTRACT

The NHTSA Advanced Frontal Impact Dummy THOR has been enhanced to include improved anthropometry and biofidelity, durability, and ease of use. The previous version, known as THOR Alpha has been revised and is now called the THOR NT. The areas of improvement include improved anthropometry and biofidelity in the head with a single, integrated head skin which meets both isolated head drop and whole-body head impact requirements; more biofidelic dynamic response of the neck, including the introduction of an atlanto-occipital joint at the top of the neck with biofidelic range of motion; improved anthropometry at the shoulder and clavicles; improved biofidelity of the ribcage to the lower speed Kroell impact; improved anthropometry in the femur including a representation of the trochanter. The external forms for the pelvis and femur skin are now based on an undeformed shape to more correctly represent the interaction with a vehicle seat. More durable materials and improved production methods have been used, including injection molding the neck and the flexible joints in the spine. The pelvis and femur skins are made of PVC and the shoulders and front of the ribcage (bib) are made of more durable materials. The paper describes the enhancements in detail and presents the results from selected certification tests.

INTRODUCTION

Since the early 1980s, the National Highway Traffic Safety Administration (NHTSA) has supported the development of an advanced frontal crash test dummy with improved biofidelity under frontal impact conditions and with expanded injury assessment capabilities. This has involved extensive research in human anthropometry, biomechanics, and dummy development [Robbins, 1983; Schneider, 1985; Melvin, 1985; Schneider, 1992].

As part of the development effort, a prototype of a frontal crash test dummy, corresponding to a 50th percentile male, was completed in 1996. The principal features of the new crash dummy, known as THOR, have been described in White[1996] and Rangarajan [1998]. The dummy was tested at a number of different laboratories and the test results reported in a number of different proceedings [Ito, 1998; Hoofman, 1998; Petit, 1999; Shams, 1999]. During the initial testing process, a number of problems were identified. These were mainly in the area of poor durability of some of the components such as the neck and flexible joints in the spine, noise in some of the accelerometers, especially in the head and lumbar spine, and problems in handling and storage. Modifications were undertaken on the prototype THOR which resulted in the introduction of THOR Alpha. A description of the modifications is given in Haffner [2001]. The intent was that these modifications would address the principal issues that were raised by some of the laboratories. An extended series of tests were conducted by the Frontal Impact Dummy consortium in Europe, which included testing at TNO, INRETS, TRL, Bast, Insia, and the University of Heidelberg [ADRIA, 2000; Vezin,2002] . Additional testing was done by the NHTSA and GESAC at the University of Virginia and at the Applied Physics Laboratories. These tests indicated some of the important durability problems such as debonding of the neck, and the spine flex joints, tearing of the pelvis skin, shoulder pads, and bib were still occurring. In addition, the NHTSA asked GESAC to look at improving the anthropometry and biofidelity of the dummy where it was appropriate. The FID consortium provided the NHTSA with a detailed summary of their findings and along with comments from other labs and the improvements sought by the NHTSA, a list of potential modifications was arrived at.

THOR NT MODIFICATIONS

An extensive set of modifications were made to the THOR Alpha during the development of the THOR NT based on user comments and the need for improving the performance of the dummy. The modifications could be roughly grouped according to the following:

- Anthropometry: Improvement in the external shape of selected segments, such as the head/neck interface, the shoulder, the pelvis, and the femur
- Durability: Improvement in the durability of many of the deformable parts of the dummy such as the neck, flex joints, and various stops, either through improved manufacturing process or redesign
- Usability: Improvement in the ease of use of the dummy, such as easier access to some instrumentation and providing a common electrical ground
- Biofidelity: Improvement in selected impact responses of the dummy, especially the thorax and head
- Fit and Finish: Improvement in the appearance of segments and the interfaces between segments

Head

The changes to the head included:

- Integrated head skin which covered both the skull and the face
- Improved chin anthropometry
- Zippered connection between head and neck skins
- Improved mounting of the nine-axis accelerometer package
- Modified mandible load plate
- Extended chin support
- Radiused edges on face plates

The most important change to the head was in going from separate head and face skins to a single, integrated head skin. It was also decided that the skin around the face should not possess any features, such as nose or lips, since a featureless face would improve repeatability during impacts.

The improved chin anthropometry was motivated by the need to improve the interaction with airbags if they happened to load the space between the chin and the neck. The bottom of the chin surface in the head skin was rounded to more closely model the 50th percentile male AATD chin. Figures 1 and 2 show the difference between the two head/face skin designs. The figures also show the improvement in the attachment of the neck skin to the head skin in the NT relative to the Alpha.

Figure 1. THOR Alpha head/face.

Figure 2. THOR NT integrated head skin.

Also in the Alpha design, with a separable neck skin, it was sometimes possible for the airbag to intrude into the space between the neck skin and the head assembly, especially in out-of-position (OOP) situations. The zippered connection between the neck skin and the head skin was introduced to avoid that possibility. Also, the chin plate was extended downward to provide load support to the whole of the face, which was further helped by rounded Delrin extensions to the chin plate. The changes to the chin face plate also involved changing the geometry of the Confor foam used as the face response element in THOR. The edges of all the face plates were radiused to reduce the possibility of tearing into the head skin. Figures 3 and 4 show the differences between the two face plate designs.

Figure 3. THOR Alpha face plates.

Figure 4. THOR NT face plates.

The final modifications to the head involved improving the mounting of the nine-accelerometer package. In the Alpha, seven of the accelerometers were mounted on a special L-shaped block which mounted directly to the base of the head. The top two accelerometers were being mounted on a plug pressed into the top of the skull. In the NT, the mounting of the top two accelerometers are now on a machined flat on the inside of the skull, which provides a more definite locating method for these two accelerometers relative to the C.G. accelerometers.

Neck

The changes in the neck included:

- Using injection molding process to make the neck instead of bonding
- Design of a new atlanto-occipital joint (A-O) which provides continuous resistance in flexion and extension
- Improved neck spring load cells
- Modification of the neck springs to include rubber inserts

The change to an injection molding process was motivated by the unreliability of the bonding method being used in the the THOR Alpha, where some necks failed early in the testing cycle. The new, molded necks are made of Butyl rubber instead of the earlier Neoprene, which provides some additional damping in the neck response. The injection molded neck is now extremely durable, repeatable, and reproducible. Up to 300 pendulum impacts were conducted on a single injection molded neck without failure. These tests were done with a pendulum pulse of 25G, but some overload tests up to 38G were also performed successfully.

The design of the A-O joint was changed to improve the response of the neck in the flexion/extension mode. The response at the A-O joint of THOR Alpha was controlled by two rubber stops which allowed for relatively free rotation of about 10° in flexion and 25° in extension. A drawing of the new cam and stop mechanism at the A-O is shown in Figure 5 and the response of the joint is compared with the original Alpha joint in Figure 6.

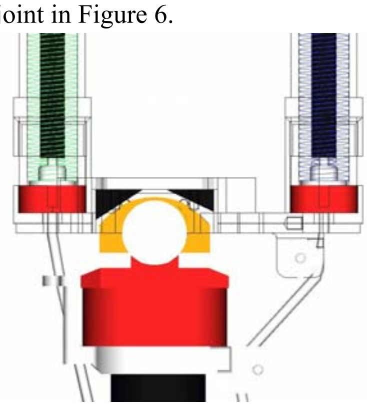

Figure 5. Cam-stop mechanism in THOR NT OC joint.

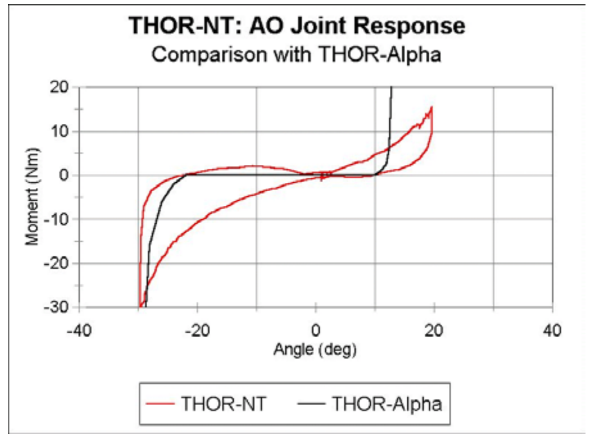

Figure 6. Comparison of response at OC in THOR Alpha and NT.

The new joint makes the response more biofidelic, with gradually increasing resistance in both flexion and extension. The resistance is controlled by the engagement of a brass cam against shaped rubber stops fore and aft of the cam. The range-of-motion at the A-O joint has been increased to 20° in flexion and 30° in extension.

A problem that was sometimes encountered with the Alpha neck was variability in the output of the uniaxial load cells when loading was not completely normal to the load cell surface. A special, miniature, uniaxial load cell from R.A. Denton (Model: 6005) is now used in this location. It has been tested and found to be less sensitive to off-axis loading.

Another response issue with the neck that was addressed in the NT modifications was the possibility of hard bottoming of the die springs that are used within the head to provide for the simulation of neck musculature. The spring-only design in the Alpha was modified to include a Tygon tube insert within the front spring and a Viton insert within the rear spring. This provided a more gradual increase in the forces generated by the spring when it was being compressed near to its limit. The strength of the die spring was modified such that the combined spring/tube stiffness would be comparable to the original spring. Figure 7 shows a comparison of the behavior of the old and new designs when bottoming does occur.

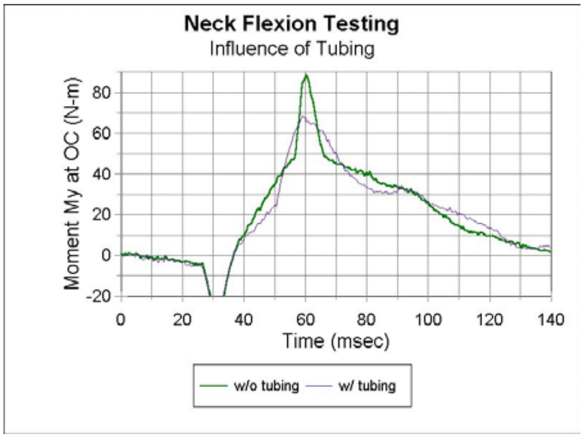

Figure 7. Reduction of bottoming effect of single spring by adding rubber tube insert.

Shoulder

There were a number of modifications made in the shoulder assembly of the THOR Alpha. These include:

- Changing the shape and material of the shoulder pads with improved anthropometry
- More robust shoulder stops
- Modified clavicle

The new shoulder pads are made from Monothane, a one-part polyurethane resin with improved durability characteristics over the two-part Urethane used in the Alpha shoulder pads. During this process, the anthropometry of the shoulder was also improved, with the shape of the new pad being obtained from the 3D representation of the 50th percentile male AATD form. Figure 8 shows a picture of the new pad on the dummy's right shoulder and the old Alpha pad on the left.

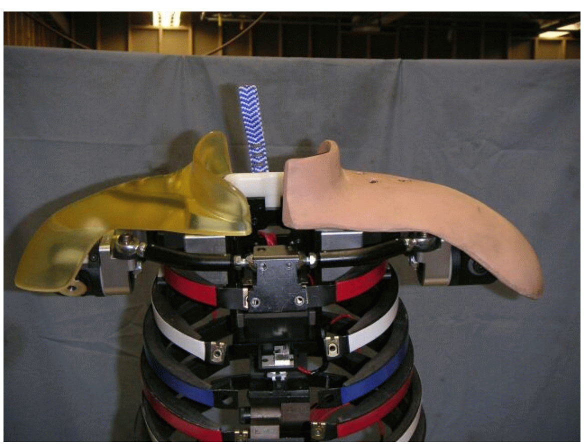

Figure 8. Comparison of new NT shoulder pad on left and original Alpha pad on right.

The stops that controlled the shoulder fore and aft motion were also modified and made more robust. The stops in the Alpha were attached using bolts that ran through the rubber material, which sometime resulted in the bending of the bolts in overload situations. The shoulder stops in the new NT design are glued to metal plates which are directly fastened to the spine. This design also improves the durability of the stops themselves with the elimination of the rather large bolt holes which had weakened the original structure. The new design increases the clearance between rib #1 and the shoulder block, where contact may occur under severe loading conditions. In addition, to simplify the assembly of the shoulder, the rib shelf, which was a separate structure, is now welded to the shoulder block. Figures 9 and 10 show the difference in the designs of the Alpha and the NT.

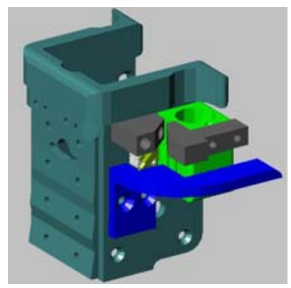

Figure 9. Shoulder block design in THOR Alpha

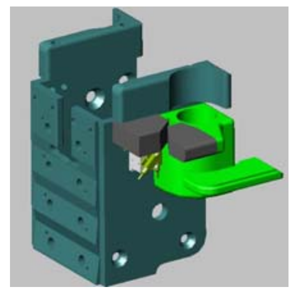

Figure 10. Shoulder block design in THOR NT.

Small modifications were also made to the clavicle. This included reducing the bend angle of the clavicle from 27° to 10°. This was meant to improve the relative distribution of belt load between the shoulder and the ribcage. The second modification was in adding a small, spherical cap to the distal end of the clavicle to improve belt retention. The cap was made to be approximately compatible with the general clavicle geometry seen in the human.

Spine

The improvements in the spine included:

- Changing to an injection molded process for making the thoracic and lumbar flex joints
- Removing protrusions at the rear of the ribs which were being used for routing of the cables
- Easier assembly of the T1 triaxial accelerometer
- Clearer markings for the spine pitch change mechanism

The bonding process used for making the two flex joints in the Alpha was changed to an injection molding process to improve the durability of the components. The new parts, like the NT neck, are also made of Butyl rubber, instead of Urethane, but the bending stiffness of the earlier design was maintained. The flex joints were tested in both static and dynamic conditions to ensure that the units were durable and repeatable over a minimum of thirty tests.

A number of smaller modifications were made to make the assembly of the spine easier and the appearance cleaner. The rear of the spine in the NT was improved by removing the wire routing clamps that were used in the Alpha. There is easier access to the T1 triaxial accelerometer block, which makes assembly and disassembly easier. Clear markings were added to the pitch change mechanism that sits at the bottom of the thoracic spine and allows the dummy to be put in four different sitting configurations.

Thorax

The changes to the thorax included:

- Changing to a Monothane bib
- Adding locating pins on the spine for attaching the ribs
- Reducing rib steel impingement on the damping material
- Modified sternum to improve frontal sternal impact response
- Modified rib #1 to improve frontal sternal impact
- Improvement in the shape of the jacket for better interface with the seat back

The new bib in the NT is shown in Figure 11.

Figure 11. Design of THOR NT Monothane bib.

The Urethane bib used in the Alpha was susceptible to damage under high belt loads. The Monothane was found to be more durable under these conditions.

The bib was especially shaped to be thicker in its lower part, where it covered the bottom three ribs. Testing at UVa had indicated that the lower ribcage in THOR Alpha was more decoupled from the rest of the ribcage, than expected for a human subject. In order to improve the coupling, the lower part was made thicker.

The addition of the locating pins to properly retain the ribs to the spine was based on comments from the FID consortium who had noticed that the ribs could be improperly assembled if care was not taken. The addition of the pins eliminates any variability during assembly.

GESAC had also observed during post-test inspections of the ribs that for certain test conditions the steel edge of a rib could load the damping material of the rib immediately below it leading to gouging. To reduce this effect, the damping material height of the lower three ribs was increased by about 1.5 mm so that contact would be between the damping material layers rather than steel with the damping material.

Both the mid-sternal mass and rib #1 were modified in order to improve the response of the thorax to sternal impact. Figures 12 and 13 show the difference between the sternal masses in the Alpha and the NT.

Figure 12. THOR Alpha mid-sternum.

Figure 13. THOR NT mid-sternum.

The Kroell tests at 4.3 m/s and 6.7 m/s are used to establish the biofidelity of the thorax under impact loading. During the original THOR development, the objective was to produce optimum response at 6.7 m/s while still ensuring that the dummy would be biofidelic at 4.3 m/s. This resulted in the dummy producing deflections at the lower end of the corridor for lower speed impact. NHTSA directed GESAC to make modifications which would result in greater deflection at the lower speed. This was motivated by analyses of test results which indicated that typical loading rates seen in most accidents with newer cars were closer to the lower Kroell impact speed.

The jacket was also modified to provide a more rounded contour at the back and a better fit over the ribcage in the front.

Pelvis

A major revision of the THOR Alpha pelvis was done to improve both the anthropometry and the durability of the segment. The changes included:

- The external shape conformed closer to the AATD shape but modified to represent an undeformed configuration in order to allow the interaction of the seat and the pelvis flesh to generate the deformation
- The skin was made of PVC rather than Urethane
- The skeletal portion of the pelvis was made of modular components instead of single cast piece

The THOR Alpha pelvis had been made of Urethane and based on a standard sitting configuration. The NT pelvis skin is made of PVC which is more durable than the Urethane and a thinner skin can be used. The external shape is based on the 50th percentile male AATD form, but instead of the deformed shape of the pelvis skin, a somewhat undeformed shape was used. Figure 14 shows a 3D CAD drawing with the undeformed section shown on the left side (in red) and the original deformed section on the right side (in yellow).

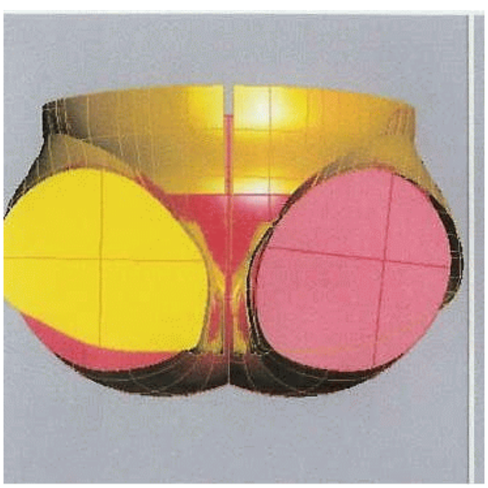

Figure 14. Comparison of undeformed and deformed pelvis sections.

Moving to an undeformed shape for the pelvis was motivated by the desire to generate the actual deformation through the interaction of the seat and the pelvis flesh. Thus the geometry of the external pelvis surface and the external femur surface (described below) was modified from the way it appears in the AATD form. Approximate undeformed measurements were taken from data obtained by McConville [1980], and from stereophotometric data obtained from 3D scans that were obtained at Wright-Patterson.

Average stiffness of the pelvis flesh was made to correlate with stiffness that has been estimated by Dabnichki, et al [1994]. The approximate compression of an adult sitting on a rigid seat was estimated to be about 20 mm. The objective in setting the flesh stiffness was to get the correct eye position when the dummy is positioned on the AATD hard seat.

The skeletal portion of the pelvis was constructed of a number of modular elements. The iliac wings were obtained by initially rapid prototyping the corresponding 3D CAD forms obtained from digitizing the original pelvis shape developed by Reynolds for a 50th percentile male [Reynolds, 1982] which served as the basis for the prototype THOR pelvis. The remaining components were machined parts which provides for symmetry, though this process adds a few more steps in the assembly of the dummy. It was also necessary to increase the mass of the pelvis over the THOR Alpha part, which required some of the components to be made of steel rather than aluminum.

Figures 15 and 16 show the skin and skeletal components of the new pelvis.

Figure 15. Vinyl pelvis skin of THOR NT.

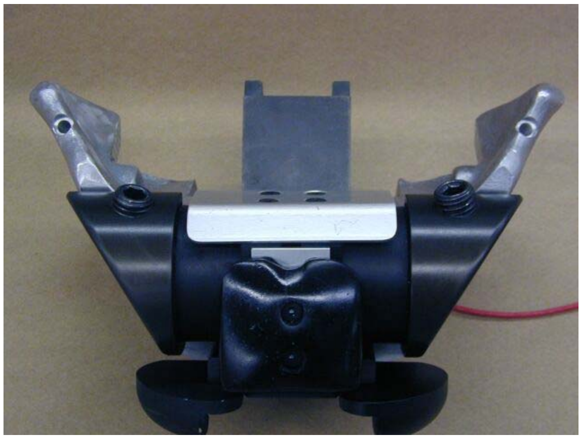

Figure 16. Front view of THOR NT pelvis (skeletal).

Femur

The changes made to the THOR Alpha femur are:

- Increased length of femur to match AATD data (hip joint - knee joint length)
- Changed femur skin to PVC with a zipper for easier access to the femur
- Added a representation of the trochanter
- Changed the femur neck from a cast part to a machined part

The THOR Alpha femur, as measured between the hip joint and knee joint, was approximately 20mm shorter than the AATD. This length has been corrected in the NT. A Delrin part has been fastened to the femur neck region to represent the trochanter. Figure 17 shows the skeletal portion of the modified femur.

Figure 17. THOR NT femur (with trochanter).

The femur skin was also modeled from the seated 50th percentile male AATD form, but with the contour in an approximate undeformed shape, in a manner similar to what was done for the pelvis skin described in the previous section. The contour of the femur was made compatible with the distal section of the pelvis contour. A zipper was added to the skin to allow for easier access to the internal femur structure (which was being included in the Alpha skins as well).

Lower Leg and Foot

Some small modifications were made to the THOR-Lx. These include:

- Pin added to ensure proper placement of the tibia tube relative to the upper tibia load cell
- Clearance added for the tibia puck fasteners to ensure no binding occurs when the puck is compressed
- Improved retention of the foot skin to the foot plate

Other Improvements

There were some general improvements made to the dummy and its handling as given below:

- Common electric ground was achieved by maintaining electrical continuity between segments which may lose continuity during a test such as across the neck. This should prove useful in tests where large static electric charge may be generated, such as airbag tests.
- New uniaxial tilt sensors replaced the biaxial ones used in THOR Alpha. These provide a linear response to angular change (the original ones had a non-linear dependence to angle)'
- In the area of handling, a more accessible lifting point is now used for lifting and moving the dummy. A new H-point tool has also been designed which only needs access to the pelvis, rather than the old design which had to be attached to both the femur and knee joint.

THOR NT CERTIFICATION

Some of the modifications, such as in the head, neck, and thorax required selected certification tests to be undertaken to ensure that the THOR NT would meet the original biofidelity requirements of the THOR dummy. The following describes the results for the selected certifications tests.

Head

A new certification test was added to evaluate the impact response of the head. Some of the laboratories indicated that they would prefer an isolated head drop test, similar to that done with the Hybrid III head. The new, integrated head skin was designed to allow for both the head impact certification test similar to that described in the THOR Certification Manual [GESAC, 2001b], and the head drop test. The requirement for the head drop test was the same as that for the 50th percentile Hybrid III, i.e. for a forehead impact from a height of 376 mm, the resultant head acceleration should be within the range of 225 g - 275 g. Figures 18 and 19 show the response for both the original whole body head impact test and the head drop test.

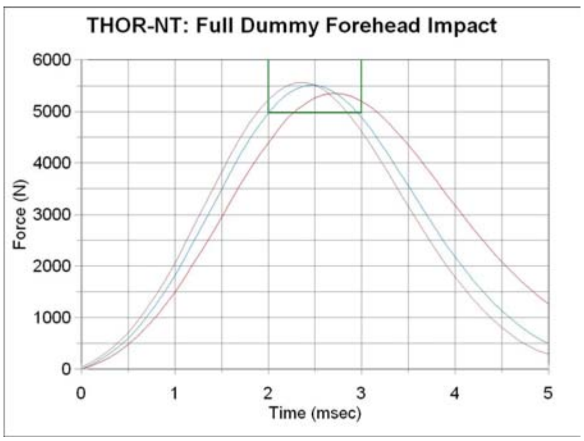

Figure 18. Response of THOR NT (whole body) to frontal head impact.

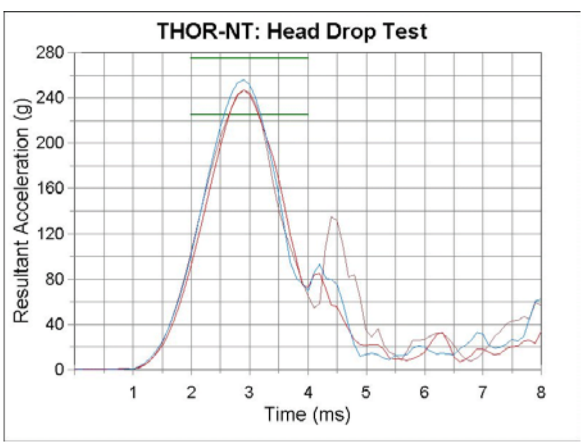

Figure 19. Response of THOR NT head to isolated head drop.

In the head drop test, a secondary impact was seen that was sometimes larger than seen with the Hybrid III head. This was attributed to the facial structure just below the forehead, which is significantly different from the aluminum face in the Hybrid III. The response from the whole body head impact was also considered to be acceptable and similar to that of THOR Alpha.

Face

During initial testing of the face with the new, integrated skin, it was found that the rod impact generated lower than expected peak force and some tuning of the skin thickness had to be done around the area of the eyes to increase the force. After this modification, both the disk and rod impacts were successfully performed on the new head. The results are shown in Figures 20 and 21.

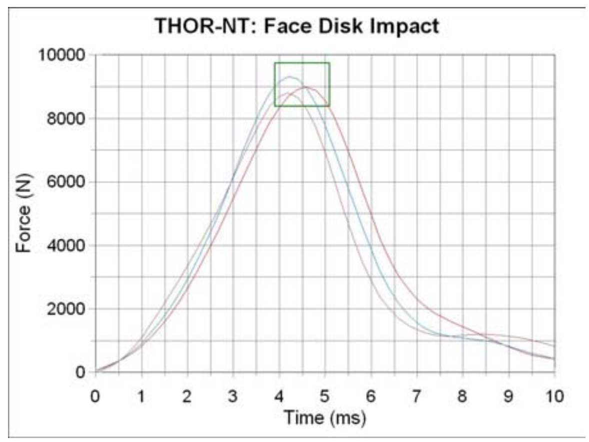

Figure 20. THOR NT face response to disk impact.

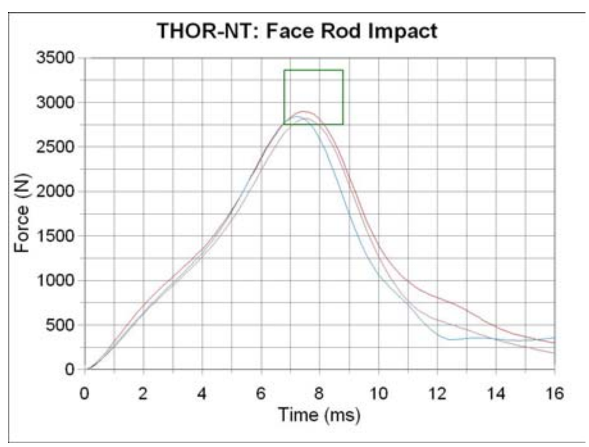

Figure 21. THOR NT face response to rod impact.

Response of the new face to both impact conditions were seen to be fairly similar to that of the THOR Alpha.

Neck

As pointed out in the discussion of the new, injection molding process used to build the THOR NT neck, a different material, Butyl rubber, was being used. A fairly lengthy series of tests were conducted to ensure that the response of the neck had not changed significantly, and that the durability, repeatability, and reproducibility were improved. As mentioned earlier, a large number of repeat tests were conducted on a single neck. Figures 22-25 show the responses of one neck at two points in its test cycle in both the frontal flexion and lateral flexion tests.

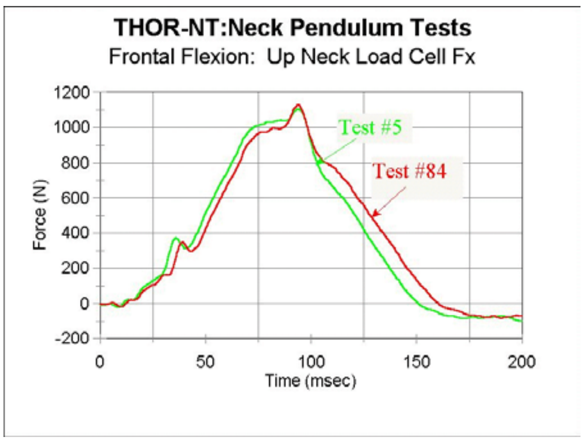

Figure 22. Repeatability of THOR NT neck Fx in frontal flexion.

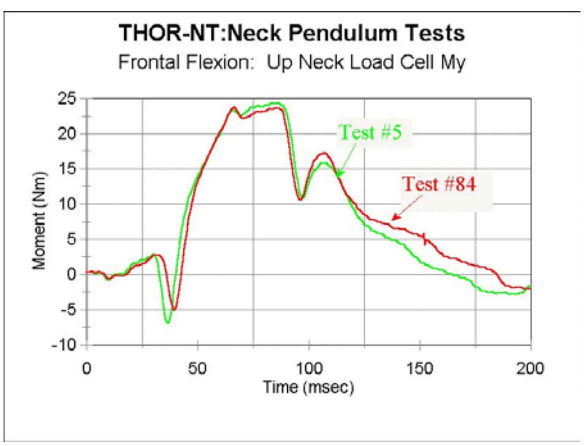

Figure 23. Repeatability of THOR NT neck My in frontal flexion

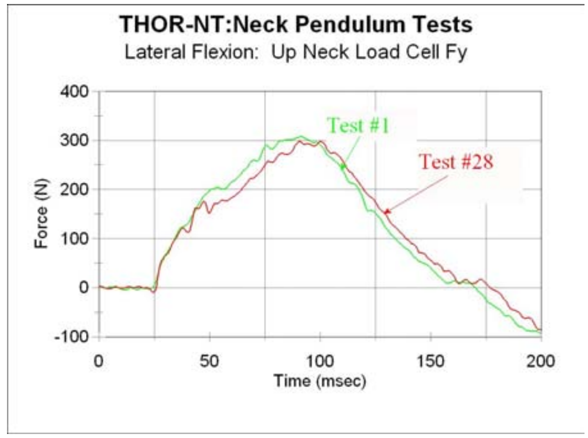

Figure 24. Repeatability of THOR NT neck Fy in lateral flexion.

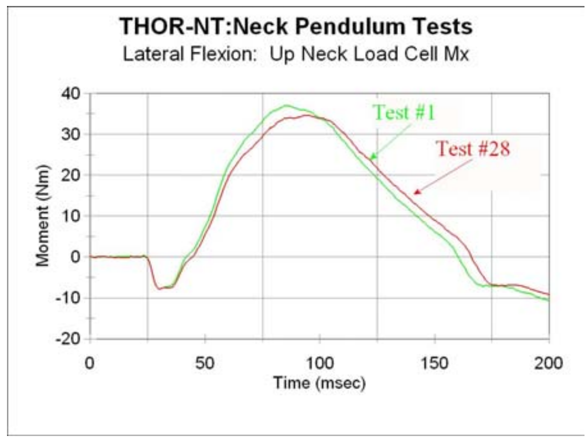

Figure 25. Repeatability of THOR NT neck Mx in lateral flexion.

It is seen that in both frontal and lateral response, good repeatability is maintained even after multiple tests.

Another important property of the new, molded necks that was evaluated was their reproducibility. Figures 26-28 show the variation in response of three different necks in frontal flexion, extension, and lateral flexion.

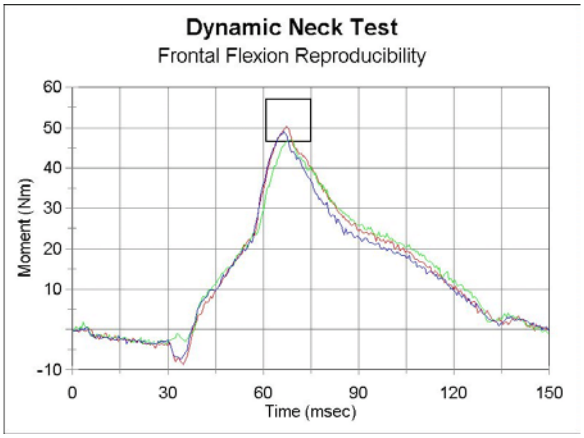

Figure 26. Reproducibility of three THOR NT necks in frontal flexion (total OC moment).

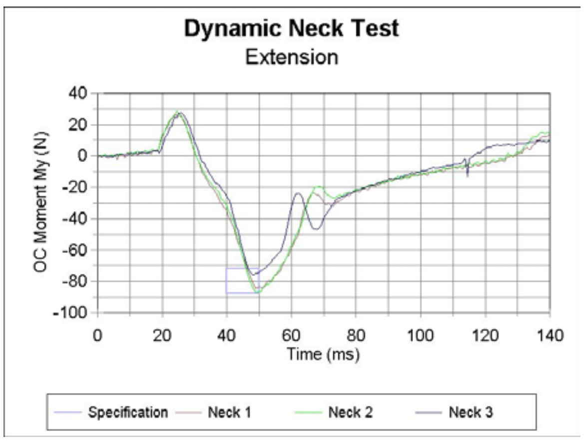

Figure 27. Reproducibility of three THOR NT necks in extension (total OC moment).

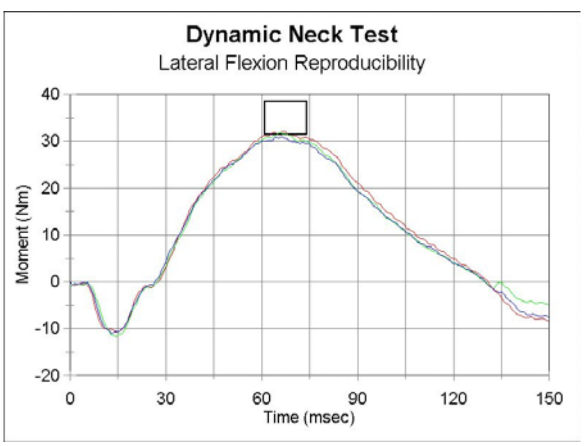

Figure 28. Reproducibility of three THOR NT necks in lateral flexion (total OC moment).

Responses of the three necks in all three directions are seen to be reproducible, though in extension some variability is seen. The responses are also close to the corridors that were developed earlier for the THOR Alpha neck (denoted by the rectangles in the above graphs). Though the NBDL type of sled tests have not been conducted with the new necks, the fact that their responses are similar to the original bonded necks, which did meet or were close to the NBDL kinematic corridors, makes it likely that the new necks will also meet the original biofidelity requirements.

Thorax

The final area where the modifications had been made that could influence its biomechanical response was in the thorax. As mentioned in the discussion of the design modifications made in the NT, they were partly motivated by the need to improve the low speed Kroell response compared to that of THOR Alpha. Figure 29 shows the response at the lower 4.3 m/s impact speed.

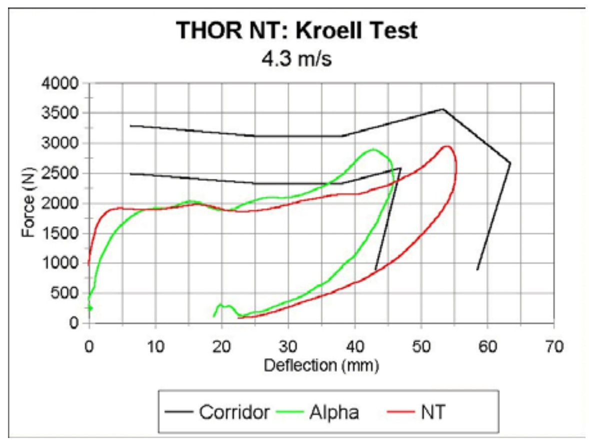

Figure 29. Comparison of THOR Alpha and NT Kroell impact response at 4.3 m/s.

It is seen that there has been a significant increase in the deflection, though no significant change in the peak force. Figure 30 shows the response at the higher 6.7 m/s impact speed.

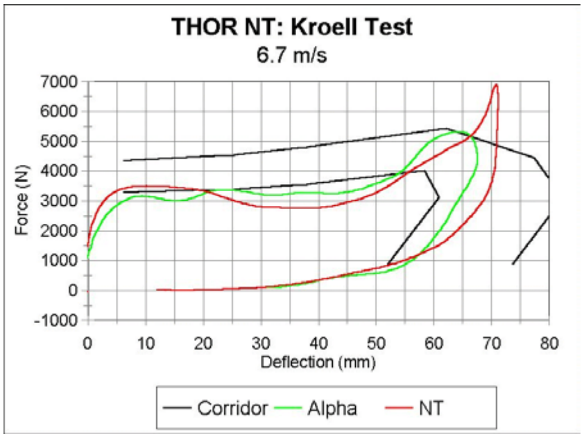

Figure 30. Comparison of THOR Alpha and NT Kroell impact response at 6.7 m/s.

In this case, it seen that peak force at the end shows a bottoming effect and results in the force exceeding the Kroell corridor. Since, the aim of the modification was to improve the response at the lower speed, and the higher impact speed was now considered something of an overload situation, the higher peak force was considered acceptable.

During the certification tests for the THOR NT, small adjustments were made to the corridors developed for the THOR Alpha for the head and face impacts, the neck response, and the Kroell tests. All the modifications were within or close to the biofidelity corridors as given in the THOR Biofidelity Manual [GESAC, 2001a].

CONCLUSION

A significant number of changes have been made to THOR Alpha in the areas of durability, biofidelity, anthropometry, and ease of use, to arrive at the NT design. The revised NHTSA Frontal Impact Dummy - THOR NT - is shown in oblique view in Figure 31.

Figure 31. View of fully assembled THOR NT dummy.

Areas of improvement include:

- Improved Durability: The components that were particularly susceptible to failure in the THOR Alpha have been modified. Among these, major improvements were made to the neck and the two flexible joints by going to an injection molded process for manufacturing the parts. The pelvic and femurs skins are now made of PVC which provide significantly greater tear strength than the older Urethane design. The material for the shoulder pads and bib were changed to Monothane which has superior tear and abrasion resistance compared to the older Urethane materials. In the head, a single, integrated head skin is used instead of separate skull and face skins in the Alpha. This provides greater protection to the face Confor foam inside. Finally, a number of smaller changes, e.g. in the shoulder stops, have been made to improve the durability of these parts.
- Improved Anthropometry: The head/neck interface geometry has been improved to provide a smoother surface for engagement with airbags. The shoulder pads have been designed to follow the external shape of the 50^{th} percentile male AATD shoulder. The external shape of the pelvis and femur skins have also been designed based on the AATD form, but modified to represent the flesh in an undeformed state, so that it can better

represent the interaction with a vehicle seat. The femur length has been corrected and a proper representation of the trochanter has also been added.

- Biofidelity: The mechanism at the A-O joint of the neck has been changed to allow for a more biofidelic response with continuously increasing resistance in flexion and extension and the range-of-motion in both directions has been increased. Parts of the ribcage and sternum have been redesigned to improve the sternal impact response in the low speed Kroell test.
- Ease of Use: Locating pins in the spine allow for easy assembly of the ribs. A similar pin in the tibia allows for proper alignment of the tibia tube. Grounding straps provide electrical continuity across the dummy.

Certification tests for the head, face, neck, and thorax were performed to ensure that the modifications did not lead to any significant change in response of the NT as compared to the Alpha. Updated certification corridors have been developed for selected tests. A head drop certification test has also been added to verify proper response characteristics of the forehead in impact. An extended series of tests were performed to evaluate the durability and response of the new molded neck, and the testing confirmed that the new necks were repeatable and reproducible.

The THOR NT has addressed many of the limitations that were noted with the THOR Alpha dummy. The next phase of the evaluation will involve testing in different sled test configurations; a number of laboratories already have or are in the process of testing the NT. Results from these tests will be used to evaluate the performance of the dummy in real-world situations.

ACKNOWLEDGMENTS

This project was supported by the USDOT NHTSA under Contract number DTNH22-99-C-07007. We would especially like to thank Rolf Eppinger, Peter Martin, Shashi Kuppa, and Erik Takhounts at NHTSA for their advice and support during the development of the THOR NT. We would also like to thank the staff of the Automobile Safety Lab at the University of Virginia and the staff of the Applied Physics Laboratories for their assistance in the development effort.

REFERENCES

ADRIA. 2000. Final Report. No. PL96-1074. Transport RTD Programme, European Commission.

Dabnichki PA, Crocombe AD, Hughes SC. 1994. Deformation and Stress Analysis of Supported Buttock Contact. Proc. Inst. Mech. Engrs. 208, pp. 9-117.

GESAC, Inc. 2001a Biomechanical Response Requirements of the THOR NHTSA Advanced Frontal Dummy. Trauma Assessment Device Development Program. Contract No. DTNH22-94-C-07010.

GESAC, Inc. 2001b. THOR Certification Manual. Trauma Assessment Device Development Program. Contract No. DTNH22-94-C-07010.

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

Hoofman, M., et al. 1998. Evaluation of the Dynamic and Kinematic Performance of the THOR Neck. Proc. of the IRCOBI Conference, pp 497-511.

Ito, M., Ono, K., Kanno, Y., Haffner, M., Rangarajan, N., Shams, T. 1998. Evaluation of the THOR Dummy Prototype Performance in HYGE Sled Tests. Proc. of the 16th International ESV Conference. 98-S9-O-09.

McConville, J., Churchill, T., Kaleps, I., Clauser, C., and Cuzzi, J. 1980. Anthropometric Relationships of Body and Body Segment Moments of Inertia. Wright-Patterson AFB, Aerospace Medical Research Laboratory, AMRL-TR-80-119.

Melvin, J., Weber, K. Eds, 1985. Review of Biomechanical Impact Response and Injury in the Automotive Environment. Task B Final Report. UMTRI, Contract No. DTNH22-83-C-07005.

Petit, P., Troisseille, X. 1999. Comparison of THOR, Hybrid III, and Cadaver Lower Leg Dynamic Properties in Dorsiflexion. Proc. Of the 43rd Stapp Car Crash Conference, SAE 99SC10

Rangarajan, N., White, R., Shams, T., Beach, D., Fullerton, J., Haffner, M., Eppinger, R., Pritz, H., Rhule, D., Dalmotas, D., Fournier, E. 1998. Design Criteria, Design, and Performance of the THOR Advanced Frontal Crash Test Dummy Thorax and Abdomen assemblies. Presented at 16th ESV Conference, 1998.

Reynolds, H., Snow, C., Young, J. 1982. Spatial Geometry of the Human Pelvis. Report No. FAA-AM-82-9. Office of Aviation Medicine, Federal Aviation Adminstration.

Robbins, D. 1983. Development of Athropometrically Based Design Specifications for an Advanced Adult Anthropometric Dummy Family. Volumes 2 & 3. DOT-HS-806-716 & 717

Schneider, L., Robbins, D., Pflug, M., and Snyder, R. 1985. Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family. Volume 1. DOT-HS-806-715

Schneider, L.W., Ricci, L.L., Salloum, M.J., Beebe, M.S., King, A.I., Rouhana, S.W., Neathery, R.F. 1992. Design and Development of an Advanced ATD Thorax System for Frontal Crash Environments, Volume 1: Primary Concept Development. DOT-HS-808-138.

Shams, T., Beach, D., White, R., Rangarajan, N., Haffner, M., Eppinger, R., Pritz, H., Kuppa, S., and Beebe, M. 1999. Development and Design of THOR-Lx: The THOR Lower Extremity. Proc. 43rd Stapp Car Crash Conference. pp 141-160. Society of Automotive Engineers, Warrendale, PA.

Vezin, P.; Bruyere-Garnier, K.; Bermond, F.; Verriest, J. P. 2002. Comparison of Hybrid III, THOR-Alpha and PMHS Response in Frontal Sled Tests. INRETS. Stapp Car Crash Journal, Vol. 46, Nov. 2002, p. 1-26.

White, R.P., Rangarajan, N., and Haffner, M., 1996. Development of the THOR Advanced Frontal Crash Test Dummy, Proc. SAFE Conference.