

MODIFICATIONS TO IMPROVE THE DURABILITY, USABILITY AND BIOFIDELITY OF THE THOR-NT DUMMY

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ABSTRACT

A series of modifications were completed to improve the durability, usability and biofidelity of the THOR-NT (THOR) frontal crash dummy. There has been growing interest in the safety community to develop a frontal crash dummy that is more sensitive to new restraint systems and more kinematically biofidelic in crash conditions with lateral components, such as narrow-offset or small-overlap impacts. As the THOR had been developed with these goals in mind, it was determined that enhancements were needed to improve the response of the THOR dummy while taking advantage of newer biomechanical data to enhance the design. So called “mod kits” were designed to make changes to the head/neck, thorax, abdomen, and knee/femur/pelvis of the dummy. This paper describes the mod kits and the resulting improvements of the THOR dummy response. Specifically, head changes were focused on improving vibration response, while neck changes included improvements to assembly and disassembly as well as improved tension response. Thoracic changes included creating new clavicle load cells and improving the thoracic deflection instrumentation. Enhancements to the abdomen involved removing redundant upper abdomen instrumentation and improving the lower abdomen displacement instrumentation. The pelvis and pelvis skin were completely changed to improve geometry and fit as well as adding enhanced load cells to the anterior-superior iliac spines. Finally, the KTH (Knee-Thigh-Hip) complexes were completely rebuilt to accommodate more deflection and meet recently established biofidelic response corridors under vehicle impact conditions. This paper will describe the efforts that went into the creation of each of the mod kits completed for the THOR dummy. The rationale, process and results of the mod kits will be explained.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) has been researching advanced anthropometric test devices (ATDs) to succeed the Hybrid III ATD since the early 1980s (Haffner,

2001). The primary design objective of this research was to represent the response of automotive occupants in sophisticated restraint systems developed since the advent of the Hybrid III, such as force-limited three-point belts and air bags. This advanced ATD first took shape in the 50th Percentile Male Trauma Assessment Device (TAD-50M), which demonstrated realistic rib cage anthropometry. The TAD-50M evolved into the Test Device for Human Occupant Restraint (THOR), first as the THOR Alpha (Haffner, 2001) and later as the THOR-NT (Shams, 2005). This evolution coincides with continued advancements in the understanding of human impact response and injury biomechanics research. This paper presents recent modifications to the THOR-NT design intended to improve biofidelity, durability, and usability.

BACKGROUND

The THOR-NT ATD has been used in hundreds of vehicle, sled, and component tests in a wide array of conditions since its inception in 2005 (Shams, 2005; Forman, 2006; Martin, 2007; Yaguchi, 2009; Shaw, 2010). Throughout this process, feedback from the test facilities and researchers responsible for carrying out these tests has been collected and evaluated in coordination with the Society for Automotive Engineers (SAE) THOR Evaluation Task Group. Additionally, progress in biomechanics research since the release of the THOR-NT technical data package (TDP) has provided the opportunity for further enhancement of the design. The SAE THOR Evaluation Task Group developed short-term and long-term recommendations for improvements to the biofidelity, repeatability, reproducibility, durability, and usability of the THOR-NT ATD. These recommendations were developed based on the feedback provided by researchers in the automotive industry, academia, and the government, as well as ATD manufacturers and global users, through participation with the SAE THOR Evaluation Task Group. Over the past two years, NHTSA, with support from contractors, has implemented modifications intended to address the highest-priority short-term recommendations. Four projects were carried out, each addressing one key body region:

the head and neck, the thorax, the abdomen, and the knee-thigh-hip (KTH) complex. For each modification intended to enhance the design of the THOR-NT, details are provided to describe the necessity for the change, the implementation of the change, and the resulting improvement in biofidelity, durability, or usability.

METHODS

In collaboration with the SAE THOR Evaluation Task Group, NHTSA developed a list of achievable short-term enhancements to the biofidelity, repeatability, reproducibility, durability, and usability of the THOR-NT ATD. One such modification that was implemented based on requests from users and ATD manufacturers was to revise the drawings for all mod kit components to utilize metric units and fasteners. Additionally, the original design called for tilt sensors to be installed in the head, neck, thoracic spine, lumbar spine, and pelvis to assist in test setup and repeatability. In order to improve the reliability of the devices while harmonizing the THOR-NT ATD with other international ATDs such as the WorldSID (ISO, 2005), NHTSA required that the tilt sensor mounting locations be designed to accept both of the commonly-used sensors, the MSC 260D/GP-[L,M] (MSC Automotive GmbH) and the IES-1402e (Humanetics Innovative Solutions).

Head and Neck

After several minor modifications to the head design in the THOR-NT, the mass, center of gravity (CG) location, and moment of inertia (MOI) had drifted away from the original design targets. The CG, along with other commonly-measured anatomical features, had no physical manifestation on the skin of the head. Additionally, it was discovered during analysis of head drop tests that the seven-accelerometer array in the head would often experience resonance at frequencies below the high-pass filter frequency specified by SAE J211.1 (SAE, 2007) for processing of accelerometers. This ringing would produce noise that prevented accurate data reduction and obfuscated test results.

During comparative testing of the THOR-NT and the Hybrid III neck in axial extension, Dibb (2006) found that both ATD necks showed a significantly stiffer response than a Finite Element (FE) model of the human neck, which was validated based on post-mortem human surrogate (PMHS) testing corrected for musculature. It was demonstrated that the THOR-NT neck was almost ten times stiffer in axial tension than the simulated human response, while removing the center safety cable reduced the axial

tension stiffness to under three times the simulated human response (Figure 1). Thus, it was recommended that the center safety cable be removed from the THOR-NT design to increase biofidelity.

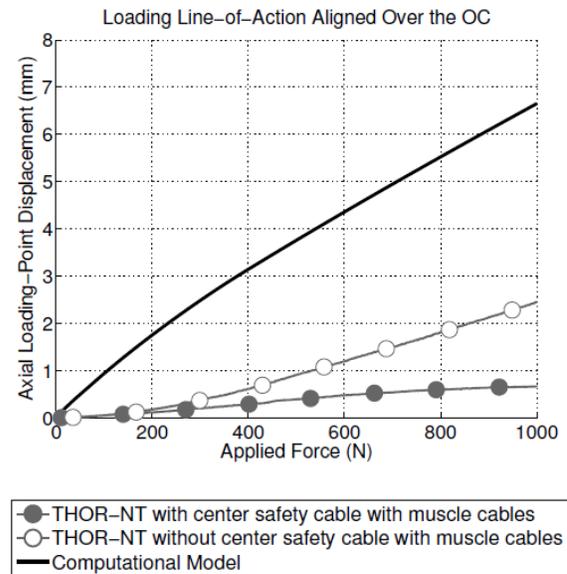


Figure 1. Axial tension of the THOR-NT both with and without the center safety cable, compared to a computer model representing PMHS response (From Dibb, 2006).

The head connects to the top of the neck at the occipital condyle (OC) joint assembly. The OC assembly consists of a bolt that spans attachments to the head and the upper neck load cell. This bolt, originally designed for the THOR Alpha ATD, interfaces with a nut, several washers, and a rotary potentiometer to provide biofidelic rotation while measuring such rotation of the OC joint. During both component and full-body testing of the THOR-NT, numerous issues have been reported with the OC assembly (Moorhouse, 2007). First, the fasteners were difficult to assemble correctly and adjust, and since they were specialty parts, they were difficult to repair or replace. For instance, a machined key washer was used to retain the position of the remaining washers during rotation of the head, but was difficult to replace if lost or damaged. Second, the potentiometer often reported non-physical measurements, potentially due to a lack of engagement of the OC bolt shaft and the potentiometer. The potentiometer itself introduced variability in the system, potentially due to wear of its plastic components during use, assembly, and disassembly. It was recommended that, since the cam and rubber stop system implemented in the THOR-NT design achieved the desired flexion-

extension response of the OC joint, the OC bolt could be simplified.

Thorax

In order to investigate the distribution of shoulder belt load during a restrained vehicle or sled test, the incorporation of load cells in the clavicle was recommended. Measurement of the load experienced by the clavicle in the anterior-posterior and vertical directions would allow a demonstration of the shoulder shielding effect that has been postulated based on PMHS test results (Shaw, 2005), as well as providing research functionality for the development of multi-point restraint systems.

In the THOR-NT design, the tri-axial accelerometer mount intended to measure the kinematics of the upper thoracic spine at the first thoracic vertebral body (T1) was attached to the lateral right aspect of the upper spine box roughly 75 millimeters inferior to the anatomical location of T1. To address this issue, it was recommended that the T1 accelerometer mount be redesigned to improve anatomical correlation.

The Compact Rotary Unit system (CRUX), installed at four locations within the thoracic cavity to measure three-dimensional rib deflection, was a frequent source of repeatability and usability complaints. Each CRUX unit consisted of three rotary potentiometers connected by two rods, the base mounted posterior to the lower spine and the arm attached anterior to the medial endpoint of the respective rib. Together, the CRUX units measured the bi-lateral three-dimensional deflection time-history of the 3rd and 6th ribs of the THOR-NT, which represent the anatomical 4th and 8th ribs. Processing of the CRUX measurements to convert the rotary potentiometer angles to three-dimensional displacements in the thorax coordinate system introduced both measurement and calculation error. Coupled with strict data acquisition system (DAS) requirements, the CRUX system compromised repeatability and reproducibility. Furthermore, the attachment of the upper rib instrumentation to the lower spine often overestimated anterior-posterior deflection, as rotation of the 3rd rib about its attachment to the upper spine would be measured as deflection relative to the lower spine. For these reasons, it was recommended that the thoracic instrumentation be redesigned.

As with the Hybrid III ATD, the original THOR-NT was required to achieve a specified thoracic force-deflection response in a sternal hub impact with a 23.4 kilogram impactor at a speed of 6.7 meters per second. However, it has since been demonstrated that sternal hub impacts at such velocities have

become rare with increases in restraint usage. In contrast to hub loading, shoulder belt loading presents a loading geometry distributed across the rib cage and loading rates in the range of 1 to 4 meters per second (Schneider, 1989). Thus, the 6.7 meter-per-second sternal impact was lowered in priority in favor of a more exposure-appropriate 4.3 meter-per-second sternal impact. The biofidelity targets for thoracic force-deflection response were determined from PMHS data (Neathery, 1974), corrected to remove the influence of muscle tensing for the 4.3 meter-per-second impact corridor (Kent, 2006).

Abdomen

The lower abdomen of the THOR-NT included two double-gimballed string potentiometers (DGSP) to measure three-dimensional deflection. The DGSP units performed a similar function to the CRUX units in the thorax, and experienced similar usability issues. Additionally, the high-tension string potentiometers required to measure high-velocity compression brought about permanent deformation of the foam lower abdomen insert. For these reasons, it was decided to replace the DGSP with a more robust instrumentation system that does not apply a static load to the abdomen.

A high-tension string potentiometer presented repeatability concerns for the upper abdomen as well, causing permanent set of the foam in the upper abdominal insert. The deflection measurement collected by the upper abdomen string potentiometer was somewhat redundant since the lower CRUX units provided a bi-lateral three-dimensional measurement of the anterior rib cage at the same inferior-superior level. Aside from use in the certification procedures, the upper abdomen string potentiometer was not often used, thus the removal of this redundant instrumentation was recommended.

The upper and lower abdomen inserts of the THOR-NT are necessarily individual units to allow for biofidelic pelvic rotation in frontal crash modes. To prevent penetration of vehicle and restraint components into the gap between the lower abdominal insert and the upper abdominal insert (also bounded by the bottom of the rib cage) metal stiffener strips were installed vertically into the jacket that serves as the thoracic flesh. Though this issue is more apparent in upright lumbar spine angles as opposed to the typical slouched or super-slouched automotive seating postures, direct impacts to this gap may not be biofidelic. Furthermore, the stiffeners may deform during routine testing, and thus require frequent inspection. As such, alternatives to the two-bag abdomen arrangement were investigated,

including options for both a fixed spine and an adjustable spine.

Knee-Thigh-Hip (KTH)

The original THOR-NT design featured a button load cell installed to the anterior surface of the anterior superior iliac spine (ASIS), which was intended to measure lap belt loads. Due to the limited size of the button load cell, the functionality of this feature was limited. To further improve the functionality of the THOR-NT in both standard and advanced restraint systems, the ASIS load cell design was revisited.

Several modifications to the pelvis flesh were investigated. First, removal of the upper femurs from the pelvis during disassembly would be facilitated by adding access holes to the pelvis flesh. Second, it had been demonstrated that the flesh, specifically below the proximal femurs, had a propensity to sag and permanently deform when rested on a rigid surface. It was recommended that this issue be addressed without changing the stiffness of the flesh or the outer contour. Finally, should a geometrical redesign result from the improved ASIS load cell, the pelvis flesh should be adapted accordingly.

Since the time of the original THOR-NT femur design, additional biomechanical data have been developed to quantify the axial compression response of the upper leg. While no biomechanical or certification requirements were specified for the THOR-NT knee slider alone, PMHS tests conducted to match the protocol defined for the Hybrid III knee slider certification procedure have indicated a new biofidelity target (Balasubramanian, 2004). Since the Hybrid III knee slider has a similar form and function to the THOR-NT knee slider, it was recommended that the Hybrid III knee slider certification procedure be adopted for the THOR-NT biomechanical requirements with the caveat that the performance targets be modified to meet the newly-developed biomechanical data (Figure 2).

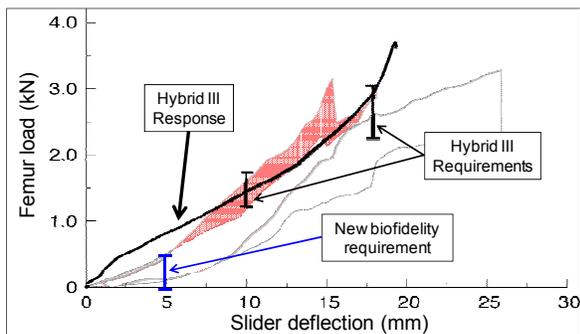


Figure 2. New response requirements for the THOR-NT knee slider during impact with a 12 kg pendulum at 2.75 m/s.

Similarly, new biomechanical corridors have been developed to describe the response of the femur when subjected to an axial impact at the intact knee while rigidly supported at the femoral head (Rupp, 2003). Whereas the existing THOR-NT certification procedures specify a response force corridor in a full-dummy seated knee impact, this additional biomechanical response requirement specifies a force-deflection corridor of the femur in isolation. Testing with the existing THOR-NT femur demonstrated an excessively stiff response compared to the PMHS corridor, as the femur puck did not allow sufficient stroke (Figure 3)

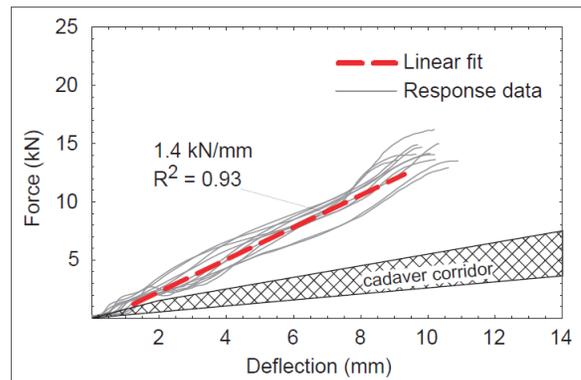


Figure 3. Force-deflection responses for loading of THOR knee/femur complex by a molded-knee interface at a 1.2-m/s platform velocity relative to the new cadaver response corridor (From Rupp, 2003).

Lower Extremity (LX)

In component, sled, and vehicle testing, the THOR-Lx lower extremity has demonstrated a need for improvement in durability and serviceability, specifically in the ankle region. Rostas and soft stops, deformable components in the ankle that represent the biomechanical characteristics of inversion/eversion (xversion) and plantarflexion/dorsiflexion (flexion), were often damaged during normal testing. In the xversion mode, the range of motion was narrower than existing biomechanical data (Rudd, 1999). Moreover, the potentiometers used to measure this motion were often subject to erroneous readings due to shaft slippage and were difficult to service and maintain. NHTSA, along with the SAE THOR Evaluation Task Group, recommended modifications intended to address these limitations.

The design of the original THOR-Lx included a molded rubber foot upon which a military-specified (MIL-spec) shoe was fitted during vehicle tests. Since the response of the leg is predicated on the impact properties of the MIL-spec shoe, which is not

controlled by NHTSA, a redesign of the foot and/or shoe was investigated.

RESULTS

The short-term recommendations made by NHTSA, in collaboration with the SAE THOR Task Force, for the improvement of the biofidelity, repeatability, reproducibility, durability, and usability of the THOR-NT ATD were implemented through four contracts carried out by three manufacturers: GESAC, Inc. (head and neck, abdomen), Denton ATD (KTH), and First Technology Safety Systems, Inc. (thorax), with additional technical and administrative support provided by the NHTSA Vehicle Research and Test Center (VRTC). One THOR-NT ATD (serial number 0007) has been adapted to include these modifications intended to enhance the performance (Figure 4).



Figure 4. THOR-NT with mod kit installed, without jacket

Head and Neck

The first modification to the head was to modify the head skin such that a uniform thickness was achieved throughout the scalp. This change allows for consistent head impact response independent of the precise location of the impact. In order to achieve a uniform head skin thickness while maintaining biofidelity of the head, the thickness of the skin at the forehead was chosen as the uniform thickness. Since the forehead was among the thinnest sections of the original THOR-NT head skin, the total mass of the head decreased as a result of this change (Table 1), as calculated using solid-modeling computer aided design (CAD) software. To rectify this change in

mass, the shape of the ballast, a steel block attached to the inside of the superior skull, was modified. The resulting mass and CG location was well within the tolerance. This CG location was marked on the head skin with a through hole, while dimples were created at the anatomical locations of the OC joint center, nasion, external auditory meatus, and infraorbital foramen.

Table 1. Inertial properties of the THOR-NT head

	Units	Target	Tol.	Original Design	w/Modified Head Skin	Final Design
Mass	kg	4.54	0.05	4.54	4.38	4.539
CG X	mm	8.80	2.5	9	9.3	8.87
CG Y	mm	0.00	2.5	-1	0.05	0.02
CG Z	mm	-58.0	2.5	-58	-56.9	-57.99

Through frequency response testing carried out by impacting the skull in various states of assembly with a hammer and analyzing the accelerometer responses using a Fast Fourier Transform (FFT), it was determined that the ringing was not caused by the seven-accelerometer array mount itself, but by the ballast attached to the inside of the superior skull. The original ballast was attached posteriorly by two screws and not anchored anteriorly, resulting in a cantilevered design. In adjusting the mass of the ballast to achieve the proper mass for the head in total, the design was adjusted such that the ballast was attached at four locations instead of two to prevent low-frequency oscillations of the front of the ballast. Subsequent to this analysis, the seven accelerometers were replaced with three orthogonal angular rate sensors (ARS) attached to the same mount.

To investigate the need for the center safety cable in the original THOR-NT neck design, repeated neck extension certification tests were carried out without the cable installed. After roughly twenty tests, inspection of the neck showed areas of separation between the butyl rubber pucks and the aluminum plates at the point of bonding. While neither the removal of the cable nor the de-bonding of the rubber pucks resulted in a noticeable change in the measured extension moment, this durability concern warranted an investigation of alternative methods of safely improving neck biofidelity. One such solution to this problem retained the center safety cable, but employed a neoprene spacer in place of the original rigid nylon spacer at the attachment point to the lower neck load cell to provide compliance in axial tension. The resulting neck design did not show an appreciable difference in flexion, extension, and lateral bending response compared to either the original neck or the neck with no safety cable installed. While it was not possible to recreate the

testing performed by Dibb (2006), a simple axial tension test demonstrated that the neck with the neoprene spacer was nearly three times more compliant than the neck with the standard safety cable installed. This design compromise allows for safety while optimizing for neck response biofidelity.

To address the unnecessary complexity of the OC, several design changes were implemented. First, a single pin held in place laterally with a screw replaced the OC bolt and all of the associated specialty washers of the previous design. Second, a set screw was installed at the end of the OC pin at the attachment to the rotary potentiometer to ensure proper engagement. A new rotary potentiometer (ECO 50 ES, Vishay Intertechnology, Inc.) was selected to replace the original model, and the housing was modified to accept the new design. Note that this model was also selected to replace all of the rotary potentiometers in the THOR-NT, including those installed at the base of each IR-TRACC in the thorax, abdomen, and lower leg (for a grand total of 17 in each dummy). Finally, the custom fasteners were replaced with commonly-available fasteners that did not require subsequent machining where possible.

Thorax

The original THOR-NT clavicle design was modified to allow the incorporation of two-axis load cells at the attachment points to the sternum medially and to the shoulder assembly laterally (Figure 5). These load cells measure forces in the anterior-posterior and inferior-superior directions, or the X and Z axes of the SAE dummy coordinate system (SAE, 2007). The capacity of each clavicle was chosen to be 4 kN (2 kN at each end) based on both the available space constraints and the capacity of the Hybrid III clavicle load cell. Structural replacements were also designed for testing that does not require the measurement of clavicle loads.



Figure 5. Integration of load cells within the clavicle.

Several alternative locations for the T1 accelerometer were evaluated. Due to interference with the lower neck and the spine box, it was not possible to locate the accelerometers directly at the anatomical location

of T1. A compromise was reached by installing the accelerometers into the shoulder neck shroud support, an existing part that attaches to the top of the spine box and prevents contact between the articulated shoulder attachment to the spine box and the neck (Figure 6). While this location is still offset from the anatomical T1 location in the lateral direction, the proximity in the vertical direction was improved.

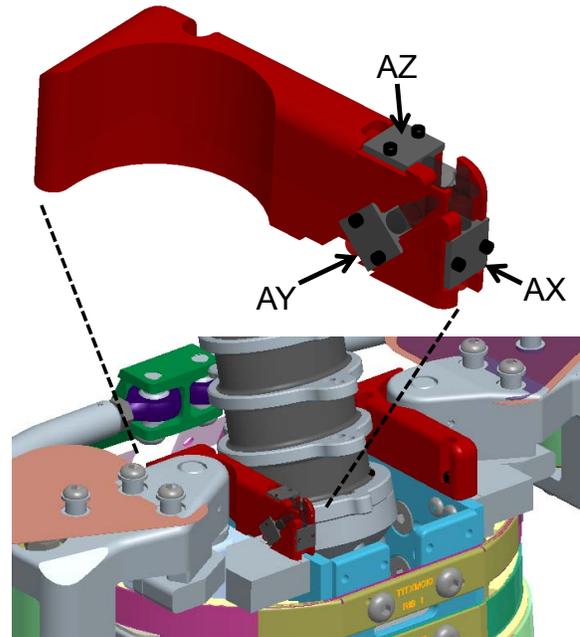


Figure 6. Installation of the T1 accelerometers in the shoulder neck shroud support.

To better evaluate the three-dimensional deformation of the rib cage, two changes were made to the existing THOR-NT design. First, the CRUX units were replaced with Infrared Telescoping Rod for Assessment of Chest Compression (IR-TRACC) linear potentiometers mounted in a double-gimballed configuration (Figure 7, Figure 8). The key benefit of the IR-TRACC units is their compact and linear nature, which allows for a greater range of rib cage deformations without interference of the instrumentation with the physical components in the thoracic cavity. Furthermore, the upper IR-TRACC units are mounted to the spine above the thoracic spine flex joint, the same rigid body to which the 3rd rib is mounted. This configuration presents a system that is less prone to measuring non-physical deflections, such as those resulting from rotation of the thoracic spine flex joint. These IR-TRACCs, on the other hand, present an elevated risk compared to the CRUX units due to the increased complexity and expense, and as such will be a key component in the evaluation of the repeatability, durability, and usability of the mod kit.

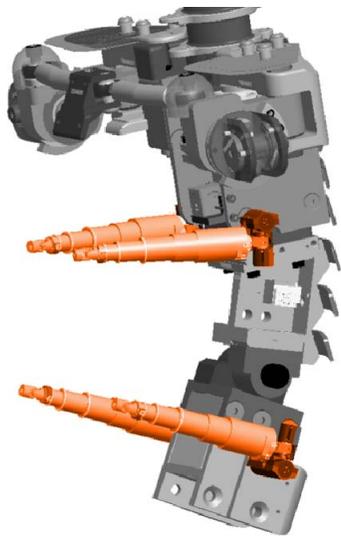


Figure 7. Installation of the IR-TRACC rib deflection measurement system.



Figure 8. Photograph of the lower left IR-TRACC assembly installed in the THOR-NT.

To improve the biofidelity of the THOR-NT in restrained impact conditions, the biomechanical response requirements, along with the certification procedures, have been modified to require agreement with response corridor in a sternal hub impact with a 23.4 kilogram pendulum traveling at 4.3 meters per second. While not required for certification, the high-speed (6.7 meters per second) thoracic impact test must be run to demonstrate that no physical interference occurs during this test. When manipulated to present deflection in the same coordinate system, the IR-TRACC demonstrates a similar response to that measured by the CRUX, though this response is not identical due to the inherent differences in the mounting locations of these instrumentation methods (Figure 9). Since the upper IR-TRACC measures rib deflection from a different measurement basis than the upper CRUX units, further investigation is necessary to refine the data processing techniques for biofidelity and certification testing.

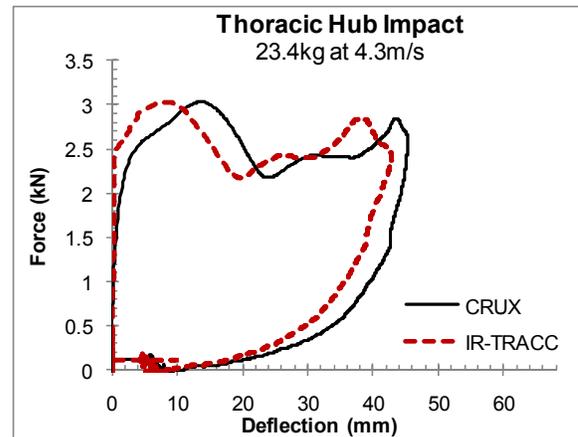


Figure 9. Response of the thorax to blunt impact with a pendulum, 23.4kg at 4.3m/s.

Abdomen

Two additional IR-TRACC three-dimensional displacement measurement devices were installed in the lower abdomen to replace the DGSP units in the original THOR-NT (Figure 10). Like the assemblies installed in the chest, two rotational potentiometers attach the base of the IR-TRACC to the measurement basis, in this case the lumbar spine. The IR-TRACC units installed in the lower abdomen have a measurement capacity of 90 millimeters, though investigation is underway to develop and install IR-TRACC units with a capacity of 120 millimeters. This additional capacity was required to capture the abdominal injury criterion of 40 percent compression proposed by the SAE THOR Evaluation Task Group, or roughly 100 millimeters for a 50th percentile male. Since the IR-TRACC units function on light emission and subsequent sensing as opposed to the original high-tension string potentiometer, there is no pre-load applied to the foam abdomen insert.

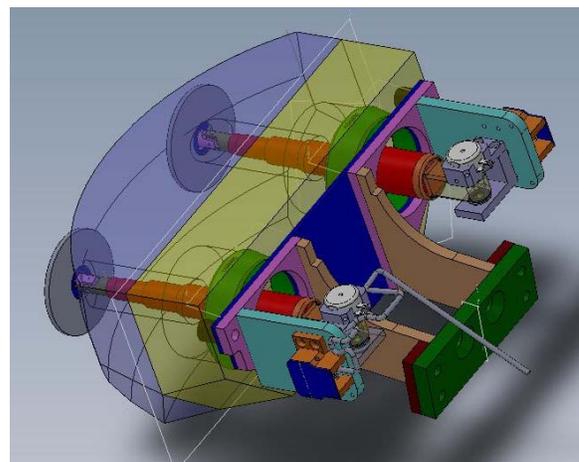


Figure 10. Bi-lateral three-dimensional displacement measurement devices (IR-TRACC, shown in red) installed in the lower abdomen insert.

In the upper abdomen, the string potentiometer was simply removed from the design. This design change required filling the holes in both the foam inside of the insert and the bracket that attached the insert to the spine. Despite a demonstration that the redesigned foam showed a similar force-deflection response in isolation (Figure 11), the resulting thoracic impact response with the new upper abdomen insert installed did not show sufficient deflection (Figure 12). A short-term solution to this problem was to re-install the original THOR-NT upper abdomen foam insert, while a longer-term solution is currently under investigation.

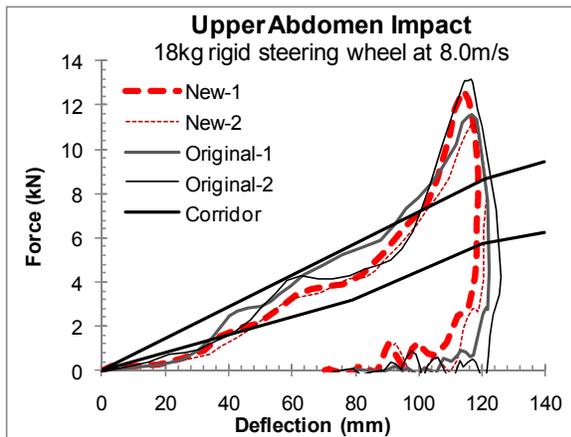


Figure 11. Comparison of the original (Dummy1, Dummy2) and modified (ua-05, ua-06) upper abdomen impact response.

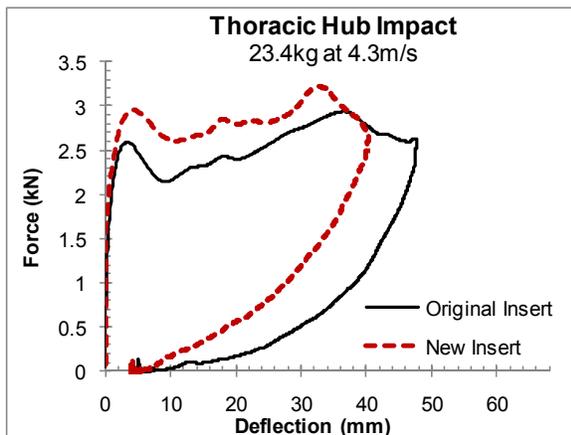


Figure 12. Comparison of the thoracic impact response with a 23.4 kg impactor at 4.3 m/s between the original and modified upper abdomen foam insert. Note that since the abdomen project was carried out before the thorax project, the responses shown here are from a different THOR with CRUX units than the responses shown in Figure 9.

An investigation of the feasibility of bridging the gap between the upper and lower abdomen inserts resulted in several design concepts. One proposed concept integrated both the upper and lower abdomen

inserts into a single pouch (Figure 13), with foam layers selected such that adjustment of the lumbar spine flexion angle by up to 30 degrees was possible without influencing impact response stiffness by more than 10 percent. Alternatively, the unified insert could be formed from expandable foam similar to that used in the pelvis or molded silicon with a rough urethane outer layer, though there would be limitations to all of these methods due to both initial position adjustability (lumbar spine pitch change joint) and dynamic rotation (flexion during restraint loading) of the spine. Thus, for the short term enhancements of the THOR-NT, the two-part abdomen was retained.



Figure 13. Unified abdomen concept.

To evaluate the influence of the existing rib stiffeners installed in the jacket to bridge the gap between the upper and lower abdomen inserts, several impacts were carried out both with and without the stiffeners installed. When viewed with respect to the pendulum response, there was no substantial influence of the stiffeners on the upper abdomen response to steering wheel rim impact at 4.5, 6.0, or 8.0 meters per second. However, when viewed by the upper abdomen string potentiometer, the response without the stiffeners showed lower deflection. This finding suggests that without the stiffeners installed, the upper abdominal string potentiometer was not engaged by the impactor, resulting in this artifactual increase in stiffness. Since a pendulum-based certification procedure will be implemented in absence of the upper abdominal string potentiometer, this finding was determined to be no longer relevant.

Knee-Thigh-Hip (KTH)

Two improvements were made to the load-sensing capability of the ASIS load cells installed in the pelvis of the THOR-NT. First, the geometry was

improved by increasing the overall surface area over which load can be measured while retaining shape consistent with the anthropometry of the human ASIS (Figure 14). Second, a two-axis load cell was designed to record not only the longitudinal force on the ASIS (FX), but also the moment about the lateral axis (MY). The addition of the moment measurement allows interpretation of the fit of the lap belt across the pelvis, including the magnitude and timing of submarining. Structural replacements were also designed for use in testing that does not require the measurement of ASIS loads. Finally, the iliac wings of the pelvis were thickened to allow for a smooth interface with the ASIS load cells or the load cell simulators.

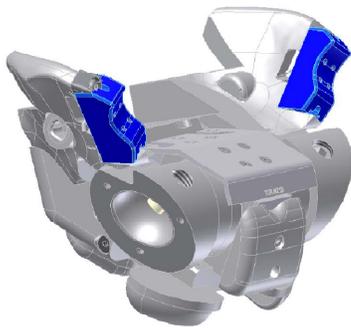


Figure 14. New ASIS load cells (in blue) incorporated into the pelvis bone.

To account for the additional mass of the load cells and the thicker iliac wings, material was removed from other bone areas. This material removal was carried out strategically to create engagement points that allowed for better fit of the pelvis flesh. Additionally, the area of the pelvis flesh near the iliac wing was adapted to create an overhang, which further prevented motion of the pelvis bone with respect to the flesh (Figure 15). To address the issue of permanent deformation of the thigh flesh under the proximal femurs, larger cutouts were created to allow an increased range of motion of the femur shaft (Figure 15). While primarily intended to prevent unnecessary loading of the flesh during storage and setup, these cutouts also allow for a decoupling of the femur with the pelvic flesh to increase biofidelity.

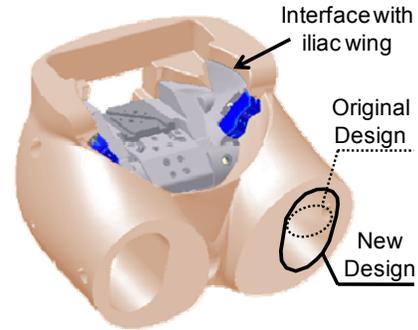


Figure 15. Modifications to the flesh around the pelvis to allow a) better engagement with the bone structure, and b) increased range of motion of the femur

To meet the newly-defined biomechanical response requirements for knee impact (Figure 2), modifications to the THOR-NT knee slider were necessary. Specifically, softening of the rubber shear section of the slider was necessary to achieve the lower force level at 5 millimeters of deflection, while a larger bump stop was necessary to achieve pass-through of the higher force level at 18 millimeters of deflection. The resulting response meets the first and third pass-through corridors, which represent the primary requirement, while the response exhibits a lower force than the second pass-through corridor, a secondary requirement (Figure 16).

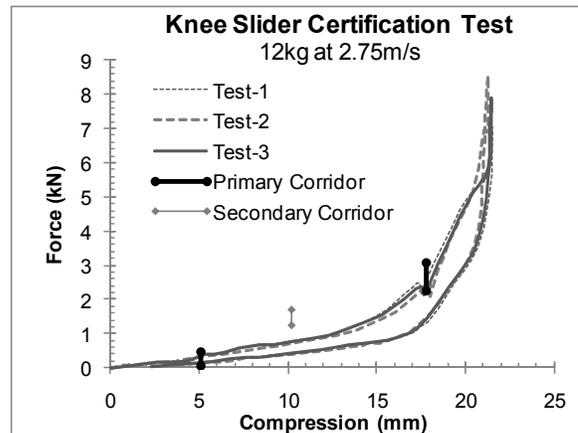


Figure 16. Response of the knee slider in impact with a 12 kg pendulum at 2.75 m/s.

For the assembled femur, it was not possible to achieve the newly-developed biomechanical response data with the original THOR-NT design. While there was a deformable element in the femur, its stiffness and maximum stroke were not sufficient to meet the proposed response corridor. Through an optimization study using the publically-available Finite Element (FE) model of the THOR-NT ATD, it was determined that a 57% increase in the length of the deformable element was necessary. The resulting femur impact response, aside from oscillations early

in the force-deflection characteristic, meets the corridor of the biomechanical requirements (Figure 17). The guide system that allows stroke of the deformable element was subsequently modified to incorporate a square shaft to reduce weight and manufacturing complexity (Figure 18). The key benefit of the femur redesign is the biofidelity of the femur in axial compression, which allows the dummy response to be evaluated directly against human injury tolerances in loading conditions such as knee bolster contact. Finally, the six-axis femur load cell currently used in the WorldSID 50th percentile ATD was installed fit the space constraints of the redesigned femur.

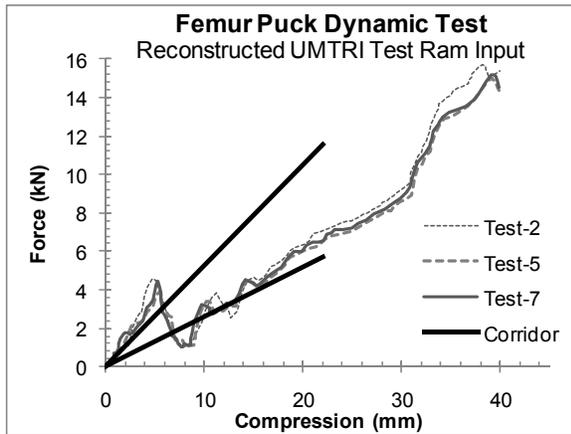


Figure 17. Force-deflection response of the assembled femur in a test condition developed to reproduce the UMTRI ram displacement-time history, compared to the biomechanical response corridor.

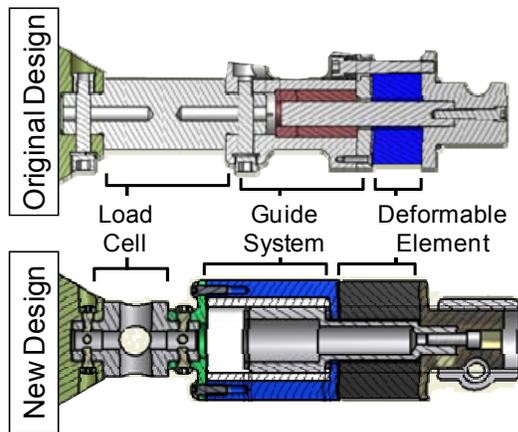


Figure 18. Comparison of the original (top) and modified (bottom) THOR-NT femur designs.

Lower Extremity (LX)

To improve the durability of the ankle joint, new materials were developed for the rostars, and a design

modification was implemented to improve the containment of the rostars in their housings. The soft stops defining the range of motion of the ankle were also improved through optimization of their size and shape (Figure 19), selection of better materials, and elimination of sharp corners that resulted in hard stops in the motion of the joint. Specifically, the xversion soft stops were modified to allow 40 to 45 degrees of motion. This increased range of motion has an additional durability benefit as a structural factor of safety in the event of extreme loading in a severe test condition. Rotational potentiometers of the same model as the OC joint potentiometer were selected for use in the ankle to provide improved accuracy, durability, and serviceability.

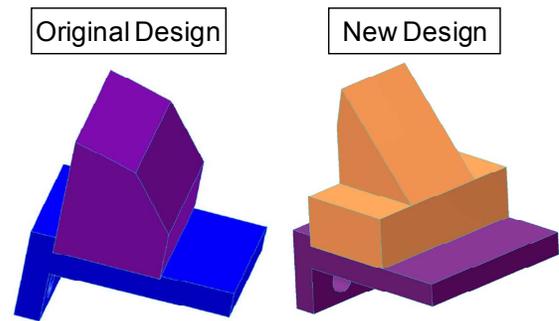


Figure 19. Comparison of the original (left) and modified (right) inversion soft stops in the THOR-Lx.

To improve the repeatability of the THOR-Lx response, a one-piece molded component was developed to represent the collective shoe and foot (Figure 20). This design, based on the molded shoe developed for the WorldSID family of dummies, effectively eliminates the uncertainty associated with the MIL-spec shoe.



Figure 20. One-piece molded shoe design with heel and toe inserts.

CONCURRENT AND FUTURE WORK

To date, one such THOR-NT mod kit ATD has been fabricated and is currently undergoing an assessment of biofidelity, repeatability, and reproducibility. Biofidelity and repeatability will be evaluated by comparing the ATD response to established biomechanical response corridors described in the THOR-NT Biomechanical Requirements manual (NHTSA, 2005a). As an additional biomechanical response evaluation, sled tests will be carried out in multiple conditions to compare the mod kit THOR-NT response to the original THOR-NT as well as the response of PMHS (Shaw, 2010). To evaluate lab-to-lab reproducibility, round-robin testing will be carried out in the same conditions at multiple test laboratories, including component, sled, and full-vehicle crash tests, ideally in the narrow-offset or small-overlap crash mode. Once more THOR-NT ATDs are upgraded with the mod kit, reproducibility between dummies will be evaluated by carrying out the same tests using multiple dummies. Throughout the biofidelity, repeatability, and reproducibility evaluation, the durability and usability of the mod kit THOR-NT, as well as its comparison to the Hybrid III 50th percentile male in like test conditions, will be documented.

Once an acceptable evaluation is achieved, the technical data package (TDP) describing the mod kit components will be finalized and published for public dissemination. This TDP will include updated versions of the Biomechanical Requirements (NHTSA, 2005a) and Certification Procedures (NHTSA, 2005b) manuals that include both newly-developed biomechanical response requirements, such as those for the knee slider and femur, as well as data processing for the improved instrumentation, such as the thoracic deflection measurement devices. The TDP will allow current owners of THOR-NT ATDs to upgrade their dummies to the current state. Coincidentally, the TDP describing the complete dummy will be updated such that full THOR-NT ATDs can be fabricated based on the latest design.

Additional work will be necessary to finalize criteria for the assessment of injury based on the measurements collected during testing. Preliminary injury criteria were discussed by the SAE THOR Evaluation Task Group; however, further research is necessary. For instance, the development of a chest injury criterion based on multi-point deflection will require the recreation of previously-conducted PMHS tests using the mod kit THOR-NT to provide the data necessary for a paired-sample study. Additionally, a seating procedure must be developed, as the existing procedures for the use of the Hybrid III 50th

percentile male ATD in federal regulation testing are not fully compatible with the different anthropometry of the THOR-NT pelvis and lower extremity. Development of the certification procedures, injury criteria, and seating procedure will be carried out by NHTSA in collaboration with the SAE THOR Evaluation Task Group.

CONCLUSIONS

Through the recommendations developed in collaboration with the SAE THOR Evaluation Task Force, NHTSA implemented a multitude of modifications intended to improve the biofidelity, repeatability, reproducibility, durability, and usability of the THOR-NT ATD. Following an evaluation of the mod kit dummy, an updated THOR-NT technical data package (TDP) will be published. A TDP describing only the mod kit components will also be published to allow owners of existing THOR-NT ATDs to upgrade their dummies to the design level of the final TDP.

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