FOUNDATIONS AND ELEMENTS OF THE NHTSA THOR ALPHA ATD DESIGN

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ABSTRACT

Early influences upon Thor ATD development are described, and the path of Thor development is traced up to the release of the current Thor ALPHA ATD design. Since the display of the first Thor ATD prototype at the 15th ESV Conference in Melbourne in 1996, Thor has undergone extensive test and evaluation on an international basis in cooperation with many partner institutions. This paper summarizes some of the lessons learned from this broad test experience, and documents actions which have been undertaken to upgrade the Thor product to ALPHA status in light of this experience.

Origins of Thor

The elapsed time required for formal introduction of a new anthropomorphic test device (ATD) into mainstream use can extend over many years, due to the time required for all potential users to gain experience in its use, and due to the deliberate pace of the regulatory process. Because of this timetable, it is not uncommon for a newly introduced ATD to become functionally dated shortly after its introduction. In the case of the Hybrid III ATD (HIII), which was released in its original form in 1976 (Foster, 1977), it became clear to the NHTSA as early as 1980 that the development of a more advanced frontal ATD could be justified, based upon the following considerations:

- New and sophisticated restraint design and occupant protection hardware and strategies were rapidly emerging, which the HIII had (understandably) not been designed to address;
- Injury patterns and priorities were shifting due to the introduction of these newer restraint technologies;
- The body of newly available anthropometric and biomechanical response data was inevitably and continually expanding. Newer injury assessment formulations were also emerging, based upon this new data.

Anthropometric Definition for Advanced ATD Development

As a first element of a program of advanced dummy development, the NHTSA commissioned a study of the anthropometry of human volunteers in realistic vehicle seated posture at the University of Michigan Transportation Research Institute (UMTRI) (Figure 1). The resulting three volume report (Schneider, et al, 1985; Robbins, 1985) included a package of 11 orthogonal view drawings which provided skeletal renderings, and which defined the coordinates of skeletal landmarks developed in the study. Also delivered under this contract effort were three full-size glass-epoxy reference surface shells representing the three occupant sizes, together with their matching reference hard seats (Figure 2). This reference surface data has since found application, in physical and digital form, in a wide variety of ATD development, math model development, and vehicle seating accommodation studies.

Figure 1 Human Subject Measurement- NHTSA/ UMTRI Anthropometry Study

Advanced ATD Concept Definition Study

Concurrent with the conclusion of the anthropometry study, the NHTSA funded a advanced frontal ATD concept definition study at based at UMTRI, which laid the technical foundation for the hardware development efforts to follow (Melvin, et al, 1985). This effort encompassed injury assessment priority analysis, an extensive review of the available biomechanical impact response and injury data relevant to the automotive environment, and preliminary development of desirable advanced ATD design characteristics and features.

Figure 2 Reference Master Surfaces and Seats from NHTSA/ UMTRI Anthropometry Study

Development of the TAD-50M ATD

Development of advanced ATD hardware was then begun at UMTRI with the participation of First Technology Safety Systems and Wayne State University, in cooperation with GM Research, under NHTSA sponsorship and direction. Emphasis was placed upon development of a new thorax/ abdomen assembly. A review of prior art had disclosed that significant innovative ATD development work had been ongoing in the UK in the early 1970's, resulting in the design of the Ogle-MIRA and OPAT dummies. (Searle and Haslegrave, 1970; Warner, 1974). This UK research legacy offered a valuable point of departure for NHTSA advanced ATD efforts (Figure 3).

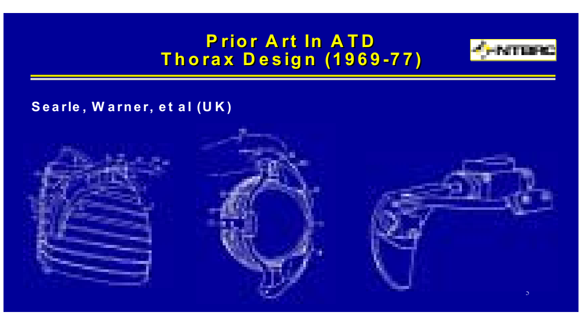

Figure 3 Ogle/MIRA and OPAT Thorax Design Concepts (1973-75)

By 1990, the UMTRI team had developed and delivered new thorax and abdomen hardware to the NHTSA, in addition to a modified HIII pelvis, fully integrated into the remaining stock components of a Hybrid III ATD (Schneider, et al., 1989; Schneider, et al., 1992). This integrated product (Figures 4 and 5) was denoted by NHTSA as the TAD-50M (**T**rauma **A**ssessment **D**evice- 50th Percentile Male) design.

Figure 4 TAD-50M Assembly

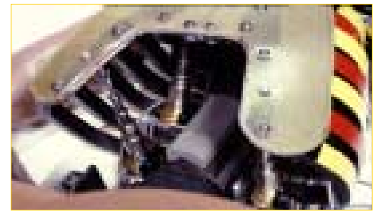

Figure 5 TAD-50M Thorax, Showing 3D DGSP Deflection Measurement Assemblies

The TAD-50M (as had the earlier Ogle-MIRA and OPAT designs) emphasized realistic external ribcage geometry and provided a representation of the clavicle, which was felt essential for proper ATD interaction with three-point belt systems. However, the TAD-50M design added a new and more mobile shoulder design concept, a single defined thoracic spine articulation element, and continuous 3D measurement of thoracic deflections at both the sternum and lower ribcage locations. Further, the TAD-50M met the Kroell blunt thorax impact requirements at the 4.3 m/s and 6.7 m/s impact speeds, and substantially met the vehicle seated anthropometry requirements which had been previously established.

Subsequent sled and vehicle tests of the TAD-50M confirmed that the design was capable of discriminating between air bag/ lap belt, three-point belt, and two-point belt performance signatures (Figure 6), providing support for the concept that a tool of this design would be of value for optimization of occupant restraint system elements.

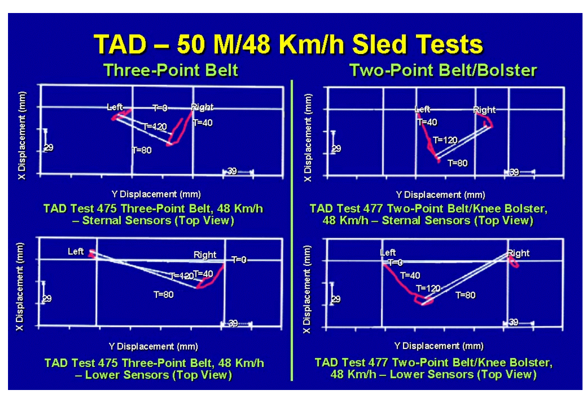

Figure 6 Comparison of TAD-50M Upper and Lower Thorax X-Y Deflection Crossplots for 3- Point and 2-Point Seat Belt Systems

Concurrent Development of Advanced Neck and Lower Extremity Concepts by NHTSA R&D

While the TAD-50M thorax/ abdomen efforts sponsored by the NHTSA at the UMTRI were underway, the NHTSA Vehicle Research and Test Center and the NHTSA Biomechanics Division were investigating new concepts for advanced ATD neck and lower extremity construction (NHTSA/ VRTC, 1985; Mendis, et al., 1989; Hagedorn and Pritz, 1995), with the expectation that progress made in the development of these components would be utilized and merged into the design of a unified advanced frontal ATD.

Integration of Component Development Efforts into Thor

The NHTSA outlined its plan for the integration of the various ATD component development efforts at the 14th ESV Conference (Haffner, 1994). Shortly thereafter, this integration effort was begun, in the form of a design and development contract awarded by the NHTSA to GESAC, Inc.

Scope of Thor Development and Integration Contract

In 1994, the NHTSA moved forward on a more aggressive schedule to refine previously designed advanced dummy components, and to complete the full development of an advanced frontal ATD, now to be named Thor (**T**est Device for **H**uman **O**ccupant **R**estraint). The Thor contract clearly involved a wide and challenging scope of effort:

- Refinement of the TAD-50M thorax and its deflection instrumentation
- Development of a new instrumented face design
- Refinement and integration of VRTC multi-directional neck concept
- Development of a new instrumented abdomen design
- Development of revised pelvic segmentation and instrumentation
- Redesign and integration of VRTC/NTBRC lower extremity concepts (the new designs were later renamed as Thor-Lx [male] and Thor-FLx [female])
- Conduct of an ATD data acquisition system options study
- Logistical and technical support of a wide-ranging internationally-based test and evaluation program

During the period 1994-96, intensive efforts resulted in completion of initial development of all dummy components, with the exception of the Thor-Lx lower extremity design. A brief summary of the form of these components follows:

Head/Face System: The face was newly designed to incorporate a reusable facial response element selected to emulate cadaver impact corridors. An array of five load cells was included in the face to measure time histories of facial loads in three geometric zones (Figures 7 & 8).

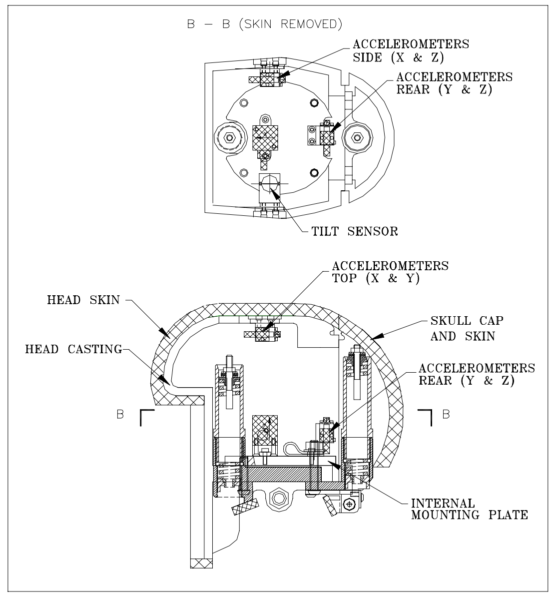

Figure 7 Thor Head Assembly

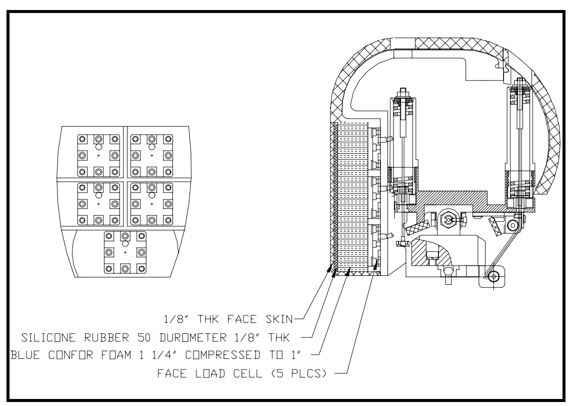

Figure 8 Thor Head/ Face Assembly

Neck : The original VRTC/NTBRC multi-directional neck concept was substantially redesigned and integrated into the Thor head and thorax. The resulting Thor head/ neck was designed to exhibit biofidelic response in both frontal and lateral directions, based upon prior extensive analyses of NBDL volunteer data:

(Spenny, 1987, Thunnissen, et al,1995, Wismans, et al, 1984, 1986a, 1986b, 1987a, 1987b, White et al, 1996). The Thor neck design, which shares cable control elements with the head assembly, is shown in Figure 9.

Abdomen: New lower and upper abdomen sections were designed and integrated into the dummy to provide biofidelic response to loading from belts and steering assemblies. Both upper and lower abdominal segments were instrumented with displacement instrumentation (Figures 13 & 14).

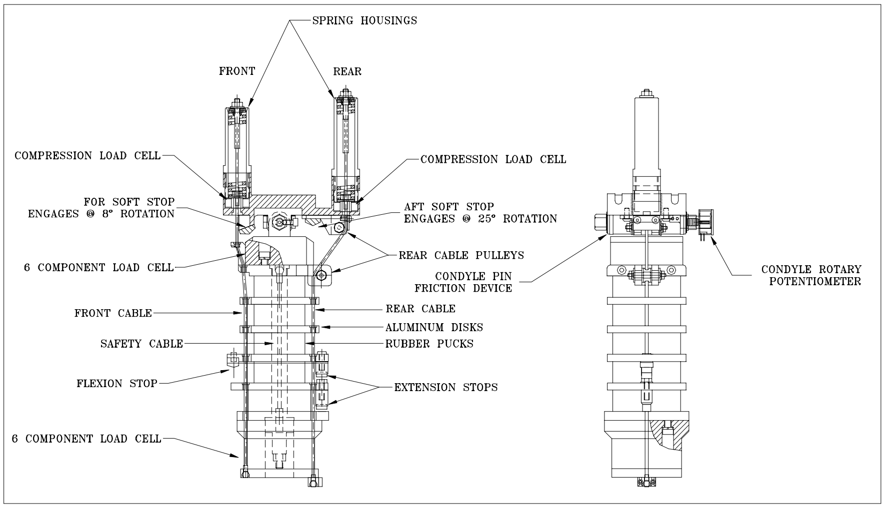

Figure 9 Thor Neck Design

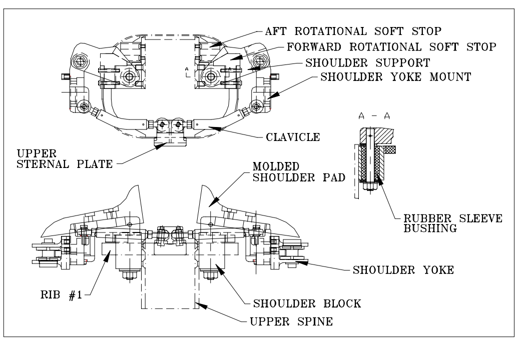

Figure 10 Thor Shoulder (as adapted from TAD-50M)

Shoulder : Many elements of the TAD-50M shoulder design were retained and refined; however, shrugging and enhanced lateral deflection capabilities were added. Molded and contoured external shoulder pads were also added to the earlier design to enhance belt interaction with the shoulder. (Figure 10).

Thorax : Ribs were modified to provide more anthropometrically correct external contour. New 3D chest compression instrumentation (denoted CRUX) was designed and integrated into the design. An adjustable thoracic spine was designed and fitted to provide for variable initial dummy posture adjustment, and a new technique which yielded significantly more durable rib bonding was developed (Figures 11 & 12).

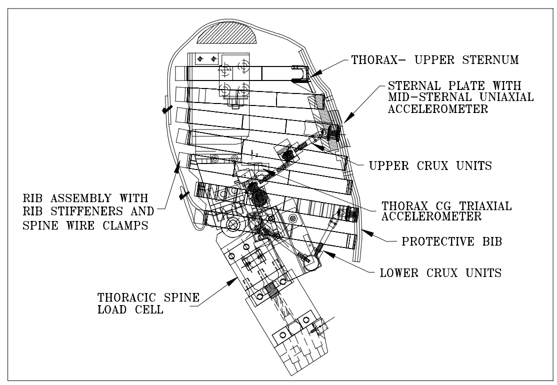

Figure 11 Side View of Thorax Assembly with Instrumentation

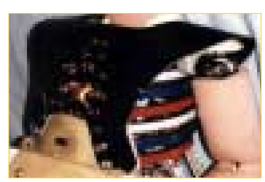

Figure 12 Thor Thorax Assembly (Shown with Integrated Abdomen Assemblies)

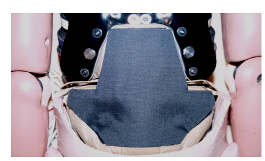

Figure 13 Integrated Upper and Lower Abdominal Assemblies-Frontal View

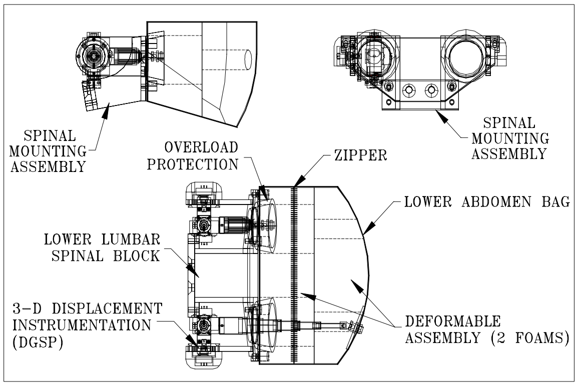

Figure 14 Lower Abdominal Assembly Showing Integral DGSP 3D Instrumentation

Pelvis: A symmetric, more anthropometrically correct pelvis was designed and developed, based upon the work of Reynolds, et al, 1982. Load cells were placed at the anterior superior iliac spine locations to act as a markers for initiation of submarining. Newly designed triaxial load cells were placed bilaterally at the acetabulum locations to monitor hip joint loads and to permit computation of load vectors acting at the hips (Figures 15 & 16).

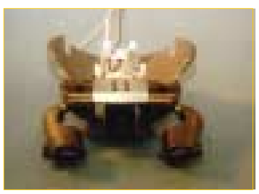

Figure 15 Machined Pelvic Assembly

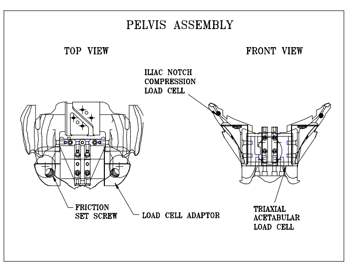

Figure 16 Pelvis Assembly Schematic

Femur: The femur was redesigned to incorporate a compliant axial element that enabled more biofidelic response to knee loading over a wider range of input energies (Figure 17).

Scope of International Thor Test and Evaluation

Throughout the initial development period, close liaison was maintained to peer review groups, both in the U.S. and overseas. Since the intent of the project was to design and develop a frontal dummy that would be acceptable internationally, significant effort was made to involve international experts in biomechanics and crash testing from the very earliest stages of the project. For example, the SAE Frontal Impact Dummy Enhancement subcommittee under the chairmanship of Mr. Roger Daniel of Ford Motor Company and EEVC Working Group 12 under the chairmanship of Dr. D. Cesari and (subsequently) Dr. JSHM Wismans were regularly briefed and consulted during the initial design phase, to solicit advice with regard to project design directions and to better understand various user concerns. In addition, when the first fully assembled Thor prototype was displayed in 1996 at the 15th ESV Conference in Melbourne (Figure 18), additional comment and technical input was solicited and obtained from many international experts. Following the display of the Thor ATD prototype in Melbourne, and following a period of internal test and shakedown (Table 1), the Thor ATD was offered for evaluation to user organizations.

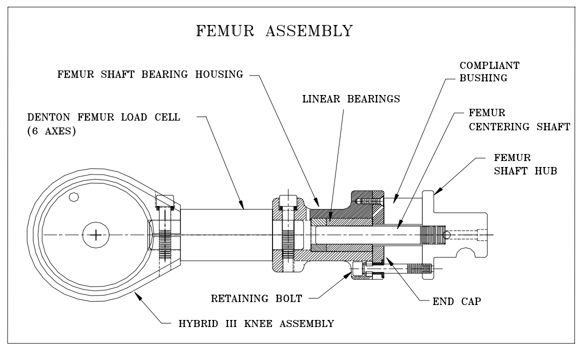

Figure 17 Thor Femur with Compliant Axial Element

Consistent with the goal of development of an ATD which could find acceptance on an international basis, the NHTSA sought the involvement of a wide variety of test partners to participate in the evaluation of the Thor design. Through the generosity and expertise of a large number of partners who responded to NHTSA's invitation, an extensive database of test results was acquired (Table 2). Over the time period 1996-1999, the list of participating organizations and laboratories included the following:

Europe

- Renault, Volvo Car, SAAB, Autoliv Research AB, Chalmers University
- *EEVC /ADRIA*: Transport Research Laboratory, TNO, Polytechnic University of Madrid

North America

- NHTSA/ VRTC

- Transport Canada
- USCAR (GM, Ford, Daimler-Chrysler)
- Honda Research of America
- University of Virginia
- U.S. Federal Aviation Administration
- U.S. Department of Defense

Asia/ Pacific

- JAMA/ Japan Automobile Research Institute
- Australia (FORS)
- Autoliv Australia

Some 150 sled test exposures at impact speeds of from 48 kph to 64 kph were conducted, with decelerations ranging from 16g to over 30g. Frontal, oblique, and rear tests were conducted in a variety of restraint systems: 3- point belts, force-limiting belts, and belt + air bag combinations. Several static OOP air bag tests were also conducted to assess ATD durability and response characteristics in this test environment.

In addition, some 15 full-scale vehicle crash tests were conducted, both in U.S. NCAP and offset deformable barrier test conditions. It may be noted that many laboratories elected to conduct baseline tests with the Hybrid III ATD, for comparative purposes.

Figure 18 Thor ATD in International Test Configuration

Table 1: Tests Conducted Prior to Release for International Evaluation

Test Site	Date	Test Type	Configuration	Accel G	No. of Tests
DCIEM, Canada	Jul, ‘96	Sled	3pt belt: taut, slack	20-22	7
VRTC, Ohio	Sep, ‘96	Sled	component - 3pt; 3pt+bag frontal; oblique	30	~100(comp) 8(sled)

Table 2: International Thor Prototype ATD Test Exposures: 1996-1999

Test Site	Date	Test Type	Configuration	Accel G	No. of Tests
JARI, Japan	Apr, ‘97	Sled	bag; 3pt; 3pt+bag driver; passenger	30	5(Thor) + 5(H3)
Volvo, Sweden	May, ‘97	Sled	bag; 3pt; 3pt+bag driver; passenger	25-30	8(Thor) + 8(H3)
Autoliv, Sweden	Jul, ‘97	Sled	std 3pt+bag; force limiting 3pt+bag	25	6(Thor) + 6(H3)
TRL, England	Oct, ‘97	Sled	3pt; - frontal; oblique anchorage loc	25	25
TNO, Netherlands	Nov, ‘97	Sled(rear) +Neck	rigid seat	-	7(rear)+ 9(neck)
UPM, Spain	Dec, ‘97	Component +Sled	rigid seat; normal seat;	25	19(Component)+ 9(Sled)
UVa, Charlottesville	Nov, ‘97	Sled	OOP	-	4
FORS/Autoliv, Australia	Feb, ‘98	Sled	3pt; 3pt+bag; std belt; force limiting + pre-tensioner	25	22 (Thor+H3)
UVa, Charlottesville	Jul, ‘98	Sled	3pt; 3pt+bag	25	5(Thor) + 5(H3)

Test Site - Continued	Date	Test Type	Configuration	Accel G	No. of Tests
CAMI, Oklahoma City	Oct, '98	Sled	2pt; horiz pulse; hor+vert pulse	16	5
DCIEM, Canada	Dec. '98	Sled	3pt	25-30	9
JARI, Japan	Dec, '98	Sled+ Vehicle (w/Thor-Lx)	frontal; ODB; rear impact	25-30 2-4	17
Honda/TRC, Ohio	Feb, '99	Sled+ Vehicle (w/Thor-Lx)	NCAP; ODB; 208	25	4
GM (OSRP), Detroit	Apr, '99	Calibration Vehicle (w/Thor-Lx)	Thorax 3pt+bag NCAP; ODB	25	5 5
Ford (OSRP), Detroit	Jun. '99	Calibration Rear + Sled (w/Thor-Lx)	Thorax 3pt+bag 3pt	35 6;10	8(Thor)+ 9(H3) 2(front) 6(rear)

Formal documentation of many of the above Thor evaluation efforts may be found in: Hoofman, et al, 1998; Ito, et al, 1998; Martinez, et al, 1999; Rangarajan, et al, 1998(a), 1998 (b), 2000; Shaw, et al, 2000; and Xu et al, 2000 .

As previously noted, the Thor ATD which circulated in the above trials was complete but for the Thor-Lx lower extremity design, which still remained under development. By late 1997, the combined efforts of GESAC and ASTC had succeeded in producing the first Thor-Lx prototype assembly. By 1998, the Thor-Lx assembly was also being actively circulated to international laboratories for biomechanical benchmarking and vehicle test, either as a separate component or as part of the full Thor ATD (Table 3).

Table 3**:** International Thor-Lx Test Exposures

Test Site	Date	Test Type	No. of Tests
UVa, Charlottesville	Jul+Sep, '98	quasi-static +dynamic	16
TRL, England	Nov, '98	EEVC impact	39 (heel+toe impact)
Renault, France	Dec, '98	pendulum + sled	5(pend)+5(sled)
JARI, Japan*	Dec, '98	sled+vehicle	frontal; ODB; rear impact
Honda/TRC, Ohio*	Feb, '99	sled+vehicle	NCAP; ODB; 208
GM (OSRP), Detroit	Apr, '99	vehicle	3pt+bag NCAP; ODB
Ford (OSRP), Detroit*	Jun. '99	rear + sled	3pt+bag
TRL, England	Jun, '99	EEVC impact	23 (heel+toe impact)
Renault, France	Jul, '99	pendulum	no data available

Note : * = Included also in full-scale test tables

Information Derived from the International Test Program

Given the extensive nature of the international Thor test experience, a great deal of valuable information was available for examination, to facilitate product improvement. GESAC and NHTSA therefore undertook a careful tabulation and analysis of comments received from each test partner. In addition, a thorough stripdown of each prototype dummy returning from test was conducted at GESAC facilities, and possible areas of improvement were noted. In general, every component of the ATD, and all aspects of dummy application and use were examined in detail.

For purpose of analysis, issues were further categorized into four main categories, as follows:

ATD design issues, durability issues, user convenience issues, and biofidelity issues.

Due to the sheer volume of testing, the lists of tabulated items in each category were extensive. While many comments received were of a favorable nature, the following listings will provide a sampling of issues or concerns which were deemed to require project attention and response:

> <u>ATD Design Issues:</u> Need for fastener size standardization; occasional belt entrapment in pelvis/ upper femur flesh interface and head/ neck junction; transducer access issues; noise in selected accelerometer data traces; upper femur skin mobility issues, irregular rib/ bib interface transition geometry; face load cells sensitive to bending moments.

> <u>Durability Issues:</u> Neck puck and spine articulation bonding durability issues; pelvis skin durability issue; wire damage/ wire routing issues; zipper durability; cable swage durability.

> <u>User Convenience Issues:</u> Lift capability needed; detailed user manual desirable; H-point tool does not accommodate all seats; spine posture adjustments require clear and accessible settings; instrument polarities require clear definition; cabling can be unwieldy- investigate DAS options; tilt sensors deemed useful; overall repeatability good.

> <u>Biofidelity Issues</u> Neck substantially meets frontal and lateral performance requirements- more effort required to meet torsional and rear response targets; shoulder biofidelity requires further study and data; thoracic spine articulation requires attention to thorax displacement computation methods.

A great many of the issues identified during the international test series could be addressed via relatively small revisions to the design. These changes were largely made as running modifications during the course of testing. However, it was also recognized that more substantive changes would also be required in some areas to more fully meet the thrust of expressed concerns. Thus the NHTSA and GESAC moved forward to development of the ALPHA version of the Thor ATD, which has recently been released.

REVISION OF THOR TO ALPHA CONFIGURATION

ALPHA designation refers to the design of the 50th percentile male Thor design, as released in the Spring of 2001. As outlined above, the Thor ALPHA version incorporates many modifications and improvements suggested by the extensive international Thor test experience to date, including the test experience gained under the EEVC ADRIA project. The Thor ALPHA version also incorporates newly available Thor-Lx lower extremity hardware. The following will describe the scope of the Thor ALPHA configuration, and the documentation which has accompanied its release.

<u>HEAD/FACE</u> (Figures 19 & 20)

- New multi-cell load cell faceplate array, utilizing custom load cell elements
- Faceplate geometry modified for improved mandible coverage
- Improved integration of mandible/ face skin into head flesh
- Redefined geometry of head nine-accelerometer array
- Head accelerometer brackets modified to eliminate structural noise

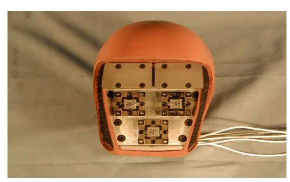

Figure 19 Thor ALPHA Face Load Cell Array (two cells not shown)

Figure 20 Thor ALPHA Mandible/ Face Skin Integration

<u>NECK</u>

- Bond durability concerns addressed

<u>SHOULDER</u>

- New, faired shoulder surface contour (Figure 21)
- Reduced structural noise at connection of shoulder yoke mount to shoulder support

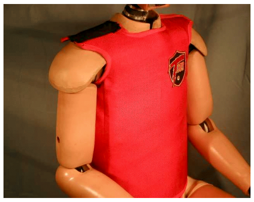

Figure 21 ALPHA Revised Shoulder Contour

THORAX (Figures 22 &23)

- Three layer bib simplified to single layer; other layers integrated into jacket
- New single bib layer reduced in size to provide more human-like anterior rib cage geometry; single bib simplifies rib cage assembly and access; "zip tie" fasteners and bib flaps that draped behind the shoulders in original Thor design eliminated (Figure 23)
- New jacket includes weighted bibs formerly attached to front of rib cage; jacket padding added to improve surface anthropometry
- Thorax accelerometer mounts modified to eliminate structural noise
- Sternal mass configuration modified

Figure 22 Original Bib Configuration

Figure 23 New ALPHA bib configuration

SPINE

- Spine posture adjustment (pitch change) markings now visible from side as well as rear of dummy (Figure 24)

  - Flexible Joints
  - Cable-generated noise in lumbar and thoracic flex joints eliminated
  - Premature damage to flexible joint cables addressed
  - Bond durability concerns addressed

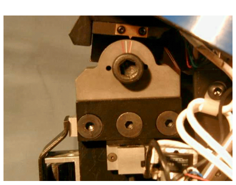

Figure 24 ALPHA Pitch Change Markings

PELVIS

- Pelvis skin redesigned (configuration and materials) to prevent belt intrusion and to improve durability and cosmetics
- Pelvis and upper femur skin integrated to improve seat pressure distribution; pelvic flexibility of current segmented design largely retained
- Accelerometer mount redesigned

FEMUR

- Thigh skin zippered to provide femur access
- Structural noise at femur load cell/ femur shaft bearing housing interface addressed

HANDLING, LIFTING, AND STORAGE

- Webbing segment attached to back of the upper thoracic spine provided for lift access; tucked in jacket when not in use (Figure 25)
- Storage procedure developed to minimize permanent set of flexible spine components and neck

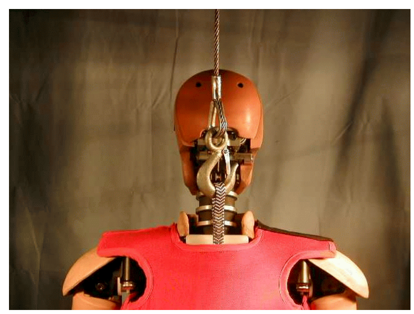

Figure 25 Thor ALPHA Lift Access

INSTRUMENTATION

- Wire routing and strain relief improved
- New absolute tilt sensor system installed

SOFTWARE

- Software updated to Windows compatible; including data processing for Thor-Lx

USERS' MANUAL

- Users' manual updated to reflect alpha level modifications

INCORPORATION OF THOR-Lx LOWER EXTREMITY DESIGN (Figures 26 & 27)

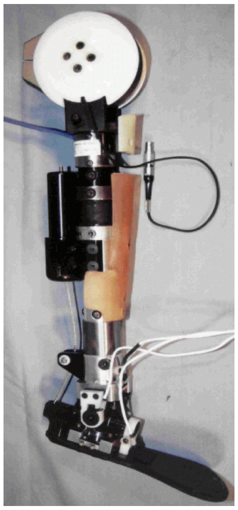

Figure 26 Thor-Lx/ HIIIr Assembly (w/o flesh)

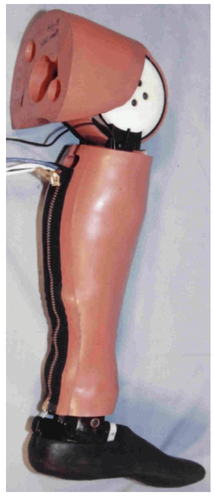

Figure 27 Thor-Lx/ HIIIr Assembly

- Thor-Lx lower extremity assembly incorporated.

- Documentation of design and performance may be found in Petit, et al, 1999; Rudd, et al, 1999; Shams, et al, 1999; and Wheeler, et al, 2000.

MISCELLANEOUS

- Head external targets added to mark head c.g. location
- Improved CRUX geometry
- Sharp edges in path of wire routes addressed
- Improved OC potentiometer wire routing
- Improved wire bundling
- Updated/ expanded certification procedures document
- Improved H-point tool provided
- Positioning instructions incorporated into users' manual

SUMMARY

The process leading up to the development and release of the Thor ALPHA design has involved close cooperation and consultation with a very considerable number of research and automotive engineering personnel worldwide; effort has been made to solicit advice and counsel from individuals with a wide variety of perspectives. The large number of cooperating institutions which participated in Thor hardware evaluations speaks clearly to the common interest worldwide in the development of unified crash test tools. The promise of the Thor program, of course, is that the end product can find acceptance on an international basis, and that Thor program products will ultimately prove useful to test engineers and research personnel alike.

The Thor ALPHA design reflects improvements made in direct response to the many inputs received from the Thor evaluators. What has emerged as a result of these efforts is a dummy that incorporates the following features :

- A more human-like thoracic structure with multiple high-speed 3D deflection instruments;
- An articulating spine with new adjustable vehicle-seated posture;
- An improved shoulder design with more human-like mobility;
- A new abdomen design featuring upper and lower modules with continuous 3D deflection measurement;
- A new pelvis design with revised anthropometry, flesh configuration, injury assessment capability at the hips, and submarining detection features;
- A new compliant femur design to assist in generating more realistic femur loads;
- A simplified load sensing face;
- A new lower extremity design with more human-like ankle/ foot motions, a representation of the Achilles tendon, and substantially improved injury assessment capabilities;
- A design intended for ease of calibration, maintenance, and use.

It is hoped and anticipated that the Thor ALPHA dummy, because of its enhanced design and measurement capabilities, will make several contributions to increasing the safety of vehicle occupants:

- Assistance in optimization of "smart" restraint systems, including setting of air bag deployment thresholds and design of integrated advanced belt restraint systems;
- Improved assessment of belt/bag interactions;
- Improved head kinematics as a result of neck and spine design upgrades;
- Improved neck injury assessment, including OOP injury assessment;
- More realistic spinal kinematics and measurement of spinal kinematics for restraint design purposes;

- Improved assessment of the effect of occupant seated posture upon restraint performance;
- Detection of air bag/ abdomen interaction;
- Detection of wheel rim involvement with the abdomen;
- Detection and measurement of belt penetration into the abdomen;
- Facility for injury assessment at the hip joint;
- More detailed assessment of foot motion and ankle/foot injury potential;
- Facility for facial injury assessment.

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