Advanced Anthropomorphic Test Device Concept Definition

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Abstract

This paper summarizes the results of Phase 1, Concept Definition, of the AATD program and identifies the reasons such a new test device is needed. The following areas are addressed: (1) injury priority from accident data; (2) current dummy design, use, and potential improvements; and (3) technical characteristics and design concepts for a new AATD, its data processing, and its certification systems.

Overview

Phase 1 of the AATD program[1] has shown that there is a need to develop a new anthropomorphic test device that has humanlike response in frontal through lateral as well as rollover impact directions, interacts realistically with restraint systems and the vehicle interior, is capable of making numerous meaningful measurements of injury assessment, is durable and easily maintained, and can be certified without disassembly. Because of the necessary time lag between design and production, current dummies are not based on currently available data. A greatly improved and expanded biomechanical data base has been developed in Phase 1, and these data form the basis for defining impact response characteristics necessary to insure that the AATD will perform in a humanlike manner.

The new dummy will have significant advantages over current ATD's. First, its shape in the seated configuration will be based on actual mid-sized-male-seated anthropometry, which will contribute to more realistic interaction with the vehicle seat and other components. Second, it will have biofidelity in frontal, oblique, lateral, and vertical impacts, to be achieved through such features as a deformable face, a multidirectional neck and chest, and a flexible thoracic spine. Thus, only one dummy will be needed for crash-testing purposes, and it will give realistic trajectory, contact-point, and loading results. Its humanlike response will also allow many more meaningful engineering maesurements to be made, which will in turn greatly enhance injury assessment capability. Next, its materials will be durable, and its designs will be rugged and repeatable but cost-effective to manufacture. Materials will be selected to minimize the sensitivity of the AATD to temperature variations. Finally, the certification process will be more efficient and repeatable between laboratories, to be achieved through the use of a whole-body certification fixture with a dedicated data processing system.

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[1] Primary participants in this program include N.M. Alem, O. Carsten, J. O'Day, D.H. Robbins, and K. Weber of the University of Michigan; P. Begeman, R. Cheng, A.I. King, and G.W. Nyquist of Wayne State University; R.H. Arendt, P.M. Miller, and D.J. Segal of MGA Research Corporation; J. Smrcka of Alderson Research Laboratories, Inc.; R.H. Eppinger and M. Haffner of the National Highway Traffic Safety Administration.

In the following sections, the results of various aspects of this program are summarized. First, we describe an analysis of accident data to determine the priority of injuries to be addressed, based on estimated cost to society. Then we present findings on the design and use of current ATD's along with suggestions for how dummies could be improved. Finally, we summarize the technical characteristics and design concepts proposed for the new AATD and for its data processing and certification systems.

Another major task in the AATD program, not summarized here, was a review of literature on biomechanical impact response and injury in the automotive environment. This review incorporates published research available through the end of 1984 and includes chapters on the head, spine, thorax, abdomen, pelvis, and lower extremities. Each chapter addresses the anatomy, clinical injury experience, and results of laboratory impact studies for the various regions. The experimental studies include information on biomechanical response to impact as well as injury mechanisms, tolerance, and criteria. For the full review, see Melvin and Weber(1).

Injury Priority Analysis

An analysis of the National Accident Sampling System (NASS) data for 1980 and 1981 places the cost of individual or aggregated groups of injuries in perspective relative to the cost of society for all AIS 2-6 injuries to automobile occupants. The NASS files were first augmented to incorporate an impairment factor that goes beyond the Abbreviated Injury Scale (AIS) by taking into account the consequences of an injury as determined by two panels of physicans as well as a percentage impairment based on American Medical Association guidelines(2). Then a factor was generated from an economic cost model to account for expected lifetime earnings had an individual person not been injured. The impairment factors for the actual NASS injuries were multiplied by the expected earnings factors for individual injured persons to create an Injury Priority Rating (IPR). These IPR's were then aggregated by body region, direction of force, and delta V and expressed in terms of a percentage of total IPR. Tables 1 through 3 show these distributions, which indicate the relative contribution of each grouping of injuries to the total societal cost of injuries to automobile occupants. It should be noted that the occupants sustaining these 2,262 injuries were nearly all unrestrained.

The primary conclusions from these and further bivariate analyses are as follows:

1. The combination of the head, face, and neck body regions accounts for 60 percent of the IPR to passenger car occupants.
2. The combination of the chest, back, and abdomen body regions accounts for 28 percent of the IPR to passenger car occupants.
3. Over one-third of driver IPR occur from collisions with a 12 o'clock direction of force. One-fifth result from collisions with nonhorizontal directions of force.
4. Oblique side collisions account for more IPR than direct side collisions. This applies both to drivers and to right-front passengers. Thus, 9 o'clock collisions account for 4.3 percent of

Table 1. IPR distribution by body region

Body Region	Distribution (%)	Body Region	Distribution (%)
Head	44.6	Ankle/Foot	0.6
Face	10.5	Lower Limb	0.0
Neck	5.1	Upper Arm	1.3
Shoulder	0.3	Elbow	0.5
Chest	18.9	Forearm	1.3
Back	1.6	Wrist/Hand	0.4
Abdomen	7.5	Upper Limb	0.3
Pelvis	1.1	Whole Body	0.9
Thigh	2.1	Unknown	0.2
Knee	1.6		
Lower Leg	1.0	TOTAL	100.0

Table 2. IPR distribution by direction of force

Direction of Force	Distrubution (%)	Direction of Force	Distribution (%)
1 o'clock	4.8	9 o'clock	3.3
2 o'clock	9.8	10 o'clock	7.9
3 o'clock	3.5	11 o'clock	5.0
4 o'clock	0.0	12 o'clock	36.9
5 o'clock	0.1	Nonhorizontal	16.1
6 o'clock	0.7	Unknown	10.4
7 o'clock	0.3		
8 o'clock	1.2	TOTAL	100.0

Table 3. IPR distribution by delta V

Delta V	Distribution (%)	Delta V	Distribution (%)
1-5 mph	0.1	41-45 mph	1.5
6-10 mph	0.6	46-50 mph	0.0
11-15 mph	2.0	51-55 mph	2.7
16-20 mph	4.3	>55 mph	3.8
21-25 mph	7.0	Unknown	68.9
26-30 mph	4.9		
31-35 mph	2.6	TOTAL	100.0
36-40 mph	1.5		

driver IPR but 10 and 11 o'clock collisions account for 11.9 percent. Similarly, 3 o'clock collisions account for 9.4 percent of IPR to right-front passengers; 1 and 2 o'clock collisions account for 19.2 percent.

5. Using only known values of delta V, 84 percent of the driver IPR with a 12 o'clock direction of force result from severe crashes, i.e., those with a delta V greater than 20mph. For right-front passengers, the figure is 97 percent. However, it should also be noted that, for cases with known delta V, 81 percent of driver IPR and 77 percent of right-front passenger IPR was attributable to crashes with a delta V of 45mph or less.
6. Again, using only cases with known delta V, 66 percent of driver IPR for injuries to the head, face, and neck result from severe crashes. For injuries to the chest, back, and abdomen, the comparable figure is 81 percent; for injuries to the upper extremities, 45 percent; and for injuries to the lower extremities, 93 percent. Thus, one might conclude that, for drivers, serious injuries to the upper extremities are the easiest to prevent because a higher proportion of them occur in less severe crashes. Next would come the combination of the head, face, and neck, followed by the combination of the chest, back, and abdomen, and last the lower extremities.
7. Comparison of IPR with the earlier Harm model(3) indicated that the two models were in complete agreement in assigning relative priority to the directions of force in the 1980 and 1981 NASS data. When ranking body regions, however, the IPR model gives higher priority to the head, face, and neck, and correspondingly less prominence to the chest, abdomen, and extremities. This is because of the relatively severe long-term consequences of injury to the head, face, or neck.

Because of limitations in the data, it was not always possible to depict, to the extent desired, the crash environment in which the IPR to the various body regions was incurred. In particular, the high rates of missing delta V meant that analysis of crash severity was often not possible. Another concern is with the comparatively small number of occupants in the NASS files that sustain serious injuries. The 1980 and 1981 NASS files combined have only some 2,262 injuries of severity AIS 2 or greater to passenger car occupants.[2] These injuries are sustained by 1,262 occupants. There are a total of 15,378 passenger car occupants in the combined 1980 and 1981 files. Thus, 92 percent of the occupants sustain no injuries, injuries of AIS 1, or injuries of unknown severity.

One solution to the shortage of cases for analysis is to incorporate additional years of NASS. It is hoped that the 1982 NASS data can be added to the existing data structure so the analyses reported here can be run with additional confidence and perhaps be extended to include such issues as contact point in more detail. Another solution would be to revise the threshold for the inclusion of cases in the NASS system or to sample at higher rates cases in which injuries greater than AIS 1 are sustained. Such a revised sampling scheme could be combined with reducing the amount of investigation carried out on cases with no injuries or minor injuries.

Finally, the reader should bear in mind that the model used here is not completely satisfactory. In particular, it does not take into account the fact that a single person may have sustained more than one injury. It is hoped to pursue the development of a multi-injury model in the future.

For further details on this analysis, see Carsten and O'Day(4).

Review of Dummy Design and Use

Dummy User Survey Results

A survey of users of the Part 572 and Hybrid III dummies was taken to determine the problems these users have encountered and their preferences for changes and improvements in dummy design. General topics included mechanical design, serviceability and maintenance, durability, certification, repeatability and reproducibility, and ease of use. The survey questionnaire was made available to a wide audience through NHTSA, SAE, ISO, and various individual contacts.

Responses were received from 38 individuals representing 29 organizations. The affiliation of the 38 respondents can be categorized as follows:

7	U.S. vehicle industry
9	Foreign vehicle industry
12	U.S. government
4	Foreign government
2	Dummy manufacturing
4	Independent research

Throughout the responses to this survey, a strong emphasis was placed on the need for a durable, stable, and repeatable test device, even at the expense of biofidelity. The lack of enthusiasm for an omnidirectional dummy, expressed by several respondents early in the survey, seemed to be based on an assumption that such a dummy could not be made to be as repeatable and reliable as a unidirectional test device, while retaining a suitable simplicity of design. Comments in later sections of the survey clearly indicated that considerable time and effort were required to prepare the Part 572 dummy for

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[2] This figure includes some injuries originally coded with an AIS of 7.

testing, and that between-test repair, replacement, adjustment, and recalibration were frequent necessities. As the survey proceeded from theoretical design to more hands-on issues, the number of respondents decreased, but the conviction and level of detail of responses increased.

Respondents were generous with their advice as to how life with an anthropomorphic test device could be made easier. Designed-in means were needed for holding onto various parts of the dummy for transporting, positioning, and storage and for holding it fixed in space for certification tests. Also needed were visible indicators of the dummy's internal structural configuration and segment centers of mass. Joints were singled out as the assemblies in particular need of redesign. In addition, it was made clear that the performance characteristics of a dummy must be built up from the smallest components, but that performance checks of components in their assembled state were also necessary.

After reviewing the responses of this international group of dummy users, the term "advanced" in AATD begins to take on a broader meaning. Not only is there an opportunity here to advance the state of the art with regard to humanlike response and innovative instrumentation techniques, but there is a necessity to make significant design and materials improvements that will result in a more durable, repeatable, and trouble-free dummy.

Anthropometric Data and Biomechanical Response Simulation for AATD Design

This section indicates the anthropometric data available for use in developing design specifications for an AATD. The use of these data is also demonstrated in a limited simulation of dummy response using the CAL-3D crash victim simulation code(5). The parameters of particular interest are those associated with spinal flexibility and shoulder mobility, which are shown to play a major role in controlling torso and head motions and applied forces.

Anthropometric Data

Several data resources are available from the recently completed dummy anthropometry project on contract DTNH22-80-C-07502(6). These include mass and inertial properties, body surface shape, seated posture, estimations for the location of the bony structure, joint locations, and range of motion at the various joint structures. These data are all static and are for a midsized male driver in an average vehicle-seated posture. Mass and inertial properties are given for a traditional linkage and segmentation of the body in the static-seated posture. The mechanical term "linkage" implies the available data are most applicable to dummies or simulations based primarily on rigid-body mechanical models. The dummy response simulation presented later uses a lumped-mass, chain-linkage, dynamic simulation software package consisting of rigid masses connected at joint structures.

Details are given in the full report(7) of the body linkages used in the simulation, as well as data sources and methods for determining the segmentation of the shoulder, neck, thoracolumbar spine, and thorax. Of particular importance are (1) the division of the traditionally rigid thorax into one rib cage, three spinal, and two shoulder segments, and (2) the approach of coupling the rib cage to the spine to achieve mobility and rotation of the thorax with respect to the spine.

Mobility and range-of-motion data are in fair supply only for static mobility and voluntary motion. In other words, it is possible to estimate how far the segments can move with respect to each other before subjects say "ouch" or before outside forcing agents must be supplied to produce further motions. Similar quantitative data for dynamic mobility (dynamic motions voluntarily made or those that occur under the influence of an outside forcing agent, such as a deceleration device) are virtually nonexistent, except for the neck and, perhaps to a more limited extent, for the thoracic and lumbar spines. Dynamic torque data are not yet available for the thoracic and lumbar regions.

Other data necessary for simulating a dummy in a crash environment include force-deformation characteristics of various body regions and data on the crash event itself. Data sources included project literature reviews, accident data analyses, and vehicle specification packages.

Regarding the status of the anthropometry data base, it was concluded that the mass and postural data are available, but body segmentation needs to be refined to include spinal and shoulder girdle masses. The data base on joints also needs to be expanded to provide torque on joints versus relative angle of the segments. The most pressing need is for additional information on spinal flexibility and torsion properties.

Biomechanical Response Simulation

The purpose of this analysis was to study the effects of spinal and shoulder flexibility on whole-body response. Degrees of freedom not found in current dummies were added to the linkage model. Comparative results for stiff and flexible joints between the thorax components are presented for belted and unbelted occupants.

Figure 1 shows the difference in head excursion for 3-point-belted occupants with a flexible three-link thoracic spine versus a stiffer linkage similar to that used in current dummies. The positions are those at 100ms, and the more restricted forward head excursion with the stiff joints is apparent. For the unbelted case, there was a

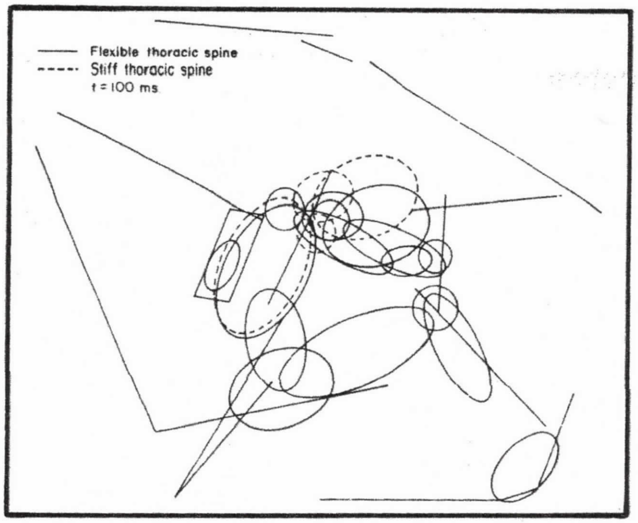

Figure 1. Effect of thoracic spine flexibility, belted case

marked reduction in the force of interaction between the thorax and the steering wheel when the shoulder masses were uncoupled from the thorax, even when the spine remained stiff.

It is clear from these exercises that crash victim simulation software can be used to study the effects of changing dummy design parameters. Specifically, it was shown that the addition of thoracic spinal flexibility has major effects on the crash victim motion. This is particularly noticeable in head excursion increases of several centimeters for belted occupants. In addition, it was shown that the uncoupling of the shoulder masses from the thorax has a major effect on the interactions of a crash victim with vehicle structures forward of the occupant, such as the steering column and the instrument panel.

ATD Critique

A review of current ATD designs was made from the standpoint of biofidelity, measurement capability, directionality, and impact testing performance. Details by body region can be found in Melvin et al.(7). Although a wide variety of currently available test devices was reviewed, primary emphasis is given here to the Hybrid III and the Side Impact Dummy (SID), since they represent test devices currently in use in research and development testing in the United States.

The Hybrid III was developed over 10 years ago, and its design is based on biomechanical knowledge available at that time. It is a frontal-loading-only ATD whose design represents an evolutionary improvement over conventional ATD design. For example, the rib cage uses the same design as the previous Hybrid II, but with altered structural stiffness to produce a humanlike impact response to midsternal moving-mass impactors. The Hybrid III also possesses humanlike hard-impact forehead response and midsagittal neck bending response. As presently configured, the Hybrid III has the greatest measurement capability of any ATD, with 44 data channels.

The SID was developed more recently than the Hybrid III and represents a modification of the chest region only in an otherwise standard (nonbiomechanical) ATD. The SID was developed to provide lateral chest response biofidelity under rigid and padded impacts. The shoulder response is included in the chest response, and, as a result, the design has no separate shoulder structure. The remainder of the SID structures are standard Part 572. Except for additional chest wall accelerations and lateral chest displacement, the SID has the same measurement capabilities as the Part 572 ATD.

Both the Hybrid III and the SID are examples of ATD's intended for use in restricted test conditions and/or directions, and as such they have only limited biofidelity in the principal directions and none in other directions. One of the most serious deficiencies of both ATD's centers around the designs of the thoraxes, both the rib cages, and the spines. The IPR analysis has indicated the great importance of the head and chest as primary sources of injury, disability, and death of unrestrained occupants. The development of effective countermeasures to minimize injury to these regions depends strongly upon having an ATD that produces realistic responses in terms of trajectories, contact points, and loadings. The combination of rigid thoracic spines with present neck designs (including that of Hybrid III) and inadequate thoracic rib-cage conformability are producing head contacts and chest/steering-system interactions that are quite unlike those in real-world crashes. All present ATD designs are quite inadequate in this respect in the crucial head/torso regions for frontal, lateral, and oblique impacts. The lack of realistic concentrated load response in the Hybrid III and SID chests is compounded for the case of shoulder-belt loading. Neither chest exhibits humanlike stiffnesses at the lower loading rates associated with belt restraint systems. This, again, will have an influence on both chest deformations and head trajectories.

To illustrate the improvement in overall effectiveness of an AATD with omnidirectional response and measurement capability in the frontal-to-lateral range, an analysis was made of the Hybrid III, SID, and AATD based solely on measurement capability and directionality. Direct-impact biofidelity was not taken into account. The IPR distribution for each body region (Table 1) was multiplied by the measurement capability of each ATD for each region, based on a rating of complete (100 percent) to partial (75 percent and 50 percent) to none (0 percent). This product was then apportioned according to the distribution of IPR to these body regions by direction of impact force. This process gave an estimate of the proportion of the IPR addressed by each ATD in a given direction. An overall effectiveness of an ATD could then be estimated by summing these IPR proportions for the range of directions from frontal to lateral.

For the left-front unrestrained driver position, it was judged that the combination of Hybrid III and SID ATD's could address directions 11, 12, and 1 o'clock (Hybrid III) as well as 9, 10, and 3 o'clock (SID). The potential gap in the oblique direction between 10 and 11 o'clock is ignored to give the Hybrid III/SID the benefit of the doubt. The 2 o'clock PDOF, however, is not included because the SID is judged to be kinematically unreliable in far-side oblique impacts. In comparison, the AATD will be able to continuously address the full range of PDOF from 9 through 3 o'clock in a clockwise direction. In addition, the more extensive measurement capability to be available on the AATD will provide a higher level of injury assessment capability in those directions. Based on the above considerations, the AATD was found to address 90.5 percent of the total IPR (see Figure 2), while the combination of the Hybrid III and SID addressed only 43.4 percent. The AATD would thus be twice as effective as the combination of the two present ATD's.

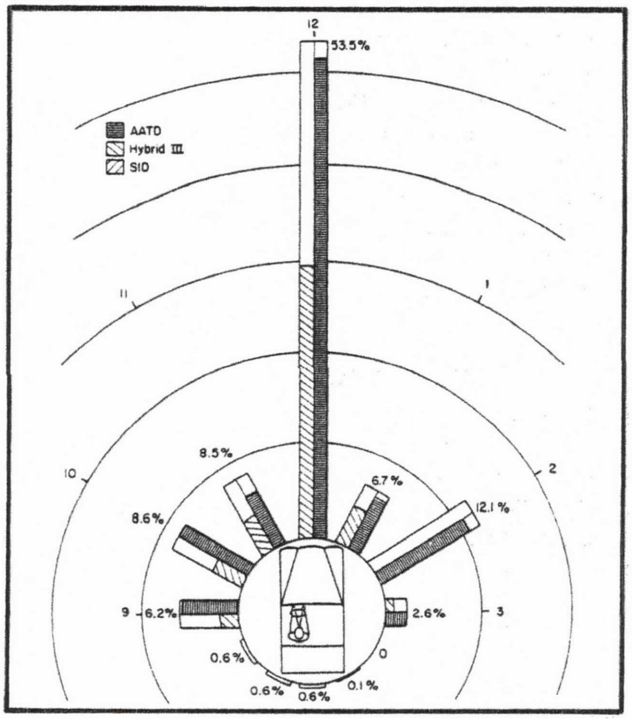

Figure 2. Estimated effectiveness of Hybrid III, SID, and ATTAD for unrestrained left-front occupants by principal direction of force (percentages denote proportion of horizontal force IPR in each direction)

Technical Characteristics and Design Concepts

This section brings together the results of our various reviews and analyses of accident data, biomechanical data, and other technical data to establish technical characteristics and to propose design concepts for the AATD and its data processing and certification systems. It is first necessary, however, to present a brief description of a major activity to develop a uniform biomechanical data base.

Biomechanical Data Base

Our ability to generate response corridors for specific body regions, but particularly for the chest, depended on the existence of a large data base whose signals could be analyzed in a uniform manner. Both previously unpublished data and those published data that warranted reanalysis were identified, consolidated, categorized, and recoded or given additional coding as appropriate. A total of 1,190 tests were initially identified by test number and source as candidates for inclusion in the data base. However, we were able to obtain and include adequate data for only 241 tests, consisting of the following:

1. A nucleus of 97 tests obtained from NHTSA that were already coded in the standard NHTSA biomechanics tape format
2. Four APR facial impacts and 41 ONSER pelvis impacts that were obtained from France on analog tapes and then digitized and coded at UMTRI
3. Fifty-eight tests conducted, digitized, and coded at UMTRI that included 26 NIOSH head axial impacts, 14 MVMA head side and frontal impacts, 11 GM whole-body sled tests, and 7 GM shoulder impacts
4. Twelve Heidelberg frontal and lateral sled tests and 5 FAT tests conducted at Heidelberg, both tapes having already been formatted

In addition, high-speed movies from 10 UMTRI thoracic tests were analyzed, and film readings were reformatted as "displacement" signals and incorporated with their corresponding sensor data. Finally, 10 Heidelberg tests containing 9 accelerometer signals were converted to the standard anatomical reference frame.

Various parameters were used as the basis for classification of the tests. These included (1) restraint type or impact surface, (2) severity of impact, in terms of impact velocity, (3) injury level, in terms of AIS rating, and (4) the subject size and condition. Test signals were further subdivided by body area, including the head, chest, spine, shoulder, and lower extremities. Once these groups were established, spectral analysis of each group was conducted to determine an appropriate filter to use for preprocessing. A procedure was developed to extract filter characteristics from the available pool of signals, and filter corners and slopes were obtained for the near side and far side of impact for the chest and head. The area determined to have the highest priority for response characterization was the thorax, and thus emphasis was placed on generating corridors for rib and sternal accelerations. Summary data plots of chest response for a variety of test conditions (shoulder belt, airbag, rigid wall, and rigid disc) were prepared, the data having been filtered and mass-scaled. These are the basis for the performance specifications of the chest.

AATD Technical Characteristics and Design Concepts

The AATD will be designed to provide omnidirectional response in the range of ± 90° from the front in the horizontal plane. This accounts for virtually all the horizontal collision IPR and 82 percent of all IPR with known principal direction of force (PDOF). The exposure severity levels associated with cumulative values of 85 percent of the IPR are delta V's of 50mph for frontal impacts and 30mph for lateral impacts. It is expected that the AATD would be used unrestrained in such severe environments only if the vehicle structures and interiors to be tested incorporated advanced crashworthiness technology. Thus, these delta V levels are taken to be upper-limit exposure levels for the velocity of interaction with protective interior systems. The AATD will also be designed for upper-body vertical (superior-inferior) impact associated with nonhorizontal collisions. Such collisions account for 18 percent of all IPR with known PDOF.

Measurements to be made by the AATD are based on an analysis of ideal versus feasible measures. This analysis identified measures that would be desirable for injury assessment, given that an ideal test device could be developed that could reproduce all the anatomy and biomechanical responses of the human body. These were tempered by the state-of-the-art of measurement technology, and measurements were determined that would be consistent with the AATD design concepts for each body region. These measures are included in the following summaries of the desired technical characteristics and associated design concepts for the AATD, schematically presented in Figure 3.

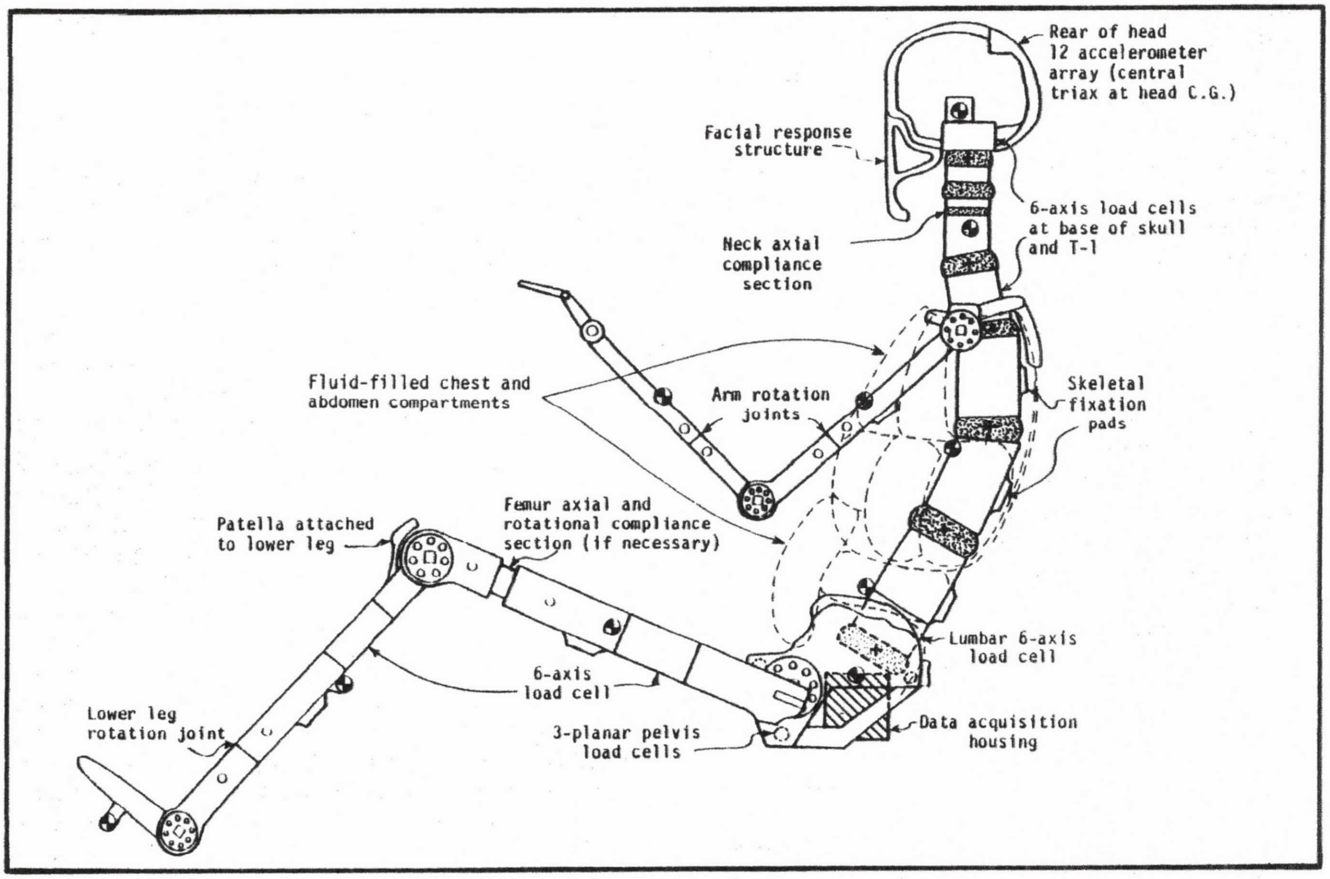

Figure 3. AATD design concepts

Head

The head will have biofidelity of response for front, side, and top rigid impacts as well as facial impact response biofidelity. Head instrumentation will consist of an array of 12 linear accelerometers to provide complete three-dimensional impact motion measurement as well as direct head center-of-gravity translational acceleration measurement. Certification testing procedures for head response will not require disassembly of the AATD.

The head will have a featureless face to aid in producing repeatable impact response. In addition, the facial structure will be designed to produce realistic head acceleration responses when the head is impacted in the face by a rigid mass. This face will be a durable structural element that can, however, be removed and replaced with an optional frangible insert for determination of facial bone fracture. The overlying soft tissue simulation of the face would similarly be replaceable with a lacerable option.

The skull of the AATD will be of cast aluminum with the front, side, and top sized to produce, in conjunction with the scalp material, biofidelity of rigid impact response. The base and rear structure of the skull will be separate from the front/side/top structure and will be designed as a mounting structure for a 12-accelerometer motion measurement array made up of four triaxial accelerometer units. As such, the base and rear structure will be very stiff to preserve the accelerometer alignment during rigid impacts to the head. The array will be configured to put one of the triaxial units at the head center of gravity for direct measurement of translational acceleration at that point and for subsequent HIC determination. The base of the skull will also serve as a mounting structure for a six-axis neck load cell.

Spine

The spine will be designed as a total system from the base of the head to the top of the pelvis. Spinal flexibility will be provided for the cervical, thoracic, and lumbar spine segments. The neck section of the spine will have biofidelity of response for frontal, lateral, and oblique indirect impacts. The specifications for these responses are based on analysis of human volunteer sled tests. These data provide static neck joint stiffness characteristics in bending (flexion, extension, and lateral), axial loading (tension and compression), and torsion, as well as dynamic head/neck junction bending moment/head-to-torso angle responses for flexion, extension, and lateral loading and accompanying head trajectory requirements. An additional requirement will be placed on matching the superior-inferior response of the head/neck system due to impacts to the top of the head. The mean force-time and acceleration-time responses of the head and spine, based on cadaver impacts, are the basis for this response requirement.

The thoracic and lumbar spine system will have biofidelity of midsagittal flexion and extension bending response based on static tests on human volunteers. The spine system will provide for adjustment of the initial spinal configuration. Six-axis load measurement (three moments and three forces) will be made at the base of the head, the base of the neck, and the base of the spine to aid in the interpretation of body loading from advanced restraint techniques.

The spinal structure will consist of a series of rigid links connected by joints at selected anatomical points. These joints will have omnidirectional motion capability and will be located at the head/neck junction, base of the neck (C7/T1), upper thorax (T4/T5), middle thorax (T8/T9), lower thorax (T12/L1), and base of the spine (L5/S1). Range-of-motion requirements in the cervical spine (75° flexion, 90° extension) require the introduction of a third neck joint near the middle of the cervical spine (C4/C5). This joint will also incorporate provisions for neck torsional stiffness and axial stiffness control.

The spine segment between T1 and T4 will provide the structural attachment for the shoulder, and the thoracic structure will be attached to the T5-T8 and T9-T12 segments. Provisions will be made at each joint to allow adjustment of the initial configuration through the use of wedge-shaped rigid blocks that can be inserted and fastened in place.

Six-axis load cells will be used at the top of the neck, base of the neck, and base of the spine to allow assessment of spinal loading due to restraint system inputs.

Shoulder

The shoulder will have a clavicle structure to carry shoulder belt and steering wheel impact loads but will also offer low lateral load resistance for side impact. The lateral stiffness and range of deflection of the shoulder will be matched to mean cadaver response. The shoulder linkage will be designed to reach its lateral deflection limit slightly after the chest reaches its lateral deflection limit.

Thorax

The thorax will be designed to provide biofidelity of response to frontal impacts for rigid disc, shoulder belt, and airbag loading conditions. Side impact response biofidelity will be required for rigid disc and rigid wall impacts. The response requirements will be met for different rates of loading as well as for different types of loading. The response specifications are based on volunteer tests at lower impact severities and on cadaver tests at the higher levels. Mean impact force-time and acceleration-time corridors for all types of direct thoracic impacts and force-deflection corridors for rigid disc impacts are the primary specifications. They will be supplemented with static load-deflection data on volunteers. Thoracic cage deformations will be measured at multiple locations to allow the assessment of global chest deformation and deformation rates.

The thorax structure will have a thin, flexible, monolithic shell to define its shape and to provide load distribution. This shell is not intended to carry significant load and therefore will not have an influence on thoracic response. The response elements in the thorax will be an array of fluid-filled bag compartments within the shell. Each bag will be constructed of cord-reinforced rubber and will represent a flexible, constant volume reservoir. There will be five bags on each of two levels, compartmentalizing the chest into upper and lower levels with frontal, lateral, and oblique sections. Each bag will communicate with a common gas-pressure-controlled reservoir (accumulator) through a single orifice into that reservoir. One-way flow-control valves will be provided in the passages from the individual bags to the reservoir to prevent flow from one bag to another instead of into the accumulator. The bag volumes, the accumulator fluid volume and gas volume, the accumulator initial gas pressure, and the orifice size will be adjusted to produce the desired thorax response. The compartmentalization of the chest will allow positional variation of local response to better match human response to asymmetric loads such as those from shoulder belts.

Each bag will have a pressure transducer mounted in it as will the gas section of the accumulator. The bag pressure transducers will indicate the region of loading and the loading rate (related to flow rate) from the resistance to flow. The central accumulator gas pressure will indicate total global deformation of the chest independent of the region of loading. The use of well-defined materials, such as silicone fluids and nitrogen gas, to control response will minimize repeatability, reproducibility, and temperature sensitivity problems.

Abdomen

The abdomen will be a deformable system with dynamic response biofidelity based on the mean rigid armrest load-deflection response of laboratory-impacted cadavers. The deformations of the abdomen will be measured at multiple locations to indicate the degree of abdominal intrusion in frontal and lateral loading. The abdomen will be of similar general design as the thorax but with only three fluid-filled compartments, lower control pressures, and a softer outer covering.

Pelvis

The pelvis and its associated covering will be designed to exhibit rigid impact response biofidelity, based on mean force-time and acceleration-time corridors for cadavers in lateral impacts, and will have humanlike mass distribution. It will also be instrumented to sense lateral loading. The pelvic structure will be designed as a simple geometric shape for the purposes of (1) providing a lightweight, rigid structure for tying the extremities and torso together, (2) allowing lateral pelvic and hip joint load measurement, and (3) providing a protected space for housing a future data acquisition system. The anatomical details of critical points for proper restraint system engagement and interaction, such as iliac bones and ischial tuberosities, will be provided for only where needed. The mass of the pelvic structure and the accompanying soft tissue mass and stiffness will be matched to provide lateral impact biofidelity.

Lower Extremities

The legs will have knee/femur/pelvis impact biofidelity in rigid knee impacts and will have humanlike skeletal mass distribution. Soft tissue coupling to the skeletal structure will also be humanlike in response, and the knee structure will have realistic geometry. Six-axis load measurements will be made in the femoral shafts, and multiaxial loads will be measured in the lower legs. The extremity joints will be single-axis planar joints or combinations of such joints to achieve appropriate degrees of freedom. The ranges of motion of the joints will be humanlike, and the resistance characteristics will be adjustable to achieve resistance ranges from 0 to 2G. The resistive torque-angle response will be humanlike as will the joint stop characteristics.

Flesh

The flesh will be developed in conjunction with the underlying skeletal structures to insure proper overall system response, including tissue shear mobility in critical loading areas such as the buttocks and upper pelvis. The durability and stability of the flesh materials will be given special consideration.

Data Processing

The data acquisition and processing techniques that are currently used by crash and sled testing facilities to measure anthropomorphic dummy response data during impact testing were reviewed, and a number of recommendations are given regarding the development of an advanced dummy instrumentation system.

Based on the projected data channel requirements of from 72 to 100 data channels on-board the advanced dummy, and based on the present size of state-of-the-art instrumentation, the development of an on-dummy instrumentation system is recommended. This system should be designed to include integral memory but with capability to conveniently expand record times through use of external memory. The on-dummy instrumentation should be developed as a microprocessor-based system to perform on-dummy analysis and control functions as well as to allow transfer of measured data to an external computer-based test set. The on-dummy microprocessor would also function to perform self tests of individual data channels under both internal and external control.

A microprocessor-based external test set should be developed as an integral part of the advanced dummy instrumentation system. The test set should be designed to allow calibration signals to be injected into individual data channels on-board the dummy. The test set would also function to perform analysis of data channel response signals. The response signals may result from injected calibration signals or actual dummy responses generated during dummy certification tests. The test set would allow for rapid turnaround of results to provide pass/fail indications of channel performance immediately after a verification test was performed.

The advanced dummy instrumentation should be developed to meet the requirements for data systems as outlined in ISO 6487, *Road Vehicles—Techniques of Measurement in Impact Test—Instrumentation.* In specialized cases, as may apply to the nine component head accelerometer array, increased accuracy may be required. The recommended performance for the advanced dummy instrumentation is summarized in Table 4.

Procedures should be developed for use in calibrating accelerometers and other sensors. ISO 6487 should serve as a basis for the procedures. At a minimum, the following parameters should be calibrated at 6-month intervals:

- Amplitude linearity at a fixed frequency
- Amplitude response versus frequency
- Phase response

The advanced dummy instrumentation should be designed to meet specified environmental performance criteria. Recommended criteria and suggested limits are summarized in Table 5.

For further information, see Arendt et al.(8).

Table 4. Advanced dummy instrumentation requirements

Amplitude Linearity	2.5%
Amplitude Resolution	12 bits (0.02%)
Time Linearity	1%
Time Synchronization	0.1 ms
Time Zero Offset	0.1 ms
Sample Rate	8000 Hz
Record Time (per channel)	500 ms
Channel Capacity	72 expandable to 100

Table 5. Environmental specifications

Parameter	Design Limits
High Temperature	180°F.
Low Temperature	-10°F.
Temperature Shock	170°F.
Humidity	85%
Acceleration (linear)	10 G
Vibration	1 G RMS Random
Shock	500 G ½ ms (Head) 200 G 1 ms (Chest, Pelvis)
EMI/RFI	Standard Industrial

Certification Test Procedures

The test procedures currently employed to certify the Part 572 anthropomorphic dummy for use in crash tests were reviewed, and approaches that appear promising for use with the advanced dummy are recommended below. These certification tests are intended to insure that dummy responses to impact stimuli are both repeatable and reproducible. A brief review of Hybrid III dummy certification procedures was also conducted.

Routine certification testing should be done on a completely assembled, advanced anthropomorphic dummy. Test procedures should involve dynamic exposure of the dummy to levels that are consistent with the automobile crash environment. That is, certification testing should mimic the in-use environment to the maximum extent possible. Test procedures and equipment must be developed that will allow efficient and rapid testing.

On-dummy instrumentation should be used in certification testing. It is recognized that additional electronic measurements may be necessary as a part of new test procedures; however, where possible, the sensors, instrumentation, etc., that are a part of the dummy should be utilized to provide certification test data. As this instrumentation is part of the dummy, it is reasonable that it should also be checked as a part of the certification process. However, a complete calibration of sensors is not viewed as necessary each time a dummy is certified. Rather, a calibration interval would be defined at which time all instrumentation would undergo calibration according to established procedures.

Performance criteria should include injury measures as well as engineering measures. That is, if HIC is used as an injury measure for the head, then a test procedure which results in a comparison of an HIC with established error bounds should be utilized. This approach results in a better knowledge of error limits on the primary dummy outputs than is currently available. It should, however, be noted that measures of response in addition to injury measures may be desirable and even necessary for identification of sources of unacceptable component response.

Dummy disassembly and component level testing should be undertaken only if whole-body testing indicates a problem in meeting response limits. That is, component level testing should be undertaken as a diagnostic aid in determining a specific mechanical item in need of repair or adjustment.

For further information, see Arendt et al.(8).

Conclusion

Past dummy development has been an evolutionary process. Such a process does not allow for significant departures from traditional design solutions, because each change must take into account its effect on other dummy components that remain unchanged. Although the best aspects of past dummy designs will be drawn from for the AATD, past designs will not limit the innovative approaches to its design and development. Only by taking a fresh look at all dummy design concepts can the desired results be achieved. The technology is presently available to develop an AATD with greatly improved impact biofidelity, measurement capability, durability, maintainability, and certification ease. Design concepts, technical characteristics, and measurement requirements have been developed in Phase 1 for all body regions. These will be further developed and result in a complete prototype AATD by the end of Phase 2.

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References

1. Melvin, J.W., and K. Weber, eds., *Review of Biomechanical Impact Response and Injury in the Automotive Environment,* Task B report on contract DTNH22-83-C-07005, Ann Arbor, University of Michigan Transportation Research Institute, 1985 (in press).
2. American Medical Association, Committee on Rating of Mental and Physical Impairment, *Guides to the Evaluation of Permanent Impairment*, Chicago, American Medical Association, 1971.
3. Malliaris, A.C., R. Hitchcock, and J. Hedlund, "A search for priorities in crash protection," *Crash Protection*, SP-513, pp. 1-33, SAE Warrendale, Pennsylvania, 1982.
4. Carsten, O., and J. O'Day, *Injury Priority Analysis*, Task A report on contract DTNH22-83-C-07005, Ann Arbor, University of Michigan Transportation Research Institute, 1984 (in press).
5. Fleck, J.T., and F.E. Butler, *Validation of Crash Victim Simulator*, Vol. 4, Report no. ZS-5881, Buffalo, Calspan Corporation, 1981.
6. Schneider, L.W., D.H. Robbins, M.A. Pflüg, and R.G. Snyder, *Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family*, 3 vols., final report on contract DTNH22-80-C-07507, Ann Arbor, University of Michigan Transportation Research Institute, 1983 (in press).
7. Melvin, J.W., D.H. Robbins, K. Weber, K.L. Campbell, and J. Smrcka, *Review of Dummy Design and Use*, Task D report on contract DTNH22-83-C-07005, Ann Arbor, University of Michigan Transportation Research Institute, 1985 (in press).
8. Arendt, R.H., D.J. Segal, and R. Cheng, *Review of Anthropomorphic Test Device Instrumentation, Data Processing, and Certification Test Procedures,* Task C report on contract DTNH22-83-C-07005, Ann Arbor, University of Michigan Transportation Research Institute, 1984 (in press).