DEVELOPMENT OF A NEW ATD THORAX

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A new prototype ATD thorax has been developed to be compatible with the G.M. Hybrid III test dummy. This new chest provides a better opportunity to incorporate certain characteristics of live human beings when subjected to upper torso belt loading. This paper describes the deflection response characteristics of the new surrogate at subinjurious and injurious impact levels. These results are compared to the responses obtained for other ATD's.

INTRODUCTION

This paper is divided into three sections. The first deals with the continuation of the research program first reported by the authors in 1982 (1). The second section describes the mechanical design of a new thorax structure. The design of the new thorax is based partly on human volunteer response to belt loading (1) and partly on cadaver response to blunt sternal loading (2-5). The third section describes the results of a sled test program designed to quantify the response of the new thorax and to study the overall ATD kinematic response in a documented injurious loading environment (6, 7).

THORACIC IMPACT RESPONSE TO STRIP LOADING

The testing described in this section is a continuation of the test program initiated in 1981 (1). The original test apparatus was developed to assist investigators in mapping thoracic deflections under static point loading, and static and quasi static strip loading (driver configuration). These tests were conducted with the subjects lying in a supine position, with a fully supported thoracic spine.

During the second phase of this program, a detailed analysis of thoracic deflections was performed only along the path of the belt, namely the right 7th rib, lower and upper sternum and clavicle locations. It was assumed that deflections in other regions of the thorax were of secondary importance in terms of overall body response. The surrogates tested were: The Part 572, Hybrid III and MIRA (OPAT) ATD's, and one human volunteer. The human subject was chosen from the pool of volunteers used in the 1982 study. During the current phase, he was re-tested for the tensed state.

Surrogate Response to Belt Loading

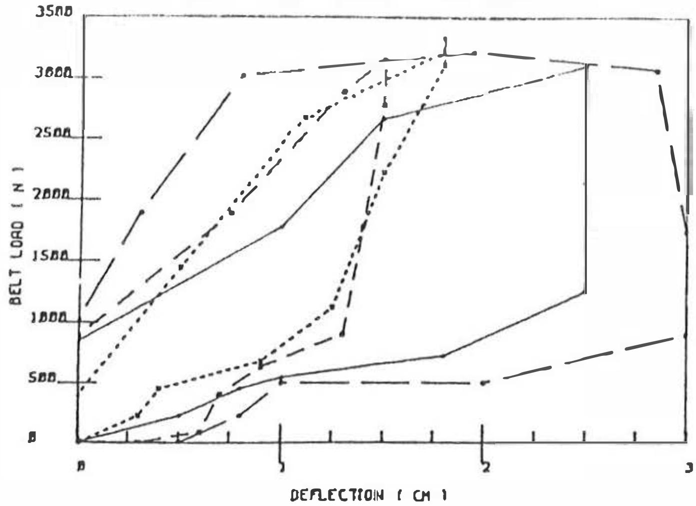
Deflection vs time traces were taken for three locations along the path of the belt. Belt force vs time was also recorded. Upon detailed examination of the test results, the human volunteer's response to loading was found to have poor repeatability. It became apparent that the degree of muscular "tensing" from one test to the next could not be controlled to the degree originally anticipated by the investigators. Interpretation of such data should thus be liberal.

Response to strip loading was also examined on the MIRA, Hybrid II (Part 572) and Hybrid III dummies. Figures 1 through 6 illustrate force/deflection responses for a 108 Joule impact, yielding an average peak belt load of 3.2 kN (see Reference 1 for measurement technique). Each surrogate was then re-tested without its standard soft tissue cover in an attempt to quantify the net effect of the soft tissue cover on the overall deflection response of the thorax.

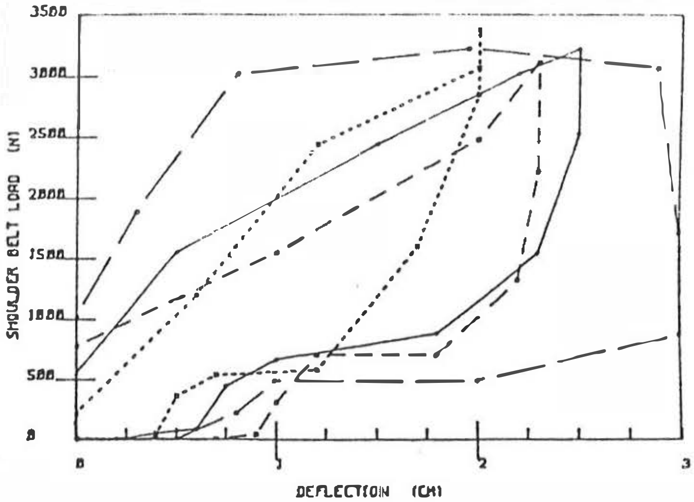
The Hybrid II chest exhibited the lowest amplitude deflection for all three locations, in some cases as much as 50% lower than the human volunteer. The Hybrid III chest response in the upper sternal region was quite similar to the

Force - Deflection Responses to Strip Loading

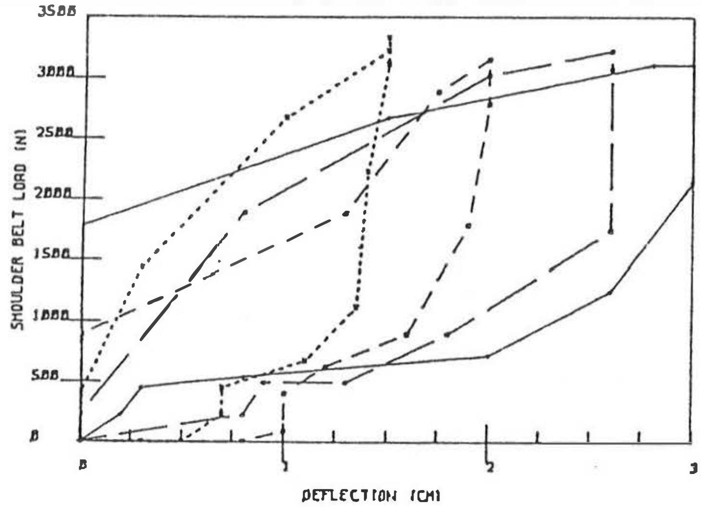
RIGHT RIB LOWER - NO SKIN FIG 1



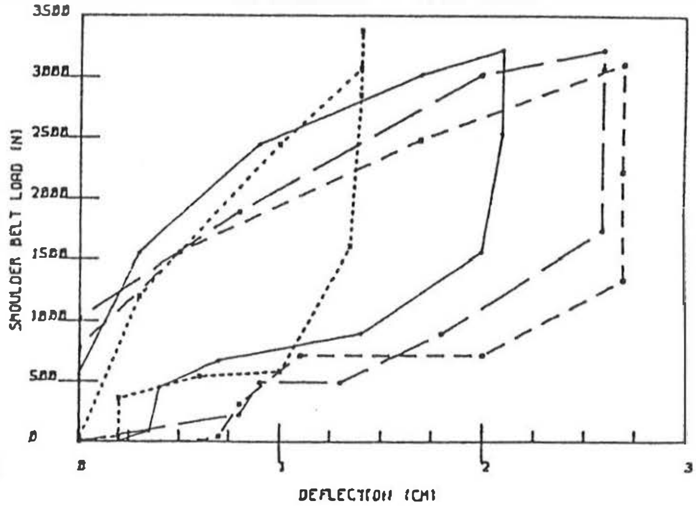
RIGHT RIB LOWER WITH SKIN FIG 2



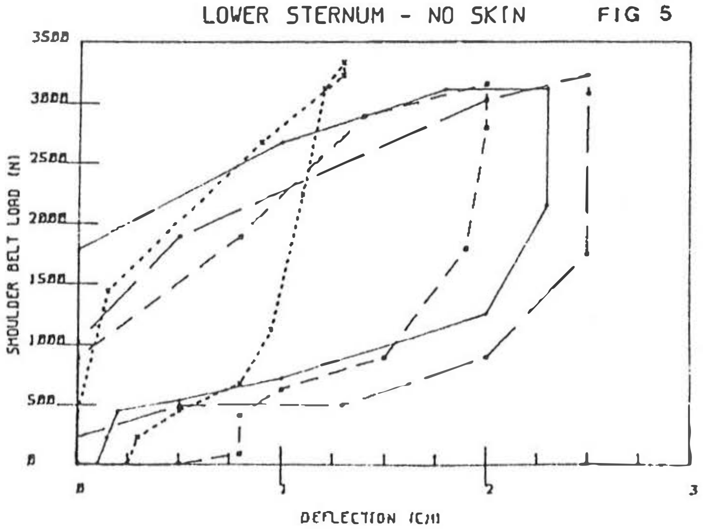
UPPER STERNUM - NO SKIN FIG 3



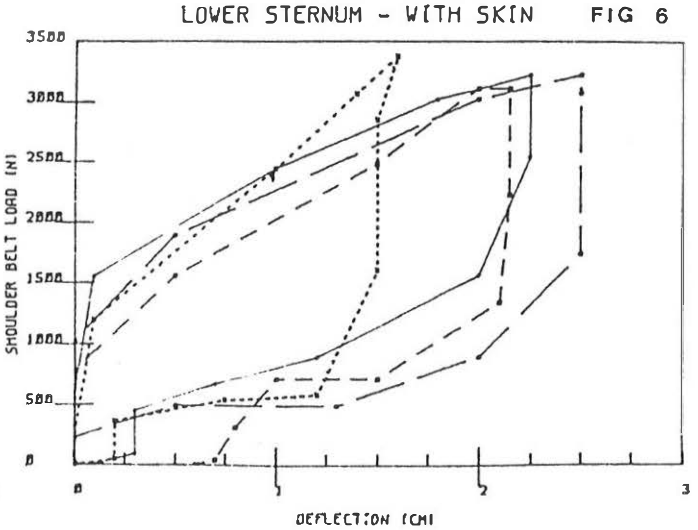
UPPER STERNUM - WITH SKIN FIG 4



LOWER STERNUM - NO SKIN FIG 5



LOWER STERNUM - WITH SKIN FIG 6



MIRA (OPAT) ————
HYBRID III — — — —
HYBRID II - - - - - -
HUMAN VOLUNTEER — —

human volunteer. The Hybrid III appeared too stiff in the right 7th rib and lower sternum locations. The MIRA gave a more human-like response in the lower rib area than both the Hybrid II and Hybrid III, however, it appeared too stiff in the sternal area.

The use of soft tissue cover has an effect on both the belt path, and on the structure's response to loading. In the lower rib, and upper sternum location, the Hybrid III and MIRA responses were markedly influenced by the soft tissue. In the lower sternum region, the soft tissue cover appears to play a prominent role in the Hybrid II response, increasing its externally measured deflection by 20%. The externally measured chest deflections are generally higher with soft tissue cover, although this is not always the rule. The MIRA exhibits the opposite result in the upper sternum location.

MODIFIED CHEST DESIGN

Upon detailed examination of the Hybrid III chest responses to belt loading, it was determined that an improvement could be made in the responses of the lower rib and clavicle regions. It was further determined that the anthropometric measurements were not 50th percentile (1) in terms of chest depth, chest length and chest breadth. The thoracic assembly had also demonstrated to be sensitive to temperature (8). Hence, a new chest structure was developed to more accurately simulate a 50th percentile human male.

Structural Design

Overall thoracic structure measurements were based on anthropometric data obtained from a sample of 50th percentile male subjects (1). The "Modified Hybrid III" (or Hybrid IIIE) chest has redesigned rib elements to improve both overall anthropometry and thoracic response to strip loading.

This new design is composed of ten rib elements which are hinged at the spine and constrained at the front by a split sternum which resembles an inverted "Y" (Figure 7). Two telescopic clavicles were also integrated into the structure. These are ball jointed at the outer extremities of the shoulder assemblies and on the top of the sternum assembly. Soft tissue covering was not used since Typical polymer foam materials serve largely to make contemporary dummies look more realistic. The present design endeavours to provide suitable force deformation characteristics without the use of such external coverings.

Inside the thoracic cavity, two adjustable linear decelerators were added to provide investigators with the option of controlling chest damping characteristics. Both dashpots are bilaterally supported by the spine box and are linked to the mid-sternal region by means of a bell-crank lever arm mechanism.

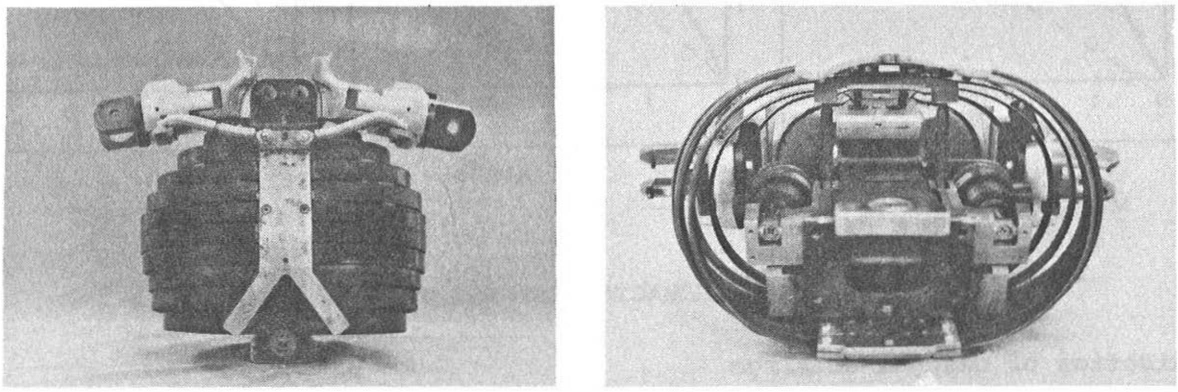


FIGURE 7: MODIFIED THORAX CONSTRUCTION

Determination of Mechanical Characteristics using Finite Element Modelling

The STARDYNE finite element modelling program was used to determine the properties of the chest. The chest structure was simulated using a 152 node, 147 beam data set. Ten ribs were modelled. They were hinged at the spine which was assumed to be restricted from motion. In addition, the top rib was restricted from lateral movement thereby simulating the presence of clavicles.

The first design phase involved determining the required sternum and rib properties. The model was used to determine the size of the rib elements in order to achieve correct stiffness under applied static loads at various sites. Member stresses were restricted to allowable levels under a 7.5 cm deflection at each rib. The thickness of certain ribs had to be doubled in order to meet this criterion.

In the second design phase, the dynamic response of the structure to low and high speed blunt sternal impacts, as specified by the Hybrid III chest calibration procedures, was determined.

The two linear variable hydraulic dashpots were then incorporated into the model and their performance characteristics were determined.

The DYNRE1 option of the STARDYNE program was then utilized to model two dynamic events: 4.27 m/s and 6.67 m/s blunt sternal impacts with a 23.36 kg impactor. The force/time functions measured during previous calibration tests on a Hybrid III chest were used as input load approximations. Force/deflection corridors (3) for the high and low speed events were used as target curves. The dynamic response was then adjusted by varying the theoretical damper resistance to fall within the desired response corridors. To validate the response, the differential equations of motion of an approximate system were solved.

Validation of Structure

The new thoracic structure was evaluated for deflection response to sub-injurious strip loading using the test method previously described (1). No soft tissue cover was employed. The rib structure was first tested with dashpots adjusted to produce no damping. The response in the lower rib and clavicle regions were demonstrated to be a marked improvement over the Hybrid III as shown in Figure 8.

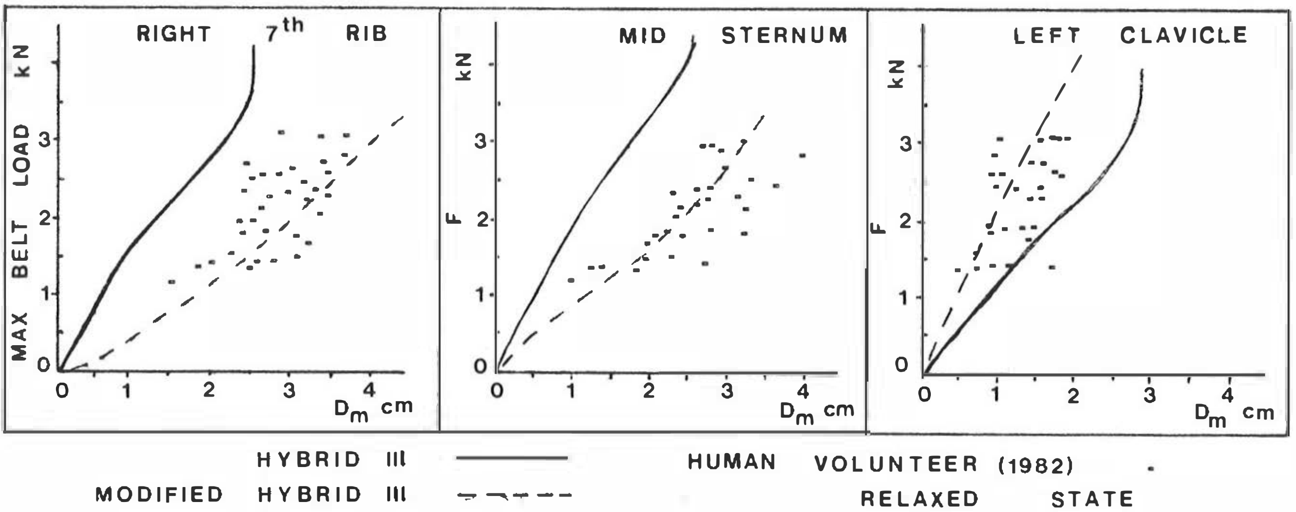


FIGURE 8: THORACIC RESPONSE TO BELT LOAD

Validation of Dashpot Settings

Upon completion of a preliminary evaluation program designed to determine the effect of damping on chest response, a specific dashpot setting was chosen for high speed impact impacts. The thorax was then subjected to the standard Hybrid III chest certification procedure. Since the structure was not covered with a soft tissue covering, the force/time response of the chest exhibited some degree of high frequency noise during the high speed impact.

Deflection response in the low speed test was "within" specifications. However, the high speed impact deflection response was 30% below specification. The chest force responses were also 25 and 33% low for the low and high velocity impacts respectively. One should note that chest forces are measured at 19 ms from time of probe contact on the chest structure. This method of evaluation may not be totally appropriate, since the response is in fact comparable to some of the cadavers upon which the Hybrid III specifications are based.

SLED TEST PROGRAM

In 1982, Kallieris et al (6) reported on a series of sled tests, using a pulse similar to the pulse from a Volvo P-140 impacting a fixed barrier at 50 km/h, in an attempt to link cadaver and accident data. In 1983, Saul (7) expanded upon the work by obtaining response comparisons for the Part 572, Hybrid III and APR dummies in the same three point belt restraint system environment. In an attempt to verify the response of the new modified Hybrid III and MIRA dummies, the same test procedures as employed by Saul were adopted in this program.

Experimental Results

The average peak acceleration of the half sine pulse in the present test series was 3.1% higher than in Saul's test program and the delta v was 9% lower. The restraint system data is summarized in Table 1, and the ATD instrumentation measurements are summarized in Table 2. Observations are summarized as follows:

- The mean values of peak shoulder belt load for the Hybrid IIIE dummy are higher than either the Part 572 or MIRA.
- The Part 572 in the current test program produced head accelerations 53.4% lower than those recorded in Saul's test series.
- In this test series, the Hybrid IIIE peak resultant head acceleration was approximately 19 g's higher than the Part 572.
- The Hybrid IIIE head acceleration was comparable to Saul's results for Part 572 and APR dummies.
- The peak resultant chest acceleration for the Part 572 in the current series is similar to that obtained in Saul's program (38.7 g's vs 38.0).
- The Hybrid IIIE chest acceleration was only 2.3 g's higher than the window containing results of the APR, Hybrid II and Hybrid III in Saul's program.
- Peak thoracic deflections for Hybrid IIIE are 9% lower than for the Hybrid III as measured in Saul's program. The Part 572 is much stiffer with 1.05 in. deflection. This measured deflection is substantially higher than results obtained by Saul (1.05 in. vs 0.28 in.). The deflection/time histories for both the Part 572 and the Hybrid IIIE exhibit substantial differences in terms of event duration. The deflection event duration was 150 ms for the Hybrid IIIE, as opposed to 100 ms for the Part 572. The shape of the curve response was also markedly different as seen in Figure 9.

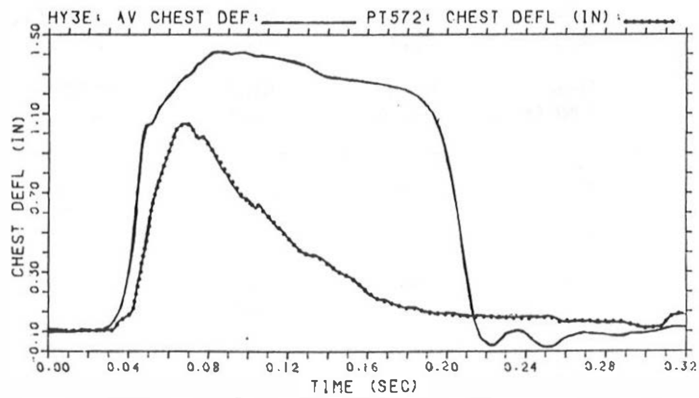


Figure 9: Part 572 and Hybrid IIIE Deflection Response

- Peak resultant pelvic accelerations are within the window of values obtained in Saul's program.
- Though two clavicle failures were recorded on the initial tests using the Hybrid IIIE, all measurements were within a coefficient of variation of 4.9%.

TABLE 1: RESTRAINT SYSTEM MEASUREMENTS

TEST SERIES	TEST #	PEAK SHOULDER BELT LOAD N (lb)		PEAK LAP BELT LOAD N (lb) OUTBOARD		COMMENT
Part 572	455	7940	(1785)	6730	(1513)	No clothing
	459	7575	(1703)	7042	(1583)	-4 Lap Belt score
	460	8171	(1837)	6695	(1505)	+4 Lap Belt Score
Part 572 (Saul)	Mean	7611	(1711)	6734	(1514)	From Reference 7
	Std. Dev.	173	(39.0)	125	(28.0)	
MIRA	456	7330	(1648)	5507	(1238)	No clothing used
	457	7691	(1729)	6356	(1429)	Clothing used
	458	7989	(1796)	6276	(1411)	Clothing used
	Mean	7669	(1724)	6045	(1359)	
	Std Dev.	330	(74.1)	469	(105.4)	All tests
	Mean	7842	(1763)	6316	(1420)	Tests using clothing
	Std Dev.	211	(47.4)	57	(12.7)	on ATD
Hybrid IIIE	461	8527	(1917)	7744	(1741)	Left Clavicle Broke (at shoulder)
	462	8309	(1868)	7855	(1766)	Right Clavicle Broke (at shoulder)
	463	8358	(1879)	8016	(1802)	
	Mean	8398	(1888)	7893	(1770)	
	Std Dev.	143	(25.8)	137	(30.7)	
Hybrid III (Saul)	Mean	8189	(1841)	8095	(1820)	From reference 7
	Std Dev.	307	(69)	320	(72)	

TABLE 2: ATD INSTRUMENTATION MEASUREMENTS

TEST SERIES	TEST #	PEAK RESULTANT HEAD ACC'N (g's)	UPPER SPINE PEAK RESULT CHEST ACC'N (g's)	PEAK CHEST DEFLECTION cm (in)	PEAK RESULT PELVIC ACC'N (g's)
PART 572	455	42.1	39.9	2.64 (1.04)	55.1
	459	38.7	38.7	2.57 (1.01)	54.0
	460	31.1	37.5	2.77 (1.09)	58.6
Part 572 (Saul)	Mean	57.2	38.0	0.71 (0.28)	54.7
	Std Dev.	4.95	1.2	0.8 (0.03)	9.8
MIRA	456	NA	52.6	NA	NA
	457		54.3	NA	NA
	458		47.8	NA	NA
	Mean	NA	51.6	NA	NA
	Std Dev.		3.4		
Hybrid IIIE	461	58.5	46.4	3.81 (1.5)	54.7
	462	56.8	42.2	3.56 (1.4)	53.8
	463	53.1	43.6	3.56 (1.4)	56.8
	Mean	56.1	44.1	3.63 (1.43)	55.1
	Std Dev.	2.8	2.1	0.15 (0.06)	1.5
Hybrid III (Saul)	Mean	74.5	40.0	3.99 (1.6)	57.6
	Std. Dev.	0.18	0.4	0.05 (0.02)	1.9

Overall the ATD thoracic responses were quite similar. As pointed out by Saul (7), these response similarities occur despite very different dummy constructions. Photographic analysis in the current study revealed that the thoracic spines underwent a displacement of approximately 30 cm. Since chest compression accounts for only 8-13% of the ATD excursion. This supports Saul's conclusion that the restraint system is a primary factor in controlling the dummy response.

Comparison to Previous Work

Available data from Kallieris (6) and Saul (7), are included in Table 3. The findings of the current study for the Part 572 are in close agreement with Kallieris' results in terms of head and thorax displacements, and lap belt loads. The Part 572 resultant thorax acceleration variance was only 4.4% among all three investigators.

TABLE 3: ATD DATA COMPARISON TO KALLIERIS AND SAUL RESULTS

ATD	SOURCE	HEAD DISPLACEMENT cm	(in)	THORAX DISPLACEMENT cm	(in)	OUTBOARD LAP BELT N (lb)	THORAX RESULTANT g's	SHOULDER BELT LOAD N (lb)
Cadaver	Kallieris	56	(22)	41	(16)	5293 (1190)	41	N/A
Part 572	Kallieris	48	(19)	25	(10)	6917 (1555)	37	N/A
Part 572	Saul	58	(23)	43	(17)	6734 (1514)	38	7611 (1711)
Hybrid III	Saul	59.7	(23.5)	40.4	(15.9)	8095 (1820)	40	8189 (1841)
Part 572	present	49	(19.3)	23.4	(9.2)	6824 (1534)	38.7	7896 (1775)
MIRA	present	52.6	(20.7)	22.9	(9)	6045 (1359)	51.6	7842 (1763)
Hybrid IIIE	present	52.8	(8.2)	20.8	(8.2)	7873 (1770)	44.1	8398 (1888)

It is interesting to note that the MIRA and Hybrid IIIE dummies, exhibited higher head displacements than the Part 572, but exhibited substantially different lap belt loads, and peak thoracic resultant accelerations. Also, based on the findings in this study, the effect of clothing on ATD kinematics are negligible in terms of head excursion, but accounts for approximately a 10% decrease in thorax displacement. The lap belt load is also approximately 15% higher and the shoulder belt load is approximately 7% higher.

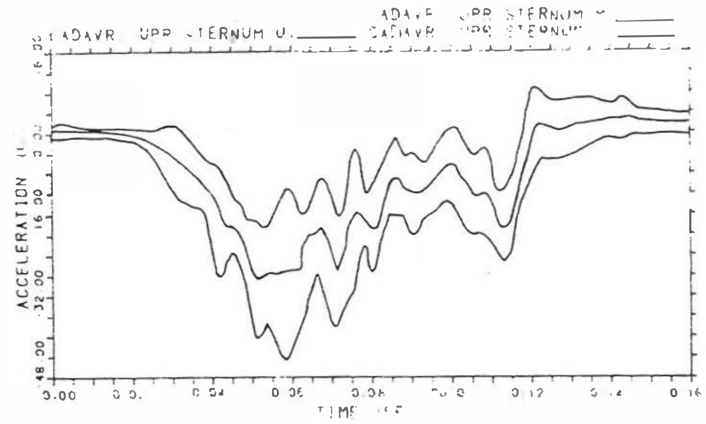
The Part 572 and Hybrid IIIE responses are quite similar to the results obtained by Saul's (7) ATD samples, except for the pelvic responses. The peak pelvic accelerations were typically higher in the present study. The MIRA sternal responses were different from the other ATD's, though no explanation is proposed. The MIRA upper spine response though repeatable, was not as smooth as the Part 572 and Hybrid IIIE.

Comparison of Overall Responses of Hybrid IIIE to Hybrid III

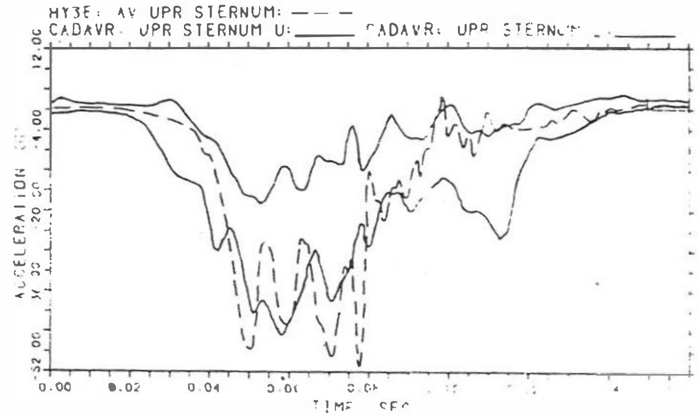
Data obtained in this program for the Hybrid IIIE was compared to the responses of the GM Hybrid III as measured by Saul (7). Mean shoulder belt and lap belt responses varied by a maximum 2.4% from the Hybrid III to the Hybrid IIIE the latter having the higher values. Mean peak resultant head acceleration was 25% higher (74.5 g's) on the Hybrid III, but peak resultant chest acceleration was 10% lower (40 g's), in comparison to the modified Hybrid III. Peak mid-sternal deflection was 9% lower for the Hybrid IIIE. Mean peak resultant pelvic acceleration were 4% higher for the Hybrid III dummy. Maximum head displacement was 12% higher for the Hybrid III compared to the Hybrid IIIE. Chest displacement was 50% lower for the Hybrid IIIE. It is interesting to note that Saul's thoracic displacement for the Part 572 was also approximately 50% higher than for the Part 572 dummy tested in the present program. The reasons for these latter differences are not apparent at the time of writing.

Comparison to Cadaver Data

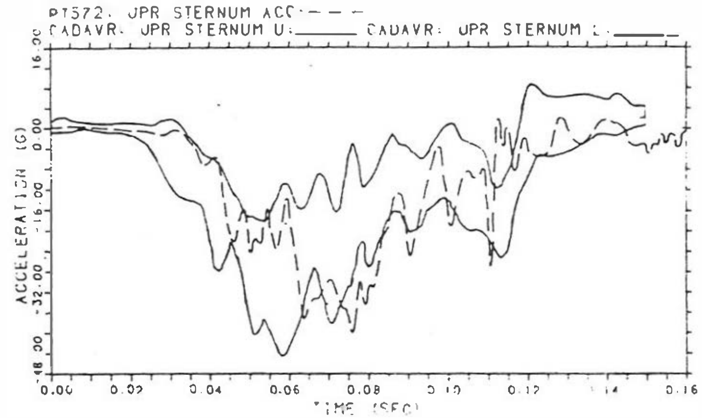
A detailed comparison was made with a data base using 13 cadaver tests as chosen by Saul (7) based on the Heidelberg cadaver data described by Kallieris (6). From these tests, ATD comparisons were made for belt loads, sternal (upper and lower), spinal (upper and lower) and pelvic accelerations. Typical comparisons appear in Figures 10 to 13.



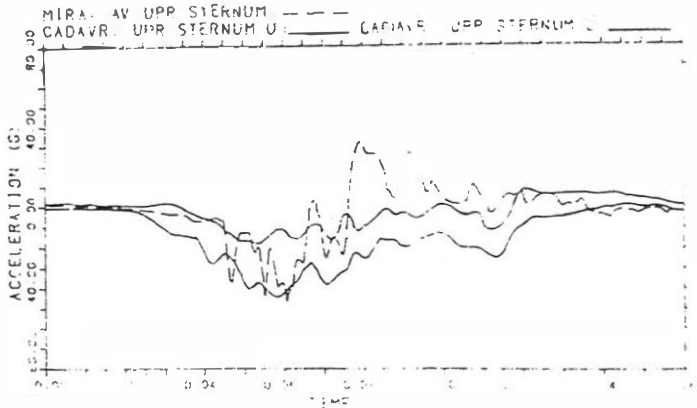
a. Cadaver



c. Hybrid III E

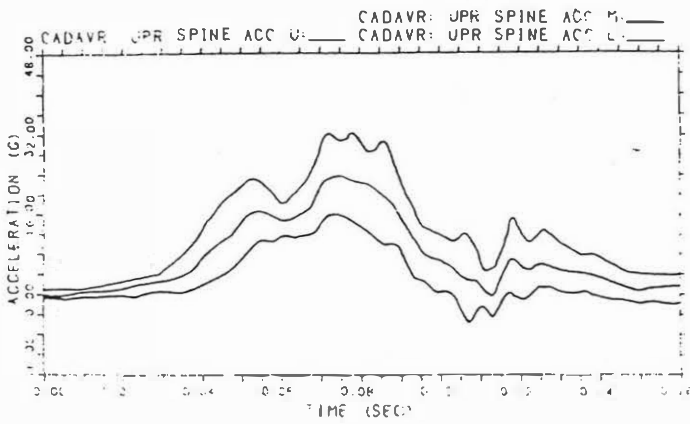


b. Part 572

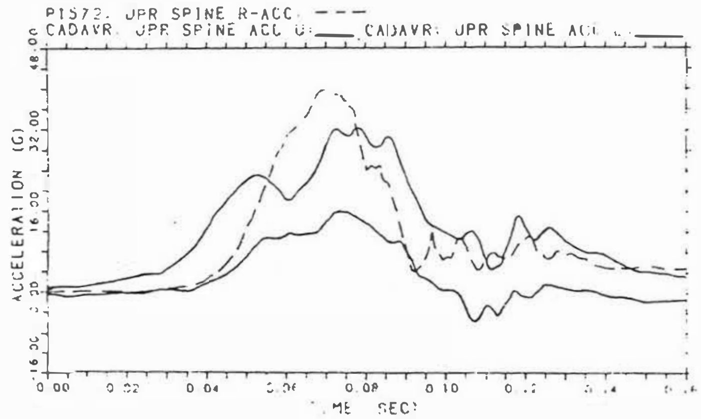


d. MIRA

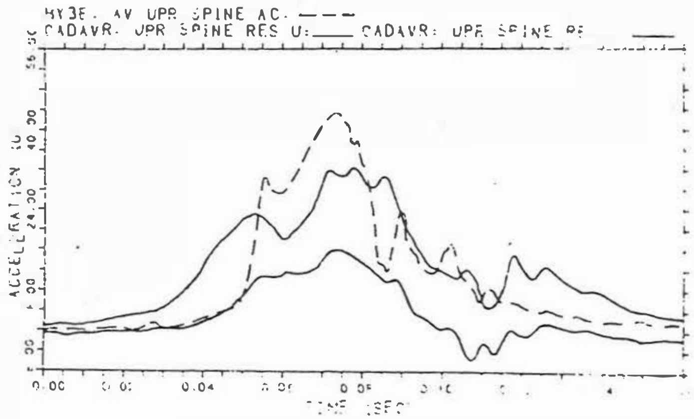
Fig. 10 Cadaver and Dummy Upper Sternum Acceleration Responses



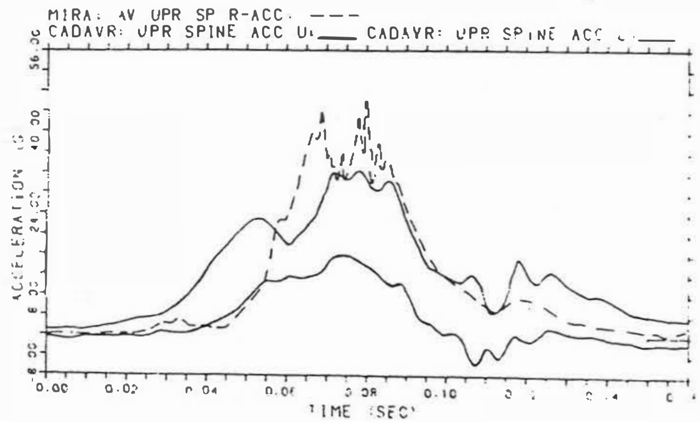
a. Cadaver



b. Part 572

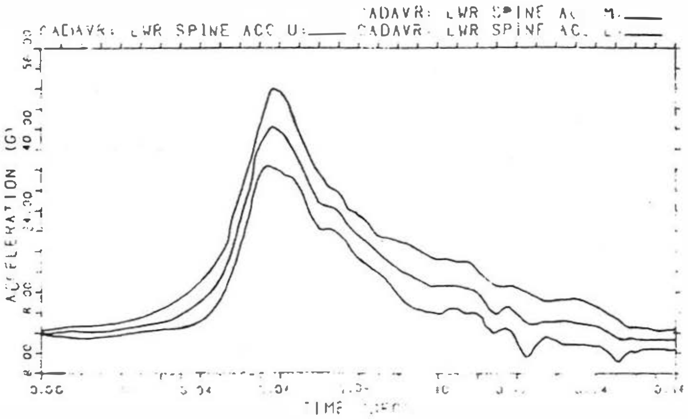


c. Hybrid III E

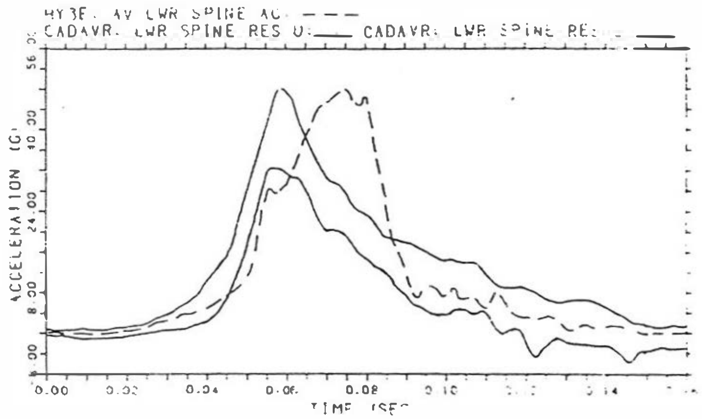


d. MIRA

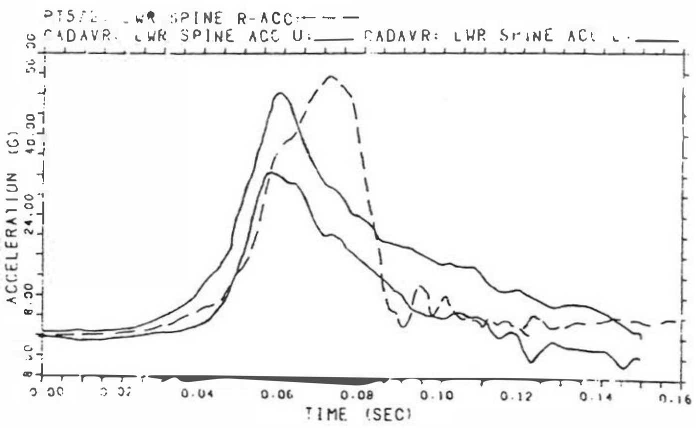
Fig. 11: Cadaver and Dummy Upper Spine Acceleration Responses



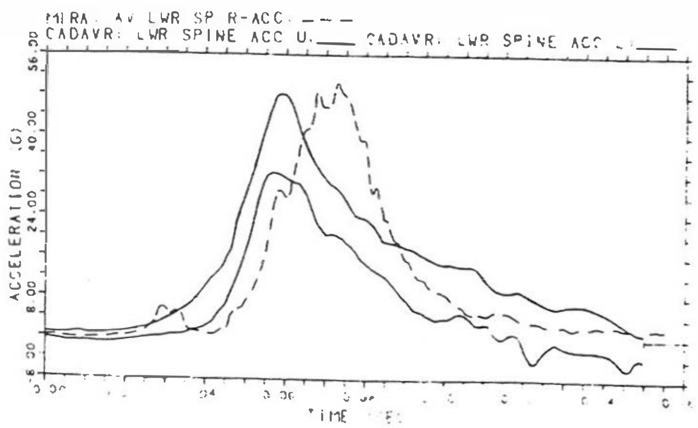
a. Cadaver



c. Hybrid III E

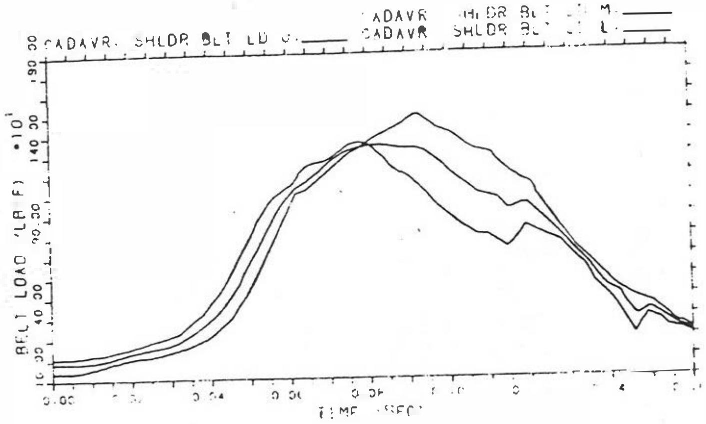


b. Part 572

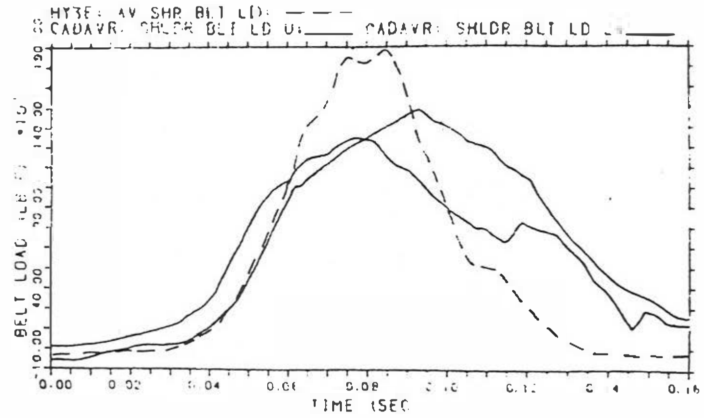


d. MIRA

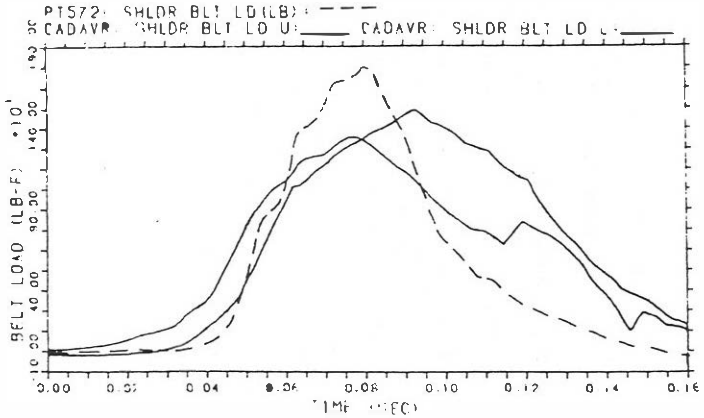
Fig. 12: Cadaver and Dummy Lower Spine Acceleration Responses



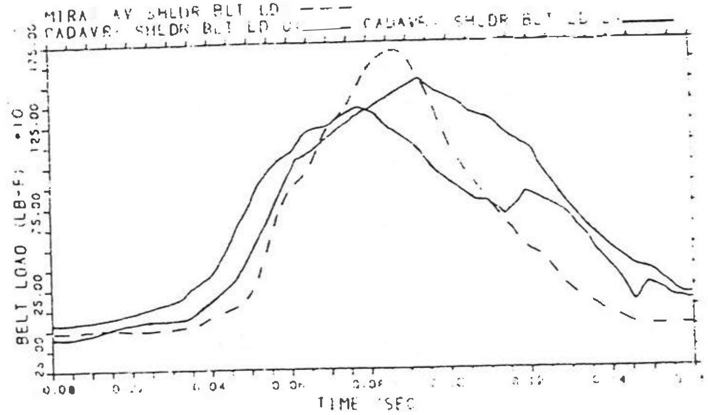
a. Cadaver



c. Hybrid III E



b. Part 572



d. MIRA

Fig. 13: Cadaver and Dummy Shoulder Belt Responses

SUMMARY AND CONCLUSIONS

Finite element modelling has proven to be a very useful tool in the design of the new ATD thorax.

The newly designed ATD thorax comprises ten rib elements, each of which are pivoted at the spine box junction. Internally, adjustable linear decelerators provide the necessary viscous properties.

Statically and quasistatically, the design has been shown to faithfully emulate the relaxed human thorax structure response to strip loading. Dynamically, the response can be made more or less human-like by adjustment of the viscous elements.

In a realistic 3-point belt system impact environment, the restraint system is the primary factor in controlling the dummy response.

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