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BIOMECHANICAL RESPONSE AND INJURY TOLERANCE IN EIGHT CADAVERIC SIDE IMPACTS

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ABSTRACT

Under the present CDC side impact grant eight cadaveric side impact sled tests have been performed. In these tests the subject's whole body impacts a rigid side wall. The tests run to date are shown in Table 1. The purpose of these tests is to ascertain the biomechanical response and injury tolerance in whole-body side impacts at four levels: shoulder, thorax, abdomen and pelvis. This paper presents the results of the eight tests run to date.

INTRODUCTION

Side impact is a most serious automotive injury problem, second only to frontal impact. Each year, about 8,000 automobile occupants are killed and thousands more injured due to side impact. In a recent review of fatality data by Viano et al (1989a), it was found that 31.8% of passenger car fatalities occur in crashes with the principal direction of force lateral to the vehicle. Of those, 2/3 of the fatalities are due to multi-vehicle crashes and the remainder involved the impact of a single vehicle with a fixed object. Multi-vehicle crashes frequently involve the older victim, over the age of 40. When side and frontal impact fatalities are compared, the age of the occupant emerges as an important factor in side impacts. Multi-vehicle side impacts represent about half of the fatalities in the age group over 40. Despite the gravity of the situation, the biomechanics community has not accepted a universal injury criterion for the thorax and the abdomen. More data is required to define the response of the torso to side impact in the sense that regional impact data need to be verified by whole-body sled tests. That is, the distribution of load to various regions of the torso can only be determined by a whole-body test in which loads encountered by each region are measured simultaneously. Such confirmation is necessary for the design and fabrication of a more human-like side impact dummy (SID).

There have been relatively few cadaveric sled tests which include impact forces as part of the measured response. A paper by Eppinger et al (1984) report on eleven tests which include thorax and pelvic forces run at the University of Heidelberg. The tests we have run under the CDC grant are the first sled tests in which shoulder, thoracic, abdominal and pelvic forces are measured separately. In addition, these tests include high speed film recordings from four to six cameras so that deformation response can be determined at the same four levels. With this data, normalized force-time history, force-deflection, and acceleration-time history corridors will be developed for use in understanding side impact response and to add much needed corridors for the development of a biofidelic side-impact dummy. In addition the film data will be used to determine VCmax and its ability to predict injury in whole body side impacts. The three test configurations (rigid wall, padded wall and pelvic offset) will be used to assess how TTI and VCmax perform as injury criteria in a variety of side wall conditions. Other injury criteria will also be evaluated.

METHODS

The surrogates used in the lateral impact tests were unembalmed human cadavers donated to the University under the Willed Body Program. The cadavers were used shortly after rigor mortis had passed. The subjects were positioned on a Heidelberg-type seat fixture (illustrated in Marcus et al, 1983) which in turn was mounted to a horizontally accelerated sled. The sled was accelerated up to velocities of 6.7 to 10.5 m/s and then rapidly decelerated so that the cadavers would continue to translate laterally on a teflon seat into the wall of the seat fixture. The cadaver was instrumented with accelero- meters and pressure transducers to record the kinetics and kinematics of impact. The impact side wall was instrumented with nine uniaxial load cells to record impact forces (Fig. 1).

Cadaver Preparation and Instrumentation

The cadavers had pre-test x-rays taken of all skeletal structures as well as abdominal and chest x-rays in order to determine existing skeletal and soft tissue anomalies. The cadavers were instrumented with accelerometers on the vertex of the skull in the 3-2-2-2 configuration described by Padgaoankar et al (1975). The twelve accelerometer thoracic array as developed by Robbins et al (1976) and by Eppinger et al (1978) was used to instrument the ribs, sternum, and thoracic vertebrae. The sacrum was instrumented with a triaxial accelerometer. Phototargets were mounted at upper and lower sternum, T1, T5, T12, sacrum, right iliac crest, right fourth rib, right eighth rib, right shoulder joint, left clavicle, and left scapula. This array of targets will be used to measure trunk deformation, rib cage rotation, and the trajectory of the shoulder during impact.

The vascular system of the cadaver was repressurized in the thorax and abdomen with balloon catheters fed through the carotid arteries and jugular veins into the thorax. Arterial pressure was measured with a pressure transducer fed from a carotid artery into the thoracic aorta. Placement was verified by x-ray. The femoral arteries and veins were tied off. Just before testing, a solution of India ink and normal saline was pumped into the vascular system from a pressurized tank. The arterial system was pressurized to 100 mm Hg, and the venous system to 50 mm Hg. The pressure tranducer monitored pre-impact and impact arterial pressure.

A tracheotomy was performed to permit access to the lungs, which were aerated five to seven times just before impact and left unpressurized.

Sled Preparation and Instrumentation

The sled used was the horizontally accelerated WHAM III. The sled measures 2.0 m wide by 3.66 m long and is accelerated on a 40 m track. The system has a pneumatic propulsion device with a 22 m long acceleration stroke. At the end of this stroke the sled is disengaged from the propulsion

TABLE 1:PARAMETERS FOR CDC CADAVERIC SLED SIDE IMPACTS SIC 01-08.

RUN NO.	RUN DATE	PELVIC OFFSET (INCHES)	WALL PAD?	VELOCITY (MPH)	VELOCITY (M/S)	CADAVER NO.	MASS (KG)	HEIGHT (M)	AGE	SEX
SIC01	1-20-89	6	NO	19.94	8.91	UM6	70.5	1.76	67	M
SIC02	1-30-89	6	NO	20.29	9.07	187	49.5	1.63	64	F
SIC03	2-03-89	6	NO	23.43	10.47	188	70.0	1.75	37	M
SIC04	4-03-89	0	NO	20.25	9.05	215	57.6	1.63	69	M
SIC05	4-10-89	0	NO	15.00	6.71	216	44.0	1.72	67	M
SIC06	4-27-89	0	NO	20.23	9.04	217	61.2	1.84	60	M
SIC07	5-16-89	0	NO	14.92	6.67	206	74.8	1.70	66	M
SIC08	8-10-89	0	NO	14.74	6.59	UM12	73.9	1.62	64	F

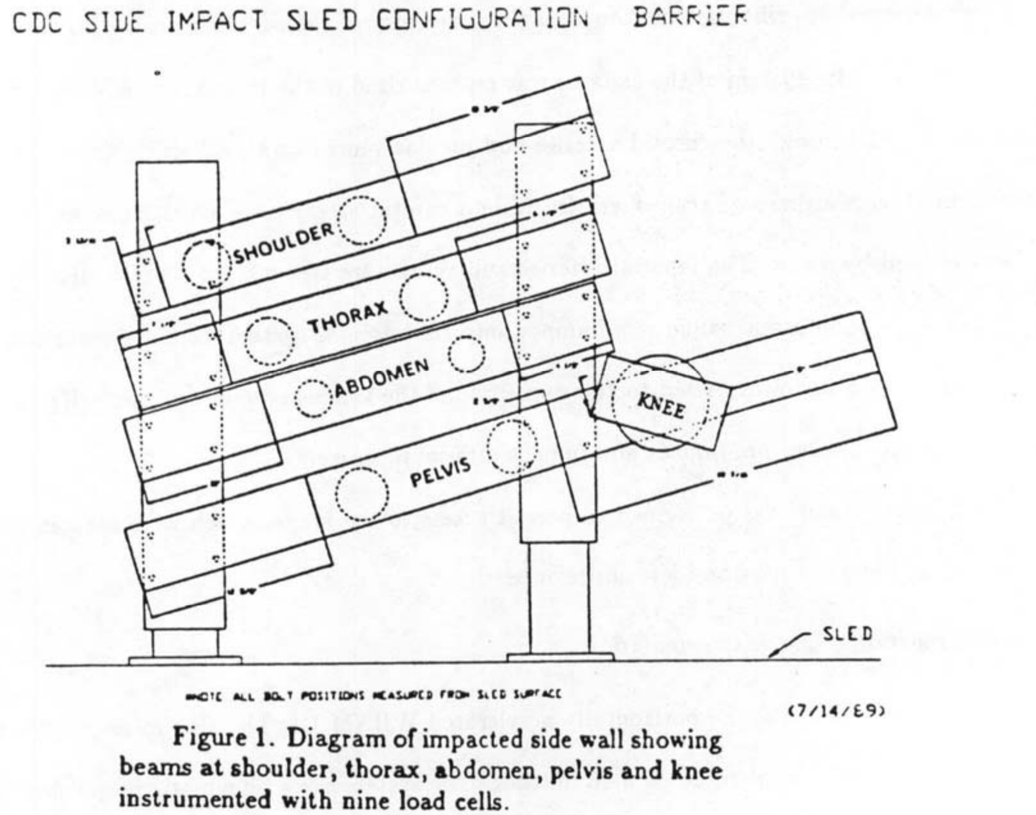


Figure 1. Diagram of impacted side wall showing beams at shoulder, thorax, abdomen, pelvis and knee instrumented with nine load cells.

mechanism and allowed to strike a hydraulic snubber. Snubber stroke was set at 0.203 m (8"). The sled was instrumented to measure sled acceleration and velocity.

Impact Test Procedure

The test subject was placed on the seat structure described above. In order to achieve a lateral impact where the subject approaches the impacting wall at a predetermined velocity, the subject was positioned parallel to and approximately one meter from the wall, with the left side (the struck side), facing the instrumented side wall. The subject sat against the two-bar seat back. In all tests the forearms were positioned slightly anterior to the mid-axillary line by tying the arms together at the wrists with duct-tape and letting the arms rest on the lap. This exposed a portion of the left side of the thorax to direct impact.

Autopsy

After the impact, x-rays were taken of the abdomen and thorax and all skeletal structures. A detailed autopsy was carried out by a board certified pathologist. The autopsy covered all regions of the body but special attention was focused on thoracic, abdominal and pelvic injuries.

Cadavers were handled with the infection control precautions we have developed as an extension of Centers for Disease Control guidelines. The protocol is in press (Cavanaugh and King, 1989).

Data Processing

Analog data were filtered at 1000 Hz (SAE class), digitized at 8000 Hz and uploaded to a Multiflow mainframe for further data processing.

RESULTS AND DISCUSSION

BIOMECHANICAL RESPONSE

The side-wall force data were digitally filtered with a 300 Hz Butterworth filter, and acceleration data were digitially subsampled and 100 Hz FIR filtered per the procedure outlined by Morgan et al (1986). The data were normalized using the equal stress-equal velocity scaling procedure outlined by Eppinger et al (1984). In this paper only the force data is presented.

Response of Individual Levels

The force-time histories at each of the four anatomical levels (shoulder, thorax, abdomen, and pelvis) are computed by summing the load cell responses of the two load cells at that level (Fig. 1). The maximum forces at the four levels vary from test to test and level to level, but, overall, increase with increasing subject mass and subject velocity. For the four impacted levels normalized force-time plots are presented for the 9 m/s unpadded wall with 0.15 m pelvic offset, 9 m/s unpadded, flush wall, and 6.7 m/s unpadded, flush wall (Figures 2a-2c, 3a-3c, 4a-4c, 5a-5c). In Table 2 are listed the maximum force responses at each level.

Shoulder

The peak shoulder forces averaged 3.93 kN in the 9 m/s pelvic offset tests, 5.47 kN in the 9 m/s flush wall tests and 3.40 kN in the 6.7 m/s flush wall tests.

In this test series we have gained some insight into how the shoulder (Fig. 6) deforms during side impact. Anterior or posterior rotation of the shoulder is not seen in the films. The clavicle does not fracture or separate from its attachment to the sternum. In many cases it separated from the scapula (acromio-clavicular separation: SIC01, 02, 04, 06, 07, 08). In two tests, (SIC05,06) review of high speed films of targets mounted to the scapula shows translation of the thoracic spine toward the scapula, and what appears to be a bottoming out of the scapula onto the thoracic spine (Fig. 7a-b). In SIC05 the spine displaced 36 mm toward the scapula. In SIC06 the spine displaced 53 mm toward the scapula (normalized displacements). The upper sternum x-accelerations are large (36-119 G's), indicating that the sternum is being pushed outward, perhaps by the clavicle at the sterno-clavicular joint. It appears that the following events occur when the shoulder is impacted laterally: translation of thoracic spine toward the scapula, acromio-clavicular separation, and movement of the sterno-clavicular joint anteriorly. These motions would account for what appears to be a virtual disappearance of the shoulder into the thorax with little anterior or posterior rotation at the gleno-humeral joint.

Thorax

If the shoulder beam is combined with the thoracic beam the area covered is the same as the thoracic plate in the Heidelberg sled tests. The peak shoulder plus thoracic forces averaged 7.41 kN in the 9 m/s pelvic offset tests, 8.48 kN in the 9 m/s flush wall tests and 5.69 kN in the 6.7 m/s flush wall tests. These peaks are less than the corresponding peaks in the Heidelberg tests as represented by the International Standards Organization (ISO) corridors for 8.9 and 6.7 m/s sled tests (Figs. 8a and 8b). This is probably due to the greater difference in velocity between the cadaver and barrier in the Heidelberg tests compared to our tests: approximately 23 mph for the 20 mph sled velocity and 29 mph for the 25 mph sled velocity, as described by Marcus et al (1983). This was due to rebounding of the sled into the direction of the cadaver during impact. WSU forces are also probably less because in these tests there was an abdominal plate directly below the thoracic plate. In the Heidelberg tests there was a 90 mm gap below the thoracic force plate, which would result in inertial forces in the abdomen being partially picked up by the thoracic force plate. The time duration of the WSU force pulses are similar to those of the Heidelberg tests.

Maximum normalized thoracic compression has been obtained in five tests thus far. The compression is defined here as the deflection of the struck side half-thorax (measured at the T5 level) divided by one-half of the chest width x 100. These values are as follows (with normalized half-thorax deflections in parentheses): SIC03: 92% (146 mm), SIC04: 69% (119 mm), SIC05: 53% (84 mm), SIC06: 63% (90mm), SIC07: 44% (72 mm). These result in average compressions of 48% in the 6.7 m/s flush wall tests, 66% in the 9 m/s flush wall tests, and 92 % in the 10.5 m/s pelvic offset test.

When the forces at the shoulder, thorax, and abdominal beams are added together, the impacted area is approximately that of the hard thorax, defined by Eppinger et al (1982). The hard thorax includes upper abdominal organs that lie within the rib cage, including the liver and spleen. As seen in the normalized data of Figures 9a-9c, the responses between tests closely match each other for tests with the same impact parameters.

Abdomen

The peak abdominal forces averaged 3.43 kN in the 9 m/s pelvic offset tests, 4.60 kN in the 9 m/s flush wall tests and 3.15 kN in the 6.7 m/s flush wall tests.

TABLE 2: INJURY AND RESPONSE DATA FOR CDC SIC 01-08.

OVERALL RESPONSE

RUN NO.	VEL. (M/S)	TOTAL KE (J)	TOTAL MOMENTUM (KG*M/S)	SUM OF AIS	NUMBER OF INJURIES
SIC01	8.91	2799	628	26	9
SIC02	9.07	2038	449	31	11
SIC03	10.47	3839	733	23	6
SIC04	9.05	2360	521	17	7
SIC05	6.71	989	295	10	3
SIC06	9.04	2504	554	12	5
SIC07	6.67	1664	499	11	4
SIC08	6.59	1605	487	25	9

THORAX

RUN NO.	AGE	MASS (KG)	MAX AIS	SUM OF AIS	AGE CORR MAX AIS	TOTAL NO. OF RIB FX	NO. OF LEFT RIB FX	300 HZ NORM FORCE (kN)	SHOULD+ THORAX FORCE (kN)
SIC01	67	70.5	5	17	4.45	31	21	4.55	7.08
SIC02	64	49.5	5	15	4.53	35	26	3.37	7.10
SIC03	37	70.0	5	20	5.20	24	16	4.07	11.06
SIC04	69	57.6	4	6	3.40	22	19	3.90	9.18
SIC05	67	44.0	4	7	3.45	20	12	1.60	5.26
SIC06	60	61.2	4	6	3.63	13	11	3.02	7.77
SIC07	66	74.8	4	6	3.48	16	13	2.62	6.02
SIC08	64	73.9	5	15	4.53	24	16	3.01	5.79

SHOULDER

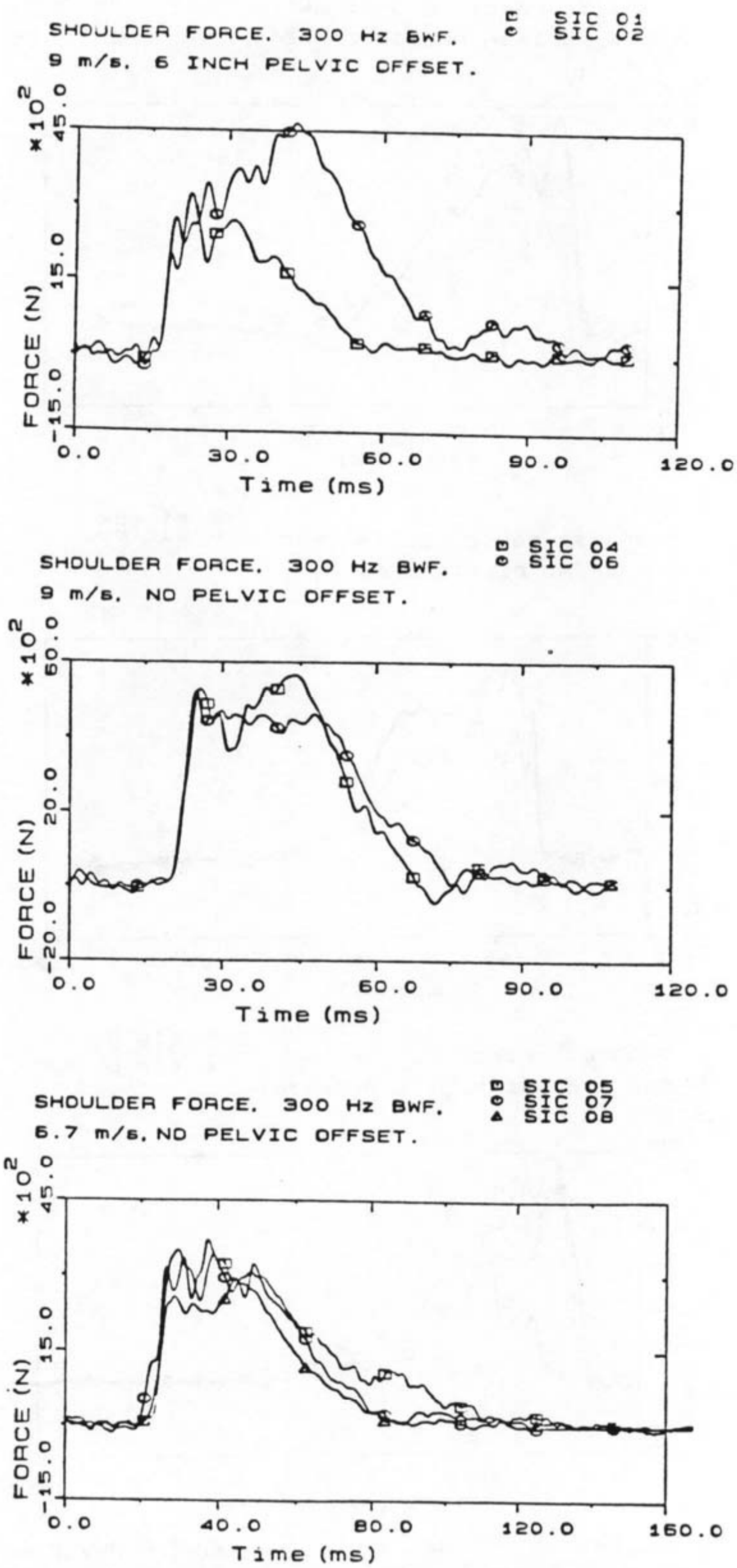
RUN NO.	AGE	MASS (KG)	MAX AIS	SUM OF AIS	300 HZ NORM FORCE (kN)
SIC01	67	70.5	2	4	3.20
SIC02	64	49.5	2	4	4.67
SIC03	37	70.0	2	0	8.30
SIC04	69	57.6	2	4	5.66
SIC05	67	44.0	0	0	3.76
SIC06	60	61.2	2	4	5.28
SIC07	66	74.8	2	4	3.52
SIC08	64	73.9	2	4	2.92

ABDOMEN

RUN NO.	AGE	MASS (KG)	MAX AIS	SUM OF AIS	300 HZ NORM FORCE (kN)
SIC01	67	70.5	2	2	3.61
SIC02	64	49.5	2	2	3.25
SIC03	37	70.0	0	0	5.53
SIC04	69	57.6	2	2	4.50
SIC05	67	44.0	0	0	3.79
SIC06	60	61.2	0	0	4.70
SIC07	66	74.8	0	0	2.83
SIC08	64	73.9	0	0	2.83

PELVIS

RUN NO.	AGE	MASS (KG)	MAX AIS	SUM OF AIS	NO. OF PELVIC FX	MASS CORR W/ LIVI INDEX (KG)	300 HZ NORM FORCE (kN)	CESARI PELVIC FORCE TOL. (kN)
SIC01	67	70.5	2	4	3	71	12.14	8.97
SIC02	64	49.5	3	5	3	52	11.29	5.31
SIC03	37	70.0	2	2	2	70	16.48	8.83
SIC04	69	57.6	2	2	1	57	12.92	6.33
SIC05	67	44.0	0	0	0	50	10.83	5.06
SIC06	60	61.2	2	2	2	67	10.76	8.31
SIC07	66	74.8	0	0	0	71	6.68	9.01
SIC08	64	73.9	0	0	0	67	6.20	8.25



SHOULDER

PEAK FORCES (kN)
300 HZ BWF

SIC01 3.20
SIC02 4.67
AVG 3.93

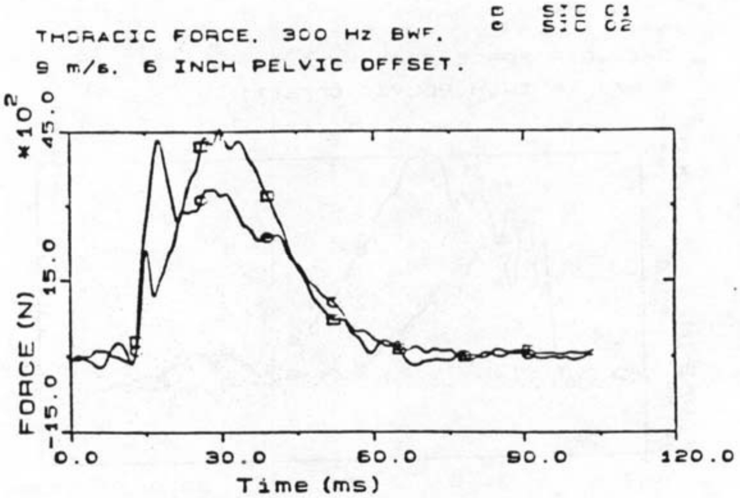
SIC04 5.66
SIC06 5.28
AVG 5.47

SIC05 3.76
SIC07 3.52
SIC08 2.92
AVG 3.40

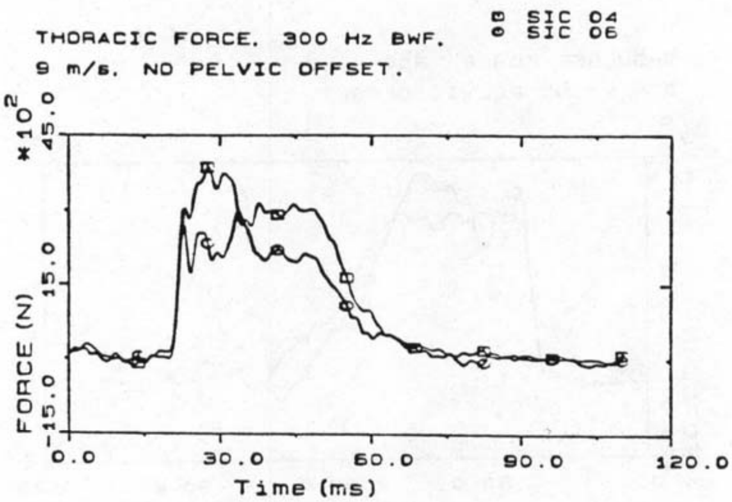
Figures 2a-2c. Force-time histories at shoulder. a. 9 m/s unpadded, 0.15 m pelvic offset tests. b. 9 m/s unpadded, flush wall tests. c. 6.7 m/s unpadded flush wall tests. Peak forces and the average of those peak forces are shown to the right of each plot.

THORAX

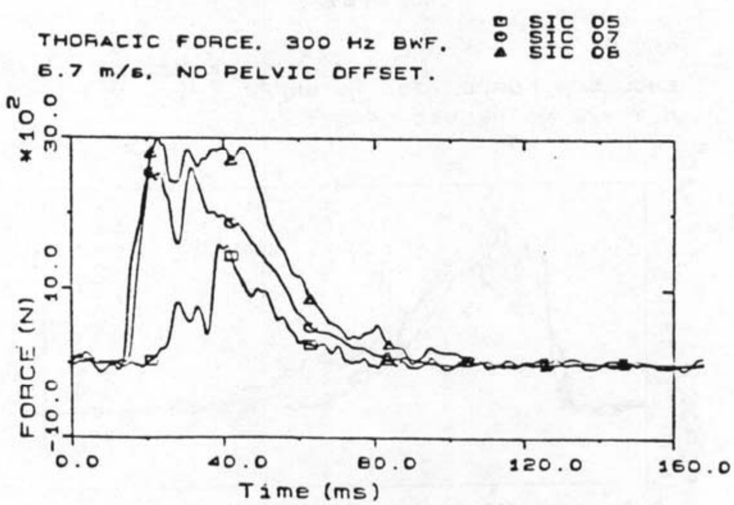
PEAK FORCES (kN)
300 HZ BWF



SIC01 4.55
SIC02 3.37
AVG 3.96

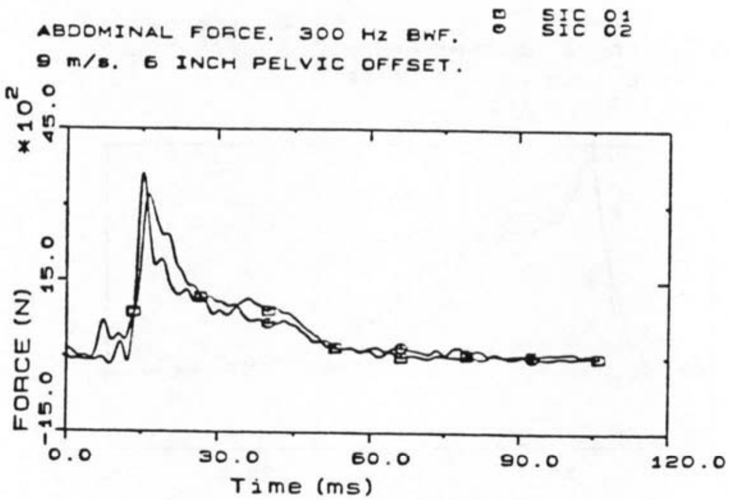


SIC04 3.90
SIC06 3.02
AVG 3.46



SIC05 1.60
SIC07 2.62
SIC08 3.01
AVG 2.41

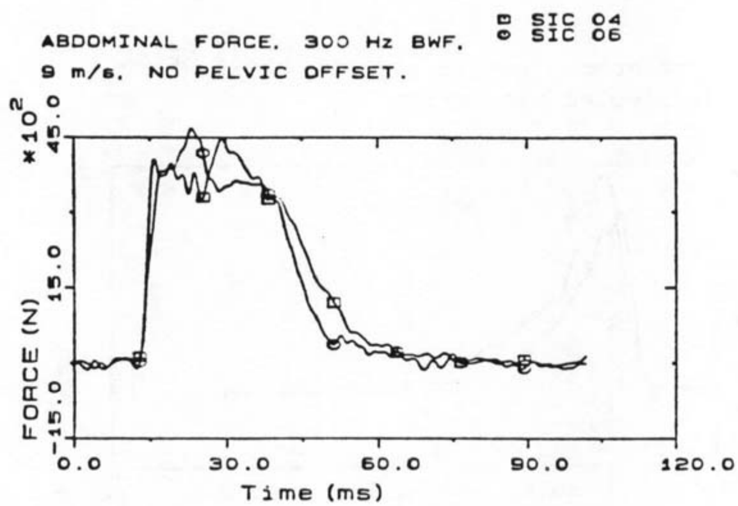
Figures 3a-3c. Force-time histories at thorax. a. 9 m/s unpadded, 0.15 m pelvic offset tests. b. 9 m/s unpadded, flush wall tests. c. 6.7 m/s unpadded flush wall tests. Peak forces and the average of those peak forces are shown to the right of each plot.



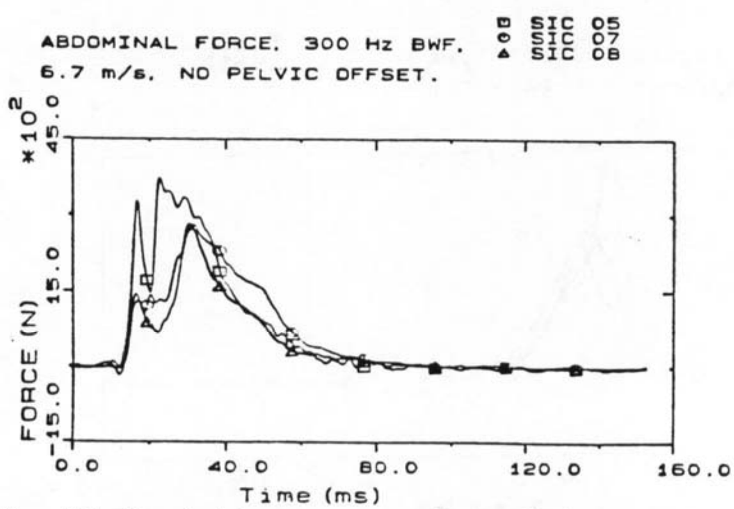
ABDOMEN

PEAK FORCES (kN)
300 HZ BWF

SIC01 3.61
SIC02 3.25
AVG 3.43

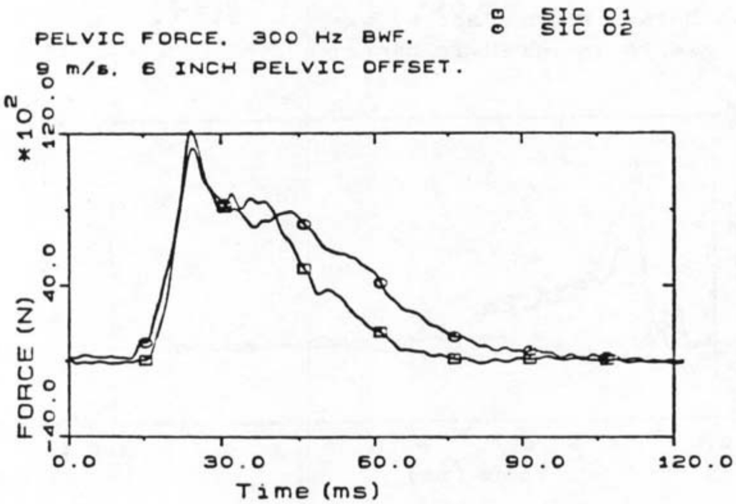


SIC04 4.50
SIC06 4.70
AVG 4.60



SIC05 3.79
SIC07 2.83
SIC08 2.83
AVG 3.15

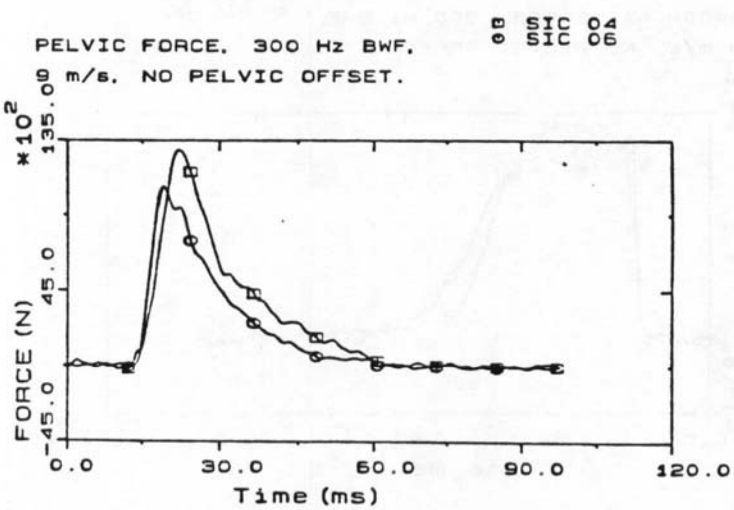
Figures 4a-4c. Force-time histories at abdomen. a. 9 m/s unpadded, 0.15 m pelvic offset tests. b. 9 m/s unpadded, flush wall tests. c. 6.7 m/s unpadded flush wall tests. Peak forces and the average of those peak forces are shown to the right of each plot.



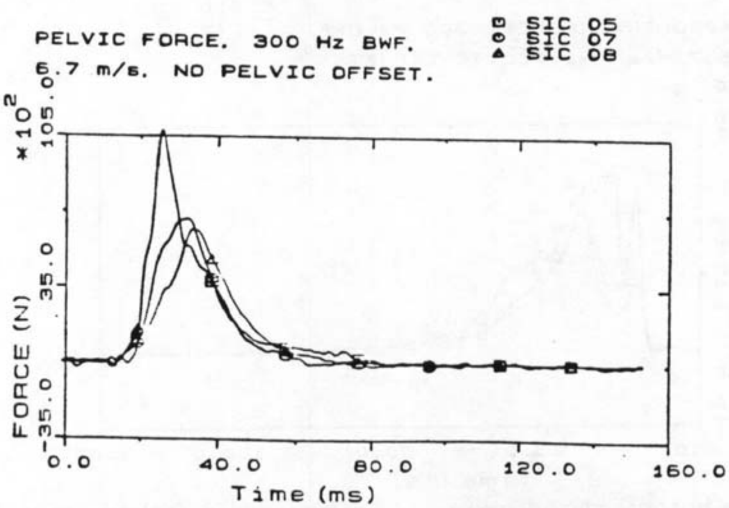
PELVIS

PEAK FORCES (kN)
300 HZ BWF

SIC01 12.14
SIC02 11.29
AVG 11.71



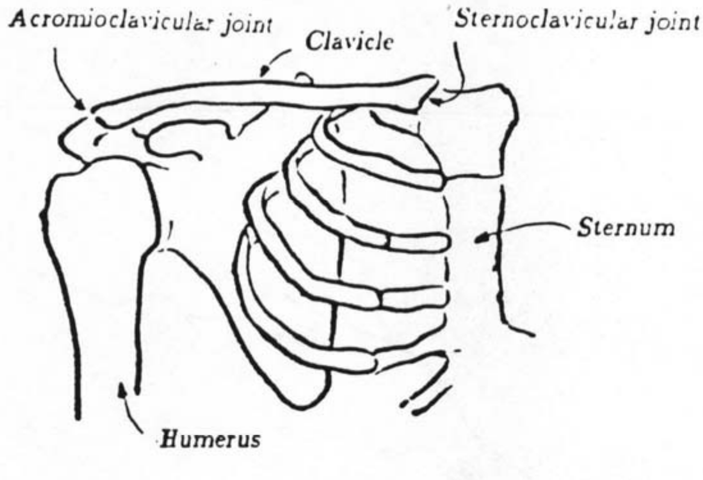
SIC04 12.92
SIC06 10.76
AVG 11.84



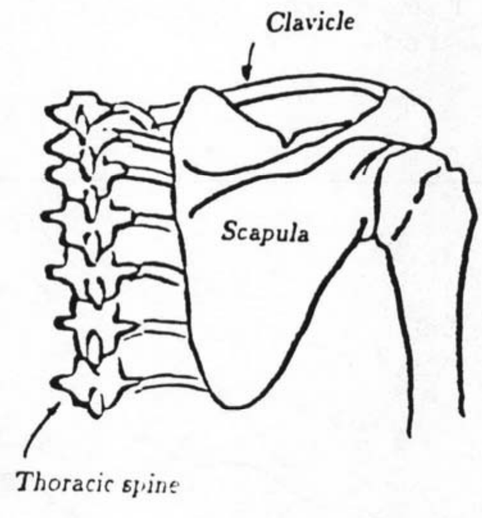
SIC05 10.83
SIC07 6.68
SIC08 6.20
AVG 7.90

Figures 5a-5c. Force-time histories at pelvis. a. 9 m/s unpadded, 0.15 m pelvic offset tests. b. 9 m/s unpadded, flush wall tests. c. 6.7 m/s unpadded flush wall tests. Peak forces and the average of those peak forces are shown to the right of each plot.

Shoulder

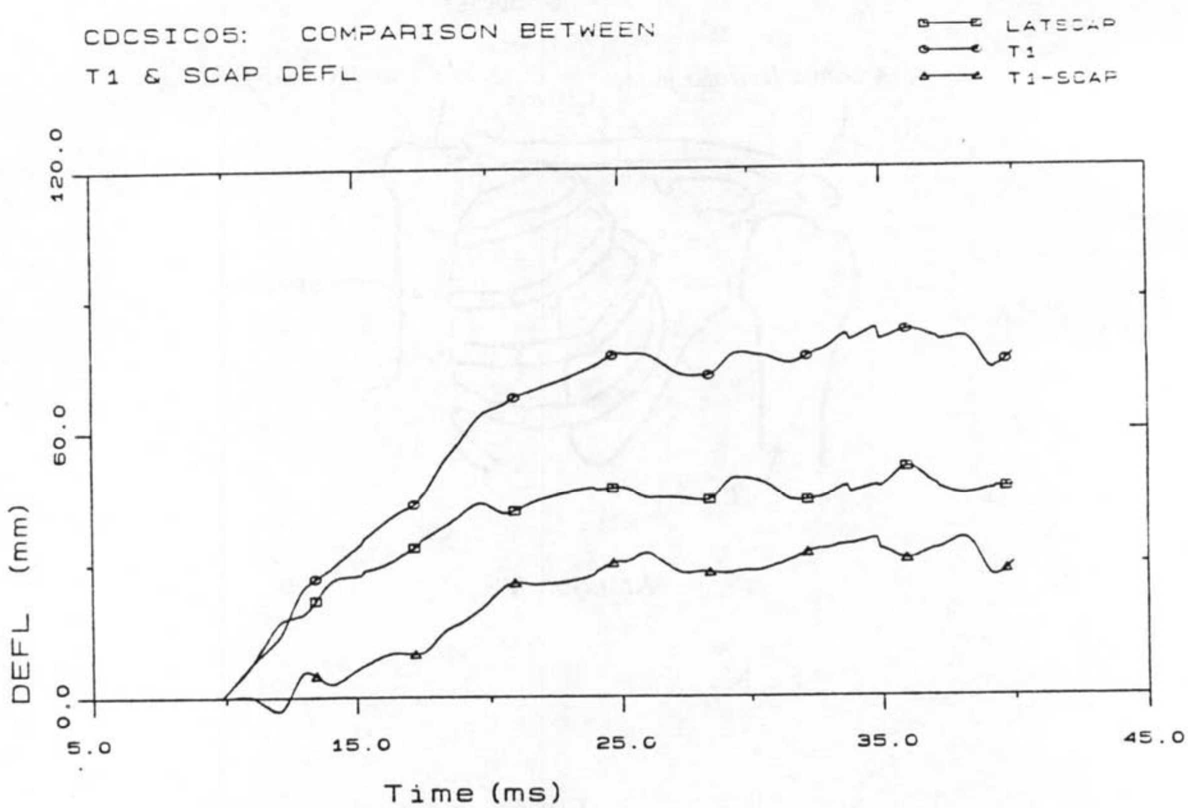


Anterior View



Posterior View

Figure 6. Skeletal anatomy of shoulder.



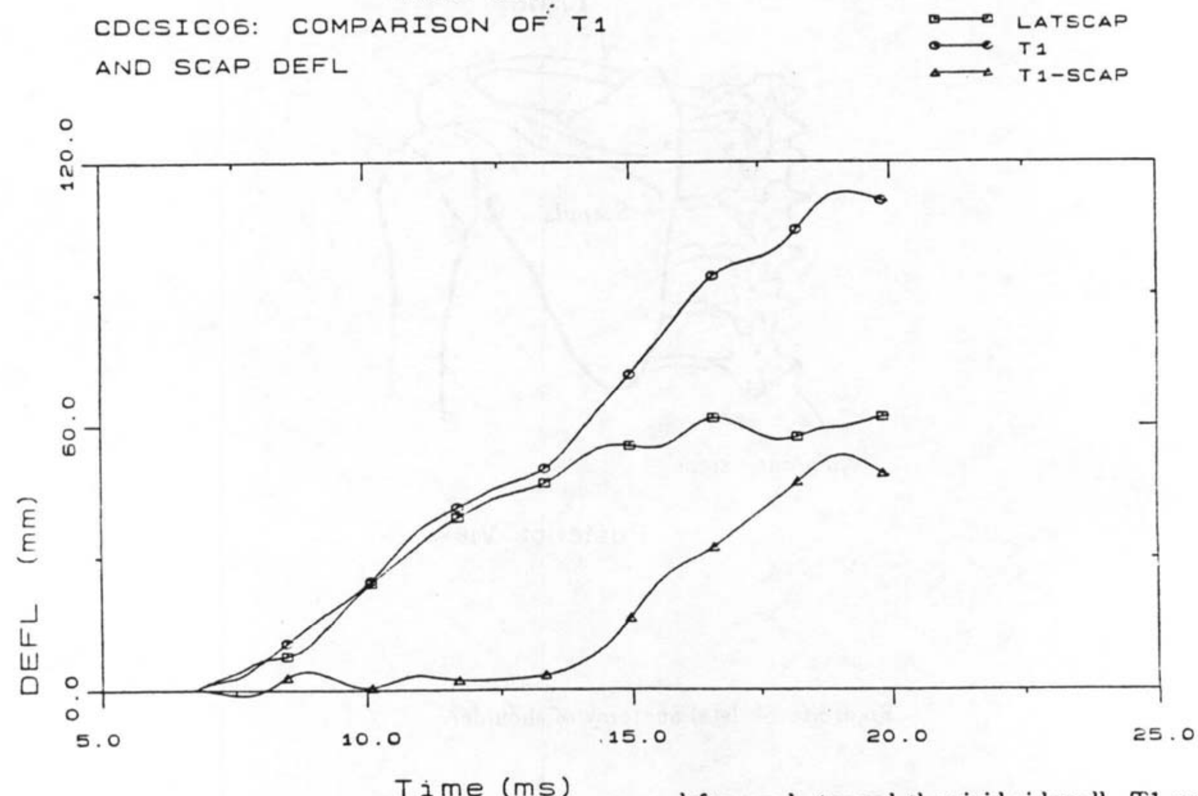
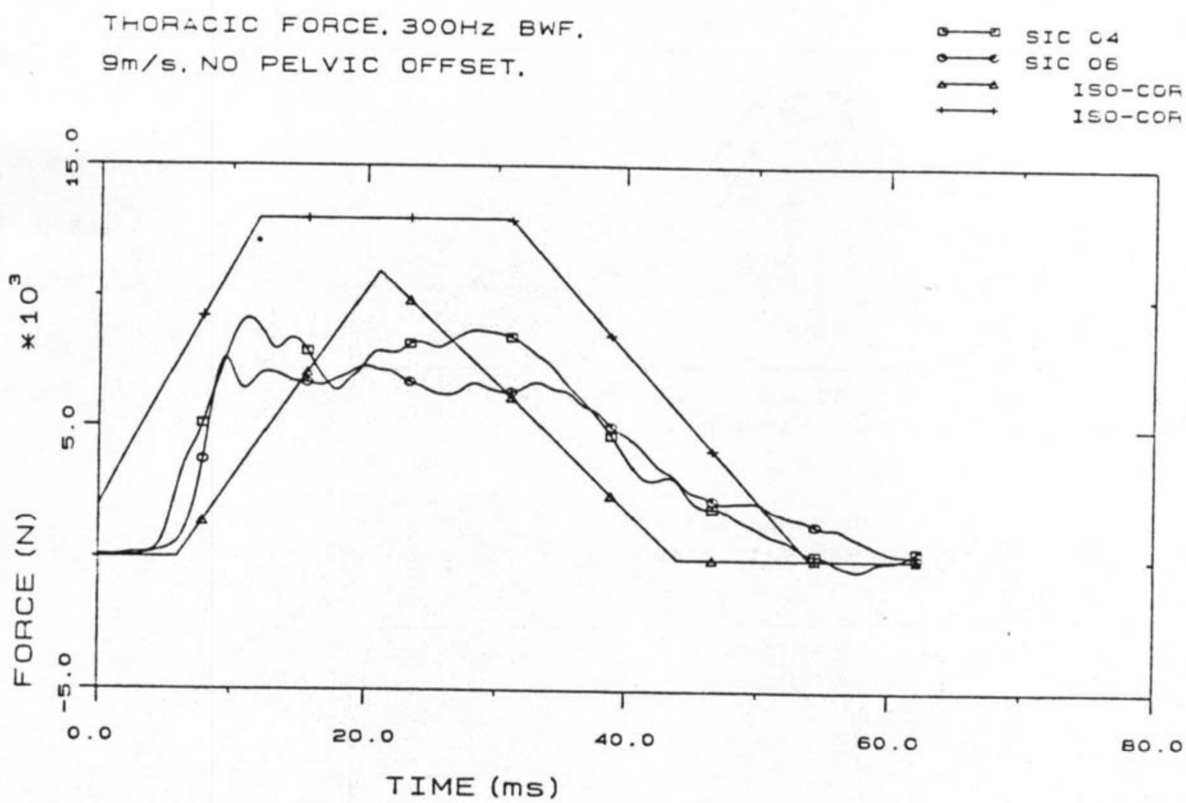
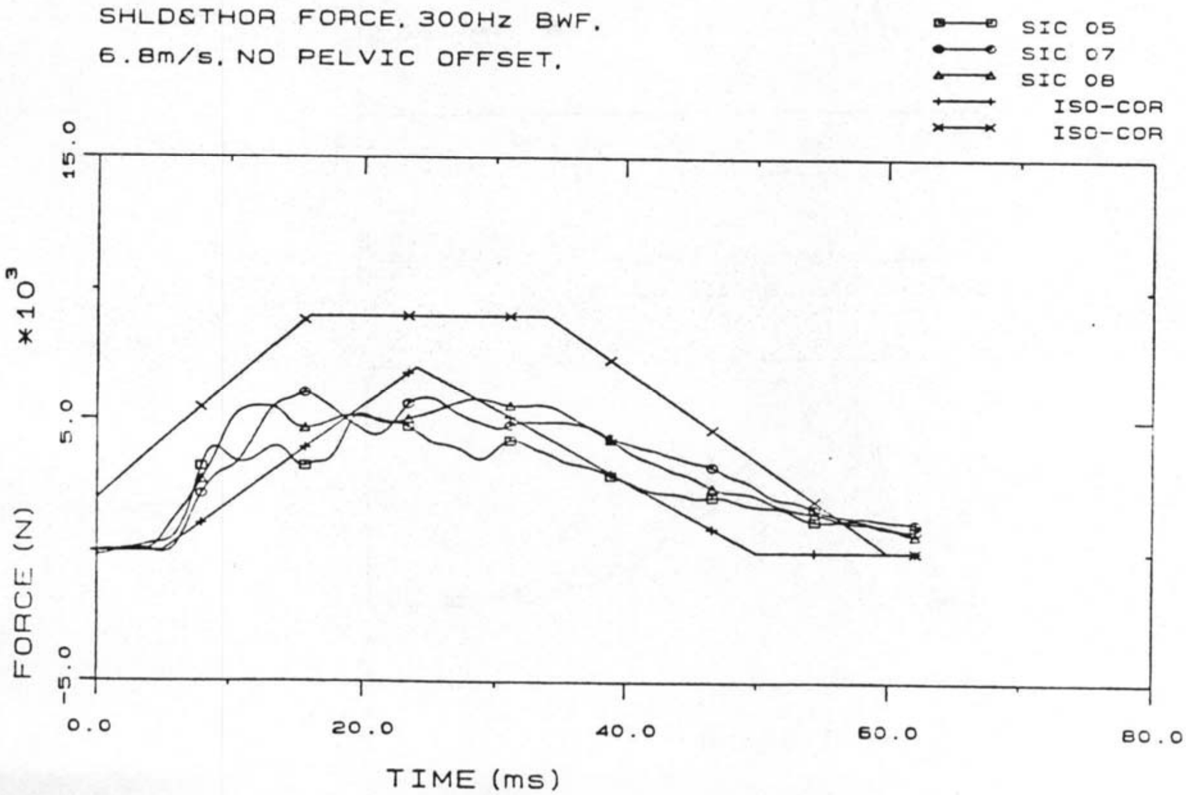


Figure 7a-7b. Deflection-time history showing amount of excursion of thoracic vertebra T1 and the left scapula toward the rigid sidewall. T1-scap indicates the relative motion of the T1 vertebra toward the scapula.





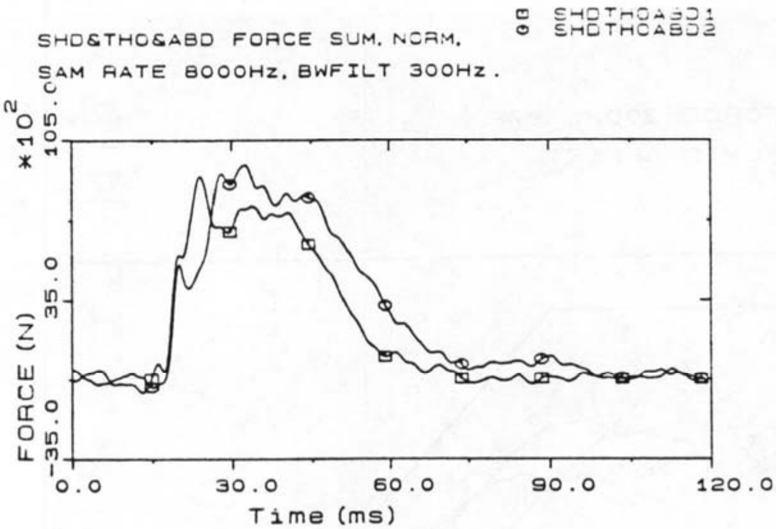
Figures 8a-b. a. Force time history of 9 m/s rigid, flush wall tests versus ISO corridor for 8.9 m/s.

b. Force time history of 6.7 m/s rigid, flush wall tests versus ISO corridor for 6.7 m/s.

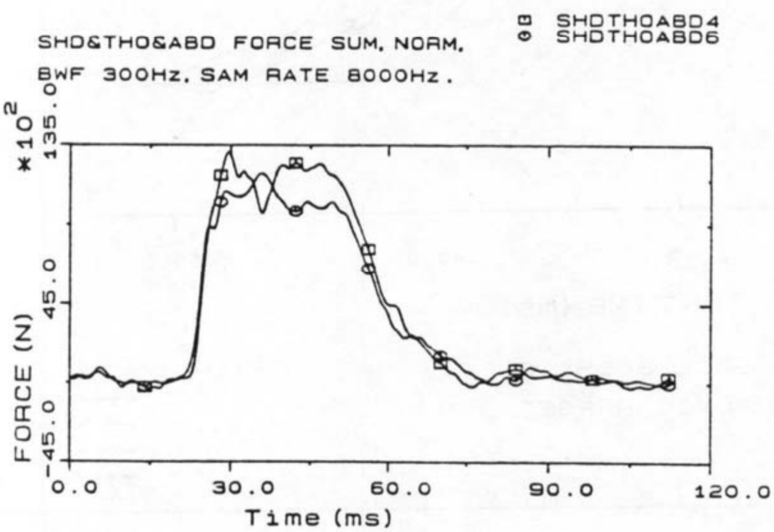
SHOULDER
+ THORAX
+ ABDOMEN

PEAK FORCES (kN)

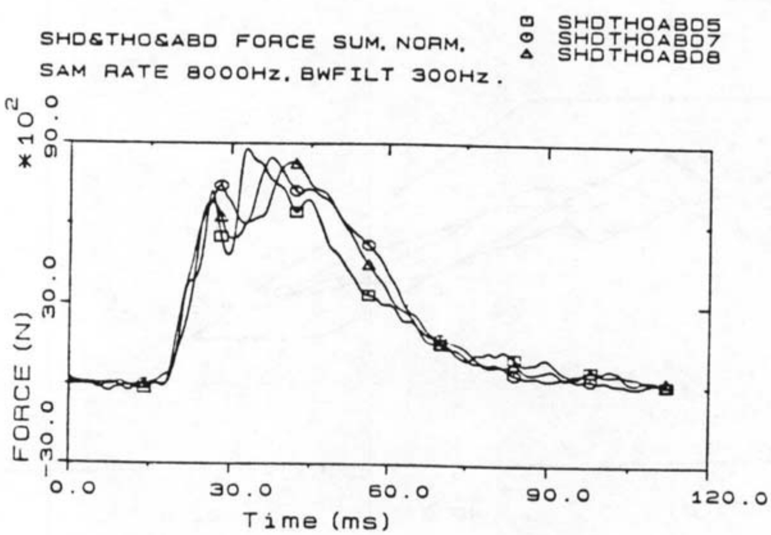
300 HZ BWF



SIC01 8.92 kN
SIC02 9.43 kN
AVG 9.17 kN



SIC04 13.12 kN
SIC06 11.91 kN
AVG 12.51 kN



SIC05 8.80 kN
SIC07 8.48 kN
SIC08 8.30 kN
AVG 8.53 kN

Figures 9a-9b. Force-time histories of hard thorax. a. 9 m/s unpadded, 0.15 m pelvic offset tests. b. 9 m/s unpadded, flush wall tests. c. 6.7 m/s unpadded flush wall tests. Peak forces and the average of those peak forces are shown to the right of each plot.

Pelvis

The peak pelvic forces averaged 11.71 kN in the 9 m/s pelvic offset tests, 11.84 kN in the 9 m/s flush wall tests and 7.90 kN in the 6.7 m/s flush wall tests.

INJURY TOLERANCE

Overall biomechanical response versus injury tolerance

Several researchers, including Eppinger and Marcus (1985), have studied absorbed energy as an injury predictor. Absorbed energy is related to the viscous response, as shown by Viano and Lau (1985), Eppinger and Marcus (1985), and Wang (1989). In the WSU sled tests, there is some correlation between the sum of AIS of all injuries for each subject versus total kinetic energy for each subject ($r = 0.37$). If only the five subjects of the same sex and age range are included (SIC01, 04, 05, 06, and 07; 60-69 year old males), the correlation is much better ($r = 0.74$). In these rigid wall impacts, total kinetic energy may be a good approximation of total absorbed energy, and may be a good predictor of overall injury.

Injury and injury tolerance at each anatomical level is reported below. All forces are normalized. Refer to Table 2 for data discussed in this section.

Shoulder

For the 9 m/s runs the average peak shoulder force with a 0.15 m pelvic offset was 3.93 kN (SIC 01, 02), and with no pelvic offset 5.47 kN (SIC 04, 06). Interestingly, maximum shoulder AIS was 2 in all four tests, indicating that the shoulder can take significant force (> 4 kN) with only moderate skeletal injury. Using the shoulder as a load path may jeopardize the cervical spine. SIC02 sustained a C5-C6 separation and SIC04 a compression fracture at C5-C6. SIC08 sustained an avulsion of the left occipital condyle and a tear of the C6-C7 disc. In live subjects these cervical injuries would likely have been accompanied by serious spinal cord injury that could not be discerned in the cadavers.

Thorax

Our studies show the following:

More thoracic injury occurred in the 9 m/s pelvic offset tests (SIC01, 02) than in the 9 m/s flush wall tests (SIC04, 06). The subject age was very similar in all tests (range 60-69 years).

More internal organ injury was sustained in the pelvic offset tests. These included multiple lung lacerations, bronchial tears, and an intimal tear of the descending aorta, all AIS 4. SIC03 sustained a laceration of the thoracic aorta which transected all layers (AIS 5). SIC04, 06, the two flush wall tests, sustained no thoracic soft tissue injury. The pelvic offset tests also sustained more rib fractures: an average of 33 in SIC01, 02 versus an average of 21 in SIC04, 06. The average sum of thoracic AIS was 16 in the two pelvic offset tests and 6 in the two flush wall tests. If shoulder injury is included, these values are 20 and 10 respectively. For the hard thorax described by Eppinger et al (1982), the sum of AIS was 18 for the two pelvic offset tests and 7 for the two flush wall tests. Maximum thoracic AIS was 5 in the two pelvic offset tests and 4 in the two flush wall tests. It appears that in the pelvic offset tests, the thorax hit the barrier at a slight angle from vertical, resulting in an impact which was not as blunt as the flush wall impacts, and consequently, more penetration into the thorax. This is also suggested by the compression data given in the BIOMECHANICAL RESPONSE section.

Normalizing AIS for age using

$$AIS - 0.025(Age - 45)$$

as suggested by Marcus et al (1983), the WSU 9 m/s pelvic offset tests had a maximum age-normalized AIS of 4.49, and the 9 m/s flush wall tests 3.51, again suggesting that the 0.15 m pelvic offset produces more thoracic injury.

Aortic rupture occurred in three tests; SIC02, 03 and 08. SIC02 sustained a tear of the intima, the innermost layer of the aortic wall (AIS 4). In the other two runs the tear transected all layers (AIS 5). In SIC08 the impact velocity was only 6.7 m/s but the tear occurred at an area of extensive athersclerosis. In all three, the tear occurred near the ligamentum arteriosum, the ligamentous attachment between the aorta and the pulmonary artery. Pferhaps the ligamentum arteriosum acts as a point of restraint for the laterally accelerating thoracic aorta, and is an area of stress concentration.

In the unpadded flush wall 8.9 m/s tests performed at Heidelberg the maximum age-normalized

AIS was 3.42 (Marcus et al, 1983), with an actual delta V between subject and wall of 10.5 m/s. In the two WSU 9 m/s flush wall tests, the maximum age normalized AIS averaged 3.51. Perhaps the Heidelberg tests averaged slightly lower AIS with a higher delta V because of the subject's arm position. In the WSU tests the arm was anterior to the mid-axillary line, while at Heidelberg the arm lies at the side.

Abdomen

Maximum AIS to the abdomen was 2 in three tests and 0 in five tests. The injuries were minor lacerations of the liver and spleen. The youngest subject (SIC03, 37 yrs old, 10.5 m/s) sustained AIS of 0 and the three lower velocity subjects (SIC05, 07, 08 run at 6.7 m/s) sustained AIS of 0. In the four 20 mph tests, peak abdominal force averaged 4.07 kN and 3 of 4 subjects sustained AIS 2, while in the three 6.7 m/s tests, the peak abdominal force averaged 3.11 kN and all three subjects sustained AIS of zero. Thus, it appears that in the abdomen the transition form AIS 0 to AIS 2 is between 3 and 4 kN in left sided impacts.

Pelvis

Our studies show the following:

1. SIC01-06 sustained a peak pelvic force > 10.6 kN and five of these had fractured pubic rami. SIC07-08 sustained a peak force of < 7 kN and had no pelvic fracture. Before each impact, the top of the iliac crest was measured in the seated subject. In SIC01-05 the iliac crest fell below the abdominal beam, so that the pelvic load path was through the greater trochanter via the pelvic beam. In SIC06-08 the iliac crest fell 13-23 mm above the bottom of the abdominal beam, so that the pelvic load path may have included the iliac wing in these three tests. In the Heidelberg tests, pelvic fracture occurred much less often, but with the larger pelvic force plate, the load path also included the iliac wing. Haffner (1985) has discussed the importance of the greater trochanter and iliac wing load paths and how they affect fracture tolerance limits.
2. Cesari and Ramet (1982) developed an equation for pelvic tolerance with the region above this line a fracture region and below the line, non- fracture. This equation was developed from pendelum impacts to the greater trochanter. The equation is

$$F = 43.58\left(\frac{23.5}{Li}\right)Wa - 1058.94$$

where

$$F = \textit{impact force in pounds},$$

$$Li = \textit{Livi index} = 10\frac{\sqrt[3]{Wa}}{Ht}$$

$$Wa = \textit{actual weight in kg}$$

$$Ht = \textit{actual height in meters}$$

In five of six tests the pelvic forces sustained were all greater than the tolerance force calculated using Caesari's equation and resulted in pelvic fracture. In two tests the pelvic forces sustained were less than the calculated tolerance force, and resulted in no fracture, suggesting that the equation is a good predictor of pelvic fracture in these sled tests.

3. In the two subjects run at 9 m/s with a six inch pelvic offset there was separation of the struck-side sacro-iliac joint. This occurred in no other tests.

CONCLUSIONS

The following preliminary conclusions can be made from these tests:

1. It appears that more injury is produced with the arm placed anteriorly (WSU tests) than with the arm placed at the side (Heidelberg tests).
2. There does not appear to be any benefit in terms of thoracic injury reduction with a 0.15 m pelvic offset in an unpadded barrier.
3. In lateral impact, the shoulder appears to deform via translation of the thoracic spine toward the scapula, with bottoming out of the medial aspect of the scapula on the thoracic spine, and posterior to anterior translation of the sternum. Acromio-clavicular separation on the struck side appears to be a characteristic of these impacts.
4. In three of seven tests, tears of the thoracic aorta occurred near the ligamentum arteriosum, which may act as a point of restraint as the surrounding aorta tries to pull away.

5. A peak impact force of greater than 10.6 kN to the pelvis results in pelvic fracture and less than 7 kN, no pelvic fracture. The pelvic tolerance equation of Cesari and Rami appears to be be a good predictor of pelvic injury tolerance in lateral impact.

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PAPER: Biomechanical Response and Injury Tolerance in Eight Cadaveric Side Impacts

SPEAKER: John M. Cavanaugh

Question: Guy Nusholtz, Chrysler

Did you have any padding on the area that was striking the pelvis?

Answer: No, we didn't.

Q. In a study I did some time ago in which I looked at the effects of various padding, with some very specific contoured padding we got forces past 15 kN without fracturing the pelvis. That fits in to your theme of the load path coming through the trochantor because what we did was padded so it would be rigid. It was able to carry the load to the iliac crest and below the trochantor so that we minimized the load through there and then we were able to get the forces very high, 15-20 kN.

A. We'll be running some tests with padding in the future.

Q. Richard Morgan, NHTSA

You mentioned that you scaled the data, I'm assuming you scaled it to the 50th percentile male.

A. Yes. We used equal stress, equal velocities: that's using a 75 kg standard mass.

Q. At one point, you were talking about the significance of the rebound velocity. I understand rebound velocity but I don't know what you mean by its signifigance.

A. I looked at the data in a paper that presented some of the Heidelberg sled tests. It 's the paper from the 27th Stapp, SAE Paper # 831634. There was a table that listed 5 tests that had a velocity of 20 mph. They indicated a thoracic delta V of ranging from 20.6 to 26 mph. This averages out to 23.3 mph.

Morgan: OK, I see what you're getting at.