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Biomechanical Response of the Human Thorax to Oblique and Lateral Impacts

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ABSTRACT

This study characterizes the human thoracic response to blunt impact in oblique and lateral directions. In previous studies a significant amount of data has been collected from lateral impacts conducted on human thoraces. Substantially less data has been collected from impacts that are anterior of lateral in an oblique direction. In the past, data collected from the handful of oblique impacts performed were considered to be sufficiently similar to the data from purely lateral impacts that the data were combined with the lateral results. Human response to oblique impact is of great importance in defining the biomechanical response of the human thorax in a vehicle crash where the loading is often anterior oblique in direction. Data in this study was obtained by affixing accelerometers to the rib cage and along the thoracic spine of a Post Mortem Human Subject (PMHS).[1] An External Peripheral Instrument for Deformation Measurement, or chestband, was placed on the thorax at the level of impact to validate the response obtained by the accelerometers. Two impacts were conducted on each of five subjects at 2.5 m/s, with one lateral impact and one oblique impact to opposite sides of each PMHS.

INTRODUCTION

A major research area for automotive safety professionals is side impact protection. The automotive safety field focused primarily on frontal impact protection for many years, and now most automobiles have standard safety features, such as driver and passenger frontal airbags and seatbelts with pretensioners, that allow them to save lives and reduce injuries in frontal accidents. More recently, the National Highway Transportation Safety Administration (NHTSA) has enacted standards that provide for side impact protection in automobiles, as stated in Federal Motor Vehicle Safety Standard 214 (FMVSS 214) (Federal Register, 1990). FMVSS 214 specifies requirements that all auto manufacturers must meet or exceed.

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[1] All cadavers were obtained through The Ohio State University Willed Body Program, and with the approval of The Ohio State University Biomedical Sciences Human Subjects Review Committee.

FMVSS 214 testing attempts to replicate the most common side impact crash, approximately 34% of all crashes in 1994, those that occur between two vehicles at an intersection (NHTSA, 2005). This is a 90° car-to-car impact where the struck vehicle is moving at approximately 15 mph, and the striking vehicle at 30 mph. To simulate the real world crash conditions, NHTSA employs a moveable deformable barrier (MDB), which is directed to strike the subject test vehicle at 27° forward from lateral.

The kinematics in the FVMSS 214 test produce a primary direction of force (PDOF) that is actually oblique in relation to the occupant. This result is consistent with actual vehicle accidents where the median PDOF is 60° for cars model year 1995 and later (Samaha et al., 2004). A search of the National Accident Sampling System – Crashworthiness Data System (NASS/CDS), between 1999 and 2002, revealed a higher frequency of 60° PDOF cases than ones with a 90° PDOF, as illustrated in Figure 1.

The directional dependence of the biomechanical response of the thorax has not been adequately quantified. The goal of this project is to determine if the oblique thoracic biomechanical response is different from that of the lateral thoracic biomechanical response.

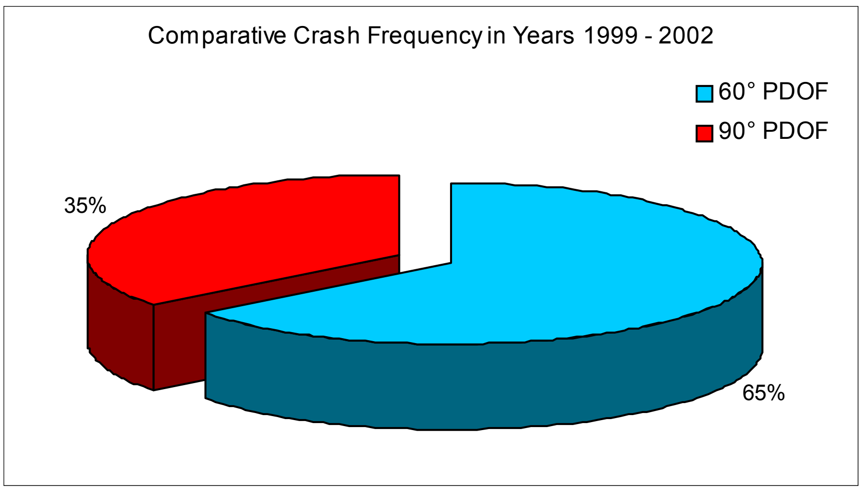

Figure 1: NASS/CDS results of lateral and oblique PDOF for years 1999 to 2002.

METHODS

A subject-selection algorithm, shown in Table 1, was created to improve consistency in selection decisions. This algorithm awards points first based on age; the younger a potential subject is, the more points it will receive. Next, the algorithm assigns a point if the subject is within a given height and weight proportion. This is to eliminate subjects that may be disproportionately tall, short, overweight, or underweight. Third, the algorithm gives a point to subjects whose bone mineral density is within the normal clinical range, subtracts a point for those with osteoporosis, and yields no points for those that are osteopenic. Lastly, if subjects have no superficial sign of damage to the thorax, e.g. scars and lesions, they are given one point. A cadaver that receives three or more points is considered acceptable and testing proceeds.

To illustrate how the scoring algorithm works, two cases will be examined. One case represents a cadaver that was accepted and subsequently tested. The other case was one in which the subject was deemed unacceptable and returned to the Willed Body Program for use in educational programs. In the first case, the subject was a 79-year-old male, which earned one point for age. The subject weighed 65.8 kg and was 180.3 cm tall, which earned another point. The BMD scan resulted in a T-score of 1.2 (1.12 g/cm^2, clinically normal), providing another point. Lastly, there were no apparent superficial signs of trauma and a final point was awarded to give a total of four points. In the second case the 72-year-old male subject received one point for age. This potential subject weighed 56.7 kg and was 165.1 cm tall yielding another point. There were no apparent signs of pre-existing trauma and a third point was awarded. However, the BMD scans showed a T-score of –3.4 (0.66 g/cm^2, osteoporotic) and a point was subtracted. This resulted in a score of two points and the potential subject was not used for testing, even though it was apparently acceptable at initial inspection.

Table 1. Cadaver scoring algorithm.

AGE	**Years**		**Score**
	> 80		0
	70 - 79		1
	60 - 69		2
	50 - 59		3
	< 50		4
HEIGHT & WEIGHT	**Height (cm)**	**Weight (kg)**	**Score**
	> 193	-	0
	185 -193	< 77	0
		77 - 104	1
		> 104	0
	173 - 184	< 59	0
		59 - 95	1
		> 95	0
	163 - 172	< 50	0
		50 - 86	1
		> 86	0
	152 - 162	< 41	0
		41 - 64	1
		> 64	0
	< 152	-	0
BMD	**BMD (g/cm2)**	**Type**	**Score**
	≥ 0.9	Normal	1
	0.75 - 0.9	Osteopenia	0
	≤ 0.75	Osteoporosis	-1
PRE-EXISTING CONDITION	**Description**		**Score**
	No superficial signs of damage to the thorax or abdomen		1
	Otherwise		0

Preparation and instrumentation

After a cadaver has been selected, it is cleaned externally with a 10% bleach solution and the lungs are pressurized, via a vent tube, to normal physiological levels (approximately 40 cmH_2O). Anthropomorphic measurements were then recorded, and notes of any superficial anomalies were made. Next, pre-test radiology was performed to obtain a baseline for mid- and post-test comparison of the thorax to detect rib fractures. Computed Tomography (CT) was the imaging modality used on all subjects. The radiologist's reports were not available before testing began, but were received after tests were completed.

After pre-test radiology had been completed, the subjects were transported back to the trauma laboratory for instrumentation. The first instrumentation step was to lay the subject in a prone position and locate the spinous processes of the first, fourth, and twelfth thoracic vertebrae (T1, T4, and T12). At each of these sites a mount was fixed to the body of the vertebrae (using a 2" drywall screw), over the spinous process, upon which a block containing two accelerometers was attached. The accelerometers were oriented in the fore-aft and medial-lateral directions; the vertical direction did not have an accelerometer since it is assumed that the subject is not falling during the impact and the loading is in a transverse plane through the thorax.

The subject was then turned over into a supine position. A similar two-axis accelerometer array was attached to the sternum using a mount with holes on the tabs through which ¾-inch #6 sheet metal screws are inserted to hold the block tightly onto the bone.

Subject positioning

Next, the subject was placed in the approximate impact position so that the remaining instrumentation could be attached. Triaxial accelerometer arrays were affixed circumferentially (in the transverse plane) to the rib cage at the level of the fourth rib mid-sagital, or approximately midsternum, even though the ribs tend to curve downward in relation to their sternal and spinal articulations. These accelerometers were placed laterally on each side of the thorax, as well as anterior and posterior of the lateral positions. Figure 2 shows the arrangement of the accelerometers about the thorax. The coordinate system shown in the figure is the specified in SAE Standard J211, where the positive x-axis is in the fore direction, the y-axis is directed laterally to the right side of the body, and the positive z-axis points inferiorly. The arrays were placed along the lateral axis through the center of gravity (CG), as well as along the anterior-posterior axis through the CG. The location of the CG was determined by the method described in the Anthropometric Source Book, Volume 1 (NASA, 1978). The CG location was defined as 44% of the depth of the abdomen at the umbilicus (navel) while the subject is supine. The CG location was then measured from the subject's back in the anterior direction from the back of the spine.

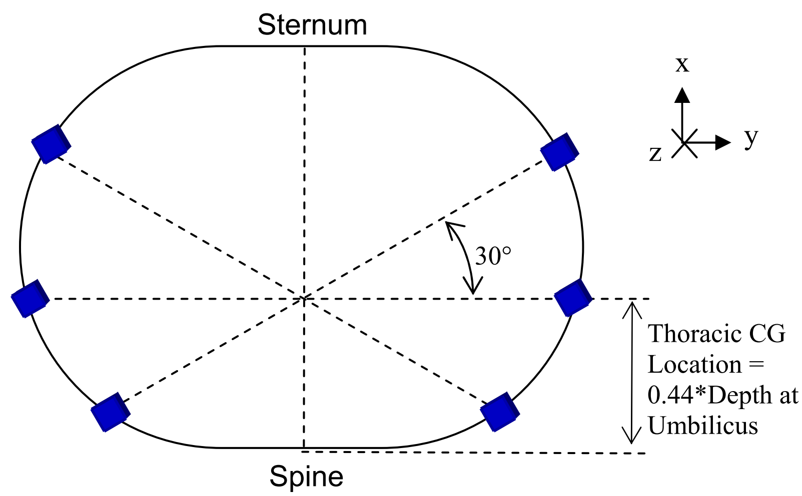

Figure 2: Accelerometer positions around rib cage shown on transverse plane at approximate level of impact (4th interspace of the sternum).

Chestband usage

An External Peripheral Instrument for Deformation Measurement (EPIDM), more commonly known as a chestband, was placed onto the cadaver's thorax at the same level as the rib cage instrumentation. The 40-channel chestband was wrapped around the subject externally and secured using tape. The band was wrapped over the top of the majority of the accelerometer arrays and always over the arrays located at the impact sites. Figure 3 shows a sectional view of an accelerometer array attached to the rib, a suture (only at impact sites), and the chestband wrapped over the array and skin.

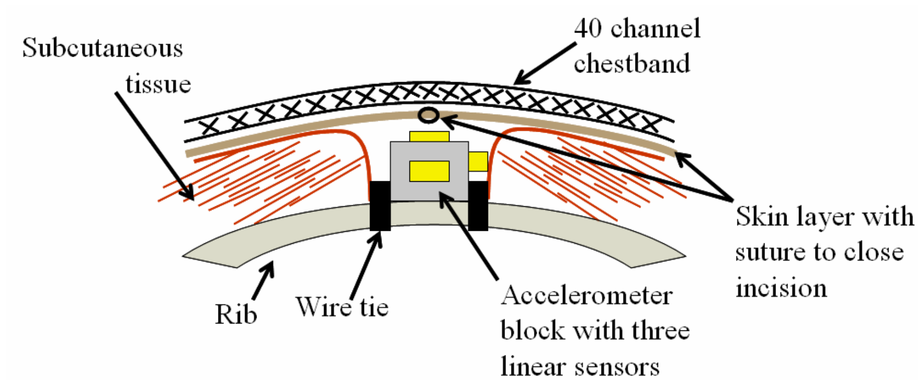

Figure 3: Section view of instrumentation on rib and thorax.

The data output for the chestband channels are processed using the program RBandPC. The program requires the user to input a 'sternum' and a 'spine' location from the band placement on the subject. Because the device was originally designed for use in frontal impact testing these monikers make logical sense. However, this input is only used to locate the band within the algorithm and can be altered for the current application. The chestband was aligned along the line of impact to find the deflection of the rib cage along that axis for this analysis.

The chestband output supplies a series of files called gauge files which list the x- and y-axis position of each of the active gauges, one file per time step. Taking the instantaneous position of the gauges of interest and subtracting the initial position gives a deflection time history of those gauges.

Test performance

After all of the accelerometer arrays were attached, the subject was ready to be positioned for the first impact. The subject was placed on a wooden seat that was set at a height so that the ram face was centered on the transverse plane through the fourth interspace of the sternum. The height was then fine tuned to place the subject high enough to avoid having the arm come in contact with the ram face during its travel. The subject's head was placed into a harness and hooked onto a magnetic release, which was suspended from a moveable track. The track could move in both the anterior-posterior and medial-lateral directions, so that proper alignment of the subject could be achieved. For each impact, the subject was positioned approximately the same distance from the ram. The arms of the subject were positioned on a strut device with the forearms crossed. The subject's arms were parallel to the floor and perpendicular to the body to eliminate excess scapular motion, to keep the scapula away from the impact point, and to keep the rib cage from expanding or lifting as can happen when the arms are raised overhead.

The first impact was conducted after the cadaver was positioned and all sensor locations digitized. A 23 kg linear pneumatic ram, traveling at a nearly constant velocity prior to the event, was used to impact the thorax. The velocity of the ram, which was tracked by an accelerometer mounted to the impact probe, decreased during the loading event and came to a complete stop before reaching maximum extension. The impacting surface was a 6 in. diameter aluminum face with a ½ in. edge radius.

Two subjects were initially tested for this program with a test velocity of 4.3 m/s. These tests resulted in massively damaged thoraces, with greater than 20 rib fractures. Therefore, the impact energy was reduced for the subsequent five tests.

The velocity of the impact was determined using biomechanical responses found by previous researchers (Kuppa, 2004; Viano, 1989). Viano found an average normalized force response of 2.25 kN from low energy impacts. Kuppa found, by analyzing data from several lateral sled tests, that a rib deflection of 30 mm has a zero percent probability of injury. Performing an energy balance with these two inputs and the known mass of the impact probe, a test velocity was determined. Such that,

$$\text{Work} = \text{Kinetic Energy}$$
$$Fd = \frac{1}{2} m v^2$$

$$v = \sqrt{\frac{2Fd}{m}}$$

where F = impact force
d = rib deflection
m = mass of the probe
v = test velocity.

Solving this equation with the inputs specified above gives a test speed of 2.5 m/s.

$$v = \sqrt{\frac{2(2.25kN)(30mm)}{23kg}} \approx 2.5m/s$$

Each subject was impacted twice: once in the lateral direction and once in the oblique direction. This methodology was selected so that the results from the same subject could be compared directly between the lateral and oblique tests. Because the impacts were at a low energy, non-injurious level, the subjects were able to sustain multiple impacts. The order of the impacts, and the side of the thorax impacted were alternated and the sequence for the tests conducted can be seen in Table 2. The information in this table is also represented graphically in Figure 4, which shows the impacts conducted on the subjects and their order.

Table 2: Test matrix.

Subject	One		Two		Three		Four		Five	
Side	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
Direction	30°	0°	0°	30°	30°	0°	0°	30°	30°	0°
Order	First	Second	First	Second	Second	First	Second	First	First	Second
Speed (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

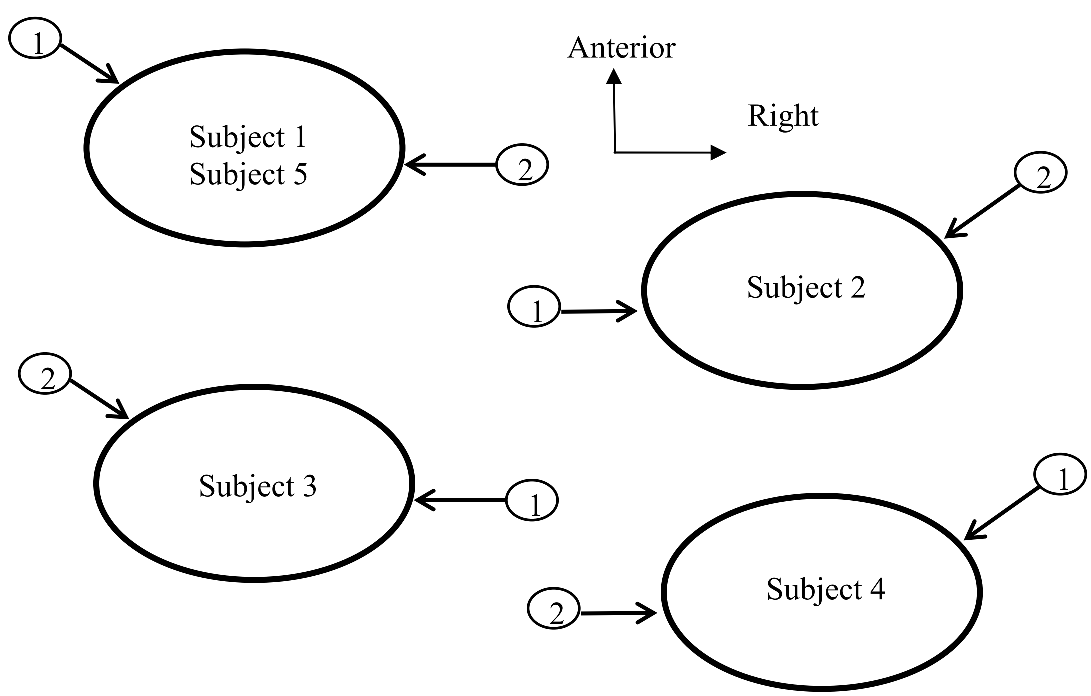

Figure 4: Tests to be conducted on subjects and their order.

A method of catching the subject was developed to prevent injury from the post-impact fall because the seat that was used did not restrain the subject's motion. The secondary injury prevention unit (SIPU) consisted of two inflatable mattresses that were placed next to and behind the seat. After the subject was impacted, it would fall onto the SIPU to prevent injuries other than those caused by the impact of the ram.

After the first impact, the subject was transported to the radiology facility and mid-test CT scans were performed. If the subject had more than four fractures from the first test, whether detected by palpation or CT results if available, the second impact would not be conducted.

If the second test was to be performed, the subject was re-seated for the second impact. The process for the second impact was the same as that of the first. Array locations were digitized again, the subject placed in test position, and the second impact conducted.

The day after testing, a final CT examination was performed, and later that day a thoracic autopsy was conducted. The autopsy was performed in a manner so as to reveal any fractures that might not have been detected on CT. The skin and subcutaneous tissue of the thorax was removed and the muscles removed individually. The ribs were cleaned to allow inspection of their superficial surface and the intercostal muscles. The chest plate was removed, and the internal thoracic viscera and great vessels were inspected for injury. Last, the organs within the upper portion of the abdominal cavity were inspected, paying particular attention to the liver and spleen.

Data was collected using a 96-channel Yokogawa Electric Corporation WE7000 data acquisition system. Signals from each sensor were sent to a central data collection system where analog-to-digital conversion was performed at a sampling rate of 20,000 Hz. The bias was removed and the data filtered according to SAE J211 standards, where spinal accelerations are at Channel Filter Class (CFC) 180, rib and sternal accelerations at CFC 1000, deflections at CFC 600, and forces and moments at CFC 600.

RESULTS

Five subjects have been tested, but the data from the last two tests are not included since it has not been fully processed at this time. Pertinent anthropometric data from the three subjects is presented in Table 3. The average age of the subjects tested was 79 years old and all subjects were male. The subjects were all approximately the same height and weight with an average height of 174 cm and average weight of 71 kg. The subjects had Bone Mineral Densities (BMD) ranging from 1.011 g/cm^2 to 1.701 g/cm^2. As previously seen in the selection algorithm, subject gender was not a criterion for inclusion or exclusion; however, all subjects that met the other criteria were male.

Table 3: Subject information.

PMHS #	Gender	Age	Height cm	Mass kg	BMD g/cm2
O-T0503	Male	79	180	65.8	1.383
O-T0504	Male	80	165	80.7	1.701
O-T0505	Male	77	178	66.2	1.011
Average		78.7	174.3	70.9	1.365

Findings from autopsy can be found in Table 4. All of the fractures were closed fractures and were at or near the sites where accelerometer blocks were fixed. Therefore the fractures were attributed to the instrumentation placed on the rib cage.

Table 4: Injuries sustained from impacts.

PMHS #	Test #	Rib Fx	Fx Location	MAIS
O-T0503	0503LTH25R01	0	N/A	0
	0503OTH25L01			
O-T0504	0504LTH25L01	0	N/A	0
	0504OTH25R02			
O-T0505	0505LTH25R01	5	R6, L5, L6, L7, L8	2
	0505OTH25L01			

A summary of the impact results is shown in Table 5. The results are listed first by subject number and then by test number. The type of impact, oblique or lateral, the order of impacts, and the side of the thorax are also listed. The target velocity for all tests was 2.5 m/s; however, the equipment used did not have that level of accuracy, and actual test velocities ranged from 2.45 m/s to 2.62 m/s with an average of 2.55 m/s. Maximum impact force, as measured by the ram load cell and compensated for inertial effects, is listed with an average of nearly 1300 N. The maximum deflection obtained, as determined from the chestband, is shown to have an average of approximately 41 mm.

Table 5: Impact types, velocities, and results.

PMHS Number	Test Number	Side	Impact	Order	V_{impact} m/s	F_{max} N	D_{max} mm
O-T0503	0503LTH25R01	R	Lateral	2	2.62	1535	29.0
	0503OTH25L01	L	Oblique	1	2.60	1331	53.9
O-T0504	0504LTH25L01	L	Lateral	1	2.58	1541	33.2
	0504OTH25R02	R	Oblique	2	2.57	1420	42.9
O-T0505	0505LTH25R01	R	Lateral	2	2.46	1170	31.1
	0505OTH25L01	L	Oblique	1	2.48	802	58.4
				Average	**2.55**	**1296**	**41.4**

Figures 5-7 show the processed chestband data with the pre-impact and maximum deflection contours overlaid. The line represents the axis along which the deflections were obtained. The image of the vertebra illustrates the position of the spine in relation to the band. The compression, C, is found by dividing all points in the time history by the initial length along the line of impact.

To compare the oblique versus lateral force deflection responses, the force response is cross plotted versus the deflection response for the two tests on each subject. Figures 8-10 show the force deflection responses for each test on the first three subjects.

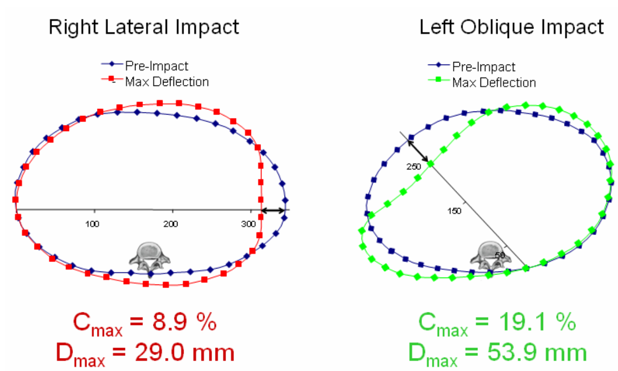

Figure 5: Subject O-T0503 chestband contours from lateral (red) and oblique (green) impacts.

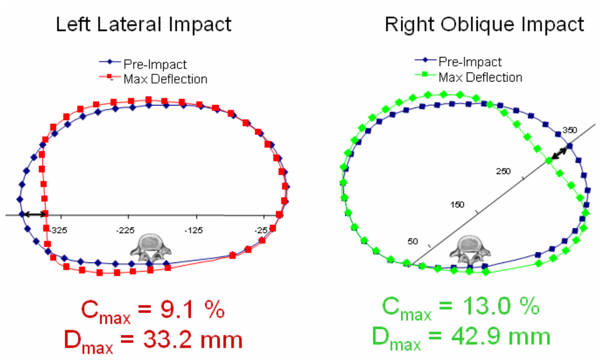

Figure 6: Subject O-T0504 chestband contours from lateral (red) and oblique (green) impacts.

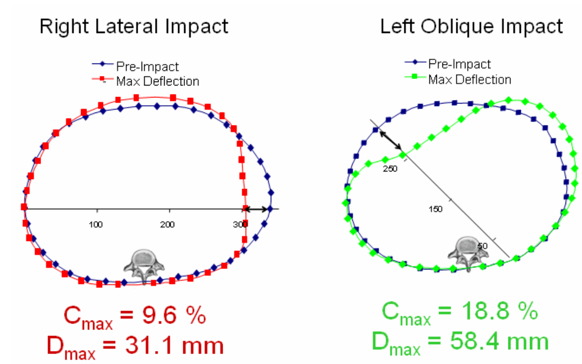

Figure 7: Subject O-T0505 chestband contours from lateral (red) and oblique (green) impacts.

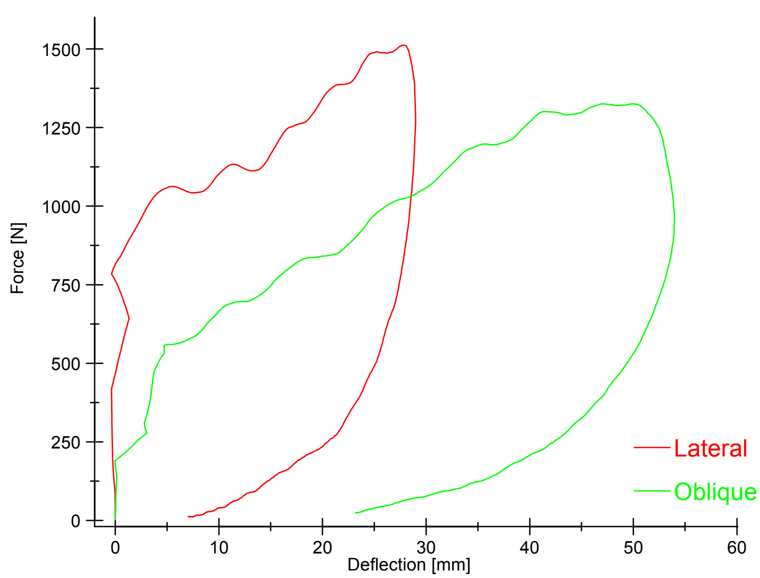

Figure 8: Subject O-T0503 force-deflection responses from lateral (red) and oblique (green) impacts.

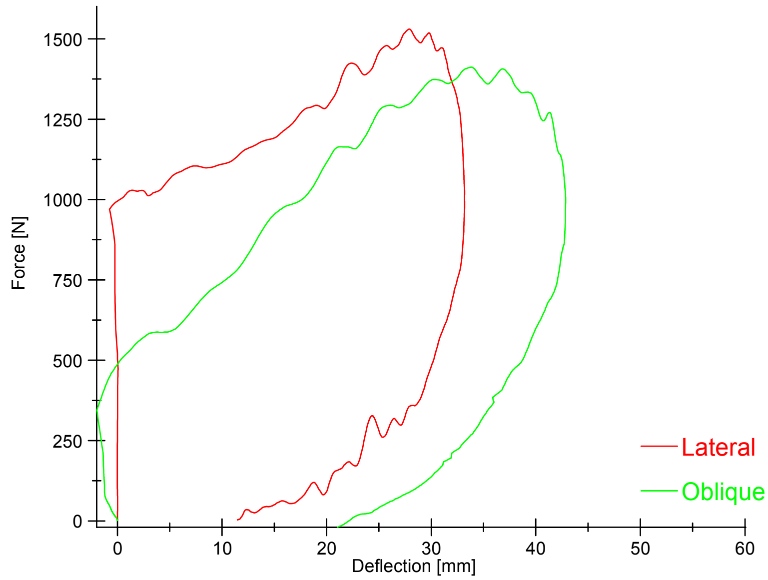

Figure 9: Subject O-T0504 force-deflection responses from lateral (red) and oblique (green) impacts.

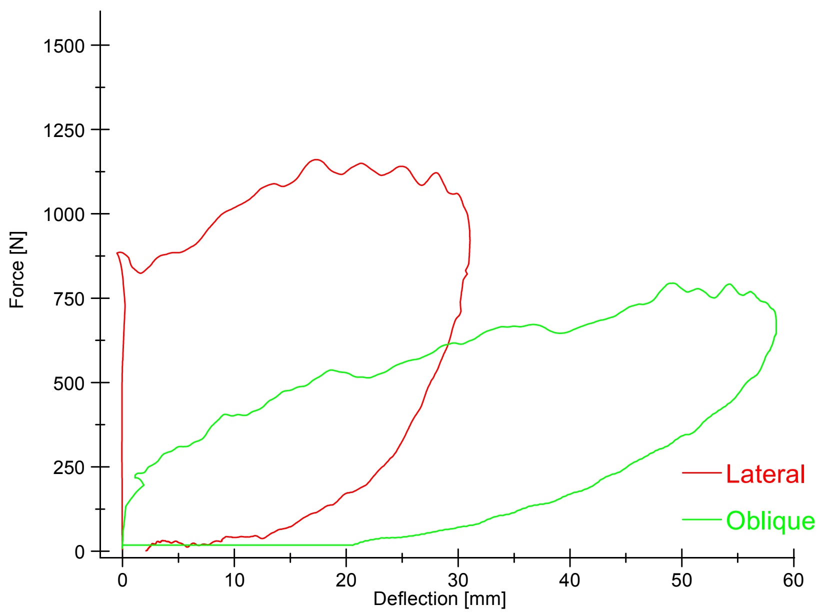

Figure 10: Subject O-T0505 force-deflection responses from lateral (red) and oblique (green) impacts.

As is evident in Figures 8-10, some impacts result in an initial negative deflection, or an initial loading before deflection; this artifact is easily explained. The geometry of the thorax is quite complex, consisting of muscles and their attachments at varying angles. The latissimus and the pectoralis are two such muscles which form an angle with the rib cage. Since the chestband was placed near the insertions of these muscles on the rib cage, the large diameter (150 mm) pendulum face could come into contact with them before the chestband was contacted and initiated deformation. Likewise, since the subject does fall minimally, less than one inch in extreme cases, the chestband can shift slightly and give the effect of a negative deflection initially.

CONCLUSIONS

From the tests completed and analyzed to date there seems to be a clear trend. For all subjects presented, the lateral force-deflection response appears to be distinctly different from the oblique force-deflection response. The impacts were all conducted at approximately the same speed, less than 0.1 m/s difference for each subject, so it is reasonable to compare the lateral and oblique responses. The comparisons are intra-subject and no scaling is required to make these direct comparisons.

The remainder of the subject data still needs to be processed, and all data scaled to a 50th percentile male. The scaled force-deflection relationships for each impact type, lateral or oblique, will then be combined and compared to further determine differences between the two. The responses will then be used to create corridors to which dummies can be compared.

ACKNOWLEDGEMENTS

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DISCUSSION

PAPER: **Biomechanical Response of the Human Thorax to Oblique and Lateral Impacts**

PRESENTER: ***Joshua Shaw, VRTC NHTSA, Transportation Research Center and Department of Anatomy, The Ohio State University***

QUESTION: *Guy Nusholtz, Daimler Chrysler*
What points in the lateral—What points are taken as your deflection? You've got a one-dimensional parameter.

ANSWER: You mean the points—these two points?

Q: Yeah. Those would be—And for the oblique, what two points are you using?

A: These two points are around the accelerometers so that we can compare accelerometers responses to chest band responses.

Q: I mean, are they the same two points?

A: On--?

Q: For the oblique versus the lateral?

A: No. On these, you'll see the little picture of the vertebra, that's the spine. So on the lateral impact, it's actually two points. You mean it is the same gage on the band or is it the same point on the thorax?

Q: Well, either way.

A: The band was removed between tests so it's not the same gage and it's also not the same point on the thorax. In the lateral impact, it's lined up at the point of impact, which is the lateral aspect of the thorax and in the contra lateral side.

Q: Okay.

A: In the oblique impact, it's impact point on the oblique aspect and then the contra lateral point on the posterior oblique.

Q: So is that a contra lateral point—

A: Along the axis.

Q: Formed by taking the perpendicular to the c camp, that tangent line across the point that you're impacting?

A: No, that's not really the perpendicular to the c camp. It's more just aligned along the two gages. It's aligned along an axis that's 30° rotated from the lateral axis.

Q: Okay. How does that—With a characteristic response, you're dealing with a one-dimensional space, but you're actually dealing with a two-dimensional, or three-dimensional phenomena and you see a very large difference in your deflection. How does that relate to the—I mean, how do you relate the two deflections? Is there a difference that's due to the way you're defining the deflection as opposed to an actual energy absorbed forced-energy relationship that's coming up? That's sort of partial concern because you're trying to approximate a two-dimensional phenomenon with a one-dimensional type of estimation.

A: We tried to compare intrasubject with compressions, which is somewhat normalized using the initial linear dimension. So, the lateral compression is—its denominator is the initial lateral dimension. The oblique compression is the initial oblique dimension along the line of impact.

Q: Okay. That part I understand, but it's still—From that, you're gonna try and have some sort of relationship. And in some cases, it looks like you're getting twice, two or three times the deflection and is that really related to a deformation, such as a pi—On lateral, and I go 80 mm or 40 mm and then I go oblique and I go 120 mm, that's a considerable amount of difference in deflection, and whether that's physically real or not needs to be questioned and addressed.

A: Right, and that's still part of our analysis. This is somewhat preliminary. With the accelerometers, you do see the thorax rotate slightly so it's not really as much of a deflection so some of that could be masked. It may not be completely deflection, but it may be—

Q: Some rigid body dynamics occurring.

A: Right.

Q: Okay. Thank you.

Q: *Frank Pintar, Medical College of Wisconsin*
When we did some of these obliques, we sometimes had to fool the chest band routine and pick two points on the spine. Did you try that? Did you see if you get any different numbers?

A: I have used it on the spine. I've done it several ways: along the line of impact, lining it up like it says with spine and sternum.

Q: Right.

A: As well as lining it along two points on the spine. If you use the two points on the spine, it actually shows more of the rotation than it does the deflection.

Q: Right.

A: So that's why I've used along the line of impact so you can try and get the one-dimensional deflection along that line.

Q: Did you find actual differences in the deflection values when you picked the different points?

A: I haven't really found the deflections from those. It's more of a calculation because you do have the rotations to account for that before you can account for the deflection. So I haven't analyzed it. I haven't analyzed the deflection responses of obtaining them [in] that method.

Q: Okay.

Q: *Chirag Shah, Wayne State Univesity*
How did you determine the CG?

A: The CG actually was from a NASA study that I've referenced down here at the bottom. It's—We're still investigating the performance of the CG location. If anyone has any comments on how to determine the CG in a quick-and-dirty method, that would be appropriate for this type of testing. I'd really enjoy to hear your comments.

Q: So, because [what] you are accomplishing will definitely have an effect if you have a rotational component and if you don't align your impact along the CG, then you will have some rotational component?

A: Right, and the impacts were aligned along this CG that we've defined or this CG that we've referenced.

Q: Thank you.

Q: *Phil Chan, Titan Corporation*
You had an accelerometer mounted on the rib?

A: Right.

Q: How many components?

A: Three.

Q: How did you mount it on the rib and how did you guarantee the direction of the accelerometer? How did you monitor it?

A: We didn't guarantee the direction, but we did a post-processing where we transformed all of the—It's just an orthogonal linear transformation from the accelerometer's three directions into the subject's J2-11 orientations.

Q: How did you mount it on the ribs?

A: With wire ties. Just wire ties. The accelerometer block has two tabs that come out the side of it and those were rigidly tied to the rib. You make an incision on the superior and inferior margin, costal margin and then just pass the wire tie through.

Q: So the data comes out okay?

A: In some tests, the data did come out okay. We are still analyzing it and what we're seeing is that the accelerometers do have a kinematic effect, which is somewhat masking the deformation response.

Q: Okay.