Response of the PMHS Thorax in Lateral and Oblique Pneumatic Ram Impacts – Investigation of Impact Speed, Impact Location and Impact Face

Heather Rhule, Brian Suntay, Rodney Herriott, Jim Stricklin, Yun-Seok Kang, and John H. Bolte IV

Abstract Previously Rhule et al. [1] impacted PMHS thoraxes at 4.5 m/s in a pure lateral or 30° anterior oblique direction. Mean normalized force-deflection responses demonstrated similar characteristics for both lateral and oblique impacts, indicating that it may be reasonable to combine lateral and oblique responses at this speed to define characteristic PMHS thoracic response, as has been done by the International Standards Organization [2]. However, the similarity in lateral and oblique thorax responses found at 4.5 m/s differed from paired lateral and 30° anterior oblique thoracic impacts on opposite sides of PMHS conducted by Shaw et al. [3] at 2.5 m/s. . Mean normalized force-deflection responses showed significantly stiffer response in the lateral direction. The current study presents results of new paired lateral and oblique thoracic impacts to five PMHS with variations in vertical impact location (xiphoid versus fourth intercostal space), impact speed (2.5 versus 4.5 m/s), and impact face shape (circular versus rectangular) to ascertain why the results of the two previous studies were different. Consistency of impact face engagement with the subject appeared to affect the lateral versus oblique response relationship, though the effects of impact location and speed were inconclusive.

Keywords force-deflection, impact, lateral, oblique, thoracic response

I. INTRODUCTION

In 1999 the International Standards Organization (ISO) published Technical Report 9790 [2], in which force versus time biofidelity response corridors were presented for lateral thoracic pendulum impacts. The corridors were developed based on tests conducted by Eppinger et al. [4] and Viano [5], who subjected post mortem human surrogates (PMHS) to thoracic pendulum impacts at 3.6 to 5.5 m/s with a 23 kg mass and 150 mm diameter impact face. Eppinger's study included four subjects impacted laterally, with no documentation of the vertical impact location. Viano's study included five subjects impacted 30° anterior to lateral, on the left or right side, at the level of the xiphoid process. ISO processed the lateral and oblique impact data using a 100 Hz Finite Impulse Response (FIR) filter and normalized it to a 50th percentile male impacted at 4.3 m/s. After excluding data from subjects with six or more rib fractures, a set of two lateral (Eppinger) and five oblique (Viano) tests were combined, since the normalized and velocity-scaled peak forces were similar, to develop the force versus time biofidelity response corridors for lateral thoracic pendulum impacts.

In 2006 Shaw et al. [3] presented results of PMHS tested at a sub-injurious speed of 2.5 m/s in lateral and 30° anterior to lateral pneumatic ram impacts to the thorax. Each PMHS was impacted a total of two times: once laterally and once obliquely on opposite sides of the thorax to examine the difference in response between lateral and oblique impacts for each subject and among subjects. The mass of the ram was 23.86 kg and the aluminum impact face was a 152.4 mm (6.0 inch) diameter circle with a depth of 50.8 mm (2.0 inches) and an edge radius of 12.7 mm (0.5 inch). For each impact, the center of the ram was located at the vertical level of the fourth intercostal space with slight downward adjustments when necessary to prevent arm interaction with the ram. Shaw et al. found that at 2.5 m/s, the lateral thoracic impact demonstrated a significantly stiffer mean normalized response than that from the 30° oblique thoracic impact.

In 2011 Rhule et al. [1] presented results of PMHS tested at a potentially injurious speed of 4.5 m/s in pure lateral and 30° anterior to lateral (oblique) pneumatic ram impacts to the thorax. Each PMHS was impacted only once on the left side, either in the lateral or oblique direction. The mass of the ram was 22.99 kg and the impact face was a rigid aluminum 152.4 mm vertical x 304.8 mm horizontal x 12.7 mm thick (6.0 x 12.0 x 0.5

H. Rhule is a Biomechanical Engineer at the National Highway Traffic Safety Administration (937-666-3320, fax 937-666-3590; heather.rhule@dot.gov). B. Suntay, and J. Stricklin are Research Engineers and R. Herriott is an Engineering Technician at Transportation

inch) rectangular plate with a 3.175 mm (0.125 inch) edge radius. For each impact, the ram was centered vertically at the level of the xiphoid. No statistically significant difference was found between the mean effective stiffness of lateral and oblique impact directions at 4.5 m/s. Figure 1 shows the mean normalized response curves with +/- 1 standard deviation biofidelity targets for the 2.5 m/s and 4.5 m/s lateral and oblique thoracic impacts presented by Rhule et al. [1] with consistent deflection measurement, normalization and biofidelity response target generation methods.

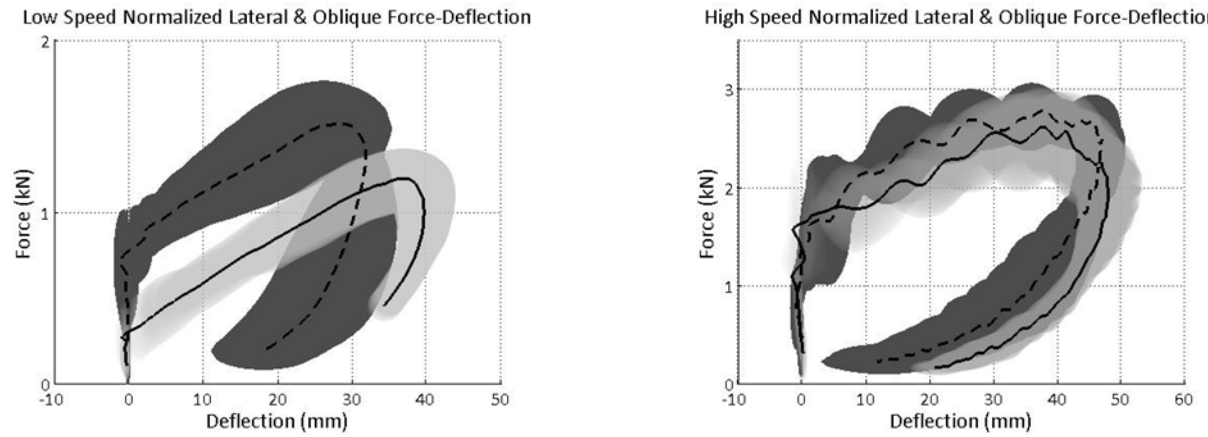

Fig. 1. Mean normalized force-deflection response curves with +/- 1 standard deviation biofidelity targets for re-processed 2.5 m/s thoracic impact data of Shaw et al. [3] (left) and 4.5 m/s thoracic impact data of Rhule et al. [1] (right); lateral response targets shown in dark gray and oblique response targets shown in light gray.

Because the observed lateral versus oblique response trends of the low-speed circular impact face tests of Shaw et al. [3] and the high-speed rectangular impact face tests of Rhule et al. [1] were different, further testing was warranted in order to examine potential causation. New paired lateral and oblique thoracic impacts on five PMHS were conducted to satisfy the following objectives :

- Examine the effects of various test parameters
  - Impact direction (lateral versus oblique)
  - Impact speed (2.5 m/s versus 4.5 m/s)
  - Vertical impact location (fourth intercostal space versus xiphoid)
  - Impact face shape (152.4 mm dia. circle versus 152.4 mm x 304.8 mm rectangle)
- Discuss possible reasons why previous lateral versus oblique response trends in 2.5 m/s and 4.5 m/s test conditions were different and whether data from certain test conditions should be combined to form biofidelity response targets

II. METHODS

In order to address the objectives directly, each PMHS was subjected to multiple paired lateral and oblique impacts under varied test conditions, so that the effect of the various conditions on response from the same subject could be compared. Pneumatic ram impacts were conducted on the thoraxes of five PMHS at either 2.5 or 4.5 m/s. The ram was centered vertically at one of two locations: either at the xiphoid process or at the fourth intercostal space. In order to not induce rotation of the thorax, the ram was centered horizontally through the approximate center of gravity of the subject, estimated at 44% of the distance from the spine, between the spine and sternum. The ram face was either a 152.4 x 304.8 x 12.7 mm (6.0 x 12.0 x 0.5 inch) rectangle with an edge radius of 3.175 mm (0.125 inch) and an impactor mass of 23.135 kg (51.0 lbs) or a 152.4 mm (6.0 inch) diameter circle with a depth of 50.8 mm (2.0 inches), an edge radius of 12.7 mm (0.5 inch) and an impactor mass of 23.994 kg (52.9 lbs). For each impact speed, location and face shape combination, one lateral impact and one 30° anterior to lateral (oblique) impact were conducted per subject. The impact speed, vertical impact location and impact face were varied to examine the effects of the test parameters on the lateral versus oblique impact response relationship of the PMHS. Table I shows the impact speed, location and face shape

Research Center Inc. Y. Kang is a Research Scientist and J. Bolte is Director of the Injury Biomechanics Research Center at The Ohio State University.

combinations for the subjects tested in each combination, with the test sequence, orientation and impact side denoted.

TABLE I
TEST MATRIX

		Low-speed (2.5 m/s)						High-speed (4.5 m/s)					
		Impact Location						Impact Location					
		Xiphoid			4th			Xiphoid			4th		
		Subject	Impact Sequence/ Orientation	Side	Subject	Impact Sequence/ Orientation	Side	Subject	Impact Sequence/ Orientation	Side	Subject	Impact Sequence/ Orientation	Side
Impact Face Shape	Rectangle	1101	1/Oblique	Left				1101	3/Oblique	Right			
			2/Lateral	Right					4/Lateral	Left			
		1201	1/Oblique	Right				1201	3/Oblique	Left			
			2/Lateral	Left					4/Lateral	Right			
		1203	1/Lateral	Right									
			4/Oblique	Left									
		1204	1/Oblique	Left									
			2/Lateral	Right									
	Circle	1202	2/Lateral	Right	1202	1/Lateral	Right				1202	5/Oblique	Left
			3/Oblique	Left		4/Oblique	Left					6/Lateral	Right
		1204	3/Lateral	Right	1203	2/Lateral	Right						
			4/Oblique	Left		3/Oblique	Left						

Subject Selection

PMHS were selected from the Anatomy Body Donation Program[1] at The Ohio State University based on the following guidelines:

- No prior invasive surgery or other events , which may have compromised the structural integrity of the thorax
- Not osteoporotic; Young adult T-score of -2.5 or above
- Body Mass Index between 18.5-29.9 (normal-overweight)
- Body mass of 95.3 kg or less (for ease of moving subject)

Unlike the 2011 study [1] only male subjects were accepted for testing in order to reduce the variation in height and mass of subjects, as well as to avoid the issue of interference of breast tissue.

Subject Preparation

Five fresh, unembalmed cadavers were prepared prior to testing. The subjects' bodies were washed with antiseptic soap and a 10% bleach solution. Anthropometric measurements were taken while the subjects were in a supine position and the subjects were visually inspected for any scars or evidence that the structural integrity of their thoraxes was compromised. After passing the visual inspection, a bone mineral density (BMD) scan was performed using a DEXA scan machine. The Young Adult T-score was reported from the L2-L4 region of the spine because it was closest to the region of impact and is an accepted location to clinically define BMD. Cadavers for which the Young Adult T-Score was found to be acceptable (Young adult T-score ≥ -2.5), then underwent pre-test Computed Tomography (CT) scans to identify any pre-existing structural damage and also for use as a baseline for post-test comparisons. After instrumentation was installed, subjects were kept in a 4.4°C (40°F) cooler for preservation overnight, prior to testing the following day. In previous tests [1] subjects attained an internal temperature of approximately 15°C (59°F) as measured through the trachea prior to testing.

[1] Research was reviewed and approved by the National Highway Traffic Safety Administration and The Ohio State University Institutional Review Board (IRB) and was conducted in accordance with the practice of the IRB.

In tests of the current study, the internal temperature was not measured; however, because the amount of elapsed time between subject removal from the cooler and impact was within an average of 1 hour from the previous study, it is believed that the subjects of this study attained an internal temperature close to 15°C by the time of the first impact, and possibly close to 20°C (68°F) by the last impact.

Instrumentation

Two strain gages (Model # CEA-06-062UW-350 w/Option P2, Vishay Micro Measurements Group, Raleigh, NC) were installed on each rib in the region of impact for ribs 3-10 on the left and right sides of the rib cage to determine when rib fractures occurred. Each rib was exposed with a three-inch long incision along the length of the rib and scraped clean of any soft tissue. Ether was applied in order to clean and dry the surface of each rib prior to gluing the strain gages. A 40-gage chest band was positioned on the subject at the level of impact (either the xiphoid or fourth intercostal space). Aluminum blocks instrumented with three linear uniaxial accelerometers and three angular rate sensors (3aω blocks) were installed on mounts at T4 on the spine and at the mid-sternum location to measure kinematic motion of the subject in the x, y and z directions.

The pneumatic ram was instrumented with a linear accelerometer on the rear side of the impact face. Velocity of the ram was determined through integration of the ram acceleration and verified using a light trap. Initial three-dimensional positions of the locations of pertinent anatomical structures and instrumentation, the ram face center and the table on which the subject was seated were recorded with a FARO arm (FARO Technologies, Inc., Lake Mary, FL).

Test Performance

The subject was positioned at a distance from the pneumatic ram face such that impact would occur upon the ram reaching constant velocity. The subject was seated on a hydraulic lift table such that the impactor was centered vertically at either the level of the xiphoid or fourth intercostal space (based on the test matrix) and horizontally through the approximate center of gravity of the subject so as not to induce rotation of the thorax. For oblique impacts, the subject was rotated such that the impact occurred 30° anterior to lateral. The arms were positioned at approximately 90 degrees relative to the body and parallel to the floor, with the forearms crossed and supported by a strut. The head was fitted with a harness, which was hooked to a magnetic release suspended from a moveable track. The track was able to move in the anterior-posterior and in the medial-lateral directions so that proper alignment of the subject could be achieved.

A foam-padded structure was positioned behind and around the non-impact side of the subject in order to prevent the subject from falling over after the impact but still allowing the subject to fully interact with the ram without being restricted by the foam-padded structure. The lungs were pressurized with approximately 45-60 cm H_2O of air through a trachea vent tube prior to impact. No pressurization of the thoracic vasculature was performed. Figure 2 shows an oblique impact setup and a lateral impact setup with the rectangular impact face centered at the level of the xiphoid prior to impact. Figure 3 shows a lateral impact setup with the circular impact face centered at the level of the fourth intercostal space.

Tests performed with the ram face centered at the vertical location of the fourth intercostal space were conducted without long underwear on the subject's upper body so that potential interaction between the scapula and the ram face could be documented with high-speed video. Impact tests were conducted at the Injury Biomechanics Research Laboratory at The Ohio State University. High-speed digital video cameras recorded the events at 1000 frames/sec. Data were recorded on a 96-channel Yokogawa Electric Corporation WE7000 data acquisition system, with a sampling rate of 20,000 Hz.

Since multiple tests would be performed with each subject, the strain gages installed on the ribs were used to monitor the occurrence of rib fractures during each test. After each test was performed, the strain gage data were reviewed for a distinct drop in strain, which has been associated with rib fracture [6]. For tests where a subsequent test was to be performed on the same side of the rib cage and the strain gage data showed more than two ribs fractured, the subsequent test was not performed. For tests where a subsequent test was to be performed on the opposite side of the rib cage and the data showed more than three ribs fractured, the subsequent test was not performed.

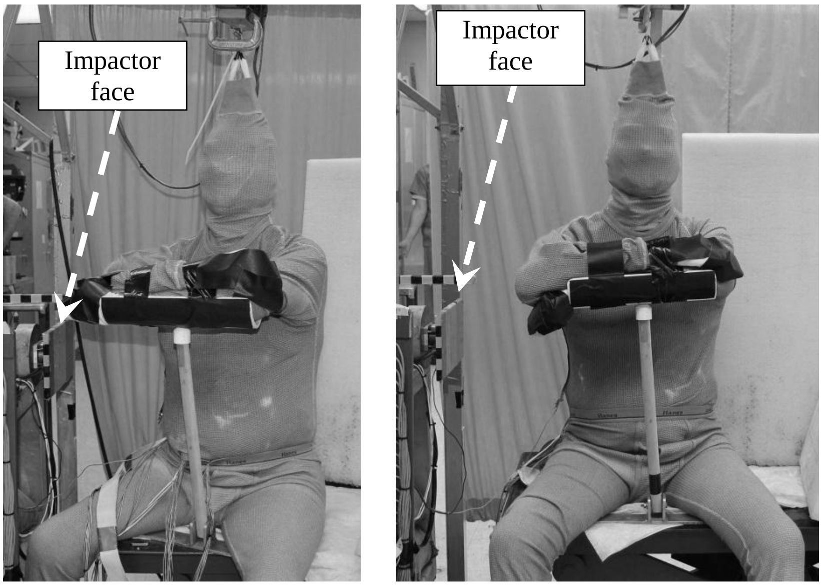

Fig. 2. Pre-test photographs showing 30° oblique (left) and 0° lateral (right) setup with rectangular impact face centered at the xiphoid.

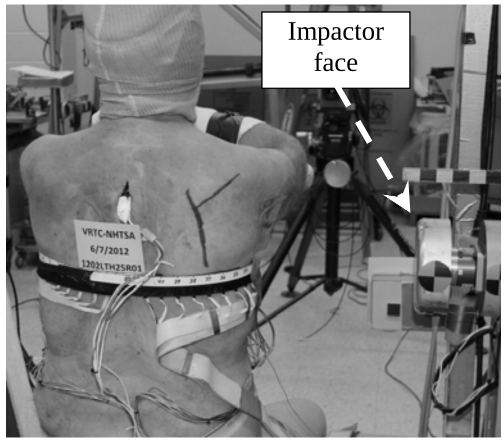

Fig. 3. 0° lateral setup with circular impact face centered at the fourth intercostal space.

Post-Test Imaging and Autopsy

A post-test CT scan was performed after the last test on each subject, followed by a detailed necropsy to identify injuries caused by the impacts. The necropsy included a complete anatomical dissection moving from superficial to deep for both the thoracic and abdominal cavities. The skin and subcutaneous tissue were removed, all muscles were dissected, and any abnormalities were documented. Following the reflection of the muscles, the skeleton was examined, which included cleaning all twelve sets of ribs, the sternum, clavicles, and scapulae. The cavities were then opened, and all internal organs in both the thoracic and abdominal cavities were checked for injury. Both sides of the subject were examined along with the intercostal spaces. The clavicles and scapulae were also examined for any damage. The AAAM Abbreviated Injury Scale 2005, Update 2008 [7] was used to assign injury descriptive values (AIS scores).

Data Processing

Data processing included filtering load cell force with a Channel Filter Class (CFC) 600 and compensating for the inertia of the mass of the ram between the load cell and the subject. Chest band data were processed using CrashStar version 2.5 [8] to produce contours of the chest band shape at each point in time. Chest deflection was determined using the forced angle method [9]. In this method, the distance is calculated between each gage on the chest band and a point along the spine-sternum line. The point, referred to as the origin, is located at half the initial chest depth (determined from the chest band gages) from the spine, along the spine-sternum line. Each gage-to-origin distance measurement is determined at each point in time and subtracted from the corresponding gage-to-origin distance established prior to the impact event. The gage on the contour which achieves the largest change in magnitude from its initial gage-to-origin distance determines the maximum deflection. The angle from the spine-sternum line to the line connecting each gage-to-origin is also measured at each point in time for each gage and the angle at which maximum deflection occurs is determined. Time zero was defined using the deflection versus time curve from the chest band gage that measured maximum chest deflection. Time zero is defined as the last time at which deflection equals zero prior to reaching maximum deflection. For the purposes of this paper, the data were not normalized. The effective stiffness was calculated for each impact over the interval of zero deflection to maximum deflection as shown in Equation 1, where x = thoracic displacement from chest band (mm) and k_{eff} = effective stiffness of thorax (N/mm).

$$\int F dx = \frac{1}{2} k_{eff} \; x_{\max}^2 \Rightarrow k_{eff} = \frac{2\int F dx}{x_{\max}^2} \qquad (1)$$

III. RESULTS

Subject Characteristics

Table II lists the characteristics of the subjects tested in the current study. All subjects were male, between the ages of 21 and 76 years old, with a height between 172 and 183.5 cm and a body mass between 67.5 and 97.5 kg. Although one subject's body mass was outside the subject selection guidelines, all other subject characteristics were within the guidelines. Chest breadth and chest depth ranged from 269.5 to 351 mm and 165.5 to 255 mm, respectively.

TABLE II
SUBJECT CHARACTERISTIC DATA

Subject	Gender	Age	Height (cm)	Body Mass (kg)	Body Mass Index (kg/m^2)	Young-Adult T-Score	Chest Breadth (mm)*	Chest Depth (mm)
1101	Male	21	173.0	67.5	22.6	-1.6	269.5	165.5
1201	Male	56	176.0	88.0	28.4	1.6	332.0	234.0
1202	Male	76	183.5	97.5	29.0	1.4	342.5	241.5
1203	Male	71	172.0	75.8	25.6	3.0	315.0	225.0
1204	Male	75	183.0	92.1	27.5	-0.1	351.0	255.0
	Min	21.0	172.0	67.5	22.6	-1.6	269.5	165.5
	Max	76.0	183.5	97.5	29.0	3.0	351.0	255.0
	Avg	59.8	177.5	84.2	26.6	0.9	322.0	224.2
	Std Dev	20.7	4.9	11.0	2.3	1.6	28.9	31.0

*average of measurements at axilla and xiphoid while subject in supine position without chest band installed

Injuries

Table III shows the injuries sustained in each impact for each subject. As shown in Table III, the majority of injuries sustained during testing included transverse, non-displaced rib fractures at the anterior location of the rib. Only one subject (1101) did not sustain any injuries. Subject 1201 sustained one left rib fracture during the third impact (first high-speed test on the left side), followed by three right ribs fractured during the fourth impact (first high-speed test on the right side). Subject 1202 sustained fractures to left ribs 6-10, but it is not known whether these occurred during the third, fourth and/or fifth impact. Since fractures to left ribs 3-5 occurred during the fifth impact (first high-speed impact to the left side), it is suspected that fractures to left ribs 6-10 also occurred during this test. However, due to issues with the strain gages on left ribs 6-10, there is no data to show when these fractures occurred. In addition, subject 1202 sustained three right rib fractures during the sixth impact (first high- speed test on the right side). Subject 1203 sustained one left rib fracture during the third test and a fracture to an additional left rib during the fourth test. Subject 1204 sustained a fracture to one left rib during the first test and

TABLE III

INJURY RESULTS

Subject #	Speed (m/s)	Location	Impact Face	Impact Side	Orientation	Test Sequence	Fx'd Ribs	Fractured Rib Locations and Type of Fracture		AIS Score (AAAM 2005, '08 update)	AIS description (AAAM 2005, '08 update)
								Anterior	Posterior		
1101	2.5	X	R	L	O	1				n/a	n/a
	2.5	X	R	R	L	2				n/a	n/a
	4.5	X	R	R	O	3				n/a	n/a
	4.5	X	R	L	L	4				n/a	n/a
1201	2.5	X	R	R	O	1				n/a	n/a
	2.5	X	R	L	L	2				n/a	n/a
	4.5	X	R	L	O	3	L5	trans., NDS		450201.1	Fractures without flail, 1 rib
	4.5	X	R	R	L	4	R5	trans., NDS		450203.3	Fractures without flail, ≥3 ribs
							R6	trans., H-shaped, NDS			
							R7	trans., NDS			
1202	2.5	4	C	R	L	1				n/a	n/a
	2.5	X	C	R	L	2				n/a	n/a
	2.5	X	C	L	O	3	**	**	**	**	**
	2.5	4	C	L	O	4	**	**	**	**	**
	4.5	4	C	L	O	5	**	**	**	**	**
							L3	trans., NDS		450203.3	Fractures without flail, ≥3 ribs
							L4	trans., DS	trans., NDS		
							L5	trans., DS	trans., DS		
	4.5	4	C	R	L	6	R8	trans., NDS		450203.3	Fractures without flail, ≥3 ribs
							R9	trans., DS			
							R10	trans., NDS			
1203	2.5	X	R	R	L	1				n/a	n/a
	2.5	4	C	R	L	2				n/a	n/a
	2.5	4	C	L	O	3	L4	trans., NDS		450201.1	Fractures without flail, 1 rib
	2.5	X	R	L	O	4	L5	trans., DS		450201.1	Fractures without flail, 1 rib
1204	2.5	X	R	L	O	1	L6	trans., NDS		450201.1	Fractures without flail, 1 rib
	2.5	X	R	R	L	2				n/a	n/a
	2.5	X	C	R	L	3				n/a	n/a
	2.5	X	C	L	O	4	L4	trans., NDS		450202.2	Fractures without flail, 2 ribs
							L5	trans., NDS			

Impact location: X – xiphoid; 4 – 4th intercostal space

Impact face: R – rectangular ; C – circular

Impact side: L – left; R – right;

Orientation: O – 30° oblique; L – lateral

NDS: non-displaced

DS: displaced

dark gray shade: ≥ 3 ribs fxd

H-shaped: 2 parallel hairline fractures in communication

trans.: transverse - across the long axis

**Could not determine which test or tests these fx occurred in due to strain gage issues (L6, L8, L9, L10 trans., NDS; L7 trans., DS)

fractures to two additional left ribs during the fourth test. The fractures sustained by subjects 1203 and 1204 occurred during low-speed tests.

Lateral Versus Oblique Response Comparisons

Five combinations of impact speed, impact location, and impact face were tested. Chest band contours for initial position and maximum deflection as well as a table of maximum chest deflection values and angle of maximum deflection are shown for each impact in the online supplemental material provided on the IRCOBI website. Table IV shows the peak non-normalized force and deflection and effective stiffness values for each test. For tests with the rectangular impact face (white cells in Table IV), peak forces were similar in paired oblique and lateral impacts for three out of six cases: 1101 and 1201 (xiphoid, low-speed) and 1101 (xiphoid, high-speed). For the remaining three cases with the rectangular face, peak forces were 17-27% less in oblique impacts compared to lateral impacts for a given subject (see bold values in Table IV). For all but one test with the rectangular face, the deflection in the oblique impact was greater than that in the lateral impact for a given subject, though the differences in deflection between oblique and lateral tests per subject only ranged from 2.8 to 8.5 mm. For all tests with the circular impact face (gray cells in Table IV), peak forces were less (21-34%) and peak deflections were greater (18-94%) per subject in oblique compared to lateral impacts.

TABLE IV

LATERAL VERSUS OBLIQUE PEAK FORCE, DEFLECTION, AND EFFECTIVE STIFFNESS VALUES

Test Parameters for Comparison	Subject	Impact Side	Orientation	Test Sequence	# Ribs Fx'd	# Ribs Fx'd on same side before this test?	Peak Non-normalized Force (N)	Peak Non-normalized Deflection (mm)	Effective Stiffness (N/mm)
Rectangle, Xiphoid, Low speed	1101	L	O	1			1141.6	19.3	90.8
		R	L	2			1089.9	10.8	178.7
	1201	R	O	1			1489.8	**22.7**	106.0
		L	L	2			1481.7	**26.4**	81.3
	1203	L	O	4	1	1	**1157.5**	30.1	64.5
		R	L	1			**1393.1**	27.3	83.2
	1204	L	O	1	1		**1019.4**	30.4	58.3
		R	L	2			**1282.6**	24.3	84.4
Rectangle, Xiphoid, High speed	1101	R	O	3			2334.8	37.2	107.7
		L	L	4			2466.0	28.7	150.6
	1201	L	O	3	1		**2462.1**	44.3	103.8
		R	L	4	3		**3353.7**	39.5	125.1
Circle, Xiphoid, Low speed	1202	L	O	3	**		1122.9	63.3	23.8
		R	L	2			1421.6	33.9	53.8
	1204	L	O	4	2	1	937.3	27.3	56.0
		R	L	3			1181.1	22.9	80.1
Circle, 4th intercostal, Low speed	1202	L	O	4	**	**	904.2	46.6	26.5
		R	L	1			1332.2	30.5	71.6
	1203	L	O	3	1		986.5	60.3	24.8
		R	L	2			1457.3	31.1	65.3
Circle, 4th intercostal, High speed	1202	L	O	5	3**	**	2135.7	63.1	37.8
		R	L	6	3		3255.7	53.3	98.5

Impact side: L – left; R – right Orientation: O – 30° oblique; L – lateral

** 5 ribs fractured on subject 1202; not known in which test(s) they occurred (3, 4, and/or 5)

(gray) Tests with circular impact face

Figure 4 shows lateral and oblique force-deflection responses for the various combinations of test parameters for all five subjects. Figures 4a-4c show that for each subject, the lateral response was stiffer than the oblique response when the circular impact face was used, though the difference in lateral and oblique stiffness response for subject 1204 was less dramatic. Figures 4d-4f do not show a clear lateral versus oblique response trend for the subjects impacted with the rectangular impact face.

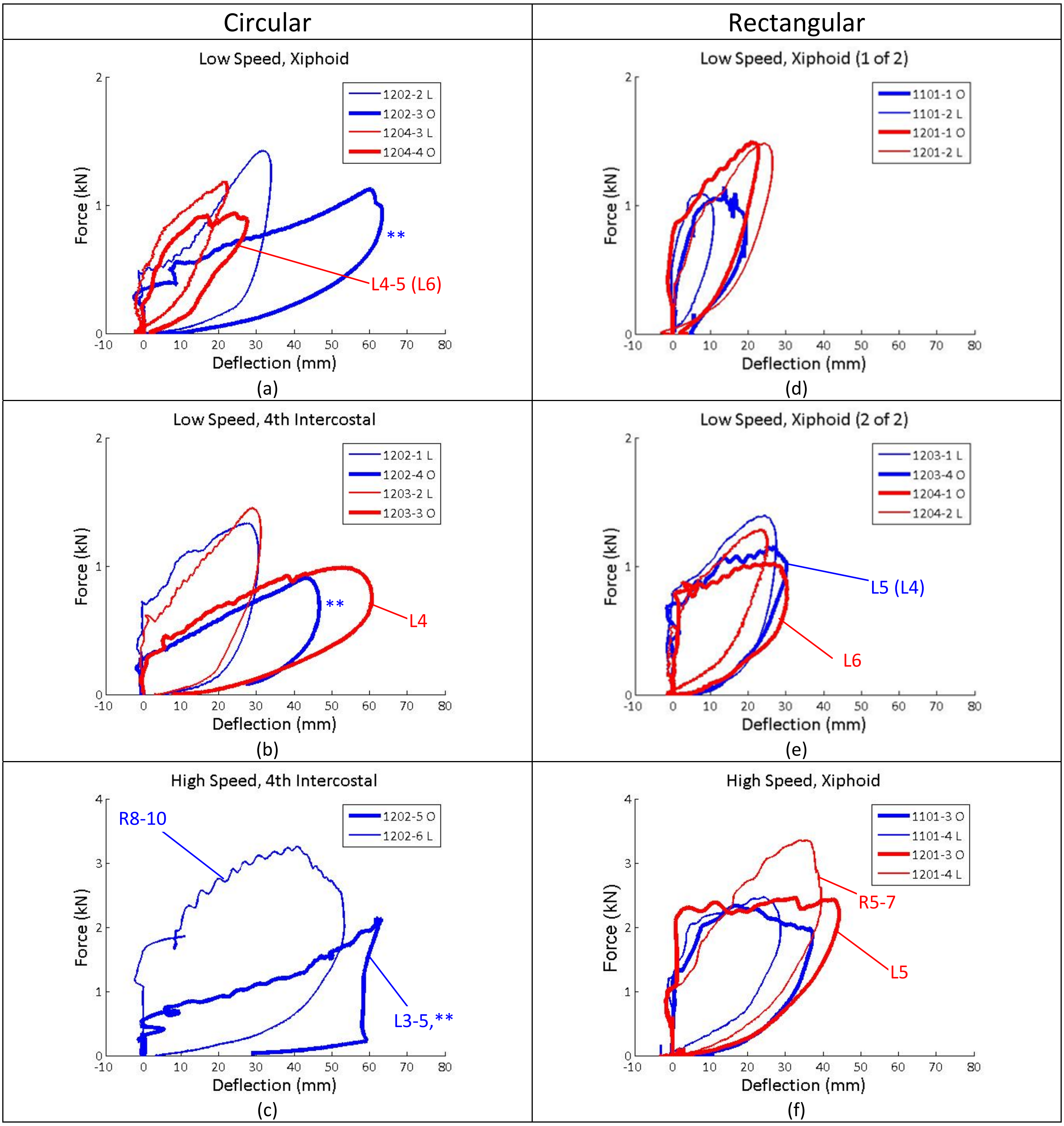

Fig. 4. Lateral and oblique force-deflection responses for each combination of impact speed, location, and face shape. Subjects are distinguished by line color. Impact orientation is distinguished by line thickness (thick = oblique; thin = lateral). Ribs fractured are noted where appropriate, but not at force/deflection of fracture occurrence, with fractures in parentheses indicating ribs previously fractured. **indicates left ribs 6-10 fractured in test 1202-3, 1202-4, and/or 1202-5.

IV. DISCUSSION

This study investigated why the lateral versus oblique mean normalized force-deflection response curves with +/- 1 standard deviation biofidelity targets are different between the low-speed tests conducted by Shaw et al. [3] at the fourth intercostal space with a circular impact face and high-speed tests conducted by Rhule et al. [1] at the xiphoid with a rectangular impact face. In order to enable direct comparisons between lateral and oblique impacts, multiple paired lateral and oblique impacts were performed on each subject. Test parameters, including vertical impact location, impact speed, and impact face shape, were varied to ascertain why the lateral versus oblique response trends in the previously mentioned studies differ.

Injuries

Because individual subjects were used as a control to remove the variation due to human subject variability and to directly compare lateral versus oblique responses in various conditions, the occurrence of injuries WAS considered with respect to the objective. For the purposes of this paper, it was assumed that one or two rib fractures would not affect the force-deflection response enough to change the lateral versus oblique response trend. Subject 1202 had questionable injury results due to problems with the strain gages in tests 3, 4 and 5 (Table III). Figure 4b shows that another subject tested in the same configuration as subject 1202 (low-speed/4th intercostal space/circular) demonstrated a similar lateral versus oblique response relationship with only a single rib fractured, indicating that either the rib fractures of subject 1202 did not occur in test 4 or that the fractures did not affect the lateral versus oblique response relationship. However, Figure 4a shows a different configuration for subjects were tested in the same configuration as subject 1202, so there was no other data to use in determining whether the lateral versus oblique response relationship was driven by the rib fractures or by the test condition. Thus, any conclusions made regarding subject 1202 in the low-speed/xiphoid/circular and high-speed/4th intercostal space/circular conditions were limited by the possible occurrence of rib fractures in tests 1202-3, 4, and 5. Though subject 1201 sustained three rib fractures during its fourth test, high-speed lateral with the rectangular impact face at the xiphoid, the peak force from this test was 892 N higher than in the paired oblique test (test 3) where only one rib fracture occurred. Even if the rib fractures from test 4 did result in a lower force and higher deflection than would have occurred without the fractures, the peak force and deflection would still have been higher and lower, respectively, than those of the oblique test 3, which would have given the same lateral versus oblique response relationship seen in Figure 4f.

Vertical Impact Location

Rhule et al. [1] speculated that the superior vertical impact location of the fourth intercostal space in the Shaw et al. [3] tests might have caused the lateral response to be stiffer due to the scapula and musculature that exists higher on the thorax, which would have interacted with the impactor in lateral impacts but not oblique impacts. The effect of the vertical impact location on the lateral versus oblique response trend is illustrated in Figure 5, where subject 1202 was impacted with the circular impact face at low-speed, and only the vertical impact location was varied. For subject 1202 (Figure 5), the vertical impact location did not appear to affect the lateral versus oblique response trend as each impact location resulted in a much stiffer lateral response as compared to the oblique response. However, it should be noted that fractures may have occurred during tests 1202-3 and/or 1202-4, which could have altered the force-deflection responses. When the responses of two different subjects were compared as shown in Figures 4a and 4b, one subject (1203, 4th intercostal) showed a much stiffer lateral (versus oblique) response. Additionally, one subject (1204, xiphoid) showed only a slightly stiffer lateral response, which, when compared to subject 1203, could be interpreted to have comparable lateral and oblique stiffnesses. Based on the results of these three subjects, it is unclear whether the vertical impact location had an effect on the lateral versus oblique response trend at low speed, even though videos from tests with the impact location at the fourth intercostal space did show scapular involvement.

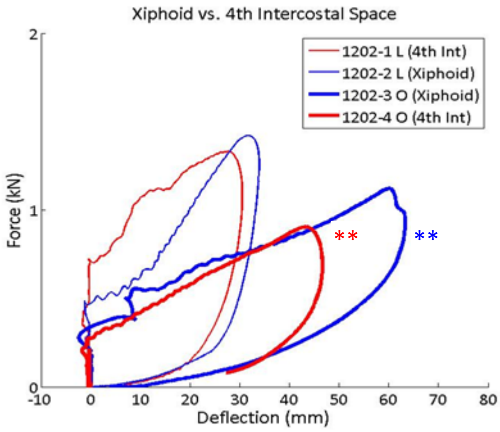

Figure 5. Lateral and oblique force-deflection responses for subject 1202 in 2.5 m/s impacts with the circular impact face at the vertical impact locations of xiphoid and 4th intercostal space.

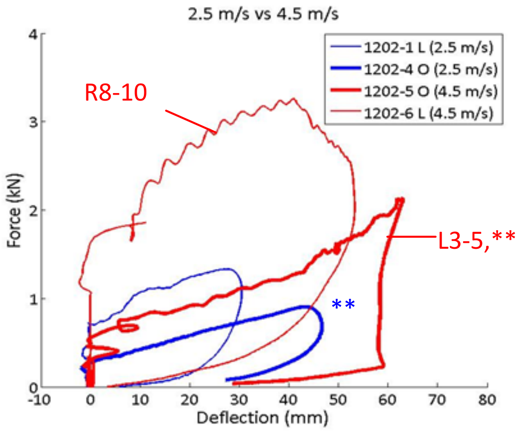

Figure 6. Lateral and oblique force-deflection responses for subject 1202 in 2.5 and 4.5 m/s impacts with the circular impact face at the 4th intercostal space.

Impact Speed

The effect of impact speed on the lateral versus oblique response trend is illustrated in Figure 6, where subject 1202 was impacted with the circular impact face at the fourth intercostal space and only the impact speed was varied, and in Figures 7 and 8, where subjects 1101 and 1201 were impacted with the rectangular impact face at the xiphoid and only the impact speed was varied. Figure 6 shows that subject 1202 demonstrated stiffer lateral responses versus oblique responses at each impact speed with the circular impact face, and Figure 7 shows similar peak forces between lateral and oblique impacts at both speeds with the rectangular impact face, with more deflection in the oblique impacts. Figure 8 shows similar peak forces and deflections between lateral and oblique impacts at low-speed and larger lateral peak force and comparable peak deflections in lateral and oblique impacts at high-speed. Though only one subject was tested at both low- and high-speed with the circular impact face, the results suggest that the impact speed does not appear to affect the lateral versus oblique response trend. However, it should be noted that the responses of subject 1202 (Figure 6) could have been affected by the multiple rib fractures sustained in the high-speed tests as discussed previously. As these impacts were conducted at high speed, it is difficult to ascertain the answer to the question regarding the effect of impact speed on the lateral versus oblique response relationship since it is likely that rib fractures will occur at this speed. With the rectangular face, subjects 1101 and 1201 showed different results. The lateral versus oblique responses from subject 1101 were similar at low- and high-speed, suggesting that impact speed may not have changed the lateral versus oblique response relationship. However, lateral versus oblique responses for subject 1201 were different between low- and high-speed, suggesting that impact speed could have affected the lateral versus oblique response relationship. The injury results from subject 1201 were not believed to be a factor in the difference in responses at low- and high-speed. From the results of one subject, it was suggested that with the circular face, impact speed did not change the lateral versus oblique response relationship; however, results from two subjects impacted with the rectangular face suggested that it was unclear what the effect of impact speed was on the lateral versus oblique response relationship.

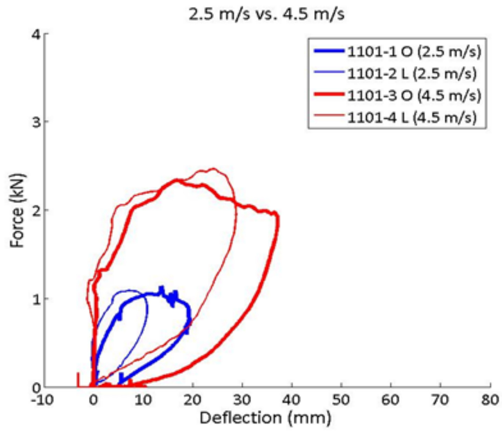

Figure 7. Lateral and oblique force-deflection responses for subject 1101 in 2.5 and 4.5 m/s impacts with the rectangular impact face at the xiphoid.

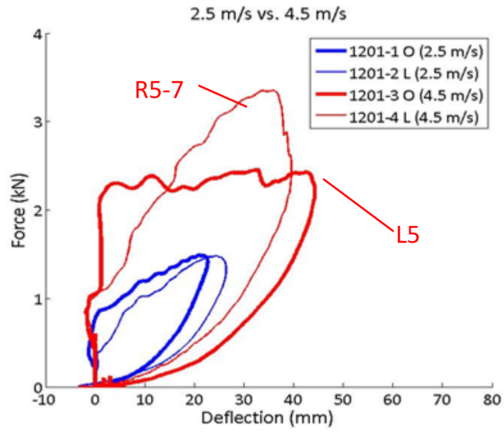

Figure 8. Lateral and oblique force-deflection responses for subject 1201 in 2.5 and 4.5 m/s impacts with the rectangular impact face at the xiphoid.

Impact Face Shape

The effect of impact face shape on the lateral versus oblique response trend is illustrated in Figure 9, where subject 1204 was impacted at the xiphoid at low-speed and only the impact face shape was varied. Figure 9 shows that each impact face shape demonstrated stiffer lateral responses versus oblique responses, though the difference in stiffness between lateral and oblique impacts was not as dramatic as that seen in subject 1202 with the circular impact face (Figure 6). It should be noted that the comparison of impact face shape was only made at the xiphoid location. If all impacts with the circular impact face were considered (Figures 4a-4c), lateral responses were generally stiffer than oblique responses per subject. If all impacts with the rectangular impact face were considered (Figures 4d-4f), the lateral versus oblique responses were generally similar per subject. These results suggested that there might be some correlation between impact face shape and the lateral versus oblique response trend, where the circular shape resulted in a more dramatic difference between lateral (stiffer) and oblique responses per subject, and the rectangular shape resulted in more similar lateral and oblique responses per subject.

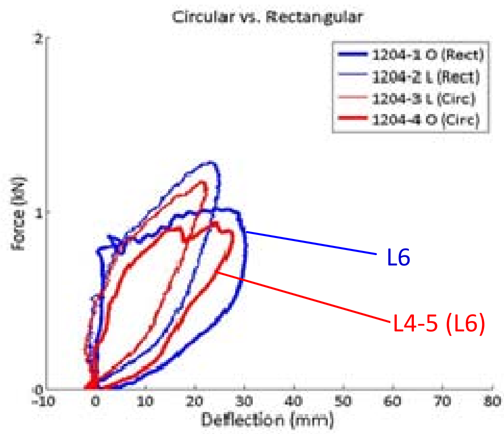

Figure 9. Lateral and oblique force-deflection responses for subject 1204 in 2.5 m/s impacts at the xiphoid with the circular and rectangular impact faces.

In order to determine if the mean effective stiffness values were statistically different between paired lateral and oblique impacts with the circle at low speed, a paired t-test was performed. The null hypothesis was chosen so that the mean difference in effective stiffness values for lateral and oblique impacts was zero. The level of significance was set at $\alpha = 0.05$. Table V shows the tests utilized for the analysis, t, critical t (t_{crit}), p values, and the result of the t-tests. The results in Table V show that the t-value (7.3) was more than the t_{crit} value (3.2), and the p-value (0.005) was less than 0.05, rejecting the null hypothesis, indicating a statistically significant difference between the mean lateral and oblique effective stiffness values for subjects impacted with the circular impact face at low speed. However, it is unknown whether fractures occurred during tests 1202-3 and 1202-4, which could have affected the stiffness response, and therefore, t-test results. A second paired t-test was performed for lateral and oblique impacts with the rectangular impact face at low speed to determine if the mean effective stiffness values were statistically different. Again, the null hypothesis was chosen so that the mean difference in effective stiffness values for lateral and oblique impacts was zero, and the level of significance was set at $\alpha = 0.05$. The results in

Table V show that the t-value (1.2) was less than the t_{crit} value (3.2), and the p-value (0.328) was more than 0.05, indicating that the null hypothesis could not be rejected and that no statistically significant difference was observed between the mean lateral and oblique effective stiffness values for subjects impacted with the rectangular impact face at low speed. Thus, it appears that the impact face shape may have affected the lateral versus oblique response trend at low speed. Rhule et al. [1] found that a statistically significant difference existed between the mean lateral and oblique effective stiffness values for subjects impacted with the circular impact face at the fourth intercostal space at 2.5 m/s, and a statistically significant difference was not observed between the mean lateral and oblique effective stiffness values for subjects impacted with the rectangular impact face at the xiphoid at 4.5 m/s. The results shown in Table V reiterate the findings of Rhule et al. [1] as well as identify the apparent cause for the difference in lateral versus oblique response trends: impactor face shape.

TABLE V

T-TEST RESULTS

	LATERAL					OBLIQUE				
	Test Series/ Subject	Impact Side	Impact Location	Test Sequence	Effective Stiffness	Test Series/ Subject	Impact Side	Impact Location	Test Sequence	Effective Stiffness
Low speed circle	1202	R	X	2	53.8	1202	L	X	3	23.8
	1204	R	X	3	80.1	1204	L	X	4	56.0
	1202	R	4	1	71.6	1202	L	4	4	26.5
	1203	R	4	2	65.3	1203	L	4	3	24.8
	Null hypothesis: mean difference = 0									α = 0.05
	t = 7.28		t_{crit} = 3.18		p = 0.0053	Result: reject null hypothesis				
Low speed rectangle	1101	R	X	2	178.7	1101	L	X	1	90.8
	1201	L	X	2	81.3	1201	R	X	1	106.0
	1203	R	X	1	83.2	1203	L	X	4	64.5
	1204	R	X	2	84.4	1204	L	X	1	58.3
	Null hypothesis: mean difference = 0									α = 0.05
	t = 1.16		t_{crit} = 3.18		p = 0.328	Result: cannot reject null hypothesis				

Due to the larger area of the rectangular impact face, the full area of the face did not engage the subject in either lateral or oblique impacts (Figure 10), whereas the full area of the smaller, circular impact face engaged the subject in both lateral and oblique impacts. Tests with the smaller, circular impact face had a consistent load distribution for both lateral and oblique impacts, resulting in a direct comparison of responses for the two impact directions. However, tests with the larger, rectangular impact face did not have a consistent load distribution for both lateral and oblique impacts, which would confound the comparison of responses for the two impact directions. For example, because the rectangular impact face was wider than the subject, when the impactor engaged the subject, a different amount of the impact face interacted with the subject in each direction depending on the size, shape, contour, stiffness, etc., of the subject. This inconsistent impactor-to-subject engagement is illustrated in Figure 10 where, in the lateral impact with the rectangular impact face, only 5-6 inches along the impact face area engaged the subject compared to 7-8 inches in the oblique impact with the rectangular impact face. Perhaps the inconsistent lateral versus oblique load distributions resulting from the larger, rectangular impact face caused the lateral and oblique responses to be more similar than they would have been if a smaller impact face with a consistent load distribution were used.

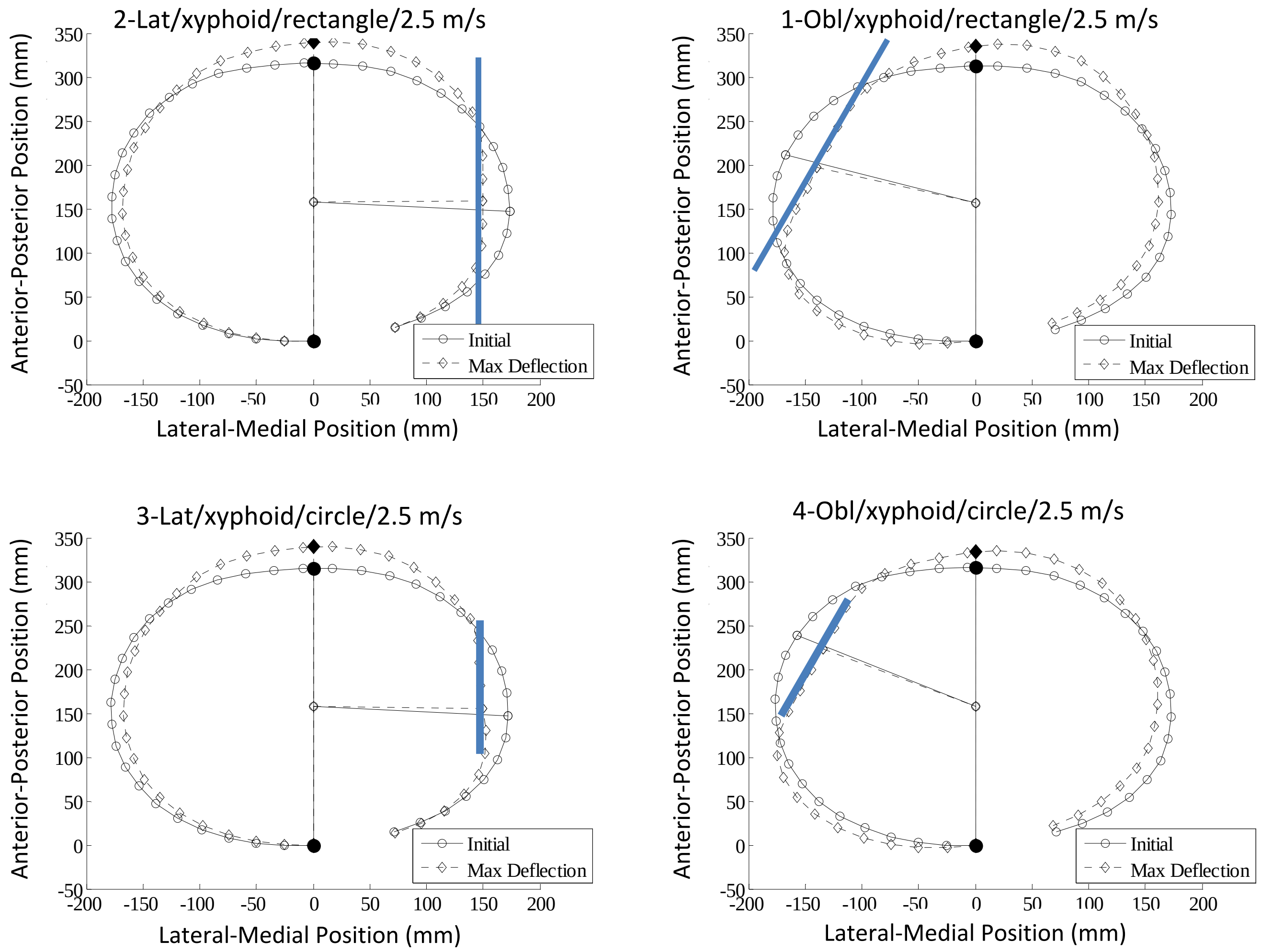

Fig. 10. Initial and maximum deflection chest band contours from subject 1204 illustrating impactor face engagement with subject for lateral and oblique impacts with rectangular and circular impact faces. Impactor face (thick line) is drawn to scale.

Perhaps, in addition to the fact that the area of the larger, rectangular impact face which engaged the subject may not have been consistent between lateral and oblique impacts of the same subject and affected the direct comparison of lateral to oblique responses, a larger impact area (as compared to the 150 mm diameter circular impact face) may have elicited a more similar response in lateral versus oblique impacts, due to the more distributed, as opposed to concentrated, load on the thorax.

Another possible cause for the significant difference in lateral versus oblique response with the circular impact face may be the edge of the impact face intruding into the rib cage during oblique impacts, causing further deflection than would have otherwise occurred. Figure 11 shows one instance where the edge of the circular impact face intruded into the thorax during an oblique impact but not in a lateral impact. This occurred several times in this test series but not every time. In addition, in the tests presented by Shaw et al. [3], only three out of fourteen cases showed chest contours in which the edge of the circular impact face intruded into the chest; however, two of those instances happened to be lateral impacts. In motor vehicle crashes, small "impactors," possibly with small edges, are probably unlikely, especially with the growth of air bags. However, the human arm may be one source of a small "impactor" which could affect the lateral versus oblique response of an occupant in a crash.

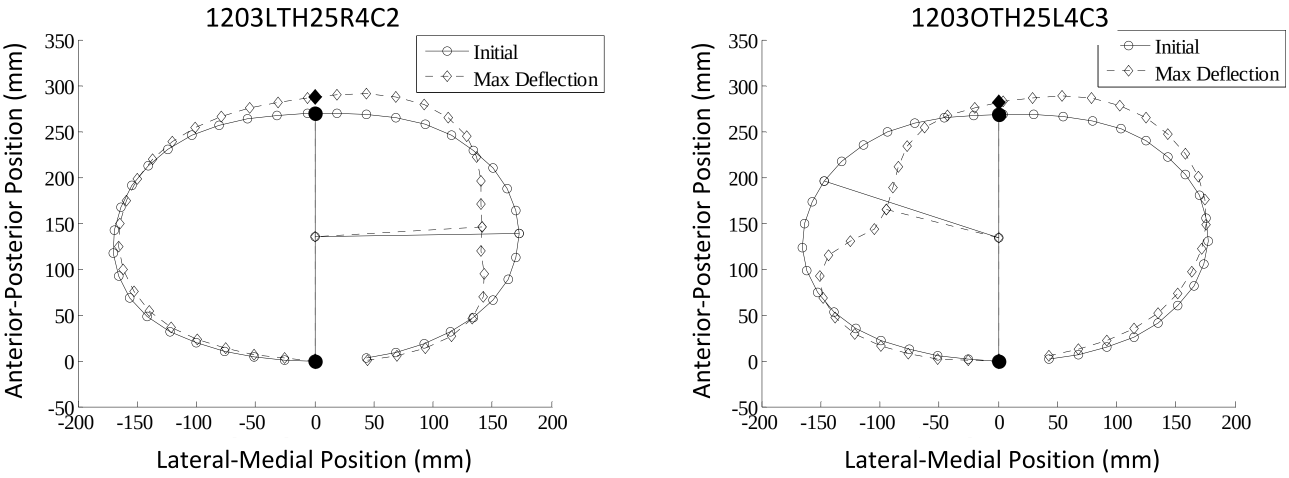

Fig. 11. Initial and maximum deflection chest band contours from subject 1203, illustrating intrusion of the circular impact face into the rib cage during oblique impact (right plot), but not during lateral impact (left plot).

Although the limitations of this study included small sample sizes, multiple impacts on individual subjects, and strain gage failures, which prevented determination of when some rib fractures occurred, results of the study suggest that the relative size of the impact face and the consistency with which the impact load was distributed on the subject could have affected the lateral versus oblique force-deflection response trend. In addition, results of the study are inconclusive regarding the effect that vertical impact location (xiphoid versus 4th intercostal space) with either the circular or rectangular impact face and impact speed with the rectangular impact face had on the lateral versus oblique response trend. With the smaller, circular impact face at impact speeds of 2.5 and 4.5 m/s, there was no apparent difference in the relationship between the lateral versus oblique response. Finally, the observations of this study suggest that the mean lateral and oblique responses and +/- 1 standard deviation biofidelity targets presented by Shaw et al. [3] and Rhule et al. [1] were valid for the test conditions employed. Because there was not a significant difference between the mean effective stiffness values in lateral versus oblique impacts with the rectangular impact face at low- or high-speed, lateral and oblique responses could be grouped together to form one biofidelity response target for each speed. Though the ISO [2] grouped normalized lateral and oblique responses together to form a force-time biofidelity response corridor because the peak forces were similar, the impactor used was a 150 mm diameter circle, as used here and by Shaw et al. [3]. It is not known why the lateral and oblique normalized peak force responses used by ISO would have been similar, which is not consistent with the findings here.

V. CONCLUSIONS

The following bullets summarize the observations of this study.

- Impactor Shape and Size:
  - With a smaller impactor (circular face), lateral impacts resulted in a stiffer response than those for oblique impacts with a statistically significant difference in mean lateral versus oblique effective stiffness, so lateral and oblique responses from smaller, circular impact face tests should not be grouped together to form biofidelity response targets. The smaller impact face was able to identify differences between lateral and oblique responses because it enabled a direct comparison of lateral and oblique impacts due to the consistent load distribution that occurred between lateral and oblique impacts.
  - With a larger impactor (rectangular face), lateral and oblique impacts resulted in similar stiffness responses with no statistically significant difference in mean lateral versus oblique effective stiffness, so lateral and oblique responses from rectangular impact face tests could be grouped together to form biofidelity response targets. Because the contact surface area was different between lateral and oblique impacts with the larger impactor face, the load distribution between lateral and oblique impacts was inconsistent. This inconsistent loading confounded the comparison between lateral and oblique impact responses with a larger impactor, as the responses could have been due to the varied loading between lateral and oblique impacts or the inherent response of

the PMHS with a more distributed load as compared to the smaller, circular impact face).

- Vertical Impact Location: The effect that vertical impact location (xiphoid versus 4th intercostal space) had on the lateral versus oblique response trend was inconclusive based on the data presented in this study, which could have been due to confounding variables (e.g., impactor shape/size, speed or subject-to-subject variability).
- Impact Speed:
  - With the smaller, circular impact face at impact speeds of 2.5 and 4.5 m/s, there was no apparent difference in the relationship between the lateral versus oblique response.
  - With the larger, rectangular impact face, the effect of impact speed (2.5 versus 4.5 m/s) on the lateral versus oblique response trend was inconclusive based on the data presented in this study.

VI. References

[1] Rhule H, Suntay B, Herriott R, Amenson T, Stricklin J, Bolte J. Response of PMHS to high- and low-speed oblique and lateral pneumatic ram impacts. *Stapp Car Crash Journal*, 2011, Vol. 55.

[2] International Standards Organization (ISO) (1999) Road vehicles – Anthropomorphic side impact dummy – Lateral impact response requirements to assess the biofidelity of the dummy. ISO/TR 9790:1999(E).

[3] Shaw J, Herriott R, McFadden J, Donnelly B, Bolte J. Oblique and lateral impact response of the PMHS thorax. *Stapp Car Crash Journal,* 2006, Vol. 50.

[4] Eppinger RH, Marcus JH, Morgan RM. Development of dummy and injury index for NHTSA's thoracic side impact protection research program. Proceedings of SAE Government/Industry Meeting and Exposition, 1984, Pp 983-1011.

[5] Viano D. Biomechanical response and injuries in blunt lateral impact. Proceedings of 33rd Stapp Car Crash Conference, 1989, Society of Automotive Engineers, Warrendale, PA.

[6] Kemper AR, Kennedy EA, McNally C, Manoogian SJ, Stitzel JD, Duma SM. Reducing chest injuries in automobile collisions: rib fracture timing and implications for thoracic injury criteria. *Annals of Biomedical Engineering*, 2011, Vol. 39, No. 8.

[7] Association for the Advancement of Automotive Medicine. Abbreviated Injury Scale © 2005, Update 2008. *Association for the Advancement of Automotive Medicine*, Barrington, IL, USA, 2008.

[8] National Highway Traffic Safety Administration. CrashStar – A post-processing program for chestband data analysis – Draft user's manual. Available upon request from heather.rhule@dot.gov.

[9] Pintar F, Humm J, Yoganandan N, Martin P. Test program to define oblique chest loading in side impact. *The 21st International Technical Conference on the Enhanced Safety of Vehicles*, 2009, Washington, D.C.

Information to be included online supplementing Rhule et al., “Response of the PMHS Thorax in Lateral and Oblique Pneumatic Ram Impacts – Investigation of Impact Speed, Impact Location and Impact Face”

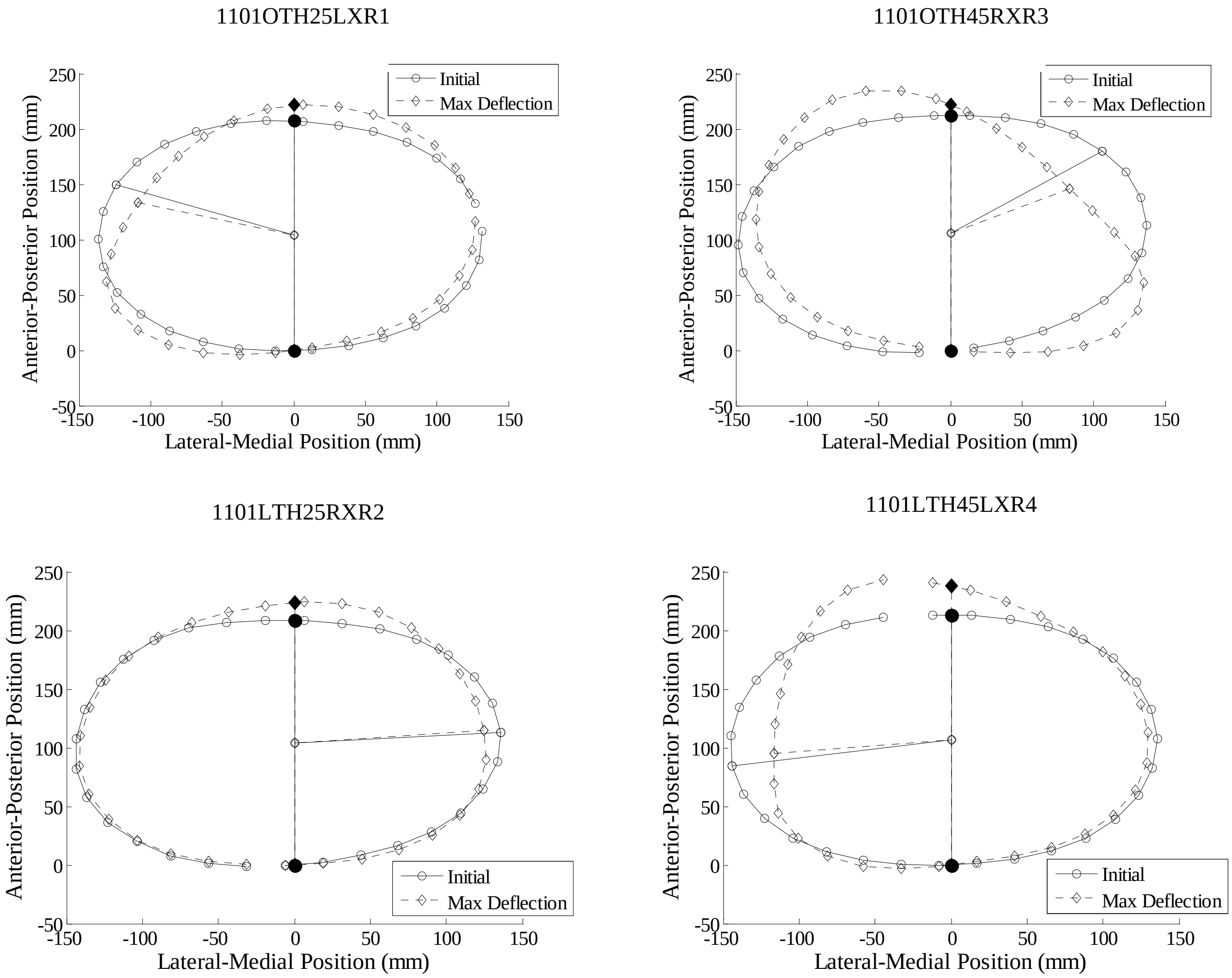

Figure 1. Chest band contours for subject 1101.

Information to be included online supplementing Rhule et al., "Response of the PMHS Thorax in Lateral and Oblique Pneumatic Ram Impacts – Investigation of Impact Speed, Impact Location and Impact Face"

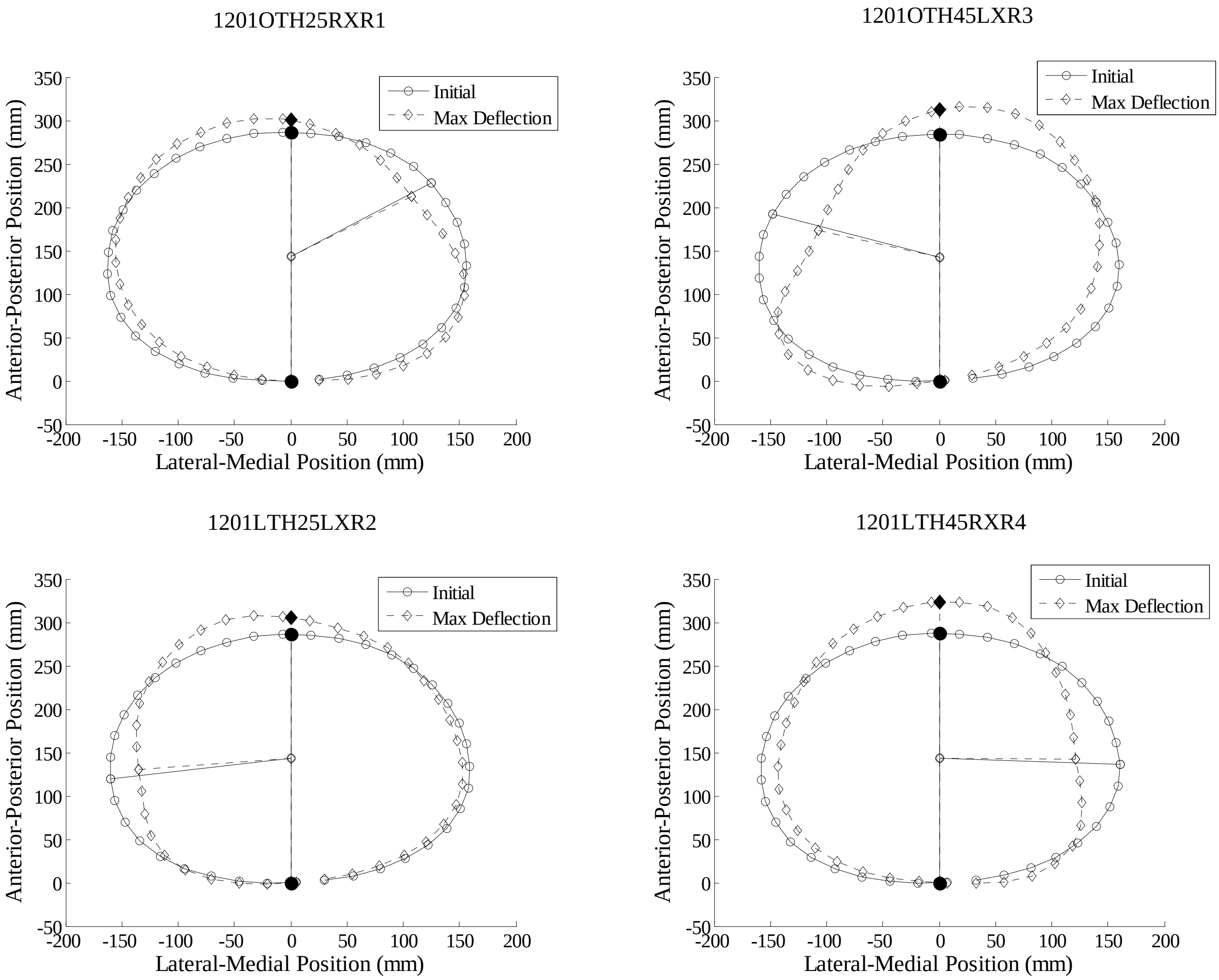

Figure 2. Chest band contours for subject 1201

Information to be included online supplementing Rhule et al., "Response of the PMHS Thorax in Lateral and Oblique Pneumatic Ram Impacts – Investigation of Impact Speed, Impact Location and Impact Face"

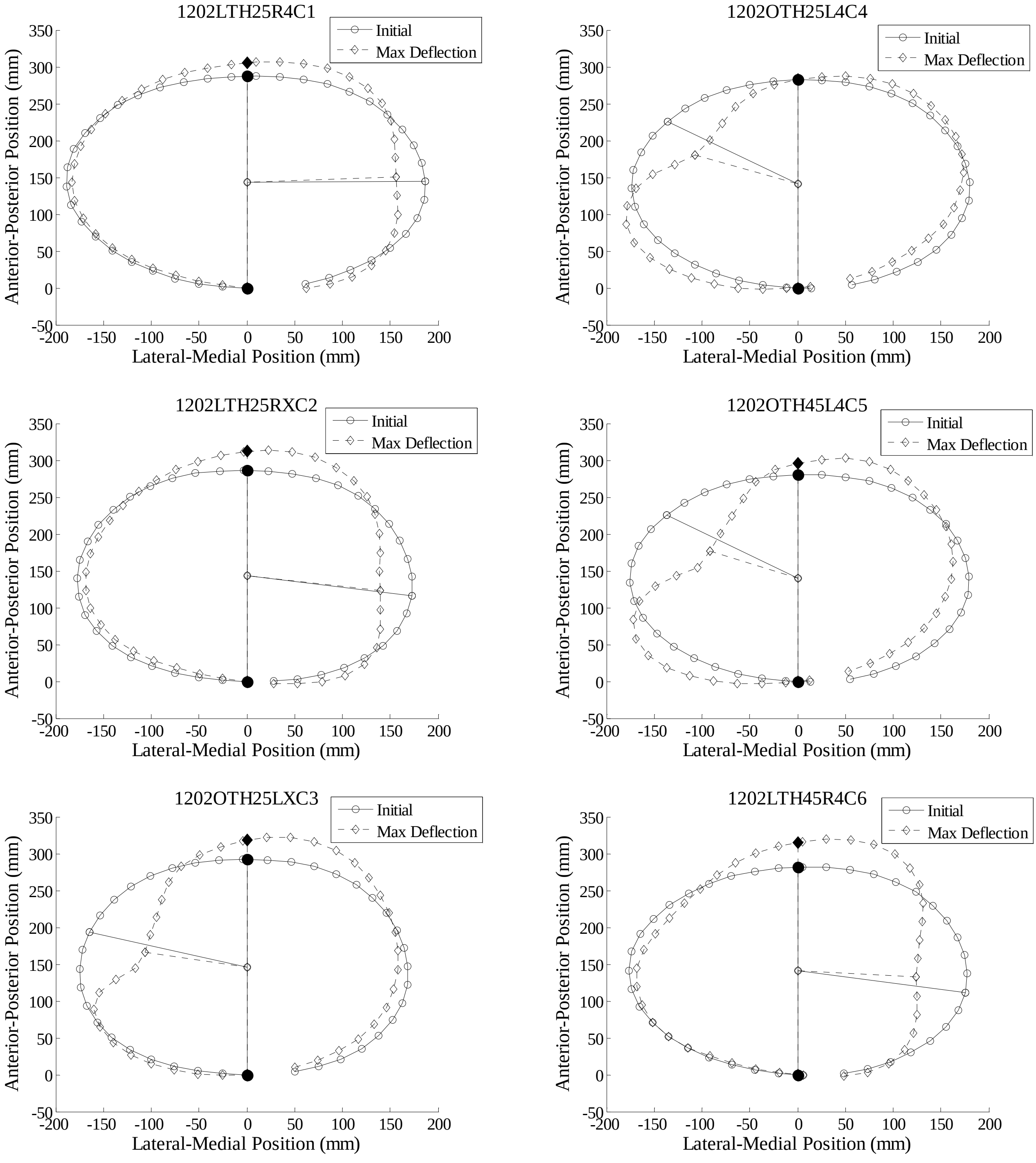

Figure 3. Chest band contours for subject 1202

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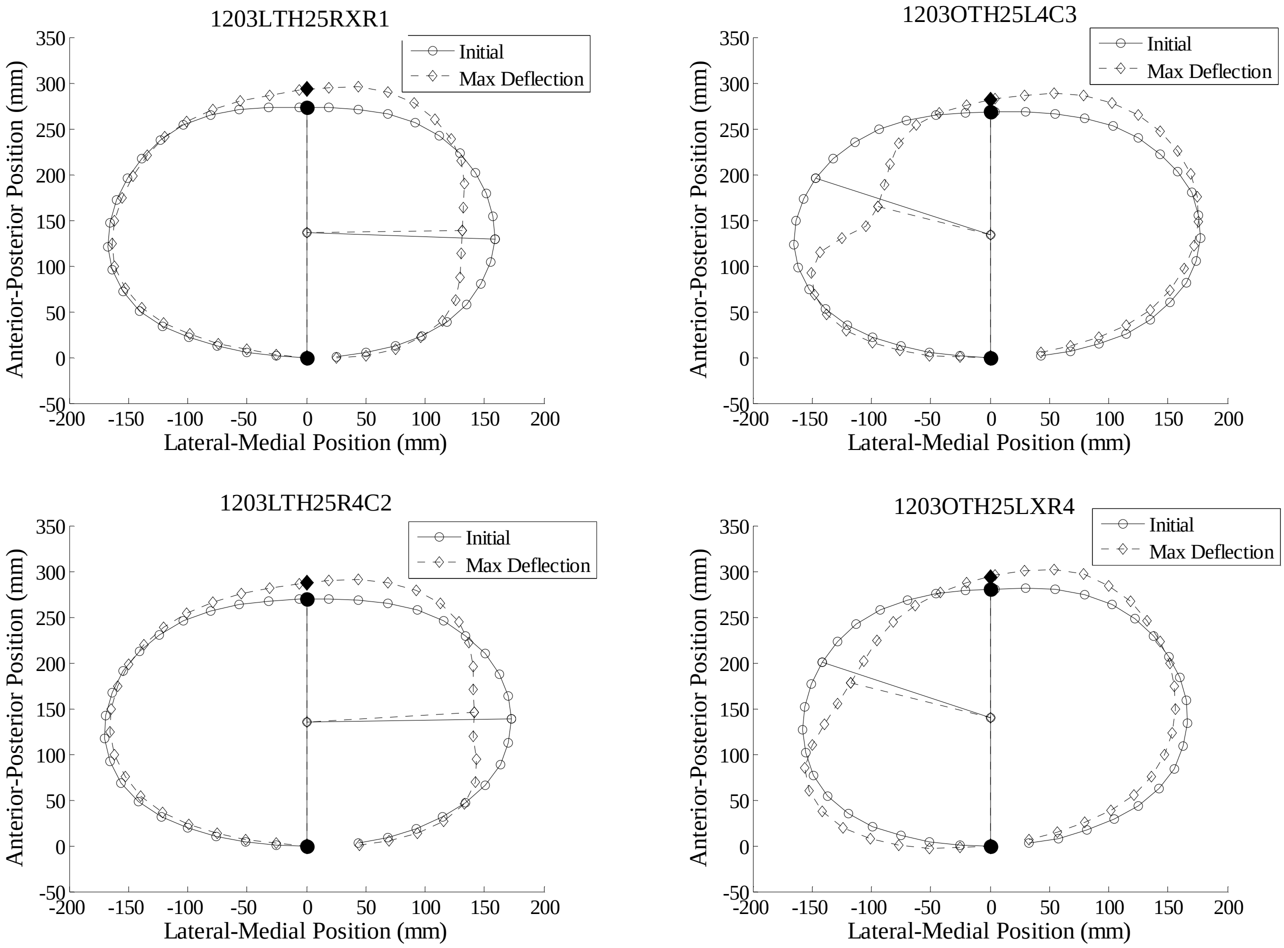

Figure 4. Chest band contours for subject 1203

Information to be included online supplementing Rhule et al., “Response of the PMHS Thorax in Lateral and Oblique Pneumatic Ram Impacts – Investigation of Impact Speed, Impact Location and Impact Face”

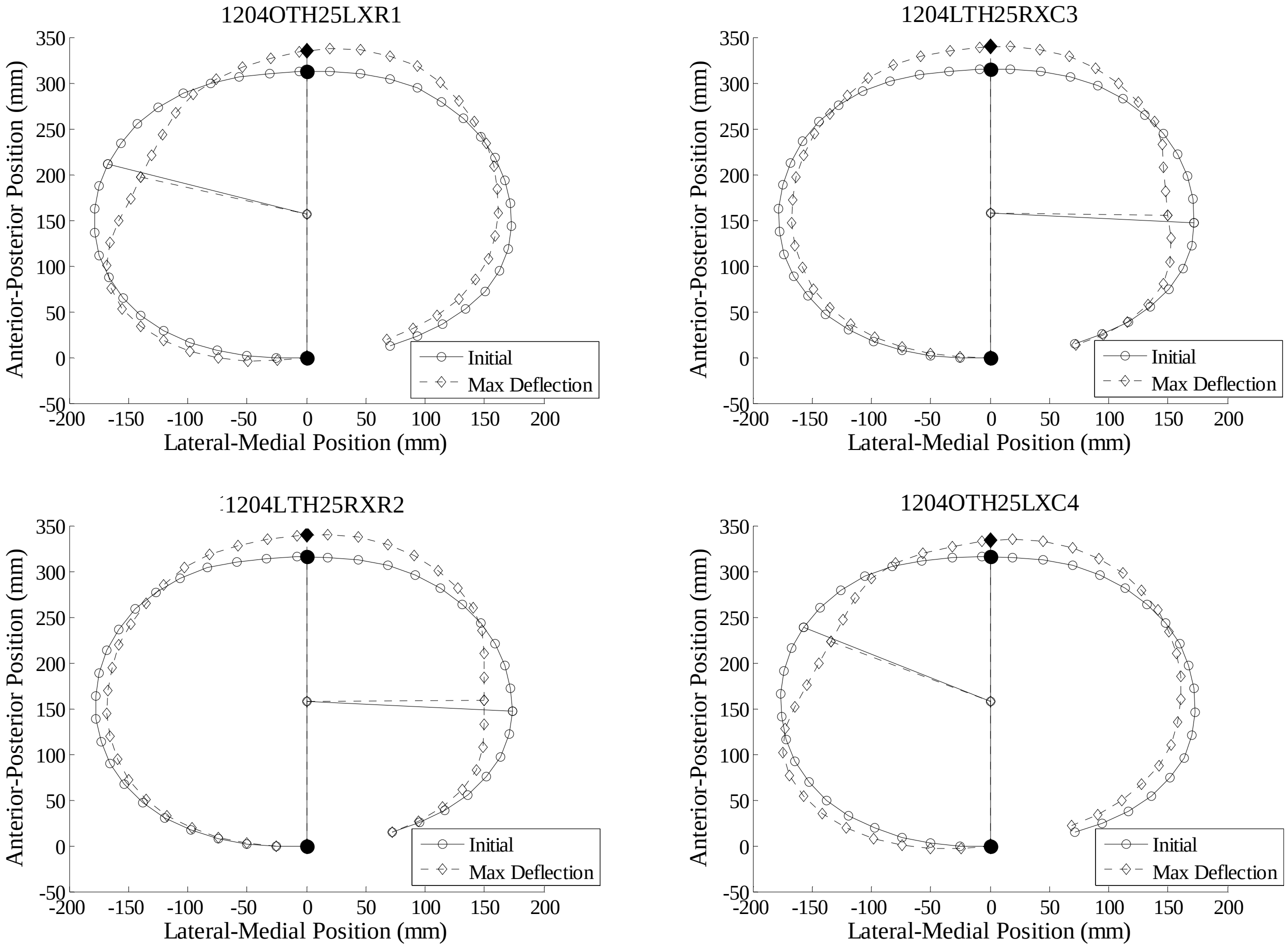

Figure 5. Chest band contours for subject 1204

Information to be included online supplementing Rhule et al., "Response of the PMHS Thorax in Lateral and Oblique Pneumatic Ram Impacts – Investigation of Impact Speed, Impact Location and Impact Face"

Table A1. Non-normalized maximum half chest deflection and angle of maximum chest deflection from the spine-sternum line for each impact

Subject	Test #	Non-normalized Max Half-Chest Deflection (mm)	Angle of Max Deflection from Spine-Sternum Line (deg)
1101	1101OTH25LXR1	19.3	74.5
	1101LTH25RXR2	10.8	85.1
	1101OTH45RXR3	37.2	64.6
	1101LTH45LXR4	28.7	95.7
1201	1201OTH25RXR1	22.7	57.3
	1201LTH25LXR2	26.4	95.3
	1201OTH45LXR3	44.3	73.9
	1201LTH45RXR4	39.5	90.7
1202	1202LTH25R4C1	30.5	87.4
	1202LTH25RXC2	33.9	98.2
	1202OTH25LXC3	63.3	79.3
	1202OTH25L4C4	46.6	70
	1202OTH45L4C5	63.1	68
	1202LTH45R4C6	53.3	94
1203	1203LTH25RXR1	27.3	89.1
	1203LTH25R4C2	31.1	85.6
	1203OTH25L4C3	60.3	72
	1203OTH25LXR4	30.1	71.9
1204	1204OTH25LXR1	30.4	73.8
	1204LTH25RXR2	24.3	89.7
	1204LTH25RXC3	22.9	90.6
	1204OTH25LXC4	27.3	64.1