Small Female Post-mortem Human Subject (PMHS) Thoracic Responses to Simplified Oblique and Lateral Loading

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Abstract This study aimed to directly collect biomechanical data for small female post-mortem human subjects (PMHS) in oblique and lateral thoracic impacts to generate female-specific response corridors and provide comparisons to existing small female thoracic response corridors generated from scaling mid-sized male responses. Thoraces of small female PMHS were impacted with a pneumatic ram in these test conditions/directions: Oblique (1) and Lateral (2) at 2.5 m/s with a circular impactor (Condition I), and Oblique (3) and Lateral (4) at 4.5 m/s with a rectangular plate (Condition II). A chestband measured external deflection and force was measured with a load cell behind the impactor. BioRank System Scores (BRSS) were utilized to compare newly generated female PMHS data to existing small female corridors. The existing scaled small female corridors were less than two standard deviations from all newly generated PMHS corridors (BRSS<2), and less than one (BRSS<1) for lateral impacts, specifically. Evaluation of scaled small female biomechanical response corridors is essential to help identify areas for improvement of current small female human body models (HBMs) and anthropomorphic test devices (ATDs) since these tools are currently designed to scaled corridors. Additional female PMHS data will be critical to continually improve female motor vehicle occupant safety.

Keywords 5th female, force-deflection, injury biomechanics, side impact, thorax

I. INTRODUCTION

Many studies that have analyzed crash databases have found that females have higher odds of serious injury compared to their male counterparts after accounting for demographic, vehicle, and other crash factors [1–3]. Furthermore, side impact crashes have the highest estimated female fatality risk factors [1–3] with the thorax being particularly vulnerable [4–6].

A small number of studies have assessed lateral thoracic response of females using sled tests with various set-ups and boundary conditions [7–10]. In general, small sample sizes of female post-mortem human subjects (PMHS) were tested and their data were often combined with male PMHS to investigate anthropomorphic test device (ATD) biofidelity. Bolte et al. [7] reported thoracic deflections in realistic near-side impact sled tests at a delta-V of 50 km/h on ten small elderly female PMHS with a focus on injury mechanisms. Marcus et al. [8] investigated four female PMHS on a sled with a rigid wall fixture but only shoulder and pelvis force versus time histories were reported. Test velocities varied between 23.5 – 40.7 km/h and resulted in lateral thoracic impacts. Ultimately, female data were combined with seven male PMHS to assess the influence of a padded wall compared to rigid wall fixture on injury outcomes at various impact velocities. Similarly, Kallieris et al. [9] evaluated eleven female PMHS in side impact conditions on the Heidelberg sled, comprised of a rigid wall with various types of padding, and impact velocities ranging from 23 – 40 km/h. In general, fewer rib fractures and less severe thorax injuries were observed for the padded conditions compared to the rigid wall condition for the female PMHS. Females and males had similar rib deflections, but females had lower max force values (354 N) than males (448 N). Finally, Morgan et al. [10] assessed six female PMHS seated in a vehicle body which underwent a 90-degree (lateral) moveable deformable barrier crash test with varying impact velocities ranging from 25 – 31 km/h. Peak T12, pelvis, upper and lower rib accelerations were compared to those for the side impact dummy (SID) ATD, but unfortunately neither force nor deflection were included.

Other studies have investigated female lateral thoracic response under more localized impactor conditions [11–15]. Female data were often combined with male data to generate response corridors with which to assess mid-size male ATD biofidelity, to assess the influence of arm position on outcomes, and to assess sensitivity of different

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kinematic and deflection criteria to input conditions. Specifically, Melvin et al. [11] evaluated two female PMHS under lateral thoracic impacts at 43 km/h, one of which was impacted with a flat rigid wall and the other with a contoured, padded surface simulating a vehicle side interior configuration. While injuries were reduced for the padded, contoured test condition, only peak acceleration data were reported for the head, thorax (T1 and T12), and pelvis. Female PMHS responses were combined with five male PMHS to assess the response of two ATDs (Part 572 test device and Transport and Road Research Laboratory side impact test device) compared to the PMHS kinematic response and accelerometer data.

Cesari et al. [12] evaluated one female PMHS using a rigid 23.1 kg spherical impactor at 18.6 km/h to the lateral mid-thorax. Peak impact force (1906 N) and struck-side transverse rib acceleration were reported. Female data were combined with seven male PMHS to assess the influence of arm position on thoracic injuries and outcomes. Additionally, Talantikite et al. [13] investigated the thoracic response of three female PMHS impacted laterally at 6 m/s with a rigid, flat, 15 cm disc linear impactor of 12 or 16 kg. These data were analyzed with eight male PMHS, and Viscous Criterion (V*C) and half thorax deflection criterion were found to be sensitive to variation of the impact masses and velocities. Peak force was greater in males, ranging from 1760 – 2880 N for females and 2230 – 3940 N for males. Peak deflection was also greater in males (62 – 102 mm) than females (63 – 87 mm). Compigne et al. [14] tested four female PMHS with a 23.4 kg rigid impactor (150 mm diameter) at 4.2 m/s to the lateral thorax. Impact force, T12 and sacrum acceleration, and spinal kinematics vs time responses were reported, but similar to previous studies, female data were combined with male PMHS data for comparison to two WorldSID ATDs (a prototype and pre-production version) for biofidelity assessment.

One impactor study directly compared male and female responses in similar boundary and input conditions; Baudrit [15] tested six small female and six mid-size male PMHS in lateral thoracic impacts. All PMHS were impacted with a 23.4 kg, 130 mm diameter (150 mm for males) flat disc impactor at 4.3 m/s in a pure lateral direction (n = 3 females, n = 3 males) or 30° anterior from lateral in an oblique direction (n = 3 females, n = 3 males). Peak thorax force and deflection and force-deflection responses were compared between males and females, with females displaying lower peak force (1050 – 1450 N) than males (1630 – 2340 N), and the authors suggested maximum force is influenced by body mass. Deflection ranges were 51 – 117 mm for females and 59 – 81 mm for males, suggesting no clear difference between the sexes in this measure.

Although some primary female data are available they are generally lacking compared to the amount of male data, and therefore, scaling methods have been utilized to create target thoracic responses for small females [16,17]. In fact, studies by Shaw et al. [18] and Rhule et al. [19] provided the foundational male data for which scaled small female thoracic response corridors are based. Shaw et al. [18] utilized seven mid-size male PMHS in which two impacts (lateral impact on one side and oblique on the opposite side) with a 152 mm-diameter face were conducted to each PMHS at 2.5 m/s. Rhule et al. [19] conducted a single lateral or oblique thorax impact to ten mid-size male PMHS and two female PMHS [19] at 4.5 m/s (n=10) and 5.5 m/s (n=2). Mid-size male response corridors were recently developed for the Shaw et al. [18] conditions and the Rhule et al. [19,20] conditions using new normalization methods [21]. Male PMHS were used from [18,20] for the Shaw conditions and from [19] for the oblique Rhule conditions. Normalized responses from two female PMHS were utilized along with four mid-size male PMHS for the Rhule lateral mid-size male response corridors [21]. These mid-size male corridors were then scaled to the small female to be used for evaluating small female side impact ATD biofidelity [21].

To further investigate thoracic response in the small female population and continue to understand and prevent injuries for females in motor vehicle crashes (MVC), sufficient female data are needed to create biomechanical corridors. Overall, a small number of previous studies have evaluated female PMHS thoracic response in sled or impactor conditions, and even fewer have provided direct comparisons or discussion assessing differences in male versus female thoracic response. Furthermore, no previous study has provided female-specific thoracic response corridors that would allow for evaluation of female ATD biofidelity or direct comparisons to scaled corridors. Ultimately, additional data generated from testing small females are necessary for comparing to existing corridors and to help evaluate the accuracy of scaled corridors since the current ATDs and HBMs were designed using the scaled corridors. Therefore, the objective of this work was to provide biomechanical data for small female PMHS in oblique and lateral thoracic impacts and generate small female-specific response corridors to be used for comparison to existing small female thoracic response corridors generated from scaling mid-sized male response corridors.

II. METHODS

Subject Selection

PMHS were ethically obtained from The Ohio State University's Body Donation Program. Small female PMHS were selected to be as close as possible to target body size parameters for 5th percentile females defined by [16] as shown in Table I. Bone mineral density (BMD) was not utilized for selection but lumbar spine areal BMD t-scores across PMHS ranged from normal (A) to osteopenic (C and D) or osteoporotic (B), likely representing real variability in the population. Exclusion criteria included pre-existing rib fractures, thoracic abnormalities, or pathological changes observed from computed tomography (CT). PMHS were prepared for testing by removing breast tissue to ensure consistency with the male PMHS data used to create the female scaled corridors utilized for comparison.

TABLE I

PMHS SUMMARY

PMHS ID	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Chest Depth (cm)	Chest Breadth (cm)	Chest Circumference (cm)
A	53	170	48.5	17	Ax: 17.2 Xi: 18.0	Ax: 23.6 Xi: 26.0	Ax: 77.6 Xi: 77.5
B	69	157	44.2	18	Ax: 11.9 Xi: 16.0	Ax: 23.8 Xi: 26.3	Ax: 72.8 Xi: 73.4
C	63	170	51.3	18	Ax: 14.9 Xi: 16.4	Ax: 28.5 Xi: 26.1	Ax: 81.5 Xi: 83.1
D	68	153	43.1	18	Ax: 14.9 Xi: 16.1	Ax: 24.1 Xi: 24.2	Ax: 72.7 Xi: 74.1*
Target [16]	--	151	46.7	20	18.7	Ax: 26.0	Ax: 79.2

Ax: measurement at axilla. Xi: measurements at xiphoid. *Measurement may be in error – taken with chestband on

Experimental Testing

A series of impacts (tests 1 - 4) were conducted on multiple small female PMHS (Table II, Fig. 1). Test Condition I mimicked experimental tests previously conducted on mid-size male PMHS [18] and included an oblique (60°) and lateral (90°) 2.5 m/s impact at the level of the 4th intercostal space. Test Condition II also mimicked experimental tests previously conducted on mid-size male PMHS [19] and included an oblique (60°) and lateral (90°) 4.5 m/s impact at the level of the xiphoid process. The goal of this work was to include at least three PMHS across all test conditions and directions such that each PMHS underwent the same series of tests, and biomechanical response corridors could be created for each. Unfortunately, for PMHS B during Test 2 the release mechanism for the head discharged before the ram moved, resulting in the PMHS dropping and rotating backwards (about +Y) and an off-axis anterior-lateral impact occurring. Therefore, no comparable data were collected for the lateral direction in Condition I for PMHS B, and a new PMHS, D, had to be utilized to obtain the third data point needed to create corridors for Condition I lateral (see Table III). PMHS D was therefore included in the test 2 corridor and the remaining corridors for tests 3 and 4, but not test 1.

All experimental boundary conditions were the same for the current study as in the previous studies [17-19] except for the impactor mass being scaled down to 14 kg and impactor face dimensions being scaled down to 125 mm diameter (Test Condition I) and 125 mm height (Test Condition II) [21]. A pneumatic ram was used to deliver all impacts and was affixed with a 125 mm diameter circular impactor face in Condition I or a 125 x 275 mm rectangular impactor face in Condition II. A six-axis load cell (Denton 2944JFL, Humanetics, Plymouth, MI, USA) was installed behind the impactor face to measure impact forces. Accelerometers (7264C-2K, Endevco, Depew, NY, USA) were attached to the impactor face to calculate velocity.

TABLE II
TEST MATRIX

Test Cond.*	Test Order	Impactor Shape	Impactor Dimensions (mm)	Target Impact Velocity (m/s)	Impact Side	Impact Direction (deg°)	Impact Level
I	1	Circle	125 diameter	2.5	Left	Oblique 60°	4th IC space
	2	Circle	125 diameter	2.5	Right	Lateral 90°	4th IC space
II	3	Rectangle	125 height x 275 width	4.5	Right	Oblique 60°	Xiphoid
	4	Rectangle	125 height x 275 width	4.5	Left	Lateral 90°	Xiphoid

*Test Condition I is based on Shaw et al. [18] and Test Condition II is based on Rhule et al. [19]

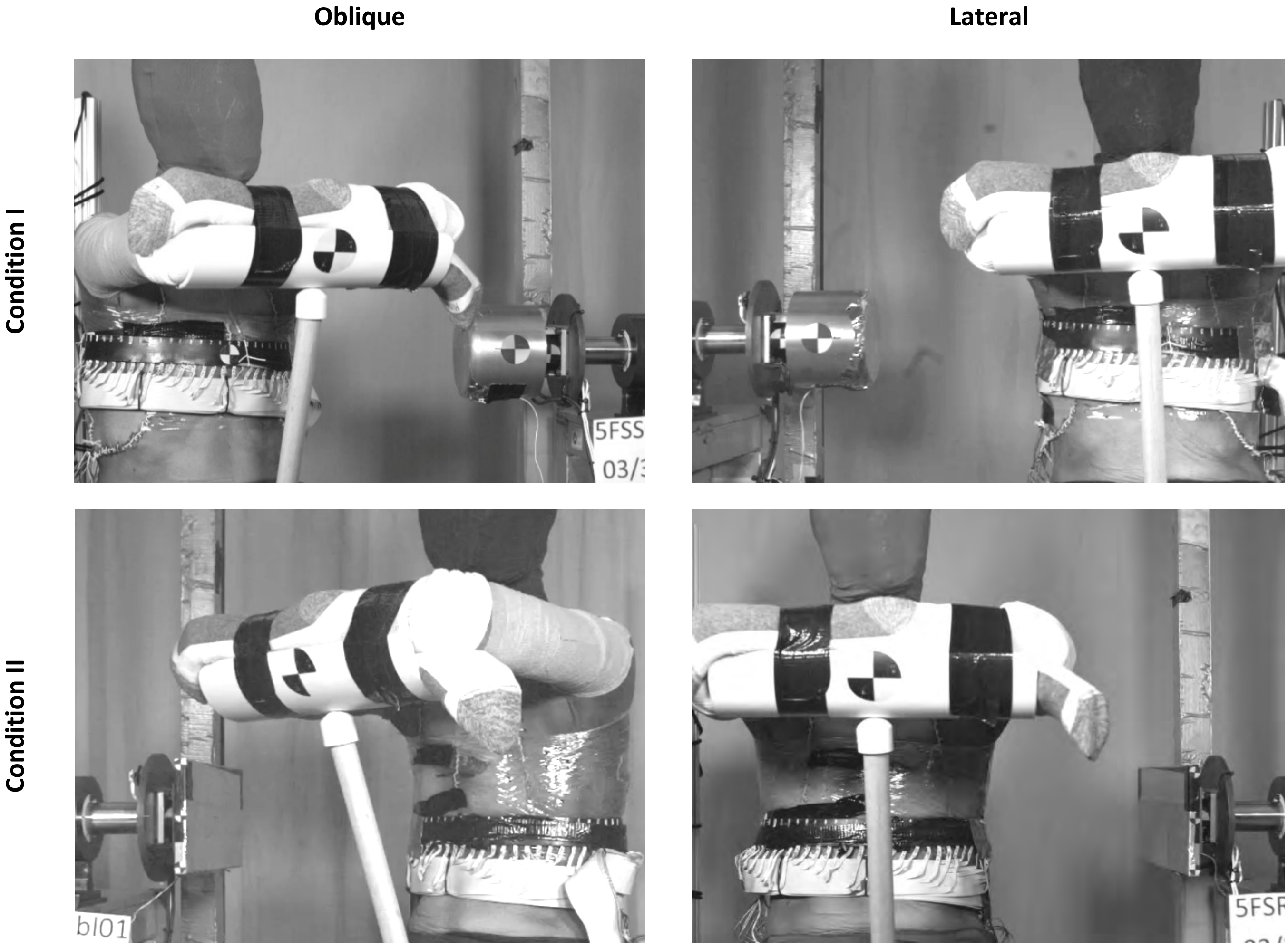

Fig. 1. Exemplary images from PMHS A showing test set-up from test 1 (top left), 2 (top right), 3 (bottom left), and 4 (bottom right).

PMHS Instrumentation

Motion blocks (6DX PRO, Diversified Technical Systems, Seal Beach, CA, USA) were rigidly installed on the posterior aspects of thoracic vertebrae T1, T4, T8, and T12 to obtain spinal kinematics. Vertebral levels were confirmed using lateral x-rays with the subject in a prone position. A chestband (model 8641 1-6, Humanetics, Plymouth, MI, USA) was sutured at four locations around the PMHS thorax at the impact level defined for each condition at 15 pounds of tension and was used to quantify chest deflection and percent chest deflection (relative to initial chest breadth at the chestband for both lateral and oblique impacts). For Test Condition I, the chestband was placed at the 4th intercostal space and for Test Condition II at the level of the xiphoid process as in [18] and [19] to allow for direct comparisons. Pre-test, in-position x-rays showing instrumentation locations are included in the Appendix (Fig. A1, Fig. A2). Strain gages (C4A-06-060SL-350-39P, Micromeasurements, Wendell, NC, USA) were installed bilaterally and anteriorly on ribs 2-8, posteriorly on ribs 3-9, and the manubrium and sternum for identification of fracture timing.

Data Analysis

Force and acceleration data were filtered using a 4th order Butterworth filter (CFC180) in accordance with SAE J211 guidelines [22]. The inertial load induced from the mass and acceleration of the impactor face was compensated to calculate forces applied to the thorax. Chestband data were analyzed using Crashstar (v2.7) to generate thoracic contours for the duration of the event. Maximum thoracic deflection was calculated following the half lateral deflection chestband methodology outlined in detail by [23] and filtered at CFC600. Time zero was defined when force measured by the load cell first exceeded 100 N. Thoracic deformation energy and stiffness were calculated using Eq. 1 and Eq. 2, respectively.

$$E = \int_0^{x_{max}} F(t)dx(t) \qquad \text{[Eq. 1]}$$

Where: E= deformation energy
F= force
x= deflection

$$k_{eff} = \frac{2E}{x_{max}^2} \qquad \text{[Eq. 2]}$$

Where: k_{eff}= effective stiffness
E= deformation energy from Eq. 1
x_{max}= maximum deflection

To generate 2D biomechanical response corridors representing the mean ± one standard deviation for both force and deflection, individual force and deflection time history curves were phase optimized first [24]. For Condition II, the deflection lag for PMHS D differed substantially from those of PMHS A, B, and C, which would have resulted in an unrealistic mean phase shift of (lateral: 8.9 ms, oblique: 3.5 ms) for locating the mean deflection curve in time [25]. As such, the magnitude of the deflection lag of PMHS D was set equal to the average of the deflection lags for PMHS A-C. All phase-optimized curves for force and for deflection were averaged for each condition and impact direction. Next, corridors for force vs. time and deflection vs. time were created for each test condition and impact direction, each representing the mean ± one standard deviation. Time-zero for force and deflection corridors was redefined to be when the mean force was first ≥ 100 N. Corridors for force-deflection (F-D) were then created for each test condition and impact direction using the mean and standard deviation of the phase-optimized force and deflection data. Force-deflection corridors were plotted utilizing the ellipse method, where the major and minor radii of the ellipse represent the standard deviations of force and deflection, respectively (described in more detail in [18]).

To compare the newly generated small female PMHS F-D corridors to small female corridors scaled from mid-size male corridors, BioRank System Scores (BRSS) were calculated according to the methodology described in detail in [26]. This was accomplished by comparing the mean curve of each dataset to the relevant corridors to generate two individual BRSS which were averaged to provide one representative BRSS for each comparison (Eq. 3). Specifically, to achieve this single average BRSS value an average was taken between the following two comparisons, as illustrated in Fig. 2:

1. The mean scaled response (dashed black line) compared to the corridor created from the response data in this study (green corridor), denoted as $BRSS_{Scaled\ vs\ PMHS}$
2. The mean response data in this study (dashed green line) compared to the scaled corridor created from previously tested 50th percentile males (gray corridor), denoted as $BRSS_{PMHS\ vs\ Scaled}$

BRSS were calculated for force-time, deflection-time and force-deflection (average of force-time BRS and deflection-time BRS) curves for each condition and impact direction, where the force-deflection BRSS is the average of force-time and deflection-time average BRS. A lower BRSS indicates better agreement, and BRSS ≤ 2 indicates that the response is within two standard deviations, on average. All scale factors reported in the results and discussion are expressed as a ratio of mid-size male values (i.e., female-to-male).

$$BRSS = \frac{BRSS_{Scaled\ vs\ PMHS} + BRSS_{PMHS\ vs\ Scaled}}{2} \quad \text{[Eq. 3]}$$

III. RESULTS

Maximum thoracic deflection results are summarized in Table III. The chestband contours showing the maximum half deflection (blue, rotated such that spine-sternum line coincides with spine-sternum line of initial contour) compared to the pre-impact contours (green) are shown for Test Condition I (Fig. A3) and Test Condition II (Fig. A4). Peak deflections were similar across all tests and Conditions, except for the lateral tests in Condition I, where average peak deflection was only 21.5 mm. This was notably less than the average peak deflection for Condition I oblique (36.4 mm) and for Condition II oblique (36.4 mm) and lateral (39.4 mm).

The average peak forces from the three PMHS tested in Condition I were 496 N and 812 N for the oblique and lateral tests, respectively. For Condition II, the average peak force for the oblique loading condition was 1527 N and for the lateral loading condition was 1685 N. Forces from tests in Condition II were higher compared to the forces in Test Condition I. When comparing lateral to oblique loading, higher average forces were seen in the lateral test conditions (Table III, Fig. A5), although the difference Condition I was more substantial than that for Condition II.

TABLE III
DATA SUMMARY

Test Cond.	Test Number	PMHS	Impact Velocity (m/s)	Max Force (N)	Max Deflection (mm)	Max Deflection (%)*	Stiffness (N/mm)	Deformation Energy (Nm)
I	1 Oblique	A	2.43	548	35.7	12.6	20.0	12.6
		B	2.28	418	33.1	11.8	20.5	8.7
		C	2.47	522	40.4	13.6	20.9	17.0
		Avg	***2.39***	***496***	***36.4***	***12.7***	***20.5***	***12.8***
		(SD)	***(0.10)***	***(69)***	***(3.7)***	***(0.9)***	***(0.5)***	***(4.2)***
	2 Lateral	A	2.39	811	17.8	6.3	78.1	11.1
		C	2.43	868	26.6	8.9	51.6	18.3
		D	2.48	757	20.2	7.6	58.8	11.9
		Avg	***2.43***	***812***	***21.5***	***7.6***	***62.8***	***13.8***
		(SD)	***(0.05)***	***(56)***	***(4.5)***	***(1.3)***	***(13.7)***	***(3.9)***
II	3 Oblique	A	4.49	1618	34.0	12.0	76.7	38.0
		B	4.33	1491	34.0	13.5	64.3	37.0
		C	4.55	1631	39.2	14.0	70.1	53.8
		D	4.54	1366	38.2	14.7	50.8	36.8
		Avg	***4.48***	***1527***	***36.4***	***13.6***	***65.5***	***41.4***
		(SD)	***(0.10)***	***(124)***	***(2.7)***	***(1.1)***	***(11.0)***	***(8.3)***
	4 Lateral	A	4.57	1948	38.5	13.6	74.9	55.5
		B	4.41	1520	38.0	15.1	67.1	48.4
		C	4.47	1755	40.6	14.6	71.8	59.3
		D	4.47	1518	40.5	15.8	58.9	48.1
		Avg	***4.48***	***1685***	***39.4***	***14.8***	***68.2***	***52.8***
		(SD)	***(0.07)***	***(208)***	***(1.3)***	***(0.9)***	***(7.0)***	***(5.5)***

*Maximum deflection calculated with respect to initial chest breadth measured from chestband

Force-Deflection Corridors

Small female force-deflection response corridors for each test are provided in Fig. 2. Individual force-time (Fig. A5) and deflection-time (Fig. A6) corridors were developed for each loading direction and condition as well. F-D corridors for the PMHS tested in this study are illustrated in green in Fig. 2. Corridors that were previously developed by the US National Highway Traffic Safety Administration (NHTSA) [21] from scaling normalized mid-size male response corridors to represent the small female are shown in gray for comparison. BRSS from these comparisons are also summarized in Table IV.

When comparing the average BRSS for force, deflection, and the combined F-D curves, the lateral tests resulted in lower BRSS than the oblique tests in all instances except for deflection in Condition I. In this exception, the average BRSS from the oblique tests was 0.47 compared to 1.07 in the lateral tests. The mean response for each corridor is shown by the dashed lines in the corresponding color in Fig. 2. All four comparisons resulted in good agreement (defined as BRSS<2) between corridors, with the best agreement found in the lateral tests in both conditions (BRSS<1) as shown in Table IV.

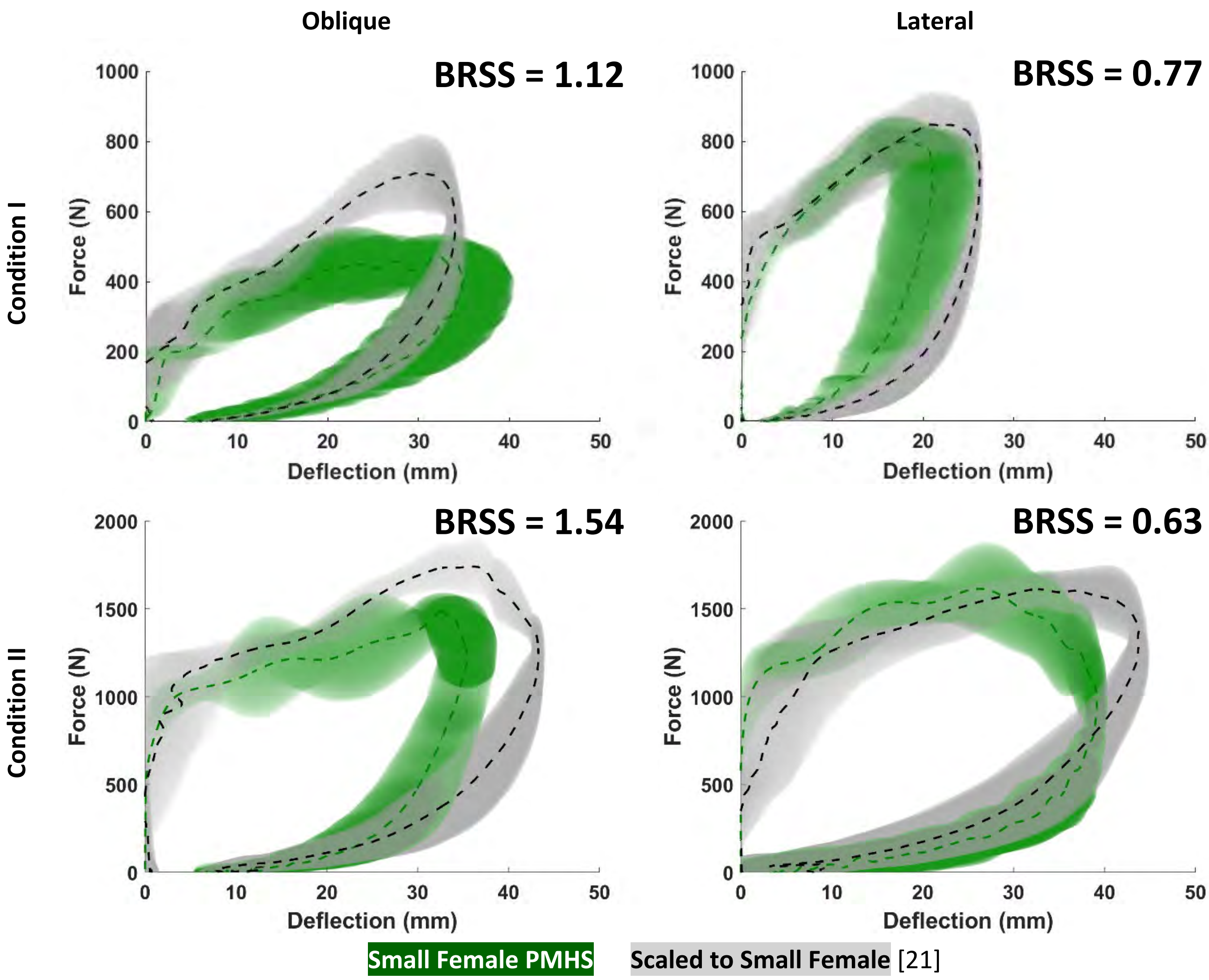

Fig. 2. Force-deflection corridors for Condition I oblique (upper left, test 1), Condition I lateral (upper right, test 2), Condition II oblique (lower left, test 3), and Condition II lateral (lower right, test 4) comparing small female PMHS corridors (green) to small female corridors scaled from mid-sized male corridors (gray) [21]. Average BRSS are included for each comparison.

TABLE IV
SUMMARY OF BIORANK SYSTEM SCORES, BRSS

	Test Condition	Oblique			Lateral		
		Scaled vs. PMHS	PMHS vs. Scaled	**Avg. BRSS**	Scaled vs. PMHS	PMHS vs. Scaled	**Avg. BRSS**
Deflection-	I	0.24	0.71	**0.47**	0.80	1.33	**1.07**
Time	II	0.85	3.05	**1.95**	0.53	0.69	**0.61**
Force-	I	1.81	1.73	**1.77**	0.67	0.30	**0.48**
Time	II	1.13	1.13	**1.13**	0.47	0.82	**0.64**
Force-	I	1.02	1.22	**1.12**	0.73	0.82	**0.77**
Deflection	II	0.99	2.09	**1.54**	0.50	0.76	**0.63**

PMHS Injuries

The only injuries that occurred in this test series were rib fractures. The number of fractured ribs (NFR) and their locations (side and level) are summarized in Table V. Condition I oblique impacts (test 1) resulted in 1-3 fractured ribs across PMHS, while Condition I lateral impacts (test 2) resulted in no rib fractures. Condition II oblique impacts (test 3) resulted in additional fractured ribs ranging in number from 2-8 across PMHS, and Condition II lateral impacts (test 4) resulted in 0-8 additional fractured ribs.

TABLE V
SUMMARY OF RIB FRACTURES INCLUDING NFR[1] AND LOCATIONS

Test Cond.	**Test Order**	**Impact Direction**	**Side**	**PMHS A**	**PMHS B**	**PMHS C**	**PMHS D**	**Average NFR**
I	1	Oblique	Left	1 (L5)	2 (L4, L5)	3 (L3-L5)	-	2
	2	Lateral	Right	0	-	0	0	0
II	3	Oblique	Right	2 (R4, R5)	8 (R3-R10)	7 (R3-R9)	8 (R1, R3-R9)	6
	4	Lateral	Left	0	4 (L5-L8)	4 (L6-L9)	8 (L1, L4-L10)	4

[1]NFR = number of fractured ribs. All rib fractures occurred on the same side as impact.

IV. DISCUSSION

Since the female tests conducted in the current study were in the same test set-ups as Shaw et al. [18] and Rhule et al. [19], it is possible to make direct comparisons between datasets comparing mid-size males to small females in these scenarios (Table VI). However, the impactor masses for the previous male PMHS tests were approximately 23 kg, and they were scaled down to 14 kg for the female tests in the current study. In addition, the impactor face sizes were 152 mm in height for the referenced studies, while the current study used impactor face heights of 125 mm. In general, females had consistently lower average force and deflection than previously tested males in each condition and direction: scale factors are Condition I oblique (0.475 force, 0.758 deflection), Condition I lateral (0.579 force, 0.621 deflection), Condition II oblique (0.601 force, 0.788 deflection), and Condition II lateral (0.577 force, 0.925 deflection) using average male and female data in Table VI. Similarly, thoracic stiffness was consistently less in females than in males with scale factors: Condition I oblique (0.611), Condition I lateral (0.888), Condition II oblique (0.680), and Condition II lateral (0.577).

Rhule et al. [20] conducted additional testing in each of the Shaw et al. [18] and Rhule et al. [19] conditions and combinations thereof, to examine the effects of the impact speed, location, and face shape. They found that with the smaller circular impactor face (i.e., Condition I in this study), thoracic stiffness was significantly greater for lateral impacts than for oblique impacts in mid-sized males. This was also true in the current study for small females with the average lateral stiffness (62.8 N/mm) being three times greater than the oblique stiffness (20.5

N/mm) in Condition I. Rhule et al. [20] also concluded there was not a significant difference in lateral and oblique thoracic stiffness when utilizing a larger rectangular impactor face at 2.5 m/s (i.e., Condition II impact face in this study) for mid-size male PMHS. The small female data in the current study at 4.5 m/s also support this finding with similar average lateral (68.2 N/mm) and oblique (65.5 N/mm) stiffness values in Condition II.

The scale factors applied to generate the scaled female corridors shown in Fig. 2 were 0.799 for the deflection and 0.753 for the force [21]. The deflection scale factor (0.799) previously used was similar to female PMHS ratios calculated from the oblique tests in this study and [18–20] (0.758 and 0.788 for Conditions I and II, respectively), but inconsistent with the lateral tests (0.621 and 0.925 for Conditions I and II, respectively). The force scale factor (0.753) previously used was larger than female PMHS ratios (0.475 – 0.601) calculated in this study [18–20], implying the scaling method should be further investigated by using biomechanical data directly measured from female PMHS, i.e., female data from the current study.

Baudrit et al. [15] directly compared mid-size male and small female thoracic responses in a simplified loading condition at a similar loading rate (4.3 m/s) as utilized here in Condition II. They scaled the impactor size down for the female impacts as compared to the males, but the impactor mass remained at 23.4 kg for both male and female tests. Tests were conducted in both lateral (90°) and oblique (60°) directions. Thoracic deflections from this study are not directly comparable since they were calculated differently (i.e., their study used external photo targets and this study used a chestband), but relative sex differences can still be generally compared. The authors attributed differences in thoracic response to size between the mid-size male and small female groups rather than sex. Regardless, similar patterns were found as described above: in the lateral direction females had less average force than males (0.714 scale factor [15]), and in the oblique direction females had less average force than males (0.625 scale factor [15]). Maximum deflection was only slightly greater in males than females in the lateral direction (63 mm vs 61 mm) but was less in males than females in the oblique direction (72 mm vs 100 mm) [15], which is different than the comparison of female data in the current study to males from [18,20]. Qualitatively, initial stiffness appeared greater in males than females in only the oblique loading direction in the Baudrit et al. [15] study.

Limitations

This study included a small sample size for creating biomechanical response corridors for small female PMHS. Furthermore, the PMHS were impacted multiple times. While it is possible to know during which test and at what time rib fractures occurred based on strain gages (Table V), it is unknown if the existence of those fractures in some conditions possibly influenced the biomechanical responses reported here for subsequent tests. This is most likely to have an influence on Condition II lateral data as the oblique test in this condition always occurred first with an average NFR of 6 (i.e., the worst outcome for any of the tests). This is also the case for two of the previous studies that we directly compared to [18,20], so despite the limitation the results are likely comparable in terms of the effects of injuries. Future work should characterize thoracic response in the context of injury risk with only one impact per PMHS to ensure rib fractures are not influencing the results. Further, much of the previous data for comparison have been normalized and none of the data provided here have been normalized. While an attempt was made to only compare to non-normalized data, the variability in reporting normalized or scaled data in the literature should be noted and as a result, further comparisons should be made with caution.

The boundary conditions imposed in these tests are relevant since they are used for ATD qualification and HBM validation, but the rigid impactors and the simplified test set-up are not realistic crash scenarios. Female-specific data should be collected and compared to male data in realistic crash-like test set-ups in future work to help establish injury tolerances and risk curves. Furthermore, the breasts of each female PMHS utilized in this study were removed to provide direct comparisons with male thoracic response data, but this is unrealistic to the female anatomy. Breast removal was a necessary step in generating small female data to satisfy the immediate goals of this research, but breast removal should not be perpetuated or accepted as good practice in PMHS testing as our community moves to make further advances in understanding female response and improving female occupant protection. Future more realistic investigations, including anything related to injury risk assessment, should include quantification of the effects of breast tissue presence, volume, and distribution, especially for oblique thoracic impacts where the breasts are likely to interact more directly with the load delivery.

TABLE VI
DATA COMPARISONS*

Test Cond.	Test Number	PMHS Size, Sex	PMHS n	Target Impact Velocity (m/s)	Average Max Force (N)	Average Max Deflection (mm)	Average Stiffness (N/mm)
I	1 Oblique	Mid-size Male[18]	7	2.5	1145	42.7	41.5[19]
		Mid-size Male[20]	2	2.5	945	53.4	25.6
		Small Female	**3**	**2.5**	**496**	**36.4**	**20.5**
	2 Lateral	Mid-size Male[18]	7	2.5	1411	38.4	73.1[19]
		Mid-size Male[20]	2	2.5	1395	30.8	68.4
		Small Female	**3**	**2.5**	**812**	**21.5**	**62.8**
II	3 Oblique	Mid-size Male[19]	4	4.5	2684	51.7	86.9
		Mid-size Male[20]	2	4.5	2398	40.7	105.7
		Small Female	**4**	**4.5**	**1527**	**36.4**	**65.5**
	4 Lateral	Mid-size Male[19]	4	4.5	2933	51.1	98.4
		Mid-size Male[20]	2	4.5	2910	34.1	137.8
		Small Female	**4**	**4.5**	**1685**	**39.4**	**68.2**

*Small female data from the current study and mid-size male data from Shaw et al. [18] and Rhule et al. [19,20] are non-normalized.

V. CONCLUSIONS

The objective of this work was to directly collect biomechanical response data for small female PMHS in oblique and lateral thoracic impacts. This was particularly important in order to create female response corridors for comparison to existing small female thoracic response corridors generated from scaling mid-sized male response corridors. The corridors created in this study from small female data were less than two standard deviations from the existing scaled corridors indicating good agreement overall (BRSS<2). However, the scale factors previously used to scale the mid-sized male corridors to those for a small female differed somewhat from the female-to-male PMHS response ratios calculated here, indicating that continued evaluation of the scaling methods is needed as more data are collected. Creation of small female biomechanical response corridors is necessary to help verify the accuracy of previous design targets (i.e., scaled corridors) for current small female ATDs and HBMs and to identify areas of improvement. Furthermore, more biomechanical data should be collected on larger samples of female PMHS to capture female-specific biological variability.

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I. APPENDIX

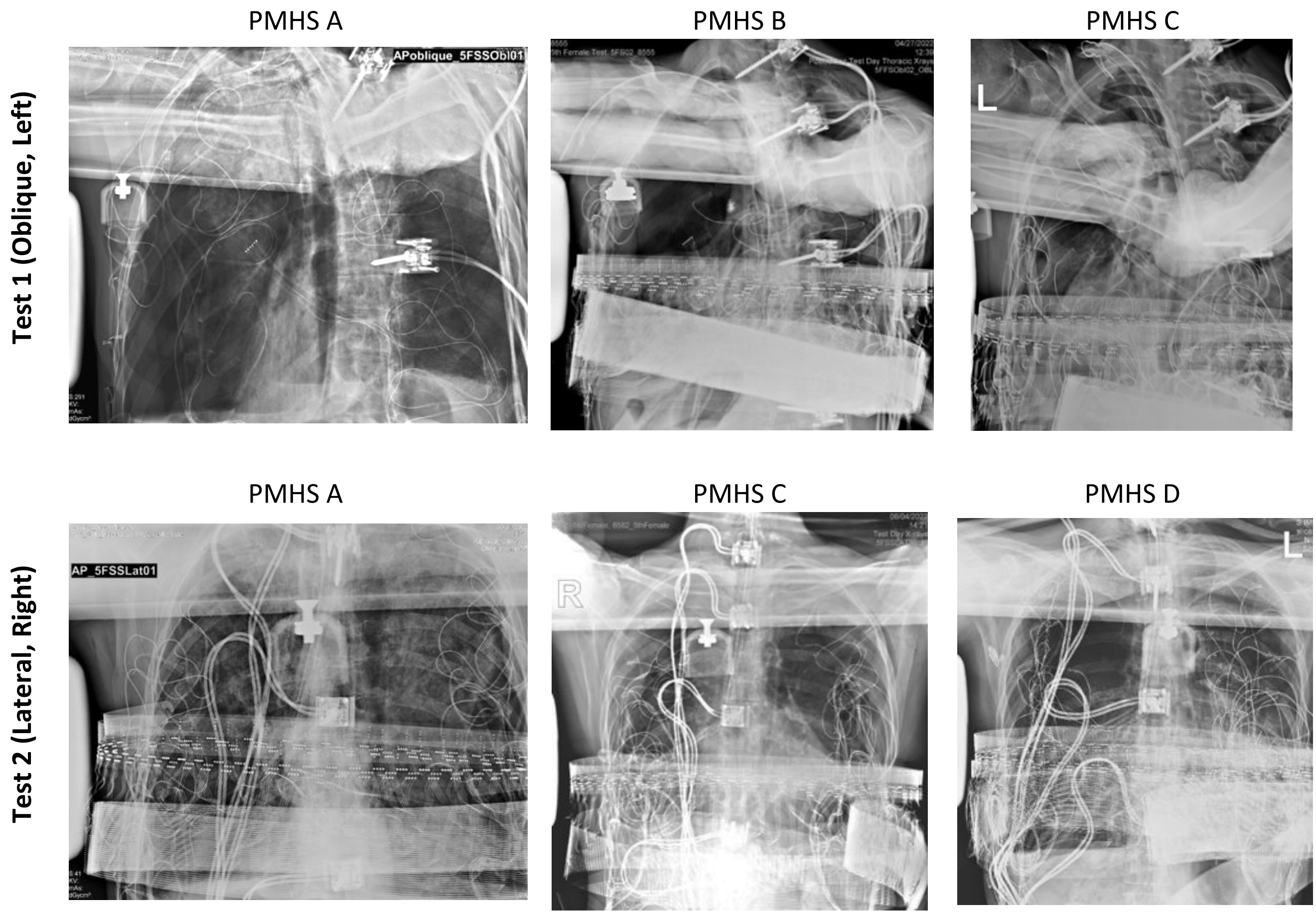


Fig. A1. Pre-test, in-position x-rays for Condition I. Test 1 x-rays are shown in the top row and test 2 x-rays are shown in the bottom row. Impactor is shown on the left side of each image.

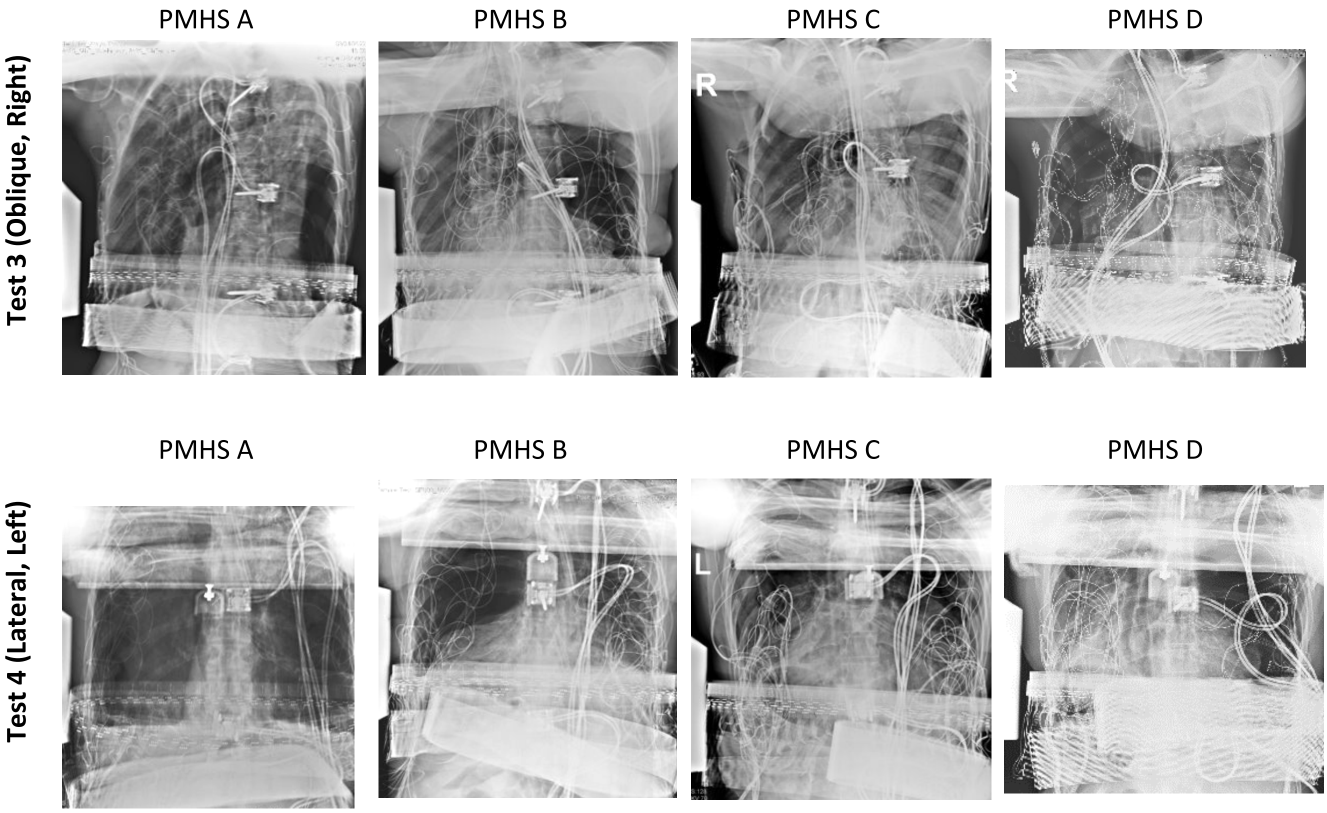


Fig. A2. Pre-test, in-position x-rays for Condition II. Test 3 x-rays are shown in the top row and test 4 x-rays are shown in the bottom row. Impactor is shown on the left side of each image.

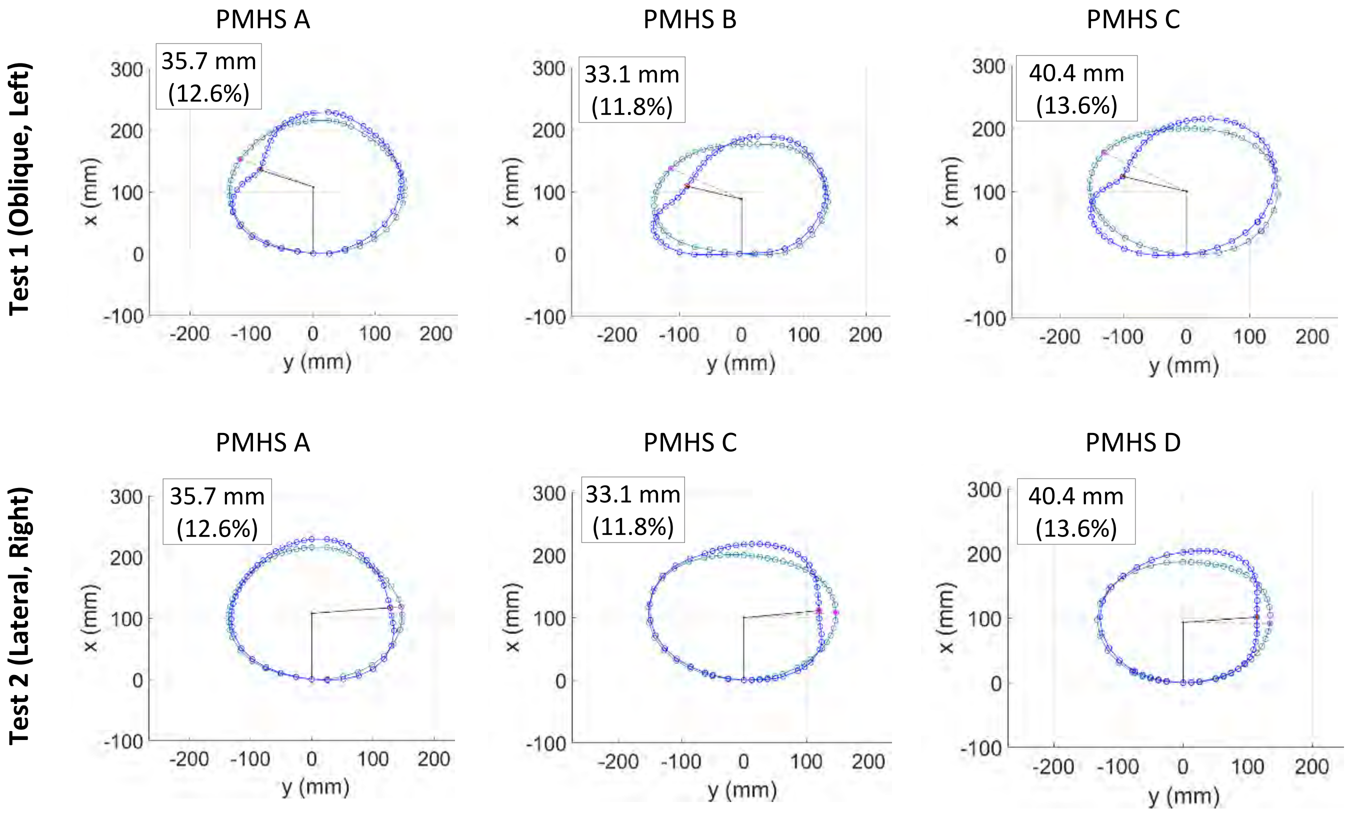


Fig. A3. Initial (green) and maximum half-lateral (blue) chestband contours for Condition I.

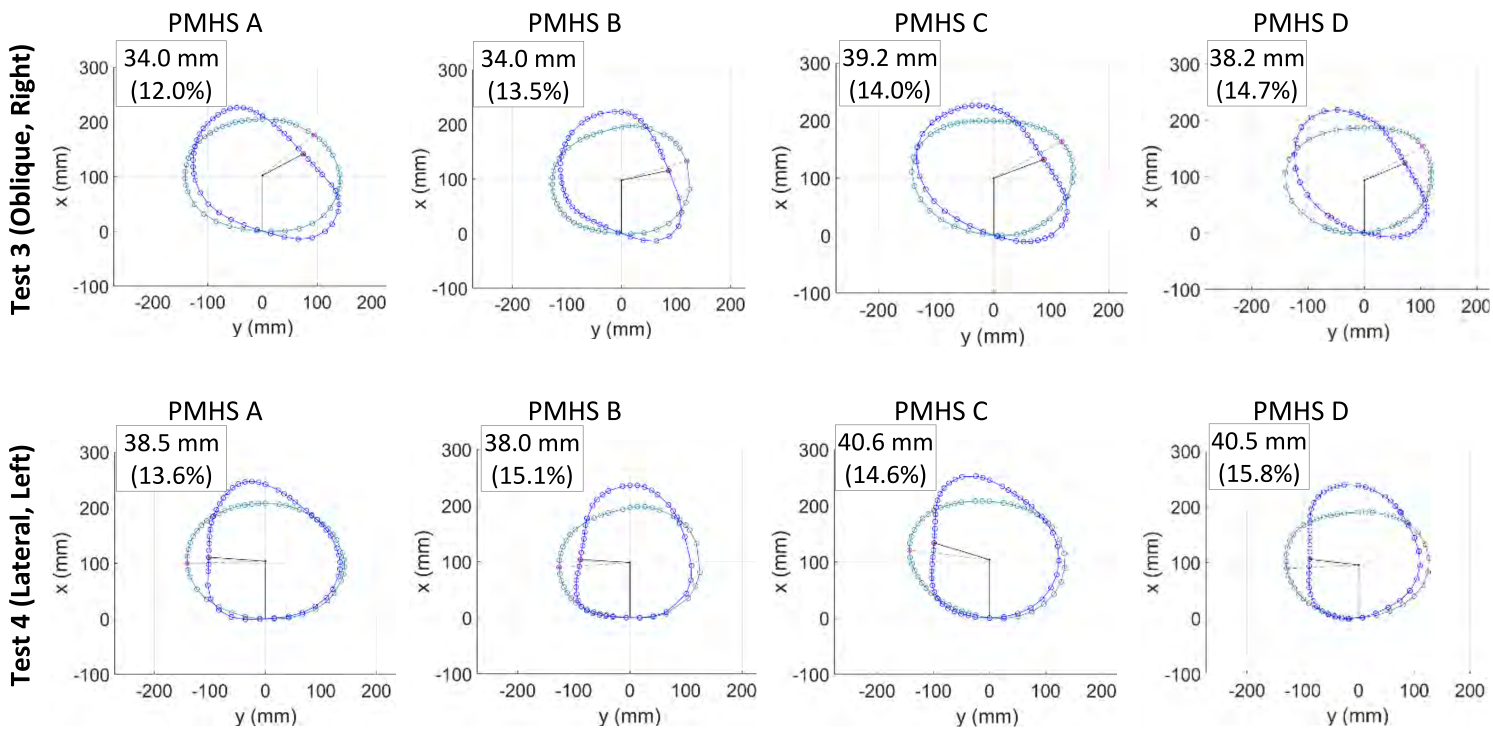


Fig. A4. Initial (green) and maximum half-lateral (blue) chestband contours for Condition II.

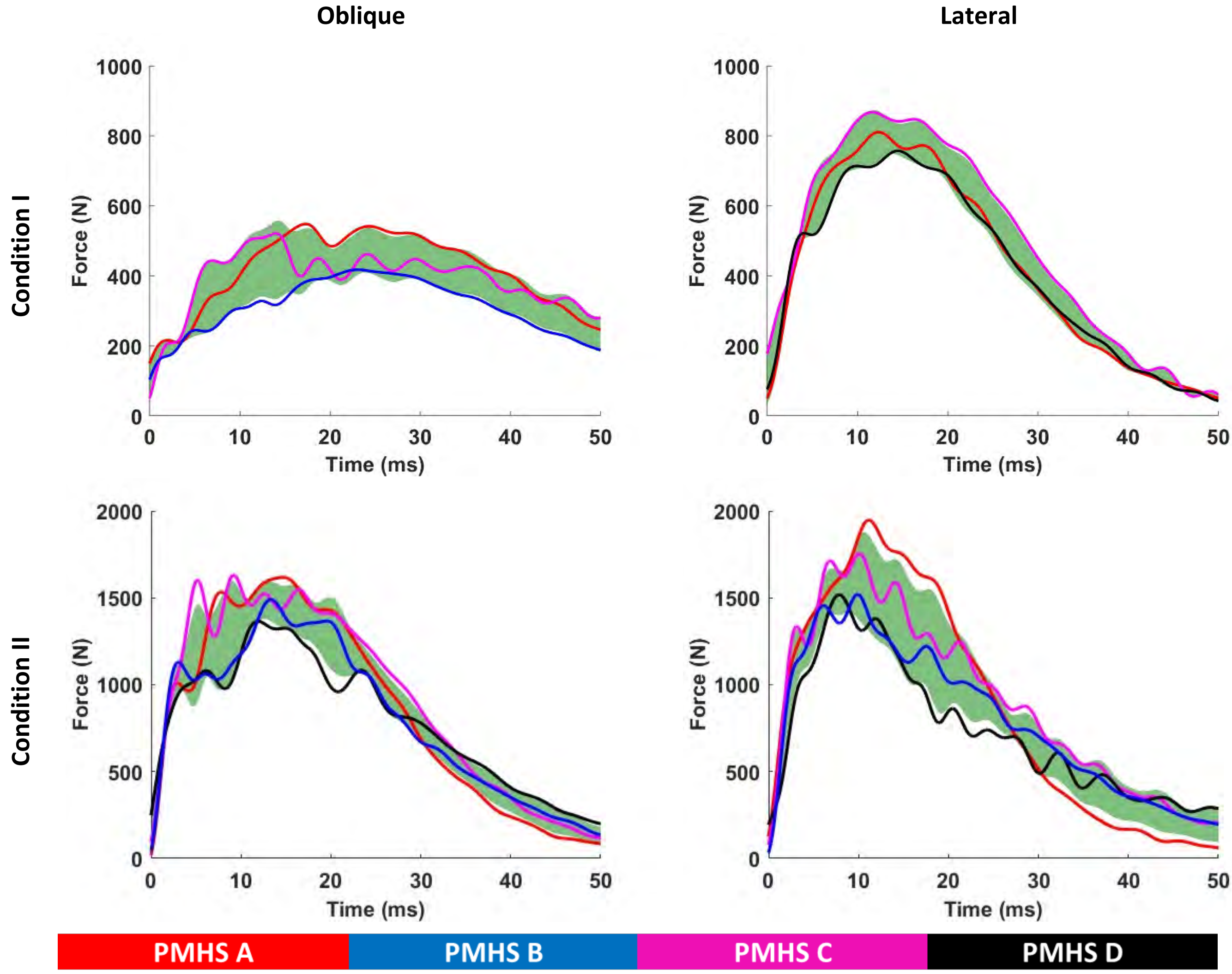


Fig. A5. Force corridors for Condition I oblique (upper left, test 1), Condition I lateral (upper right, test 2), Condition II oblique (lower left, test 3), and Condition II lateral (lower right, test 4) comparing individual PMHS curves.

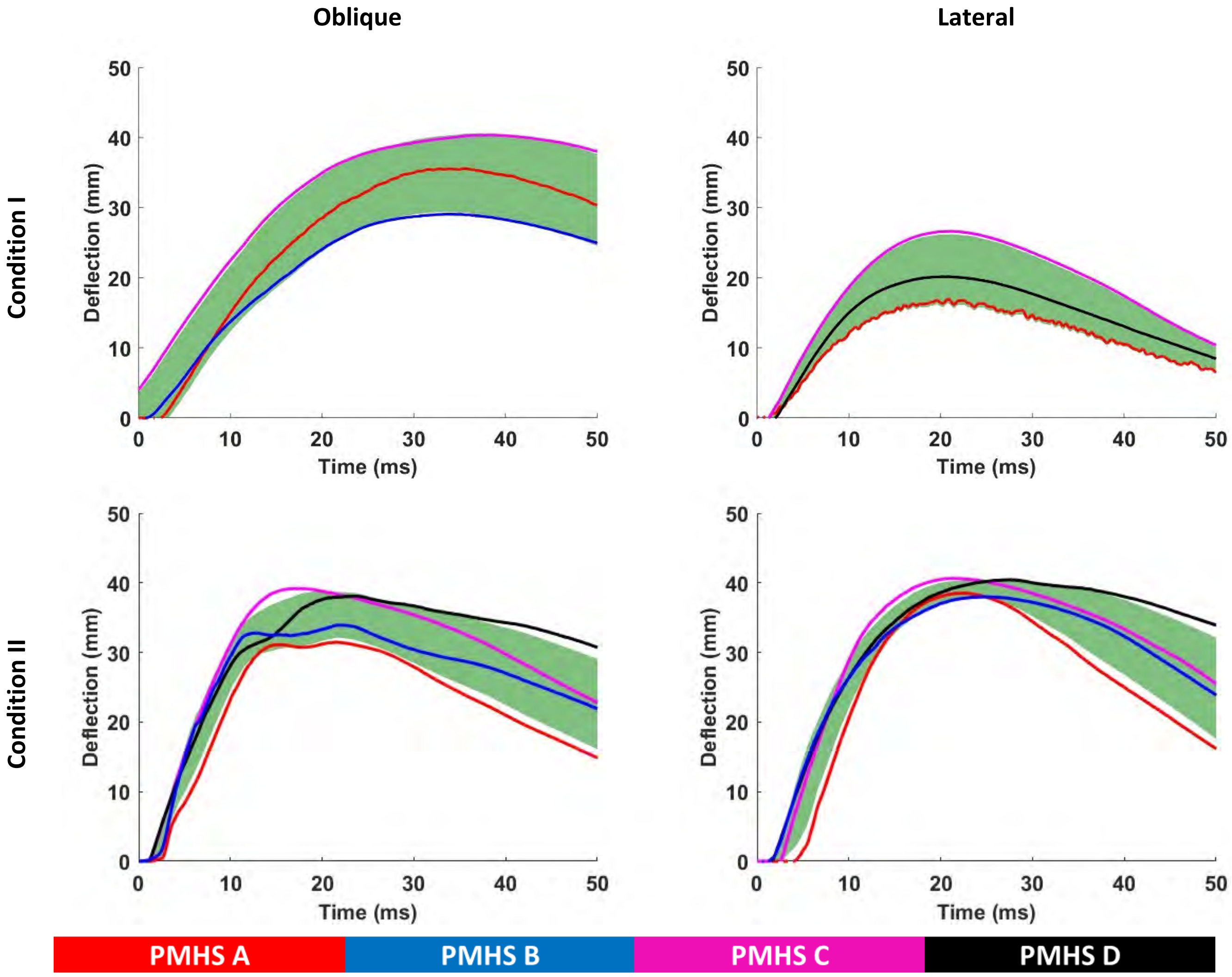


Fig. A6. Deflection corridors for Condition I oblique (upper left, test 1), Condition I lateral (upper right, test 2), Condition II oblique (lower left, test 3), and Condition II lateral (lower right, test 4) comparing individual PMHS curves.

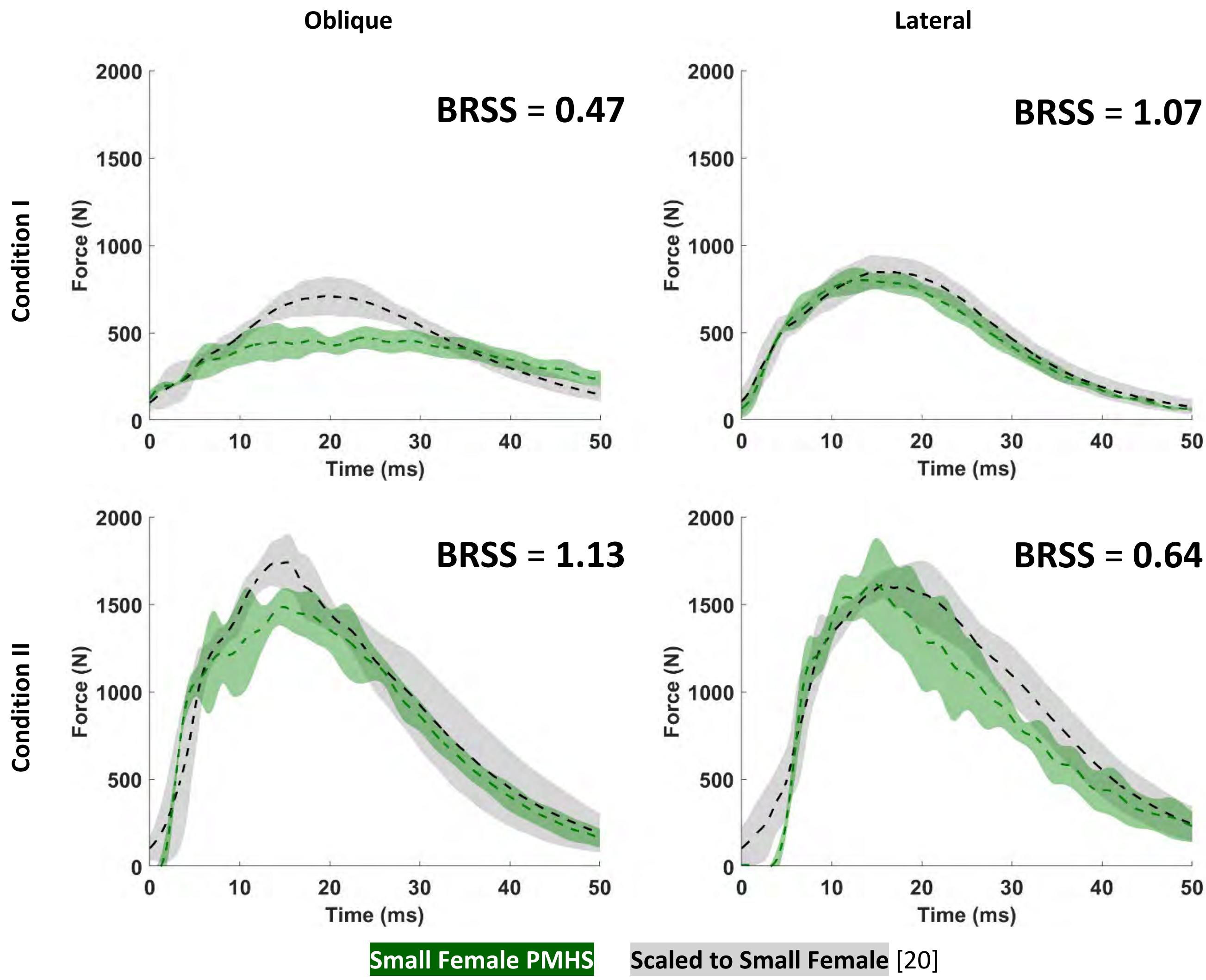
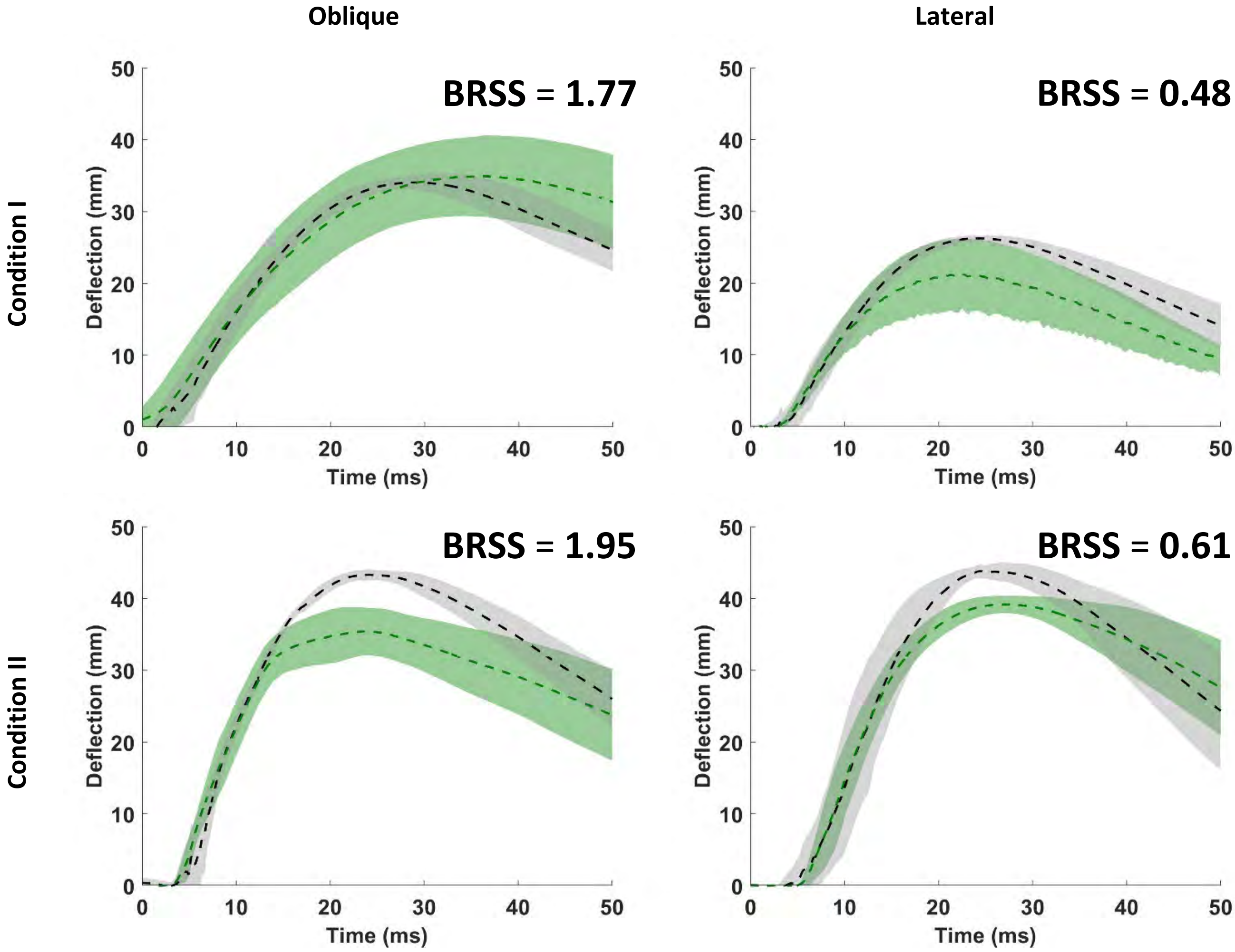


Fig. A7. Force-time corridors for Condition I oblique (upper left, test 1), Condition I lateral (upper right, test 2), Condition II oblique (lower left, test 3), and Condition II lateral (lower right, test 4) comparing corridors generated directly from small female PMHS data (green) to corridors scaled for the small female using mid-sized male data (gray) [21]. Average BRSS are included for each comparison.



Small Female PMHS **Scaled to Small Female** [20]

Fig. A8. Deflection-time corridors for Condition I oblique (upper left, test 1), Condition I lateral (upper right, test 2), Condition II oblique (lower left, test 3), and Condition II lateral (lower right, test 4) comparing corridors generated directly from small female PMHS data (green) to corridors scaled for the small female using mid-sized male data (gray) [21]. Average BRSS are included for each comparison.