Development of Response Corridors for the Compressive Stiffness of the Male and Female Arm in Lateral Loading

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ABSTRACT

The biofidelity of side impact ATDs is crucial in order to accurately predict injury of human occupants. Although the arm serves as a load path to the thorax, there are currently no biofidelity response requirements for the isolated arm. The purpose of the study was to characterize the compressive stiffness of male and female upper arms in lateral loading and to develop corresponding biofidelity stiffness corridors. This was accomplished by performing a series of pendulum tests on sixteen isolated upper arms, obtained from four male and four female cadavers, at impact velocities of approximately 2 m/s and 4 m/s. The upper arms were oriented vertically with the medial side placed against a rigid wall in order to simulate loading during a side impact automotive collision. The force versus deflection response data was normalized to that of a 50th percentile male or a 5th percentile female and then response corridors were developed. For both impact rates the cadaver arms exhibited a considerable amount of deflection under very low force, i.e. toe region, before the any substantial increase in force. The deflection at which the force began to increase substantially was found to be similar to the average difference in thickness between the initial and compressed volunteer arm thickness measurements for both the 5th percentile female and 50th percentile male. Although the response of the SID-IIs arm was similar in shape to that of the female cadaver arms for both impact rates, the SID-IIs arm did not exhibit a considerable toe region and therefore did not fall within the response corridors for the 5th percentile. The results of the current study could lead to an improvement in the overall biofidelity of side impact ATDs by providing valuable data necessary to validate the compressive response of ATD arm independent of the global response.

INTRODUCTION

Approximately 8,000 automobile occupants are killed and 24,000 seriously injured each year in automotive side impact collisions [2]. For all types of side impact collisions the second leading source of fatality, next to head injuries, is chest injuries (29%) [2]. The development of anthropometric test dummies (ATDs) specifically designed for side impact testing has helped automotive safety engineers evaluate and improve new and evolving occupant protection technologies. One such dummy is the SID-IIs, which represents the 5th percentile human female. Accurate biofidelity for side impact ATDs, such as the SID-IIs, is crucial in order to accurately predict injury of human occupants. A recent area of concern is the biofidelity of the arm of side impact ATDs. There have been several studies that have investigated the tolerance of the upper extremity in three-point bending and side airbag deployments [1, 2, 3, 4, 5, 6, 8]. However, the characterization of the compressive stiffness of the arm has been limited [9, 10]. Given that the arm serves as a load path to the thorax, the response characteristics of the upper extremity can influence the thoracic response in side impact test dummies. Although there are biofidelity evaluations for the global response of the side impact ATD arm and thorax combined, there are currently no biofidelity evaluations with respect to the compressive characteristics of the isolated arm. Therefore, the purpose of the study was to characterize the stiffness of the male and female upper arm in lateral compressive loading and to develop corresponding biofidelity stiffness corridors.

METHODS

A total of 18 pendulum impacts were performed on 9 matched arms, 5 female and 4 male obtained from fresh previously frozen post mortem human subjects (PHMS). The arms were obtained from 9 fresh previously frozen human cadavers, 5 female and 4 male (Table 1). In addition, a total of 4 pendulum impacts were performed on the standard arm of the Sid-IIs dummy using the same experimental setup to provide means of comparison.

Table 1: Subject Information.

Subject ID	Gender (F/M)	Age (yrs)	Mass (kg)	Height (cm)
Cadaver 1	Female	72	64	165
Cadaver 2	Female	77	55	160
Cadaver 3	Female	87	82	173
Cadaver 4	Female	76	70	157
Cadaver 5	Female	73	100	170
Cadaver 6	Male	76	44	170
Cadaver 7	Male	62	60	178
Cadaver 8	Male	67	105	183
Cadaver 9	Male	71	105	188

Experimental Setup

The primary component of the test setup was a 14 kg pendulum with a rigid 152 mm diameter impacting surface (Figure 1). The impactor was supported by 8 steel cables in order to provide smooth pendulum travel with no rotation or translation. The pendulum was instrumented with a single axis accelerometer (Endevco 7264B, 2000 G, San Juan Capistrano, CA). The arm was then placed against a polyethylene backing surface, which was mounted to a rigid aluminum plate. The reaction force was measured using a single axis load cell (Interface 1210AF-22,240 N, Scottsdale, AZ) mounted to a rigid wall with the use of a rigid aluminum plate. The data acquisition system and high-speed video were triggered with the use of a contact strip placed on the soft tissue of each arm at the point of initial impactor contact.

The arms were oriented vertically and suspended with a rope tied around the head of the humerus (Figure 2). The superior skin and muscle of the arm were held taught by with the use of sutures and string attached to the suspending rope. The arms were positioned so that the center of the impactor was in-line with the humerus bone. Special care was taken to ensure that only the main shaft of the humerus was in front of the polyethylene backing surface. In order to provide a comparison to the response of the dummy arm, matched tests were performed on the arm of the SID-IIs dummy (Figure 2).

The arms were randomly divided into two groups, where each group contained one specimen, right or left arm, from each of the 9 matched pairs. The first group was subjected to a 2.0 m/s impact (20.3 cm drop height). The second group was subjected to a 4.0 m/s impact (81.5 cm drop height). Pre-test measurements were taken of each test specimen to document anthropometrical data of the arms with soft tissue attached (Table A1). The thickness and circumference of each specimen was measured after the specimen was positioned on the experimental test setup. Post-test measurements were taken of each test specimen to document anthropometrical data of the humerus bone (Table A2).

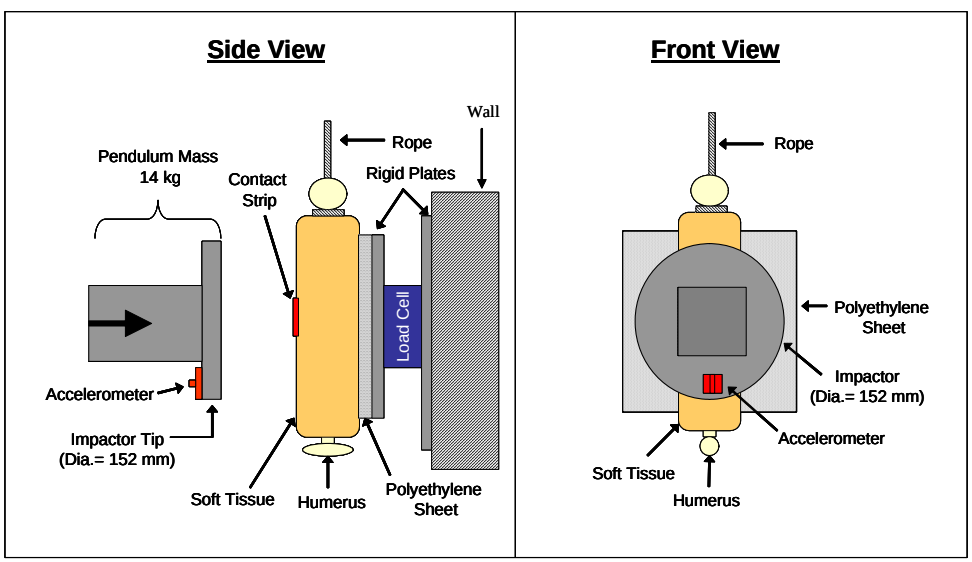

Figure 1: Pendulum impact experimental test setup.

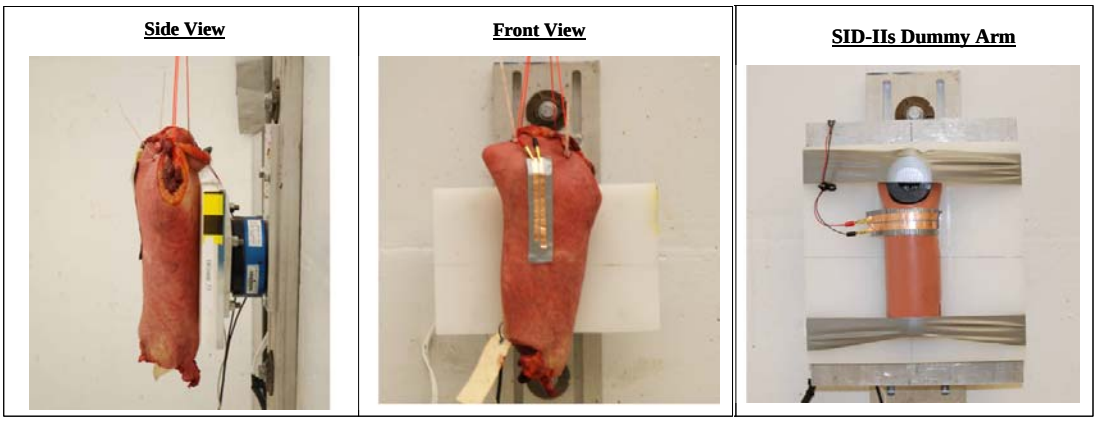

Figure 2: Cadaver and SID-IIs arm positioning.

Data Acquisition and Processing

All data was recorded at a sampling frequency of 30,000 Hz (Iotech WBK16, Cleveland, OH) and filtered to Channel Filter Class (CFC) 600. The impactor force was calculated as the product of impactor acceleration and impactor mass, 14 kg. High-speed video (Phantom V9.1, Vision research) was recorded at a sampling rate of 2000 Hz at a resolution of 864 x 1000 pixels (Figure 4). The camera was positioned to obtain video perpendicular to the impact direction. The positions of the impactor targets were tracking using Phantom software. In order to obtain medial-lateral deflection, the position of the impactor at the point of initial contact from subtracted from the impactor position at each point in time

Volunteer Measurements

In order to obtain a indication of the toe region of the arm due to medial-lateral compression, the upper arms of 16 male, approximately 50th percentile, and 4 female, approximately 5th percentile female, volunteers were measured (Figure 3, and Table 2). To measure the thickness of the arm in the vertical position, a flat plate was inserted between the body and the arm of a standing volunteer. The volunteer was asked to relax their muscles and maintain contact between the plate and elbow joint with the arm hanging vertically in a relaxed position. The thickness was measured with a combination square, perpendicular to the plate, and from the plate to the midpoint of the arm. A second thickness measurement was taken by compressing the arm to a tolerable limit. This measurement was taken to give an indication of the toe region that would result from compressing the soft tissue.

Initial Thickness (No Compression) **Compressed Thickness** (Compressed to a Tolerable Level)

Figure 3: Arm thickness measurements taken on a volunteer.

Table 2: Average arm thickness measurements for 20 volunteers.

Gender	Number of Subjects	Average Age (yrs)	Mass Range (kg)	Average Initial Thickness	Average Compressed Thickness	Average Difference b/w Initial and Compressed
Male	16	21	68 -84	78.5	45.4	33.1
Female	4	19	42 -52	66.3	36.5	29.8

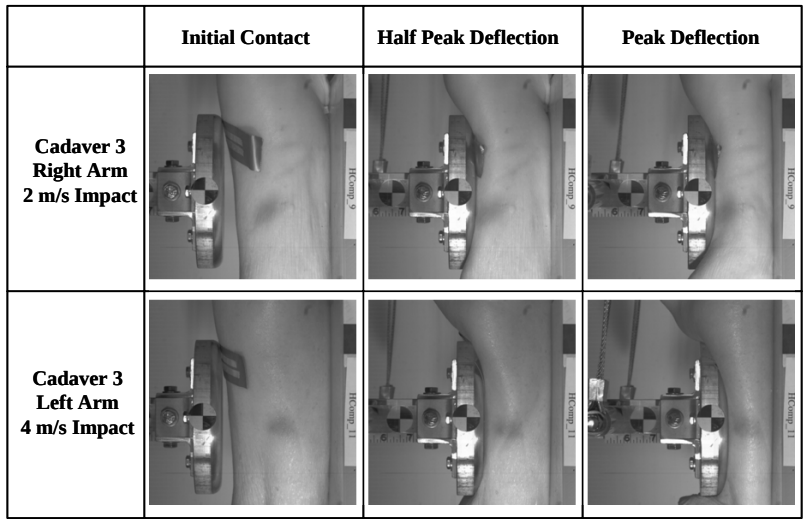

Figure 4: High speed video stills used to determine medial-lateral deflection.

Data Scaling

In order to minimize the variations in subject response due to individual geometry and inertial properties, the force and deflection were scaled to the response of a standard subject. A number of different standard scaling techniques were evaluated: Eppinger et al. (1984); Mertz (1984); ISO/TR-9790:1999. However, the scaling the procedure detailed by Eppinger et al. (1984) was found to be the most effective [12, 13, 14]. The scaling factors are defined below (Equations 1-3). In the scaling factor equations, m_i is the mass of the cadaver, m_s is the mass of a standard subject. The mass of the standard 5th percentile female is 46.9 kg, and the mass of the standard 50th percentile male is 76 kg [15]. The scaling factors used to normalize the response of each cadaver arm are reported in Table 3.

Table 3: Scaling Factors.

Subject ID	Gender	Scaling Factors	
		Deflection (Rx)	Force (Rf)
Cadaver 1	F	0.90	0.82
Cadaver 2	F	0.95	0.90
Cadaver 3	F	0.83	0.69
Cadaver 4	F	0.87	0.76
Cadaver 5	F	0.78	0.60
Cadaver 6	M	1.20	1.44
Cadaver 7	M	1.08	1.18
Cadaver 8	M	0.90	0.81
Cadaver 9	M	0.90	0.81

$$\lambda = \left(\frac{m_s}{m_i}\right)^{1/3} \qquad \text{Eqn (1)}$$

$$Force_{scaled}(t) = \lambda^2 * Force_{imp}(t) \qquad \text{Eqn (2)}$$

$$Deflection_{scaled}(t) = \lambda * Deflection(t) \qquad \text{Eqn (3)}$$

RESULTS

The non-scaled force versus deflection responses of each arm were plotted for each loading rate (Figures 5, 8, 11, and 14). The scaled force versus deflection responses of each arm were plotted for each loading rate (Figures 6, 9, 12, and 15). In addition, the average difference in thickness between the initial and compressed volunteer arm thickness was plotted along with the scaled data.

Arm Stiffness Response Corridors

Force versus deflection response corridors were developed using the characteristic average approach for both male and female arm responses at each impact rate (Figures 7, 10, 13, and 16) [11]. The upper bound corresponds to the positive standard deviation in force vs. the negative standard deviation in deflection. The lower bound corresponds to the negative standard deviation in force vs. the positive standard deviation in deflection.

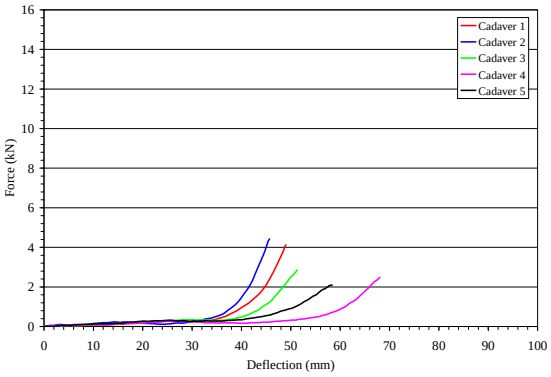

Figure 5: Female arm force vs. deflection responses- 2 m/s.

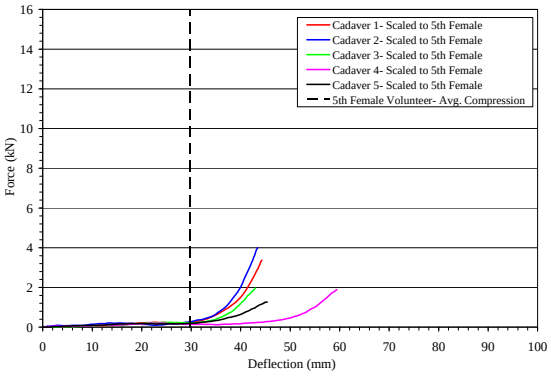

Figure 6: Scaled female arm force vs. deflection responses - 2 m/s.

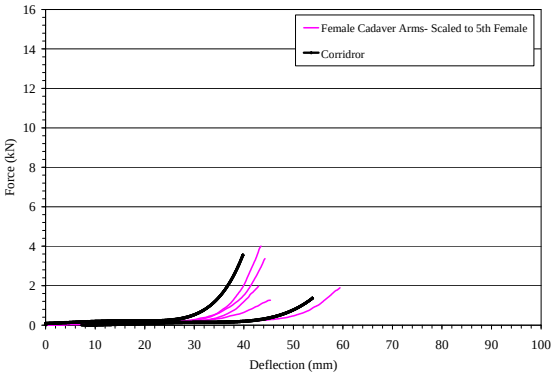

Figure 7: Scaled female arm force vs. deflection response corridors - 2 m/s.

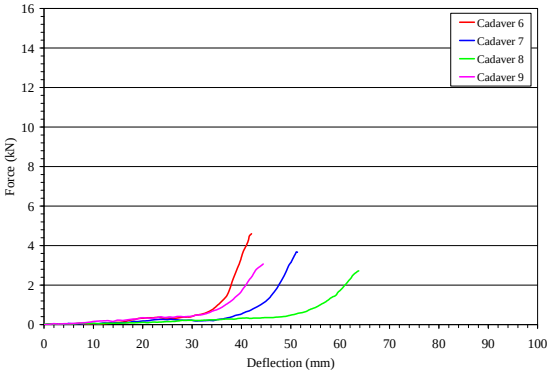

Figure 8: Male arm force vs. deflection responses - 2 m/s.

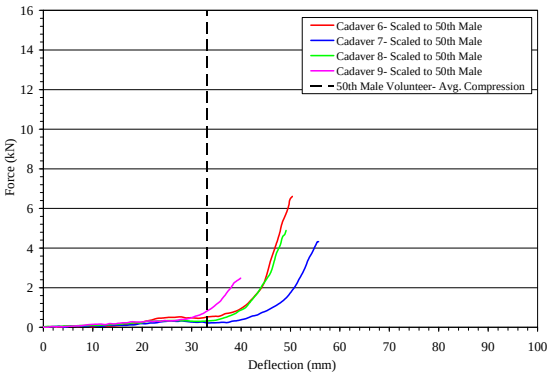

Figure 9: Scaled male arm force vs. deflection responses - 2 m/s.

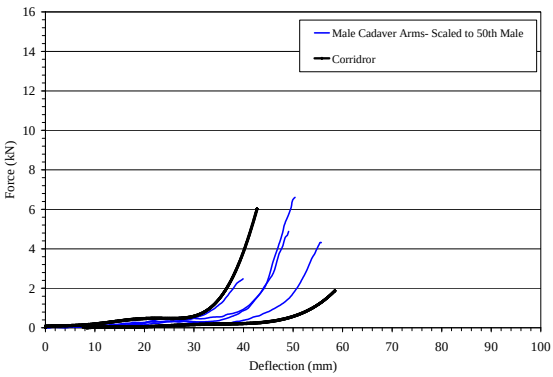

Figure 10: Scaled male force vs. deflection response corridors - 2 m/s.

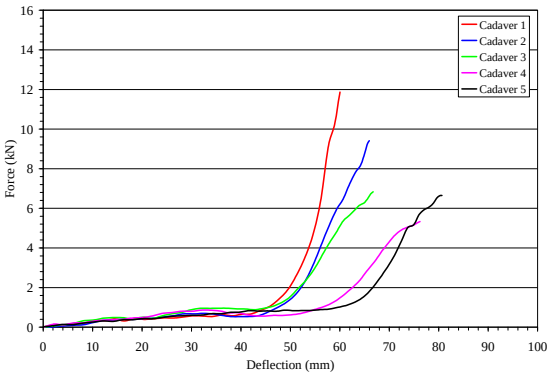

Figure 11: Female arm force vs. deflection responses - 4 m/s.

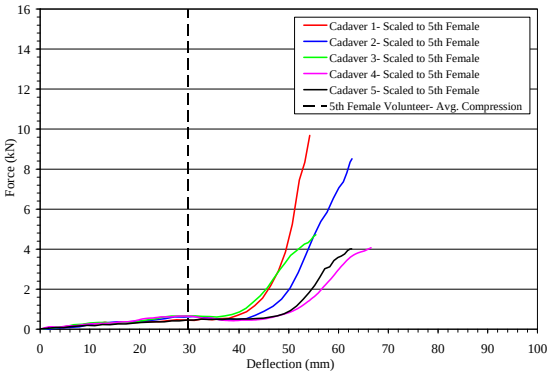

Figure 12: Scaled female arm force vs. deflection responses - 4 m/s.

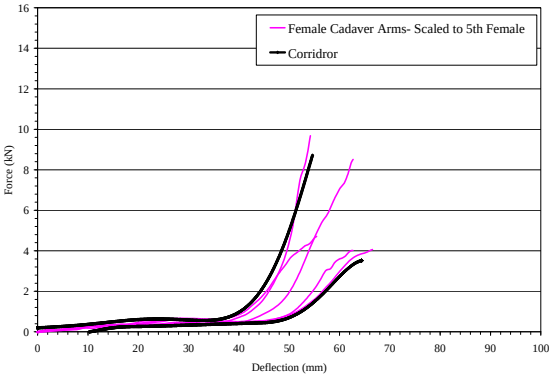

Figure 13: Scaled female force vs. deflection response corridors - 4 m/s.

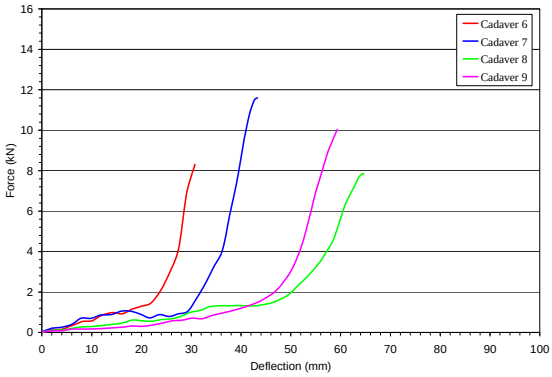

Figure 14: Male arm force vs. deflection responses - 4 m/s.

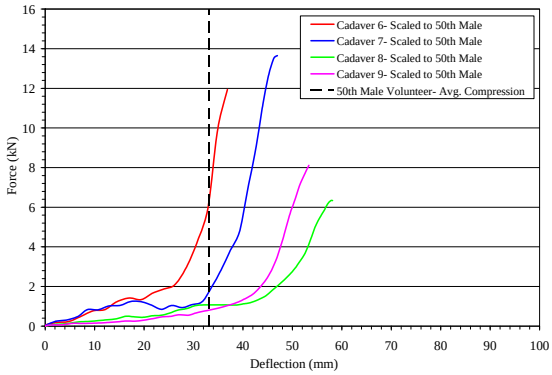

Figure 15: Scaled Male arm force vs. deflection responses - 4 m/s.

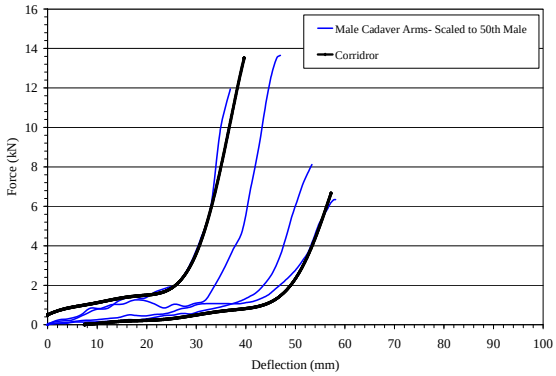

Figure 16: Scaled male force vs. deflection response corridors - 4 m/s.

Scaled Female vs. SID-IIS Response

The SID-IIs dummy arm did not exhibit a considerable toe region before the any substantial increase in force. For means of comparison, the scaled force versus deflection responses of the female arms were plotted along with the responses of the Sid-IIs dummy arms for both loading rates (Figures 17 and 18). The comparison clearly shows that the response of the SID-IIs does not lie within the response corridors for the 5th percentile female due to a lack of any considerable toe region.

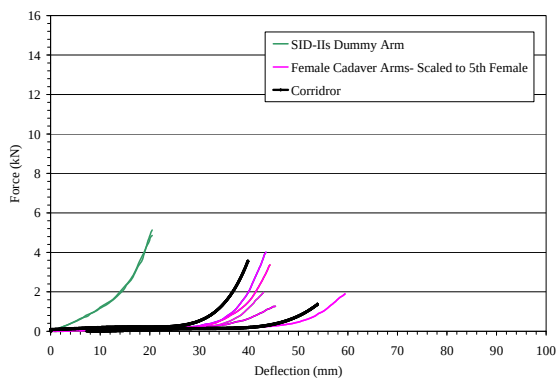

Figure 17: SID-IIS versus scaled female force vs. deflection responses- 2 m/s.

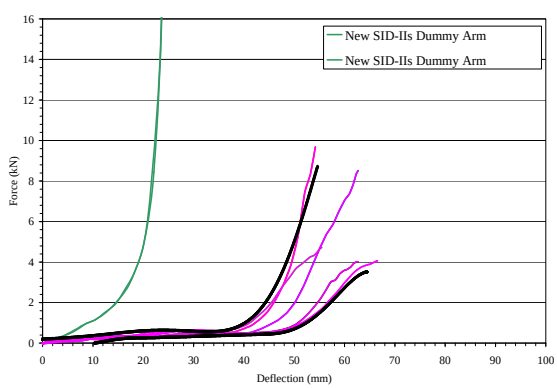

Figure 18: SID-IIS versus scaled female force vs. deflection responses- 4 m/s.

DISCUSSION

Although, the scaling the procedure detailed by Eppinger et al. (1984) was found to be the most effective method out of the standard scaling methods evaluated in the current study, this method is based on total subject mass and does not account for the differences in the ratio of arm mass to total body mass or arm thickness Given that the arm in constrained by the backing surface, the changes in the thickness of the soft tissue between subjects dominates the changes in the force versus deflection response between subjects. Therefore, an alternate scaling method based solely on arm thickness is proposed here. This method assumes that the material properties of the soft tissue do not change between subjects, but the amount, or thickness, of the tissue does. The scaling factors based on arm thickness alone are defined below (Equations 1-6, Table 4). In the scaling factor equations, t_i is the medial lateral arm thickness of the cadaver, t_s is the medial lateral arm thickness of a standard subject. The medial lateral arm thickness of the standard 5th percentile female is 67 mm, and the medial lateral arm thickness of the standard 50th percentile male is 86 mm [15].

$$\lambda_t = \left(\frac{t_s}{t_i}\right) \qquad \text{Eqn (4)}$$

$$Force_{scaled}(t) = \lambda_t * Force_{imp}(t) \qquad \text{Eqn (5)}$$

$$Deflection_{scaled}(t) = \lambda_t * Deflection(t) \qquad \text{Eqn (6)}$$

Table 4: Scaling Factors Based on Maximum Arm Thickness.

Subject ID	Gender	Impact Speed	Scaling Factor
Cadaver 1	F	2 m/s	0.86
		4 m/s	0.77
Cadaver 2	F	2 m/s	0.83
		4 m/s	0.71
Cadaver 3	F	2 m/s	0.65
		4 m/s	0.63
Cadaver 4	F	2 m/s	0.55
		4 m/s	0.54
Cadaver 5	F	2 m/s	0.58
		4 m/s	0.52
Cadaver 6	M	2 m/s	1.19
		4 m/s	1.54
Cadaver 7	M	2 m/s	0.93
		4 m/s	1.16
Cadaver 8	M	2 m/s	0.78
		4 m/s	0.79
Cadaver 9	M	2 m/s	0.97
		4 m/s	0.88

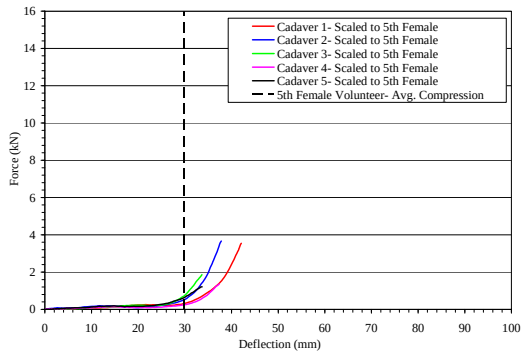

Figure 19: Scaled female arm force vs. deflection responses based on thickness- 2 m/s.

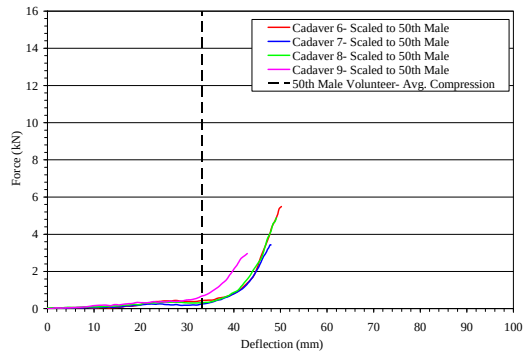

Figure 21: Scaled male arm force vs. deflection responses based on thickness - 2 m/s.

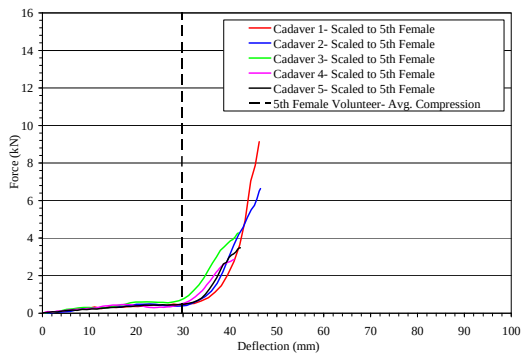

Figure 20: Scaled female arm force vs. deflection responses based on thickness - 4 m/s.

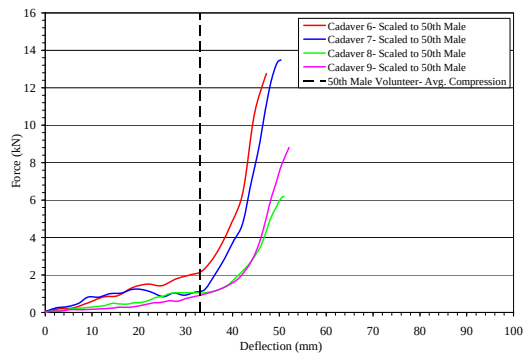

Figure 22: Scaled male arm force vs. deflection responses based on thickness - 4 m/s.

CONCLUSIONS

The study presents results from 18 medial-lateral pendulum impacts performed on 9 human arm matched pairs with a 14 kg pendulum at 2 m/s or 4 m/s. Force versus deflection response corridors were developed for both the 50th percentile male and the 5th percentile female arm response at each impact rate. In addition, 4 pendulum impacts performed on a Sid-IIs dummy arm using the same experimental setup for means of comparison. For both impact rates the cadaver arms exhibited a considerable amount of deflection under very low force, i.e. toe region, before the any substantial increase in force. The deflection at which the force began to increase substantially was found to be similar to the average difference in thickness between the initial and compressed volunteer arm thickness measurements for both the 5th percentile female and 50th percentile male. Although the response of the SID-IIs dummy arm was similar in shape to that of the female cadaver arms for both impact rates, the SID-IIs dummy arm did not exhibit a considerable toe region before the any substantial increase in force. Therefore, the SID-IIs response force vs. deflection response did not lie within the response corridors for the 5th percentile female. The results of the current study could lead to an improvement in the overall biofidelity of side impact ATDs by providing valuable data necessary to validate the compressive response of side impact ATD arms independent of the global ATD response.

ACKNOWLEDGMENTS

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APPENDIX

Table A1: Cadaver arm pre-test anthropometric measurements.

Subject ID	Right/Left Arm	Arm Measurements with Soft Tissue				
		Arm Mass	Medial-Lateral Thickness		Circumference	
			[center of plate]	[maximum]	[center of plate]	[maximum]
		(g)	(mm)	(mm)	(cm)	(cm)
Cadaver 1	Right	1480	69.0	78.0	22.5	26.5
	Left	1320	80.0	87.0	23.5	26.0
Cadaver 2	Left	1450	81.0	81.0	25.5	27.0
	Right	1550	85.0	95.0	26.0	27.0
Cadaver 3	Right	2335	95.0	103.0	32.5	33.0
	Left	2355	102.0	107.0	31.0	34.0
Cadaver 4	Left	2900	115.0	122.0	35.0	36.0
	Right	3430	116.0	125.0	37.5	39.5
Cadaver 5	Right	2980	112.0	116.0	37.5	38.5
	Left	3445	115.0	128.0	37.5	43.5
Cadaver 6	Right	1445	55.0	72.0	18.5	21.5
	Left	1185	51.0	56.0	17.5	19.5
Cadaver 7	Left	2020	72.0	92.0	25.0	30.0
	Right	2060	68.0	74.0	25.0	28.0
Cadaver 8	Right	2995	93.0	110.0	34.0	37.0
	Left	3035	98.0	109.0	34.0	37.5
Cadaver 9	Left	2300	80.0	89.0	31.0	33.5
	Right	2385	77.0	98.0	30.5	35.5

Table A2: Cadaver arm post-test anthropometric measurements.

Subject ID	Right/Left Arm	Humerus Bone Measurements				
		Total Length	Length of Main Shaft	Midpoint Diameter		Circumference
				[medial-lateral]	[anterior-posterior]	[midpoint]
		(cm)	(cm)	(cm)	(cm)	(cm)
Cadaver 1	Right	32.0	21.0	2.22	1.80	6.50
	Left	32.0	21.0	2.22	1.88	6.50
Cadaver 2	Left	32.5	20.5	2.03	2.06	6.75
	Right	33.0	21.0	2.03	2.18	6.50
Cadaver 3	Right	32.5	21.5	1.93	1.84	6.25
	Left	32.5	21.0	1.91	1.88	6.25
Cadaver 4	Left	31.0	20.0	2.22	2.16	7.50
	Right	31.0	20.0	2.22	2.17	7.50
Cadaver 5	Right	31.5	22.0	2.13	2.16	7.00
	Left	31.5	22.0	1.92	2.16	7.00
Cadaver 6	Right	35.5	22.0	2.10	2.39	7.00
	Left	35.5	22.0	1.75	2.79	7.00
Cadaver 7	Left	33.5	22.0	2.41	2.54	8.00
	Right	34.0	22.5	2.50	2.54	8.25
Cadaver 8	Right	36.0	24.0	2.41	2.35	7.50
	Left	36.0	23.5	2.41	2.35	7.25
Cadaver 9	Left	35.0	21.0	2.06	2.25	7.50
	Right	34.5	22.0	2.13	2.03	7.50