BIOFIDELITY OF THE SID-IIs AND A MODIFIED SID-IIs UPPER EXTREMITY: BIOMECHANICAL PROPERTIES OF THE HUMAN HUMERUS

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ABSTRACT

Accurate biofidelity for side impact dummies is crucial in order to accurately predict injury of human occupants. One such dummy is the SID-IIs, which represents the 5th percentile human female. A recent area of concern is the biofidelity of the upper extremity of side impact test dummies. Since the upper 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. However, there are currently no biofidelity evaluations with respect to the characteristics of the arm its self. The purpose of the study was to characterize the biomechanical properties of male and female humeri and to assess the biofidelity of the SID-IIs and a modified SID-IIs upper extremity. Results from two types of tests are presented. First, whole bone three-point bending tests were performed on eight isolated humeri from male and female human cadavers at static and dynamic loading rates 0.01 m/s and 3.0 m/s. Second, a series of compression tests were performed at two dynamic rates, 2 m/s and 4m/s, on a total of eight male and female humeri with all soft tissues attached. Then matched compression tests were preformed on the SID-IIs and the modified SID-IIs humerus segment. The impact direction for all tests was from lateral to medial in order to simulate a side impact collision. All test results and biofidelity corridors are presented in the full paper. The test results show that for both the SID-IIs and modified SID-IIs, the force vs. deflection response transitions from a linear response to an exponential response at deflections of approximately 15 mm and 25 mm, respectively. The male and female human humeri exhibited a similar trend but to a lesser extent. However, the force vs. deflection response of the modified SID-IIs upper extremity was more representative to that of the female human humeri then the original SID-IIs upper extremity. For example, the linear stiffness corridor from the 2m/s humerus compression tests was between 79.17 kN/m and 86.36 kN/m. For the same testing speed, the modified SID-IIs had a linear stiffness of 71.78 kN/m, while the SID-IIs had a linear stiffness of 183.9 kN/m. In summary, it is recommended that the modified SID-IIs upper limb should be used in place of the current SID-IIs upper limb in order to improve the biofidelity of the thoracic measurements of the SID-IIs.

INTRODUCTION

About 8,000 automobile occupants are killed and 24,000 seriously injured each year in side impact collisions [1]. The development of anthropometric test dummies specifically designed for side impact testing have helped to 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 dummies, 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 upper extremity of side impact test dummies. Since the upper 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. However, there are currently no biofidelity evaluations with respect to the characteristics of the arm its self. Even though, for all types of side impact accidents the second leading source of fatality, next to head injuries, is chest injuries (29%) [1].

Additionally, although airbags have reduced the risk of fatal injuries in automobile collisions, they have increased the incidence of some nonfatal injuries including upper extremity injuries [3]. Duma [3] found chondral and osteochondral fractures in the elbow joint for seven out of the 12 cadaver tests that had been subjected to upper extremity loading from a deploying seat mounted side airbag. Kallieris [8], who used the Hybrid III 50th percentile male dummy and male cadavers, found one humerus fracture out of five cadaver tests.

The first step in reducing these injuries is to determine applicable upper extremity injury criteria [6]. Duma [4] produced injury risk functions for the forearm and humerus fracture of the 5th percentile female based on mid-shaft bending moments. Duma [5] developed a multivariate risk function based upon the 5th percentile female that predicts a 50% risk of elbow fracture at a compressive elbow load of 1780 N and load angle of 30° superior to the longitudinal axis of the forearm. Duma [7] developed dynamic hyperextension injury criteria for the female elbow joint based on dynamic hyperextension tests on 24 female cadaver elbow joints.

The purpose of the study is to characterize the biomechanical properties of male and female humeri and to assess the biofidelity of the SID-IIs and a modified SID-IIs upper extremity. Results from two types of tests are presented. First, the results from whole bone three-point bending tests performed on eight isolated humeri from male and female human cadavers at static and dynamic loading rates, 0.01 m/s and 3.0 m/s, are presented. Second, the results from a series of compression tests performed at two dynamic rates, 2 m/s and 4 m/s, on a total of eight male and female humeri, with all soft tissues attached, and the SID-IIs and a modified SID-IIs upper extremity are presented.

METHODS

A total of 16 tests performed on fresh frozen human cadaver humeri in two parts. In part 1, 8 tests of 4 human humerus matched pairs were subjected to three-point bending using a hydraulic Material Testing System (MTS) at two impact rates. In part 2, 8 tests on 4 human humerus matched pairs and 6 tests both a Sid-IIs original and modified dummy arm subjected to compression loading on a drop tower at two dynamic impact rates.

Part 1: Humerus Three-Point Bending Tests

Dynamic humerus three-point bending tests were performed using a hydraulic Material Testing System (MTS 810, 13.3 kN, Eden Prairie, MN) at two loading rates on 8 unembalmed fresh human humeri obtained from 4 matched pairs.

Subject Test Data

Male and female matched pair humerus specimens ranging from 18 to 73 years of age were used for the three-point bending tests. For comparison with the standard population, Osteograms were performed on the left hand of each cadaver. The left hand of the cadavers was x-rayed and scanned by CompuMed incorporated (Los Angeles, CA). The BMD results are reported with respect to the normal population (Table 1). The t-score should be used to compare the cadaver's bone mineral density with that of the general population. In addition, the z-score can be used to compare the bone mineral density of the subjects with the average for their age. A t-score of -1 corresponds to one standard deviation below the mean for the general population (30 year olds), meaning the individual is at or above the -63rd percentile for bone mineral density, or close to normal. T-scores of 2 and 3 correspond to 97th and 99th percentiles, respectively.

Table 1.
Test subject data.

Subject Number	Gender	Age	BMD	T-Score	Z-Score
1	Female	46	93.7	-1.6	-1.6
2	Male	73	75.7	-3.2	-1.4
3	Male	18	138.3	3.2	3.2
4	Male	45	81.4	-2.7	-2.0

Experimental Setup

The primary component of the three-point bending test setup was a hydraulic Material Testing System (MTS 810, 13.3 kN, Eden Prairie, MN) (Figure 1). To stabilize the humerus in the test configuration, tissue was removed from the specimen and each end was inserted into a rigid square aluminum potting cup with polymer filler (Bondo Corporation, Atlanta, GA). During the potting process, care was taken to ensure the width between the supports for all specimens was 200 mm [8]. To maintain bending in the frontal plane, a pin was inserted through the left potting cup and a semicircular roller was attached to the right potting cup.

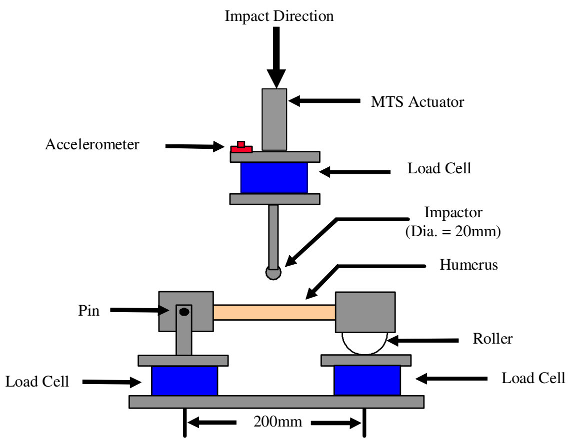

Figure 1. Humerus three-point bending test setup.

The humeri were randomly divided into two groups, where each group contained one specimen from each of the 4 matched pairs. The first group was subjected to a 0.01 m/s impact. The second group was subjected to a 3.00 m/s impact. Each humerus was instrumented with a uni-axial strain gage mounted to the mid-shaft bottom of the specimen (Vishay Measurements Group, CEA-06-062UW-350, Malvern, PA). The impactor assembly was instrumented with a five axis load cell (Denton 1968, 22,240 N, Rochester Hills, MI). Three axis load cells (Denton 5768, 11,120 N, Rochester Hills, MI) were mounted to each of the support towers. An accelerometer (Endevco 7264B, 2000 G, San Juan Capistrano, CA) was attached to the impactor head to allow for inertial compensation. Displacement was measured using the MTS internal LVDT. Data from the load cells and accelerometers were recorded at a sampling frequency of 30,000 Hz for the 0.01 m/s tests and 50,000 Hz for the 3.00 m/s tests (Iotech WBK16, Cleveland, OH). Pre and post test measurements were taken of each humerus three-point bending test specimen (Table 2).

Table 2.
Humerus three-point bending pre and post test specimen data.

Tests ID#	Subject Number	Right/Left Humerus	Diameter M-L	Diameter A-P	Uncut Length	Distance form Fracture to Strain Gage
			(mm)	(mm)	(mm)	(mm)
Hum_S_1	1	Right	0.912	0.807	321	9.0
Hum_S_2	2	Left	0.952	0.950	327	0.0
Hum_S_3	3	Right	0.974	0.847	362	1.0
Hum_S_4	4	Left	0.816	0.881	350	10.0
Hum_F_1	1	Left	0.964	0.895	313	10.0
Hum_F_2	2	Right	0.863	1.010	330	6.0
Hum_F_3	3	Left	0.875	0.882	360	3.0
Hum_F_4	4	Right	0.764	0.960	355	4.0

Part 2: Humerus compression tests

Dynamic compression tests were performed at two loading rates on 8 unembalmed fresh human humeri obtained from 4 matched pairs using a drop tower with a 16 kg impactor. In addition to the human humeri, both a Sid-IIs original and modified upper arm, provided by Toyota Motor Corporation, were tested at the same two loading rates using the same test setup in order to compare their responses to the responses of the human humeri.

Subject Test Data

Male and female matched pair humerus specimens, removed from subjects ranging from 56 to 87 years of age, were used for the tests (Table 3). The mass of the subjects ranged from 44.81 kg to 100.45 kg. The height of the subjects ranged from 152.4 cm to 180.34 cm.

Table 3.
Test subject data.

Subject Number	Gender	Age	Mass (kg)	Height (cm)
5	Male	56	81.37	170.18
6	Male	70	100.45	180.34
7	Female	61	44.81	152.40
8	Female	87	74.09	160.02

Experimental Setup

The primary component of the test setup was a drop tower with a 16 kg impactor (Figure 2). In order to simulate the response of the upper arm of a cadaver subjected to a side impact crash, the soft tissue was left on the human humeri for all compression tests. The ends of the humeri were constrained in order to prevent the human humeri from rotating or translating during the impact event (Figures 2 and 3).

The humeri were randomly divided into two groups, where each group contained one specimen from each of the 4 matched pairs. The first group was subjected to a 2.0 m/s impact (29.85 cm drop height). The second group was subjected to a 4.0 m/s impact (83.82 cm drop height). The impactor head and reaction plate were instrumented with single axis load cells (Interface 1210AF-22,240 N, Scottsdale, AZ). An accelerometer (Endevco 7264B, 2000 G, San Juan Capistrano, CA) was attached to the both the impactor head and reaction support plate to allow for inertial compensation. A potentiometer (SpaceAge Control 62-60-8242- 2159mm, Palmdale, CA) mounted to the base of the drop tower was used to measure the displacement of the impactor. Data from the load cells, potentiometer, and accelerometers were recorded at a sampling frequency of 30,000 Hz for the slow tests and the fast tests (Iotech WBK16, Cleveland, OH).

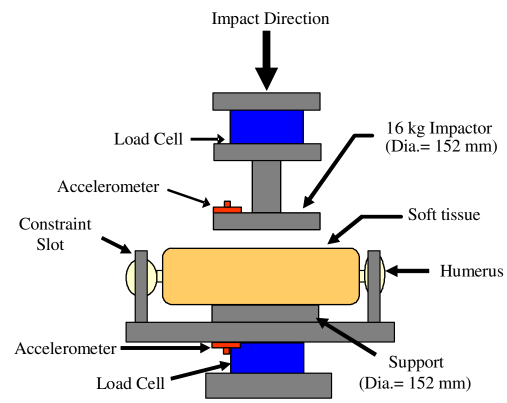

Figure 2. Humerus compression loading test setup (Front View).

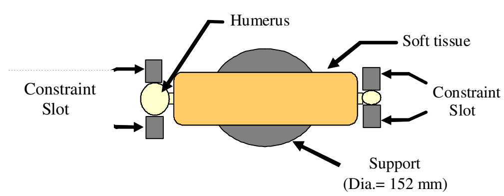

Figure 3. Humerus compression loading test setup (Top View).

Pre test measurements were taken of each humerus compression test specimen to document anthropometrical data (Table 4). The thickness of each specimen was measured after the specimen was placed on the support plate of the test setup.

Table 4.
Humerus compression test specimen data.

Tests ID#	Subject Number	Right/Left Humerus	Thickness (mm)	Humerus M/L Diameter (mm)	Uncut Length (mm)
Cad_1	5	Right	61.91	24.4	341.6
Cad_2	6	Left	46.04	22.9	335.3
Cad _3	7	Right	55.56	20.3	294.6
Cad _4	8	Left	63.50	22.9	325.1
Cad _5	5	Left	61.91	24.4	339.1
Cad _6	6	Right	46.04	22.9	335.3
Cad _7	7	Left	60.33	20.3	293.4
Cad_8	8	Right	58.74	22.9	321.3

The upper arm of the SID IIS, as well as automobile occupants, hangs vertically from the body when seated. Since the humeri tested were laid horizontally on a disc, the tissue flattened, causing the measured thickness to be less than when the arm hangs vertically.

In contrast, the dummy arm did not show any difference in thickness in the horizontal orientation. Therefore, the human humeri tests were not representative of a human occupant or similar to the dummy arm tests. To correct for this, the upper arms of 35 male and 35 female volunteers were measured (Table 5, Appendix A, and Appendix B). These measurements were taken with the arm in the vertical and horizontal positions, against surfaces representative of the tests in this report (Figure 4).

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. For measurements taken in the horizontal position, the volunteer laid their arm flat on a 152 mm diameter disk. The disk location was adjusted so it was centered in the middle of the humerus, and the volunteer adjusted the height of their shoulder until the humerus appeared flat on the disk. A combination square, perpendicular to the disk, was used to measure the thickness of the middle portion of the arm.

In addition to the vertical and horizontal thickness measurement, a third thickness measurement was taken by compressing the upper 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.

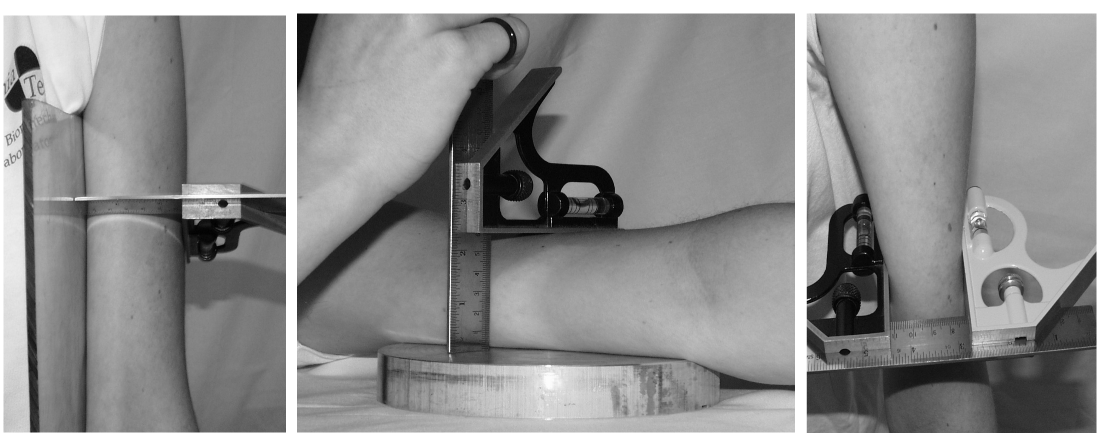

Figure 4. **Upper arm thickness measurements taken on a volunteer, Vertically oriented (left), horizontally oriented (middle), and compressed to a tolerable limit (right).**

Table 5.
Averages and standard deviations for 70 volunteer arm thickness measurements.

Gender	n	Average Height (m)	Average Mass (kg)	Vertical Thickness (mm)	Horizontal Thickness (mm)	Compressed Thickness (mm)	Ver -Hor (% diff)	Ver -Com (% diff)
Male	35	1.81 ± 0.07	82 ± 13	82 ± 8	72 ± 8	48 ± 6	14.7 ± 6.5	41.4 ± 5.9
Female	35	1.65 ± 0.07	61 ± 08	72 ± 6	64 ± 5	42 ± 5	12.3 ± 5.1	40.7 ± 4.5
Total	70	1.73 ± 0.11	71 ± 15	77 ± 9	68 ± 8	45 ± 6	13.5 ± 5.9	41.1 ± 5.2

RESULTS

The humerus data for both Task 2.1 and 2.2 is presented in the raw filtered form, as well as being mass scaled to the exact 5th percentile female and the 50th percentile male. This will allow for direct comparison to the dummy humerus values. All load cell and accelerometer data for both the three-point bending tests and compression tests was filtered at CFC 600. The potentiometer data for both compression tests was filtered at CFC 60 in order to eliminate excessive noise.

Part 1: Humerus three-point bending tests

The peak inertially compensated impactor force, peak deflection, peak strain, and the linear force increase for the 0.01 m/s and 3.00 m/s impact tests are presented (Table 6). The peak inertially compensated impactor force was mass scaled to either the 5th percentile female (Hum_S_1, Hum_F_1) or the 50th percentile male (Hum_S_2, Hum_S_3, Hum_S_4, Hum_F_2, Hum_F_3, Hum_F_4). The force vs. deflection data is presented in the raw filtered form, as well as being mass scaled to the exact 5th percentile female and the 50th percentile male (Figures 5-8). This will allow for direct comparison to the dummy humerus values.

Table 6.
Humerus three-point bending test results.

Tests ID#	Impactor Speed	Peak Bending Force (N)	Peak Moment (N/m)	Peak Deflection (mm)	Peak Strain (mstr)	Linear Force Increase (N/mm)	Scaled Peak Bending Force (N)	Scaled Peak Moment (N/m)
Hum_S_1	0.01 m/s	1347 *	134.7 *	7.72 *	16547.4	313.1	759 *	75.9 *
Hum_S_2	0.01 m/s	2889	288.9	10.38	23121.2	487.9	2745	274.5
Hum_S_3	0.01 m/s	4323	432.3	12.65	N/A	600.6	3673	367.3
Hum_S_4	0.01 m/s	3462	346.2	10.07	34548.9	566.5	3592	359.2
Hum_F_1	3.00 m/s	1574 *	157.4 *	4.79 *	7656.3	673.7	887 *	88.7 *
Hum_F_2	3.00 m/s	3684	368.4	8.22	14671.9	911.3	3501	350.1
Hum_F_3	3.00 m/s	4773	477.3	10.54	25876.2	959.0	4055	405.5
Hum_F_4	3.00 m/s	4460	446.0	9.67	20691.6	1441.9	4628	462.8

Note: * Designates that the maximum value was not at the time of fracture.

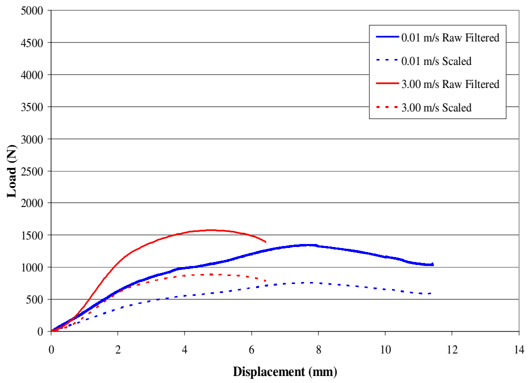

Figure 5. Subject 1 Three-Point Bending Force vs. Deflection
(Raw Filtered and Scaled to 5th Percentile Female).

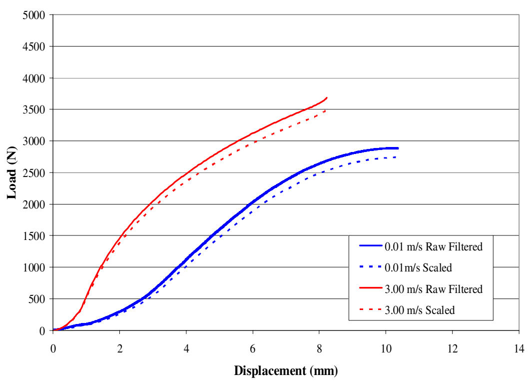

Figure 6. Subject 2 Three-Point Bending Force vs. Deflection
(Raw Filtered and Scaled to 50th Percentile Male).

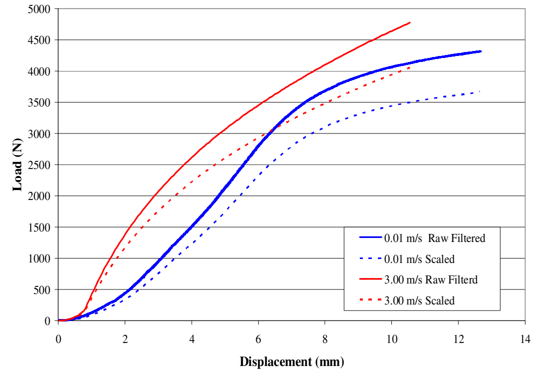

Figure 7. Subject 3 Three-Point Bending Force vs. Deflection
(Raw Filtered and Scaled to 50th Percentile Male).

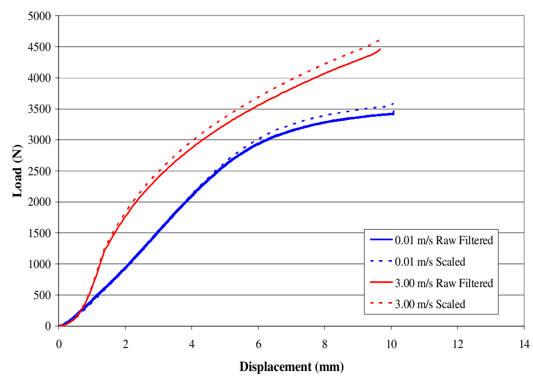

Figure 8. Subject 4 Three-Point Bending Force vs. Deflection
(Raw Filtered and Scaled to 50th Percentile Male).

Part 2: Humerus compression tests

The percent difference in thickness between the horizontal and vertical orientations for all volunteers was found to be 13.5%. In order to compensate for the loss in tissue thickness due to the horizontal testing orientation, the force versus deflection figures for the human humeri tests were shifted by 1.135 times the horizontal thickness measured when the humerus was placed on the test apparatus. The shifted force versus deflection responses of the human humeri for both dynamic compressive loading rates, 2.0 m/s and 4.0 m/s, were plotted along with the responses of the Sid-IIs original and modified dummy arms (Figures 9 and 10).

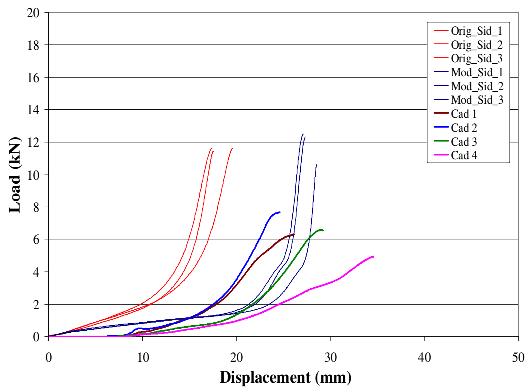

Figure 9. Shifted Dummy and Cadaver 2 m/s Compression Tests.

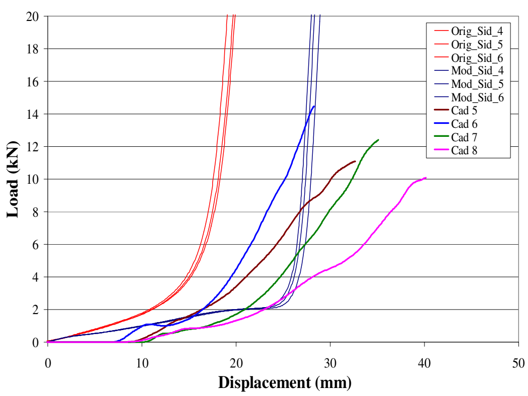

Figure 10. Shifted Dummy and Cadaver 4 m/s Compression Tests.

The shifted force versus deflection responses of the human humeri were then scaled to either the 5th percentile female or the 50th percentile male and plotted along with the responses of the Sid-IIs original and modified dummy arms for both loading rates (Figures 11 and 12).

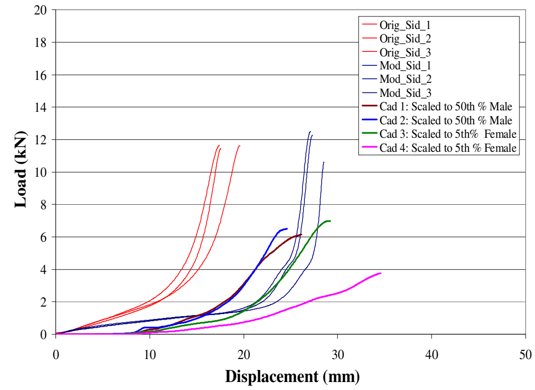

Figure 11. Shifted Dummy and Mass Scaled Cadaver 2 m/s Compression Tests.

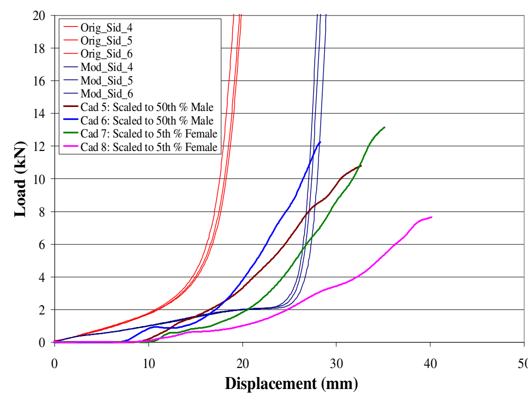

Figure 12. Shifted Dummy and Mass Scaled Cadaver 4 m/s Compression Tests.

CONCLUSIONS

Part 1: Humerus three-point bending tests

The scaled and non-scaled force vs. deflection responses for the 3.0 m/s impact tests both showed an increase in peak force and a decrease in peak deflection from the 0.01 m/s impact tests for all matched pairs. In addition, the male humeri exhibited a higher peak moment and peak strain than the female humeri.

Part 2: Humerus compression tests

The results show that for both impact rates, 2.0 m/s and 4.0 m/s, the modified Sid-IIs dummy arm force vs. deflection compression response is more representative to the scaled and non-scaled human humeri force vs. deflection compression responses than the original Sid-IIs dummy arm. Therefore, it is recommended that the modified SID-IIs upper limb should be used in place of the current SID-IIs upper limb in order to improve the biofidelity of the thoracic measurements of the SID-IIs.

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APPENDICES

Appendix A.
Male Volunteer Arm Thickness Measurements

subject	sex	age	height (m)	mass (kg)	vertical (mm)	horizontal (mm)	compressed (mm)	ver-hor % diff.	ver-com % diff.
1	m	25	1.70	68	80	67	43	19%	46%
2	m	24	1.93	84	80	69	47	16%	41%
3	m	28	1.75	73	76	74	47	3%	38%
4	m	22	1.73	94	93	83	54	12%	42%
5	m	23	1.83	75	75	65	50	15%	33%
6	m	22	1.80	75	77	68	43	13%	44%
7	m	26	1.80	84	91	78	51	17%	44%
8	m	25	1.88	82	78	65	51	20%	35%
9	m	27	1.88	98	87	82	53	6%	39%
10	m	26	1.83	91	84	73	43	15%	49%
11	m	19	1.73	75	95	76	48	25%	49%
12	m	23	1.85	98	86	83	62	4%	28%
13	m	22	1.73	91	91	83	56	10%	38%
14	m	21	1.85	86	86	80	55	8%	36%
15	m	19	1.85	96	92	82	57	12%	38%
16	m	18	1.80	84	87	72	48	21%	45%
17	m	18	1.75	70	83	73	46	14%	45%
18	m	24	1.70	65	77	67	46	15%	40%
19	m	21	1.90	109	92	78	56	18%	39%
20	m	19	1.75	61	69	59	40	17%	42%
21	m	20	1.83	88	86	84	60	2%	30%
22	m	20	1.88	93	89	69	48	29%	46%
23	m	24	1.85	75	74	65	53	14%	28%
24	m	21	1.75	91	87	79	46	10%	47%
25	m	22	1.93	118	88	81	47	9%	47%
26	m	19	1.83	68	67	59	43	14%	36%
27	m	18	1.88	75	76	62	44	23%	42%
28	m	19	1.88	70	68	62	40	10%	41%
29	m	20	1.80	78	92	74	44	24%	52%
30	m	19	1.83	84	86	79	48	9%	44%
31	m	20	1.80	77	75	64	44	17%	41%
32	m	18	1.68	63	69	61	38	13%	45%
33	m	19	1.75	73	76	64	44	19%	42%
34	m	21	1.83	75	76	62	39	23%	49%
35	m	22	1.88	82	88	72	47	22%	47%
male ave.		***21.5***	***1.81***	***82***	***82***	***72***	***48***	***14.7%***	***41.4%***
male std.		***2.8***	***0.07***	***13***	***8***	***8***	***6***	***6.5%***	***5.9%***

Appendix B:
Female Volunteer Arm Thickness Measurements

subject	sex	age	height (m)	mass (kg)	vertical (mm)	horizontal (mm)	compressed (mm)	ver-hor % diff.	ver-com % diff.
1	f	19	1.57	59	69	64	43	8%	38%
2	f	20	1.65	77	80	71	44	13%	45%
3	f	19	1.62	66	78	63	42	24%	46%
4	f	18	1.60	63	76	72	51	6%	33%
5	f	19	1.73	61	66	59	43	12%	35%
6	f	20	1.62	61	73	68	46	7%	37%
7	f	23	1.62	58	72	63	39	14%	46%
8	f	20	1.52	57	80	73	56	10%	30%
9	f	21	1.78	84	88	76	52	16%	41%
10	f	19	1.57	56	72	63	41	14%	43%
11	f	19	1.75	84	84	73	46	15%	45%
12	f	19	1.62	64	71	62	42	15%	41%
13	f	17	1.55	50	71	62	41	15%	42%
14	f	21	1.73	63	66	61	44	8%	33%
15	f	18	1.62	63	71	62	43	15%	39%
16	f	18	1.70	63	74	68	44	9%	41%
17	f	19	1.60	52	66	57	38	16%	42%
18	f	18	1.60	54	64	58	42	10%	34%
19	f	21	1.70	61	72	63	42	14%	42%
20	f	18	1.80	67	74	67	42	10%	43%
21	f	21	1.73	61	68	65	46	5%	32%
22	f	20	1.62	59	64	62	39	3%	39%
23	f	20	1.70	52	62	52	33	19%	47%
24	f	20	1.70	58	64	61	38	5%	41%
25	f	19	1.60	54	70	58	39	21%	44%
26	f	20	1.62	49	66	54	34	22%	48%
27	f	19	1.68	63	74	69	43	7%	42%
28	f	19	1.70	60	71	60	41	18%	42%
29	f	19	1.70	68	72	62	41	16%	43%
30	f	19	1.52	54	72	64	43	13%	40%
31	f	38	1.62	61	73	67	44	9%	40%
32	f	16	1.62	55	69	64	38	8%	45%
33	f	18	1.62	57	68	58	37	17%	46%
34	f	21	1.68	61	69	64	40	8%	42%
35	f	21	1.68	61	76	69	47	10%	38%
female ave.		***19.9***	***1.65***	***61***	***72***	***64***	***42***	***12.3%***	***40.7%***
female std.		***3.4***	***0.07***	***8***	***6***	***5***	***5***	***5.1%***	***4.5%***