DEVELOPMENT OF BIOFIDELIC UPPER ARM FOR SID-IIS AND IMPROVEMENT OF THORACIC BIOFIDELITY WITH THIS ARM

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ABSTRACT

Side impacts present a severe collision mode from the perspective of occupant protection because there are relatively few vehicle structural components (such as a center pillar and door) and relatively little vehicle crush space exist. In recent years, technology has advanced including enhanced body structural integrity, torso air bags and curtain air bags. Further advances in these technologies are anticipated in the future. A dummy with excellent biofidelity is indispensable for such advanced technical development, and it is reported that the recently developed SID-IIs, exhibits better biofidelity compared with previous side impact dummies ES-1 and DOTSID.

However, when considering the compression characteristic of the upper arm of SID-IIs, it was found that the stiffness is excessively high compared with post mortem human surrogate (PMHS) data. It is thought that this characteristic can have considerable influence on thoracic rib deflection in side impacts because the upper arm transmits force from the door and/or the side airbag to the thorax.

In this study, a new upper arm component for SID-IIs has been developed to provide a better interaction with the thorax rib. According to the ISO guideline of side impact biofidelity evaluation, a series of tests with the new arm were conducted on the dummy.

It was shown that the biofidelity of the dummy with the modified arm, especially its thoracic responses, was improved by replacing the original arm with the newly developed one.

INTRODUCTION

Side impacts are a severe type of collision from the perspective of occupant protection. This is partially due to the fact that in the event of a side impact there are few vehicle structures for absorbing the energy from a side impact and little vehicle crush space in the event of a side impact as compared to other types of collisions.

Side impact tests are generally performed using a moveable deformable barrier (MDB) representing a passenger vehicle, which collide with a vehicle. In order to promote higher degree of occupant protection performance, an impact test using an MDB corresponding to an SUV is used for impact testing. A test method in which the side of a vehicle collides with a fixed pole-shaped object was also developed and put into practice.

Occupant protection technologies have also progressed in recent years, which can be seen by the application of technologies including vehicle structures with superior integrity, as well as curtain and torso side airbags. Further advances in these technologies are anticipated from these technologies in the future. In order to evaluate such new occupant protection technologies, a dummy with high biofidelity and injury measuring capabilities is essential.

The SID-IIs is a side impact dummy representative of a small human female. Development began in 1993 by the Occupant Safety Research Partnership (OSRP) with the intent of adding a high biofidelity dummy representative of small females. In 1995, the dummy was completed, and the structure and characteristics were announced [1]. The biofidelity of the SID-IIs was also evaluated by OSRP, which reported results showing superior biofidelity to other side impact dummies [2]. The evaluation method with target corridors for the biofidelity of side impact dummies is set forth in ISO 9790[3]. However, ISO 9790 defines corridors for the 50th percentile adult male (AM50), not a small female. Thus, a scaled corridor was used by OSRP to evaluate the SID-IIs. The results show a high score of 7.01 out of a total 10 possible points.

Furthermore, ISO 9790 includes biofidelity corridors regarding the head, neck, shoulders, thorax, abdomen, and pelvis. Although ISO 9790 covers most main parts of the body, it is still lacking on some points.

For example, observations of collisions between the dummy and the interior during side impacts and the constraint posture resulting from the side impact airbag often showed the arms sandwiched between the chest and the door or the airbag. Based on these observations, it is reasonable to assume that arm characteristics influence both the dummy reaction force to the vehicle and dummy internal response. However, current biofidelity evaluations do not define characteristics of the arm itself, and no framework exists for defining the influence of arms from the two aspects mentioned above. Therefore, studying arm characteristics and their influence is considered essential to developing a dummy with higher biofidelity.

According to the literature of SID-IIs development [1], the structure and characteristics of the shoulder and arm of the SID-IIs are summarized as the following.

The shoulder is structured for lateral displacement, and the attached arm takes on a rounder shape than BIOSID with a higher stiffness than EuroSID-1. The arm length is 7 mm shorter than that of the AF05 Hybrid-III dummy, so as not to provoke deformation of the abdominal ribs. A pad corresponding to the height of the upper arm shoulder is used to control the initial impact pulse. The shoulder characteristics target a corridor that scales from the characteristics in ISO 9790.

It is not clear in the description whether the shape and characteristics of the arm itself were compared to an actual human arm.

Research regarding arm characteristics often focus on tolerance and characteristics such as three-point bending. However, there is little research on the lateral compression characteristic of the arm. Kanno (1993) has performed a study to obtain the lateral compression characteristic of the arm [4]. The study used an impactor with 152 mm diameter, 16 kg mass, and speeds of 2 and 4 m/s to impact two PMHS arms, respectively (Figure 1). Fixed to a flat plate, the circumference of these arms was 32cm. The arm's compression characteristic from the 4m/s test is shown (Figure2).

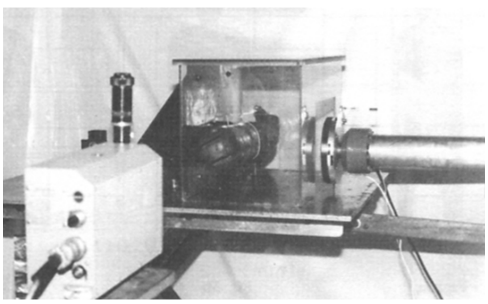

Figure 1. A dummy arm in pre-impact test position, actual tests unembalmed PMHS arms were used [4].

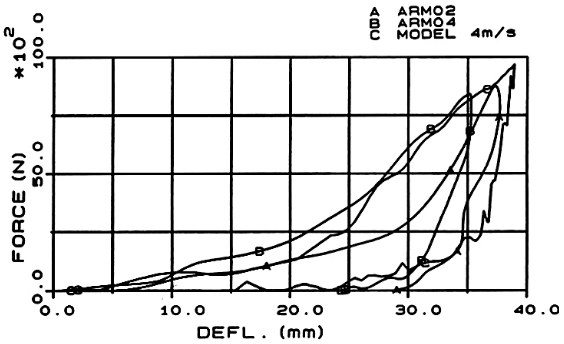

Figure 2. Force-deflection curves of PMHS arms (ARM02, ARM04) for 4m/s pendulum impacts [4].

Recently, anther research was conducted at Virginia Tech by Kemper et al (2005) to evaluate the compressive response of human humeri with soft tissue [5]. These compression tests were also performed at 2.0m/s and 4.0m/s loading rates on 4 whole unembalmed fresh human humeri obtained from 2 matched pairs (Table 1) using a drop tower with a 16 kg impactor (Figure 3). The ends of the humeri were constrained in order to prevent the human humeri from rotating or translating during the impact event (Figure 3). The arm was placed on the support with a 152mm diameter and impacted. The arm's characteristics are shown (Figure 4).

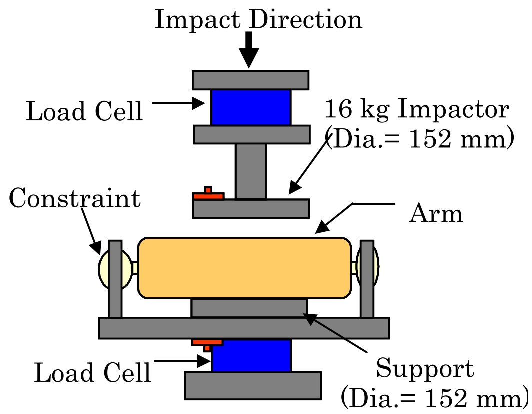

Figure 3. Humerus compression loading test setup (Front View).

Upon comparing the arm characteristics of SID-IIs under similar conditions, it was found that the arm of SID-IIs differed from that of the human (Figure 4).

In light of the above background, this paper explores improvements of the upper arm biofidelity and their influence on the dummy response for SID-IIs. The content of this paper focuses on the following three points: (1) development of an upper arm with excellent biofidelity for use in the SID-IIs; (2) verification of the biofidelity of the SID-IIs dummy in which this arm is used, and (3) determination of the influence on measured dummy injury values when using this arm.

Table 1. PMHS upper arm data for arm compressive tests [5].

Tests ID#	Test Speed (m/s)	Subject Number	Mass (kg)	Height (cm)	Breadth (mm)	Humerus Circumference with soft tissue (cm)
Arm 1	2.00	A	44.81	152.4	55.56	24.13
Arm 2	2.00	B	74.09	160.02	63.5	24.77
Arm 3	4.00	A	44.81	152.4	60.33	24.13
Arm 4	4.00	B	74.09	160.02	58.74	27.31

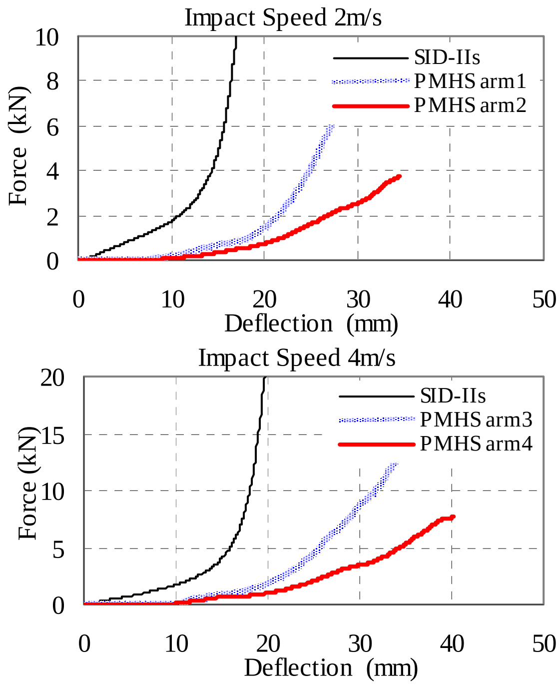

Figure 4. Comparison of Arm Force-deflection Curves Between PMHS and Dummies.

ARM DEVELOPMENT

Arm Design Targets and Test Method

The following items were used as design requirements for the upper arm of the SID-IIs.

<u>Dummy Exterior Shape</u>

The shoulder width dimension of the dummy was not changed.

<u>Human Body Dimensions and Mass</u>

Targets for arm thickness, width, length, and mass were set based upon data for the AF05's upper arm from UMTRI [6] (Table 2).

<u>Upper Arm Lateral Compression Characteristic</u>

The upper arm lateral compression characteristic of dummy was compared to that obtained from the PMHS test performed by Kemper et al. (2005).

Table 2. Dimensions and Mass of SID-IIs and Human Arms (AF05).

Arm	Mass (kg)	Breadth (mm)	Depth (mm)
SID-IIs	0.89	56	74
Human	1.12	67	89

Arm Development and Arm Biofidelity Test (Upper Arm Lateral Compression Characteristic) Results

<u>Upper Arm Shape and Mass</u>

The major and minor axes of the elliptical cross section of the arm were matched to human dimensions (UMTRI). However, 9 mm were eliminated from the inner side of the arm. This is because the arm contacts the thorax rib and will not rest alongside the chest when the breadth (minor axis) is set to 67 mm without modifying the shoulder width (Table 3).

Table 3. Improved Arm Dimension and Mass.

Arm	Mass (kg)	Breadth (mm)	Depth (mm)
UMTRI	1.12	67	89
Modified	1.06	58	89
Original	0.89	56	74

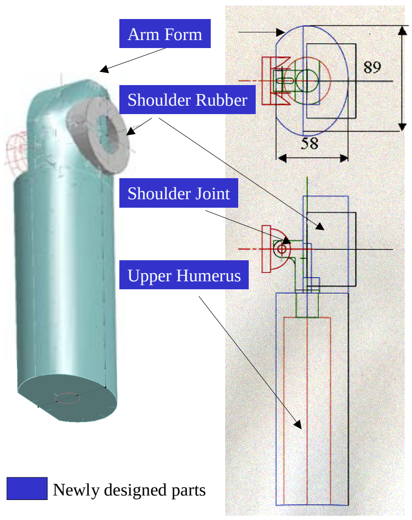

Figure 5. Modified SID-IIs Arm.

The cross section of the steel, representing bone, has a circular shape, and the position of the shoulder joint was displaced outward in order to set the bone at the center of the arm. In order for the arm mass to correspond to that of a human body (UMTRI AF05), the diameter of the steel bone was adjusted (Figure 5).

Selection of Arm Foam Materials

Of the three types of EPDM (ethylene-propylene rubber) arms with different compression characteristics the arm (Modified A) had a compression characteristic closest to the target characteristic was selected (Figure 6). As a result, an arm was developed with characteristics more closely resembling those in a human body than the characteristics of the arm prior to modification.

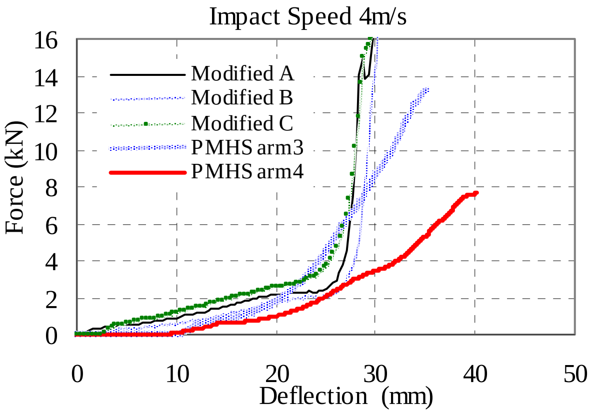

Figure 6. Force-Deflection Responses of Target and EPDM Arm.

DUMMY BIOFIDELITY EVALUATION

Dummy Biofidelity Evaluation Method

Biofidelity tests were performed mainly for the purpose of evaluating the influence of the new arm development on dummy response.

The evaluation method was based on the test method set forth in ISO 9790: 1990 (E) [3], which is employed as a general test method of side impact dummy biofidelity.

However, the small female (AF05) corridor necessary for evaluation is not given in ISO 9790[3]. Therefore, corridors scaled to the AF05 were developed [2] based upon ISO 9790.

Among the ISO test methods, those tests for the neck, shoulder and thorax, which are considered to be most affected by modifications of the arm, were performed. However, the tests listed below were not conducted because the results are unlikely affected by the arm modifications.

Thorax Tests 1, 2: The test method consists of setting the arm at a 90-degree angle to the thorax and hitting the thorax with a pendulum. Therefore, the arm modifications would have no influence on the results.

Thorax Test 4: The special pad defined for use in this test cannot be obtained at present, thus the test could not be performed.

The tests performed and not performed are shown (Table 4).

Table 4 Biofidelity Test Matrix

Requirement		Test Description	Tested
Neck	Test 1	7.2G Sled Impact	Done
	Test 2	6.7G Sled Impact	Done
	Test 3	12.2G Sled Impact	Done
Shoulder	Test 1	4.5m/s Pendulum	Done
	Test 2	7.2G Sled Impact	Done
	Test 3	12.2G Sled Impact	Done
	Test 4	8.9m/s Padded WSU Sled	Done
Thorax	Test 1	4.3m/s Pendulum	Not tested
	Test 2	6.7m/s Pendulum	Not tested
	Test 3	1.0m Rigid Drop	Done
	Test 4	2.0mPaddeddrop	Not tested
	Test 5	6.8m/s Rigid Heidelberg Sled	Done
	Test 6	8.9m/s Padded WSU Sled	Done

Neck Biofidelity Tests

Neck Test 1

Method

The dummy was placed on a seat fixed perpendicular to the thrusting direction of the sled so that the dummy's neck is vertical. The dummy was restrained by two wooden plates to suppress rotation of the arms and thorax, the shoulders and pelvis were restrained by belts. The upper ends of the plates were 50 mm below the top of the shoulders. The following items were evaluated: T1 acceleration (y-direction), relative movement of T1 with respect to the sled (y-direction), relative movement of head center of gravity position with respect to T1 (y- and z-directions), time of maximum movement of head center of gravity position, head center of gravity acceleration (y- and z-directions), neck lateral bending angle, and neck torsion angle.

Results

The sled speed was 6.83m/s with the maximum acceleration of 6.8G inside of the corridor. The individual data and biofidelity score for this test are shown (Table A1 and A2). Other than the maximum horizontal displacement of the T1 rib, there are no substantial differences between the current arm and modified arm. Modified arm biofidelity is 7.4, and exceeds 7.15 of current arm in Test 1.

<u>Neck Test 2</u>

Method

A rigid seat, with its back inclined 15 degrees, was fixed perpendicular to the thrusting direction of the sled. A plate was fixed perpendicular to side surface of the seat, and the dummy was placed in the seat with its thorax and lumbar region contacting this plate. The upper end of the plate was 50 mm below the top of the shoulder.

A thorax cross belt, waist belt and horizontal thorax belt were also used for restraint. The following items were evaluated: neck lateral bending angle, neck lateral bending moment, neck anteflexio moment, neck torsional moment, neck lateral shearing load, neck longitudinal shearing load, and head composite acceleration.

Results

The sled speed was 5.79m/s and peak acceleration was 6.92G. The individual data and biofidelity score are shown (Table A3, A4 and Figure A1). There is a difference between the current and modified arms under tensile load. The biofidelity score of current arm is 3.99, and exceeds the score of 3.53 of modified arm.

<u>Neck Test 3</u>

Method

The dummy was restrained by two wooden plates to suppress rotation of arms and thorax. Belts were used to restrain the shoulders and pelvis. The following items were evaluated: T1 acceleration (y-direction), head center of gravity acceleration (y-direction), relative movement of head center of gravity position with respect to T1 (y-direction), neck lateral bending angle, and neck torsion angle.

Results

The sled decelerated at 7.0 m/s; its maximum deceleration was 11.44G within the corridor. The individual data and biofidelity score for this test are shown (Table A5, A6 and Figure A2). There are some differences between the current and modified arms for horizontal acceleration and transversal deflection angle of T1 rib. The biofidelity score of modified arm is 5.34, which exceeds the score of 5.26 of current arm.

Shoulder Biofidelity Tests

<u>Shoulder Test1</u>

Method

A 150 mm diameter pendulum weighing 14 kg was targeted to impact the shoulder at 4.5 m/s, with the dummy arm in a resting state (down). The pendulum load and maximum displacement of the dummy shoulder rib were evaluated.

Results

For pendulum load, neither the SID-IIs current arm nor the modified arm fell into the standard corridor. The biofidelity score for both arms was 5 points.

Regarding the maximum displacement of the shoulder rib in a corridor of 22 to 30 mm, both the current arm and modified arm received no points. According to the biofidelity formula defined by ISO, they scored 5.0 points. The test results and scores are shown (Table A7, A8 and Figure A3).

<u>Shoulder test 2</u>

Method

Test method was similar to that of Neck Tests 1. T1 acceleration (y-direction) and relative movement of T1 with respect to the sled (y-direction) were evaluated.

Results

The individual data and biofidelity score are shown (Table A9 and A10). The biofidelity point of modified arm is 7.5, which is higher than 6.25 of current arm.

<u>Shoulder test 3</u>

Method

Test method was similar to that of Neck Tests 3. T1 acceleration (y-direction) was evaluated.

Results

The individual data and biofidelity score are shown (Table A11 and A12). The Biofidelity Point of current arm is 10.0, which is higher than 5.0 of modified arm.

<u>Shoulder Test 4</u>

Method

This was a padded Wayne State University (WSU) sled test performed at 8.9 m/s. The test setup is shown (Figure 7). The seat and seat back are Teflon-coated so that there is no effect on the dummy due to friction during sled motion. A load meter for the impact surface was fixed perpendicular to the sled direction. Regarding the dummy posture, the sagittal plane was set upright and the arm angle was inclined 45 degrees forward of the thorax. The sum of shoulder and thorax loads was evaluated.

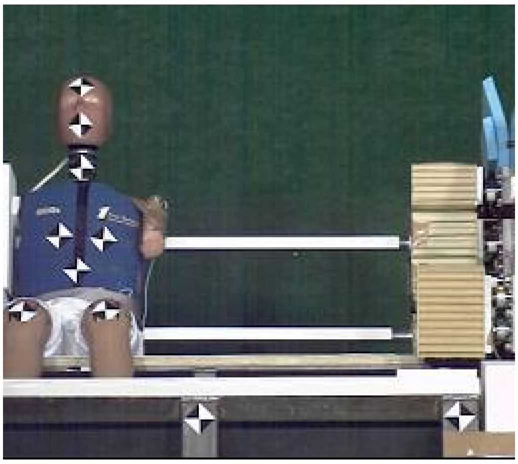

Figure 7. Shoulder and thorax test jig.

Results

For the sum of the shoulder and thorax loads, both the current and the modified arm received a biofidelity score of 5.0 points. In addition, evaluation of T12 movement was eliminated from the judgment factors because the human body corridor was not deemed reliable enough. According to the biofidelity formula defined by ISO, therefore both arms scored 5.0 points. The test results and overall scores are shown (Table A13, A14 and Figure A4).

Thorax Biofidelity Tests

<u>Thorax Test 3</u>

Method

The dummy was faced sideways and hung in a horizontal position, and the arm angle was inclined 20 degrees from the spine toward the front of the dummy. With this orientation, the dummy was dropped in free fall from a height 1.0 m above a rigid plate (impact surface). In this test, the load on the thorax rigid plate and maximum displacement of the thorax upper rib were evaluated.

Results

For the thorax plate load, both the current arm and modified arm were within ±1 corridor, thus receiving a biofidelity score of 5 points. However, for the maximum displacement of the thorax upper rib, the current arm received 2.5 points from 2 out of 3 test results, whereas the modified arm received 5 points. According to the biofidelity formula defined by ISO, the current arm scored 5.0 points for an overall evaluation of “marginal”, and the modified arm scored 5.0 points. Test results and overall scores are shown (Table A15, A16, A22 and Figure A5).

<u>Thorax Test 5</u>

Method

The test was performed in a similar format to the testing that was carried out at Heidelberg University (HU). A rigid plate was used as the impact surface at 6.8 m/s. The setup was similar to Shoulder Test 4 (Figure 7). The arm is at rest (down) in the test. The distance from the dummy to the impact surface was set to 0.35m. The following items were evaluated: shoulder/thorax plate load, T1 maximum acceleration, T12 maximum acceleration, and maximum acceleration of the thorax upper rib.

Results

Both the current and modified arm received 10 points with respect to the shoulder/thorax plate load. T1 (lateral direction) maximum acceleration responses in the lateral direction were within –1 corridor. Similar to T1, both arms received 0 points for T12 maximum acceleration responses in the lateral direction. For maximum acceleration in the lateral direction of the thorax upper rib, the current arm received 5.0 points, while the modified arm received 10.0 points. According to the biofidelity formula defined by ISO of one out of three tests, the current arm scored 3.75 points, and the modified arm scored 4.11 points. The test results and overall scores are shown (Table A17 and A18).

<u>Thorax Test 6</u>

Method

The test method was similar to that of Shoulder Tests 4. The sum of the shoulder and thorax plate force was evaluated.

Results

The individual data and biofidelity score for Thorax Test 6 are shown (Table A19, A20 and Figure A6). The biofidelity score of the current arm is 5.0 points, which is equal to that of the modified arm.

Biofidelity Evaluation Scores

Biofidelity scores based upon biofidelity tests with the current arm and modified arm are summarized (Table A21). The scores for the current arm regarding each measurement item and each test are compared with those of the modified arm. These results show that the modified arm leads to an increased score in Neck Tests 1, 3, Shoulder Test 2 and Thorax Tests 3, 5, and a reduced score in Neck Test 2 and Shoulder Test 3.

Summary of Biofidelity Evaluation

Some biofidelity tests were not performed because the results would not be affected by the arm modifications.

Due to the arm modifications, the thorax score increased, although the shoulder score decreased. The class designation by level was "good" for the thorax, while the shoulder and neck remained unchanged with a "fair" evaluation.

INFLUENCE ON INJURY VALUES ASSOCIATED WITH ARM MODIFICATION

In order to determine how dummy injury values (ex. Thorax rib deflection) changed, the biofidelity test analysis and full scale SUV MDB side impact tests were conducted.

Comparison of Thorax Injury Values in Biofidelity Tests

In the thorax biofidelity test 3, middle rib deflection and thorax plate force are the items used to evaluate biofidelity. However, in this test, thorax deflection and abdomen deflection were measured to determine the extent of the influence arm modifications have on injury values for the thorax and abdomen.

Results of Analysis on Biofidelity Test

The shoulder, abdomen and thorax injury values of SID-IIs in biofidelity test are shown (Figure 8).

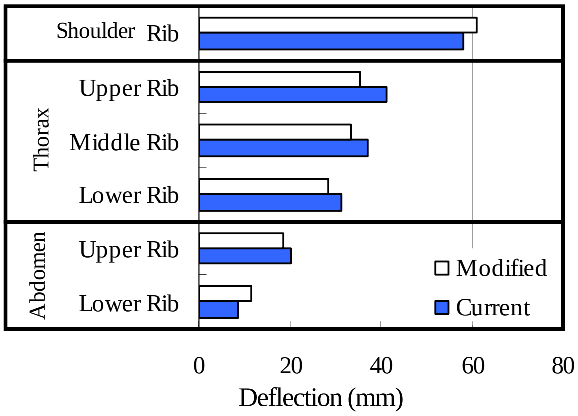

Figure 8. Dummy Injury Measurements in Biofidelity Thorax Test 3.

In the thorax biofidelity test 3 results, shoulder deflection increased. However, there was no significant change in plate force (Fig A5).

Furthermore, thorax deflection was reduced in the case of the modified arm.

Full Scale SUV MDB Side Impact Test

In order to investigate how dummy injury values change due to the modifications of the SID-IIs arm, the dummy was evaluated in SUV MDB impacts to the side of a vehicle at 50 km/h performed by IIHS. The vehicle was a sedan sold in the U.S. market, which was equipped with curtain airbags in the front and rear seats, and side torso airbags in the front seats. SID-IIs dummies were placed in the front and rear seats on the impact side. The front seats were equipped with side airbags. The rear seats were not equipped with side torso airbags.

For comparison purposes, the test was performed twice: dummies having current arms were placed in one vehicle, and dummies with the modified arms were placed in the other vehicle.

Result s of Full Scale SUV Side Impact

The front seats were equipped with side airbags. Thorax and abdomen deflection of the dummy are shown (Figure 9).

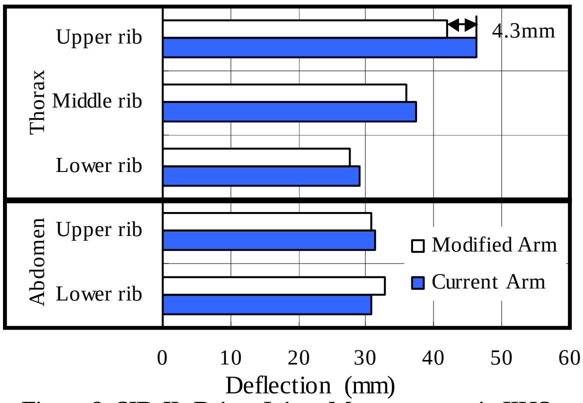

Figure 9. SID-IIs Driver Injury Measurements in IIHS SUV MDB Side Impact.

Compared to the current arm, the modified arm of the dummy in the driver position showed a decrease of 4.3mm in deflection of the thorax upper rib. Other thorax ribs showed approximately the same values.

The rear seats were not equipped with side torso airbags. Deflection of thorax and abdomen ribs of the dummy in the rear seat is shown (Figure 10).

Compared to the current arm, the modified arm of the dummy in the rear passenger position showed a 13.5mm decrease in thorax upper rib deflection, and a 7.6mm decrease in thorax middle rib deflection. There was no significant change in results for the abdomen. A comparison of the upper rib G waveforms in the impact is shown (Figure 11).

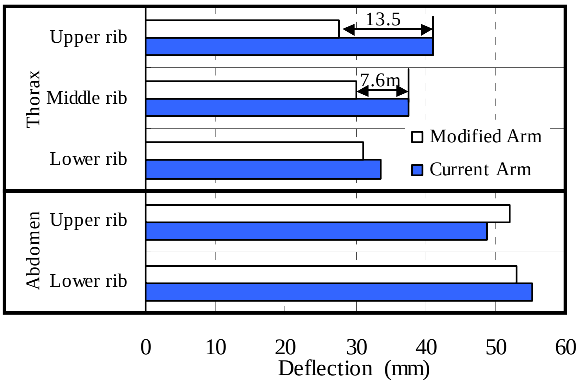

Figure 10. SID-IIs Rear Passenger Injury Measurements in IIHS SUV MDB Side Impact

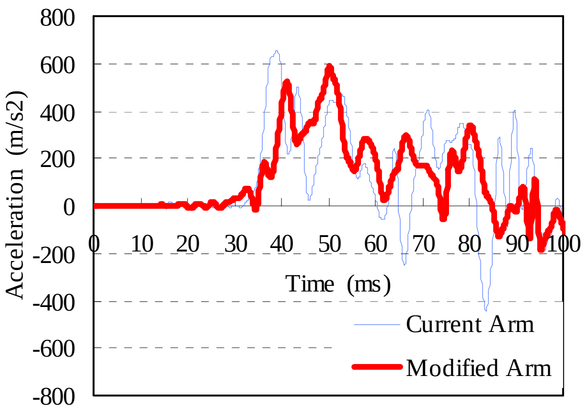

Figure 11. Rear Passenger Upper Rib Acceleration Response

DISCUSSION

Influence on Dummy Biofidelity

Biofidelity tests were performed in all conditions believed to be affected by modifications made to the arm. These results and the evaluation scores for all items are defined in ISO 9790

The results show a slight improvement in biofidelity due to the arm modifications without leading to deterioration in the overall biofidelity of the SID-IIs. The modifications are considered beneficial.

Influence of Arm Modifications on Thorax Injury Evaluation

By comparing thorax injury values in Thorax Test 3, shoulder deflection increased while thorax rib deflection decreased in the case of modified arm. However, there was no significant change in the impact load.

The decrease of thorax rib deflection is the result of softening arm skin characteristic, which led to a smaller reaction force from the thorax rib on the arm inner side and further deformation of the shoulder rib. A small reaction force from the rib on the arm means that the force of the arm pressing on the rib is also small, thus reducing thorax deflection.

Vehicle full-scale test results showed some differences between the current and modified arms in the front seat at which side airbags deployed. Compared to the current arm, the modified arm showed a slight decrease in deflection of the thorax upper rib. Other thorax ribs showed approximately the same values.

Furthermore, a notable difference was observed in the rear seat where airbags were not equipped. Compared to the current arm, the modified arm showed a significant decrease in thorax upper rib deflection, and also a decrease in thorax middle rib deflection. There was no significant change in results for the abdomen.

Accordingly, since the characteristic of the current arm is harder than a human arm, it appears that the thorax deflection value may be excessive in cases where the current arm and thorax rib come into contact.

CONCLUSIONS

1. The current SID-IIs arm does not accurately represent the human body in terms of compression characteristics, dimension, and mass. Thus, a modified SID-IIs arm was developed to more closely simulate these properties.
2. According to a series of tests, thorax biofidelity improved through the use of this modified arm. Although the shoulder became slightly worse, the overall biofidelity of the SID-IIs improved.
3. In cases where the arm came into contact with the thorax during a side impact, it was found that arm characteristics influence the thorax injury values. For this reason, dummy arm characteristics need to more closely represent a human arm.
4. The following were observed in full-scale vehicle tests, (IIHS SUV 50 km/h side impact test):

4-1. No unique phenomena due to arm modifications were found.

4-2. Small differences exist in thorax deflection due to arm modifications in driver seat, which was equipped with a torso airbag.

4-3. Large differences in thorax deflection exist due to arm modifications in rear seat without torso airbag.

5. The modified arm increases the ability of the SID-IIs to accurately predict injury during side impact events.

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ATTACHMENT

ISO 9790: 1990 Biofidelity Evaluation Results

The corridor used in the attachment is from SAE paper 983151.

Table A1: Neck Test 1 Current Arm Results (7.2G Sled)

7.2G Sled Weight factor $V_{2,1}$=7	Weight Factors $W_{2,1,k}$		Corridor		Current arm Results						Avg of Rating $R_{2,1,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
Hori. Acc. of T1(g)	$W_{2,1,1}$	5	10	15	9.0	5	8.8	5			5	7.15
Hori. Disp. of T1 Relative to Sled (mm)	$W_{2,1,2}$	5	38	51	36.9	5	38.3	10			7.5	
Hori. Disp. of Head C.G. Relative to T1(mm)	$W_{2,1,3}$	8	106	132	121.9	10	122.6	10			10	
Vert. Disp. of Head C.G .Relative to T1(mm)	$W_{2,1,4}$	6	63	96	48.2	5	51.2	5			5	
Head Excursion Time (s)	$W_{2,1,5}$	5	0.151	0.166	0.191	0	0.193	0			0	
Lat. Acc. of Head(g)	$W_{2,1,6}$	5	7	9	9.4	5	9.6	5			5	
Vert. (Downward) Acc. of Head (g)	$W_{2,1,7}$	5	7	8	7.5	10	7.6	10			10	
Flexion Angle(degrees)	$W_{2,1,8}$	7	48	65	53.3	10	54.3	10			10	
Twist Angle(degrees)	$W_{2,1,9}$	4	-45	-32	-36.3	10	-38.3	10			10	

Table A2: Neck Test 1 Modified Arm Results (7.2G Sled)

7.2G Sled Weight factor $V_{2,1}$=7	Weight Factors $W_{2,1,k}$		Corridor		Modified arm Results						Avg of Rating $R_{2,1,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
Hori. Acc. of T1(g)	$W_{2,1,1}$	5	10	15	9.7	5	9.7	5	9.7	5	5	7.4
Hori. Disp. of T1 Relative to Sled(mm)	$W_{2,1,2}$	5	38	51	43.0	10	42.9	10	41.8	10	10	
Hori. Disp. Of Head C.G. Relative to T1 (mm)	$W_{2,1,3}$	8	106	132	126.6	10	123.8	10	123.9	10	10	
Vert. Disp. of Head C.G. Relative to T1 (mm)	$W_{2,1,4}$	6	63	96	54.6	5	56.2	5	54.5	5	5	
Head Excursion Time (s)	$W_{2,1,5}$	5	0.151	0.166	0.195	0	0.193	0	0.194	0	0	
Lat. Acc. of Head(g)	$W_{2,1,6}$	5	7	9	10.1	5	10.1	5	10.0	5	5	
Vert. (Downward) Acc. of Head (g)	$W_{2,1,7}$	5	7	8	7.7	10	7.7	10	7.7	10	10	
Flexion Angle(degrees)	$W_{2,1,8}$	7	48	65	55.9	10	56.0	10	56.0	10	10	
Twist Angle(degrees)	$W_{2,1,9}$	4	-45	-32	-39.2	10	-38.5	10	-38.7	10	10	

Table A3: Neck Test 2 Current Arm Results (6.7G Sled)

6.7G Sled Weight factor $V_{2,2}$=6	Weight Factors $W_{2,2,k}$		Corridor		Current arm Results						Avg of Rating $R_{2,2,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
Flexion Angle (degrees)	$W_{2,2,1}$	7	44	55	51.6	10	54.7	10			10	3.99
Bending Moment of A-P Axis at O. C. (Nm) Mx	$W_{2,2,2}$	7	22	27	17.3	5	18	5			5	
Bending Moment of R-L Axis at O. C. (Nm) My	$W_{2,2,3}$	3	11	16	3.3	0	3.6	0			0	
Twist Moment (Nm) Mz	$W_{2,2,4}$	4	8	11	7.3	5	7	5			5	
Shear Force at O. C. (N)	$W_{2,2,5}$	7	500	567	353	0	351	0			0	
Tension Force at O.C.(N)	$W_{2,2,6}$	3	233	267	287	5	325	0			2.5	
P-A Shear Force (N)	$W_{2,2,7}$	4	217	250	79.2	0	84.7	0			0	
Resultant Head Acc.(g)	$W_{2,2,8}$	7	15	20	12.8	5	12.5	5			5	

Table A4: Neck Test 2 Modified Arm Results (6.7G Sled)

6.7G Sled Weight factor $V_{2,2}=6$	Weight Factors $W_{2,2,k}$		Corridor Lower Bound	Corridor Upper Bound	Modified arm Results Run 1	Rating	Run 2	Rating	Run 3	Rating	Avg of Rating $R_{2,2,k}$	Test Rating
Flexion Angle (degrees)	$W_{2,2,1}$	7	44	55	54.3	10	50.5	10	54.5	10	10.0	3.53
Bending Moment of A-P Axis at O. C. (Nm) Mx	$W_{2,2,2}$	7	22	27	16.6	0	15.7	0	18	5	1.7	
Bending Moment of R-L Axis at O. C. (Nm) My	$W_{2,2,3}$	3	11	16	3.8	0	4.3	0	3.6	0	0.0	
Twist Moment (Nm) Mz	$W_{2,2,4}$	4	8	11	7.6	5	8.7	10	7.5	5	6.7	
Shear Force at O.C.(N)	$W_{2,2,5}$	7	500	567	359	0	359	0	362	0	0.0	
Tension Force at O.C.(N)	$W_{2,2,6}$	3	233	267	307	0	290	5	355	0	1.7	
P-A Shear Force (N)	$W_{2,2,7}$	4	217	250	77.1	0	81	0	80.5	0	0.0	
Resultant Head Acc.(g)	$W_{2,2,8}$	7	15	20	12.7	5	12.8	5	13.1	5	5.0	

Table A5: Neck Test 3 Current Arm Results (12.2G Sled)

12.2G Sled Weight factor $V_{2,3}=3$	Weight Factors $W_{2,3,k}$		Corridor Lower Bound	Corridor Upper Bound	Current arm Results Run 1	Rating	Run 2	Rating	Run 3	Rating	Avg of Rating $R_{2,3,k}$	Test Rating
Lat. Acc. of T1(g)	$W_{2,3,1}$	5	14	19	18.8	10	18.5	10			10	5.26
Lat. Acc. of Head C.G.(g)	$W_{2,3,2}$	5	21	39	12.8	0	13	0			0	
Hori. Disp. of Head C.G. Relative to Sled (mm)	$W_{2,3,3}$	8	151	185	191	5	195	5			5	
Flexion Angle(degrees)	$W_{2,3,4}$	7	68	82	66	5	72.17	10			7.5	
Twist Angle (degrees)	$W_{2,3,5}$	4	62	75	48.52	0	51.23	5			2.5	

Table A6: Neck Test 3 Modified Arm Results (12.2G Sled)

12.2G Sled Weight factor $V_{2,3}=3$	Weight Factors $W_{2,3,k}$		Corridor Lower Bound	Corridor Upper Bound	Modified arm Results Run 1	Rating	Run 2	Rating	Run 3	Rating	Avg of Rating $R_{2,3,k}$	Test Rating
Lat. Acc. of T1(g)	$W_{2,3,1}$	5	14	19	19.7	5	20.9	5	19.5	5	5	5.34
Lat. Acc. of Head C.G.(g)	$W_{2,3,2}$	5	21	39	13.5	0	13.8	0	13.3	0	0	
Hori. Disp. of Head C.G. Relative to Sled (mm)	$W_{2,3,3}$	8	151	185	201	5	206	5	206	5	5	
Flexion Angle(degrees)	$W_{2,3,4}$	7	68	82	75.4	10	76.7	10	75.8	10	10	
Twist Angle (degrees)	$W_{2,3,5}$	4	62	75	53.77	5	54.12	5	53.40	5	5	

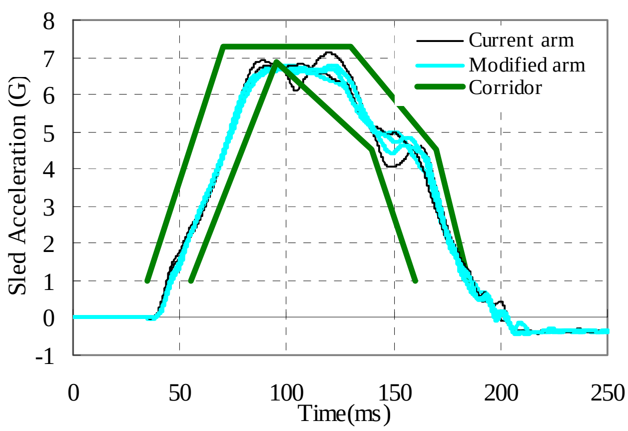

Figure A1. Sled Acceleration of Neck Test 1

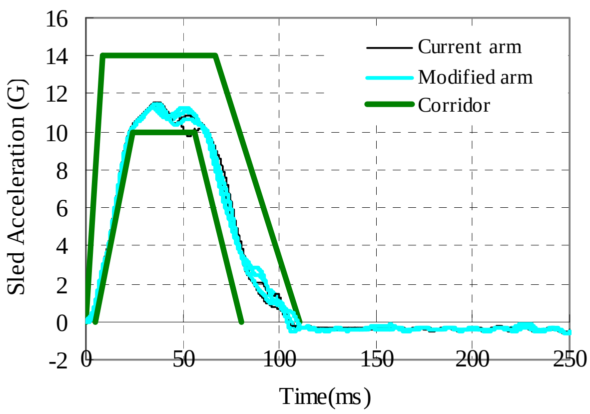

Figure A2. Sled Acceleration of Neck Test 3

Table A7: Shoulder Test 1 Current Arm Results (4.5m/s Pendulum Impact)

4.5m/s Pendulum Impact Weight Factor $V_{3,1}$=6	Weight Factors $W_{3,1,k}$		Corridor		Current arm Results						Avg of Rating $R_{3,1,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
Pendulum Force(N)	$W_{3,2,1}$	8	FigureA3			5		5		5	5	5.00
Shoulder Deflection(mm)	$W_{3,2,2}$	6	22	30	36.7	5	36.7	5	36.4	5	5	

Table A8: Shoulder Test 1 Modified Arm Results (4.5m/s Pendulum Impact)

4.5m/s Pendulum Impact Weight Factor $V_{3,1}$=6	Weight Factors $W_{3,1,k}$		Corridor		Modified arm Results						Avg of Rating $R_{3,1,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
Pendulum Force(N)	$W_{3,2,1}$	8	FigureA3			5		5		5	5	5.00
Shoulder Deflection(mm)	$W_{3,2,2}$	6	22	30	37.2	5	37.9	5	36.7	5	5	

Table A9: Shoulder Test 2 Current Arm Results (7.2G Sled)

7.2G Sled Weight factor $V_{3,2}$=5	Weight Factors $W_{3,2,k}$		Corridor		Current arm Results						Avg of Rating $R_{3,2,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
T1 Horiz. Acc. (g)	$W_{3,2,1}$	6	10	15	9.0	5	8.8	5			5	6.25
T1 Horiz. Disp. Relative to Sled (mm)	$W_{3,2,2}$	6	38	51	36.9	5	38.3	10			7.5	

Table A10: Shoulder Test 2 Modified Arm Results (7.2G Sled)

7.2G Sled Weight factor $V_{3,2}$=5	Weight Factors $W_{3,2,k}$		Corridor		Modified arm Results						Avg of Rating $R_{3,2,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
T1 Horiz. Acc. (g)	$W_{3,2,1}$	6	10	15	9.7	5	9.7	5	9.7	5	5	7.50
T1 Horiz. Disp. Relative to Sled (mm)	$W_{3,2,2}$	6	38	51	43.0	10	42.9	10	41.8	10	10	

Table A11: Shoulder Test 3 Current Arm Results (12.2G Sled)

12.2G Sled Weight factor $V_{3,3}$=3	Weight Factors $W_{3,3,k}$		Corridor		Current arm Results						Avg of Rating $R_{3,3,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
T1 Horiz. Acc. (g)	$W_{3,3,1}$	6	14	19	18.8	10	18.5	10			10	10.00

Table A12: Shoulder Test 3 Modified Arm Results (12.2G Sled)

12.2G Sled Weight factor $V_{3,3}$=3	Weight Factors $W_{3,3,k}$		Corridor		Modified arm Results						Avg of Rating $R_{3,3,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
T1Horiz. Acc. (g)	$W_{3,3,1}$	6	14	19	19.7	5	20.9	5	19.5	5	5	5.00

Table A13: Shoulder Test 4 Current Arm Results (8.9m/s Padded WSU Sled)

8.9m/s Padded WSU Sled Weight factor	Weight Factors $W_{3,4,k}$		Corridor		Current arm Results						Avg of Rating $R_{3,4,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
Shoulder+Thoracic Plate Force(N)	$W_{3,4,1}$	9	Fig A4			5		5		5	5	5.00

Table A14: Shoulder Test 4 Modified Arm Results (8.9m/s Padded WSU Sled)

8.9m/s Padded WSU Sled Weight factor	Weight Factors $W_{3,4,k}$		Corridor		Modified arm Results						Avg of Rating $R_{3,4,k}$	Test Rating
			Lower Bound	Upper Bound	Run 1	Rating	Run 2	Rating	Run 3	Rating		
Shoulder+Thoracic Plate Force[N]	$W_{3,4,1}$	9	Fig A4			5		5		5	5	5.00

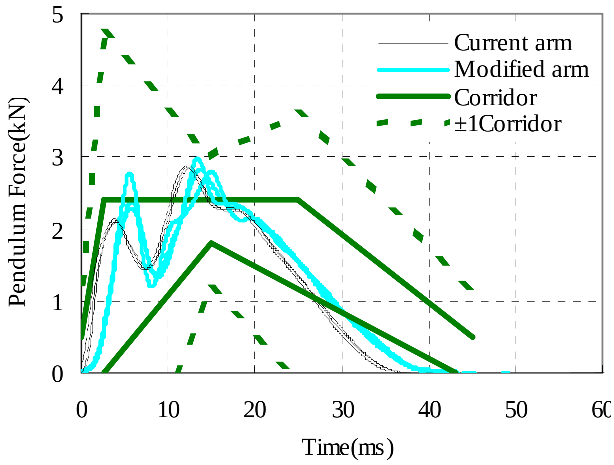

Figure A3. Pendulum Force of Shoulder Test 1

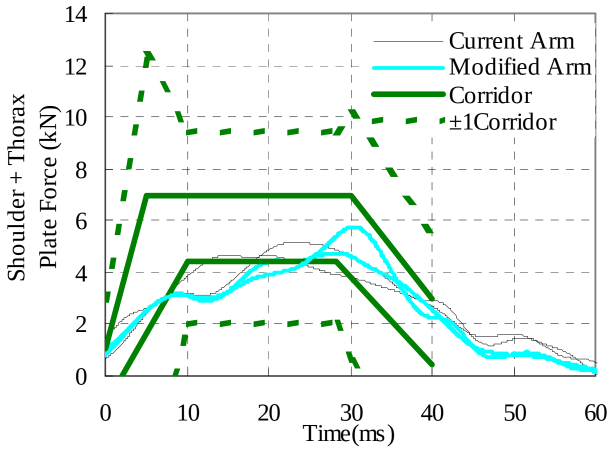

Figure A4. Shoulder Plate Force of Shoulder Test 4

Table A15: Thorax Test 3 Current Arm Results (Rigid 1.0m/s Lateral Drop)

Rigid 1.0m/s Lateral Drop Weight factor $V_{4,3}$=6	Weight Factors $W_{4,3,k}$		Corridor		Current arm Results						Avg of Rating $R_{4,3,k}$	Test Rating
			Lower Bound	Upper Bound	Run1	Rating	Run2	Rating	Run3	Rating		
Thorax Plate Force(N)	$W_{4,3,1}$	8	FigureA5			5		5		5	5.0	2.5
Deflection of Impacted Rib(mm)	$W_{4,3,2}$	8	24	32	42.1	0	40.6	0	41.3	0	0.0	

Table A16: Thorax Test 3 Modified Arm Results (Rigid 1.0m/s Lateral Drop)

Rigid 1.0m/s Lateral Drop Weight factor $V_{4,3}$=6	Weight Factors $W_{4,3,k}$		Corridor		Modified arm Results						Avg of Rating $R_{4,3,k}$	Test Rating
			Lower Bound	Upper Bound	Run1	Rating	Run2	Rating	Run3	Rating		
Thorax Plate Force(N)	$W_{4,3,1}$	8	FigureA5			5		5		5	5.0	5
Deflection of Impacted Rib(mm)	$W_{4,3,2}$	8	24	32	35.3	5	35.2	5	33.3	5	5.0	

Table A17: Thorax Test 5 Current Arm Results (6.8m/s Lateral Sled into Rigid Heidelberg type Wall)

6.8m/s Lateral Sled Rigid Heidelberg type Wall Weight factor $V_{4,5}$=7	Weight Factors $W_{4,5,k}$		Corridor		Current arm Results						Avg of Rating $R_{4,5,k}$	Test Rating
			Lower Bound	Upper Bound	Run1	Rating	Run2	Rating	Run3	Rating		
Thorax Plate Force(N)	$W_{4,5,1}$	8	FigureA6			5		5		5	5.0	3.75
Lat. T1Acc. (g)	$W_{4,5,2}$	7	99	133	61.3	0	62.9	0	60.3	0	0.0	
Lat. T12Acc. (g)	$W_{4,5,3}$	7	105	143	71.2	5	71.1	5	70.8	5	5.0	
Lat. Upper Thorax Rib Acc.(g)	$W_{4,5,4}$	6	87	117	128.2	5	135.0	5	132.3	5	5.0	

Table A18: Thorax Test 5 Modified Arm Results (6.8m/s Lateral Sled into Rigid Heidelberg type Wall)

6.8m/s Lateral Sled Rigid Heidelberg type Wall Weight factor $V_{4,5}$=7	Weight Factors $W_{4,5,k}$		Corridor		Modified arm Results						Avg of Rating $R_{4,5,k}$	Test Rating
			Lower Bound	Upper Bound	Run1	Rating	Run2	Rating	Run3	Rating		
Thorax Plate Force(N)	$W_{4,5,1}$	8	FigureA6			5		5		5	5.0	4.11
Lat. T1Acc. (g)	$W_{4,5,2}$	7	99	133	59.6	0	64.7	0	58.7	0	0.0	
Lat. T12Acc. (g)	$W_{4,5,3}$	7	105	143	75.2	5	80.5	5	74.4	5	5.0	
Lat. Upper Thorax Rib Acc. (g)	$W_{4,5,4}$	6	87	117	78.6	5	84.0	5	94.3	10	6.7	

Table A19: Thorax Test 6 Current Arm Results (8.9m/s Padded Sled WSU Type Wall)

8.9m/s Padded Sled WayneState typeWall Weight factor $V_{4,6}$=7	Weight Factors $W_{4,6,k}$		Corridor		Current arm Results						Avg of Rating $R_{4,6,k}$	Test Rating
			Lower Bound	Upper Bound	Run1	Rating	Run2	Rating	Run3	Rating		
Shoulder+Thorax Plate Force(N)	$W_{4,6,1}$	9	FigureA7			5		5		5	5.0	5

Table A20: Thorax Test 6 Modified Arm Results (8.9m/s Padded Sled WSU Type Wall)

8.9m/s Padded Sled WayneState typeWall Weight factor $V_{4,6}$=7	Weight Factors $W_{4,6,k}$		Corridor Lower Bound	Corridor Upper Bound	Modified arm Results Run1	Rating	Run2	Rating	Run3	Rating	Avg of Rating $R_{4,6,k}$	Test Rating
Shoulder+Thorax Plate Force(N)	$W_{4,6,1}$	9	FigureA7			5		5		5	5.0	5

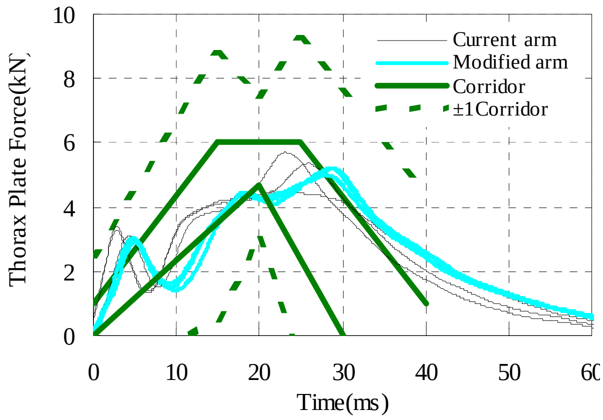

Figure A5. Thorax Plate Force of Thorax Test 3

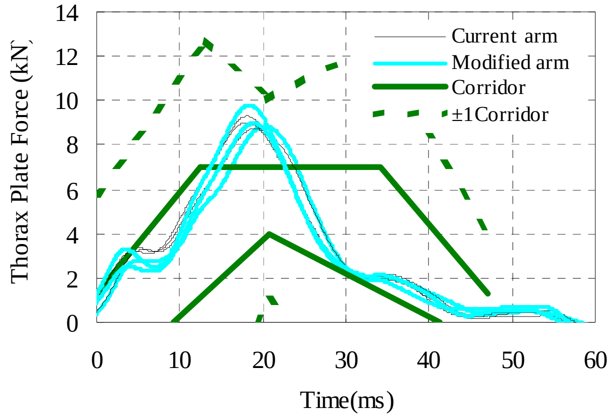

Figure A6. Thorax Plate Force of Thorax Test 5

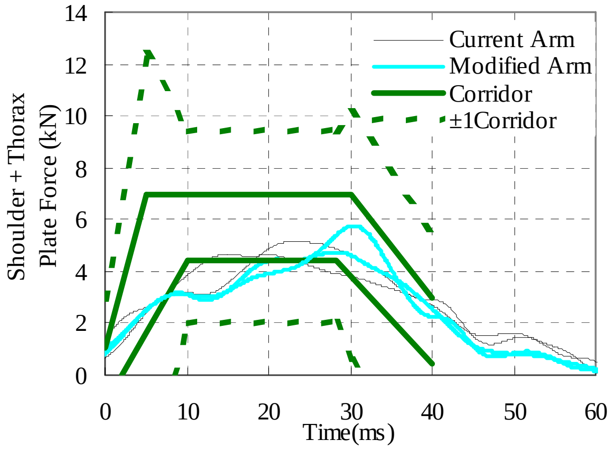

Figure A7. Thorax Plate Force of Thorax Test 6

BIOFIDELITY POINT

1. Neck, Shoulder and Thorax Biofidelity regulated by ISO 9790

・Arm modification gets the thorax biofidelity point up, the neck and shoulder ones down.
・Thorax biofidelity is good. Neck and shoulder biofidelities are fair. There is no change in biofidelity class.

Table A21 Biofidelity Point of Neck, Shoulder and Thorax

Body Region	Test condition	Weight Factors		Current Arm Test Rating	Current Arm Biofidelity Rating	Modified Arm Test Rating	Modified Arm Biofidelity Rating
Neck	Test1-7.2G Sled	V2,1	7	7.15	5.61	7.40	5.56
	Test2-6.7G Sled	V2,2	6	3.99		3.53	
	Test3-12.2GSled	V2,3	3	5.26		5.34	
Shoulder	Test1-4.5m/s Pendulum Impact	V3,1	6	5.00	6.01	5.00	5.6
	Test2-7.2G Sled Impact	V3,2	5	6.25		7.50	
	Test3-12.2GSled Impact	V3,3	3	10.00		5.00	
	Test4-8.9m/s Padded WSU Sled	V3,4	7	5.00		5.00	
Thorax	Test1-4.3m/s Pendulum Impact	V4,1	9	10.00	6.74	10.00	7.2
	Test2-6.7m/s Pendulum Impact	V4,2	9	10.00		10.00	
	Test3- Rigid 1.0m/s Drop	V4,3	6	3.00		5.00	
	Test4-Padded 2.0m/s Drop	V4,4	0	0.00		0.00	
	Test5-6.8m/s Rigid Heidelberg	V4,5	7	3.75		4.11	
	Test6-8.9m/s Padded WSU Sled	V4,6	7	5.00		5.00	

Good: 6.5≦B<8.6
Fair: 4.4≦B<6.5
Marginal: 2.6≦B<4.4

2. Overall Biofidelity regulated by ISO 9790

・ Arm modification gets the increase of 0.11 point about overall biofidelity.
(Notice※ : In ISO calculation method, weighting factor of the thorax is 10, and shoulder one is 5. So, thorax point has more contribution to overall than that of shoulder)

Table A22: Biofidelity Point (Body Region and Overall)

Body Regions	Weight Factors		Prototype Body region Rating	Prototype Overall Rating	Current Arm Body region Rating	Current Arm Overall Rating	Modified Arm Body region Rating	Modified Arm Overall Rating
Neck	U2	6	4.9	6.59	5.61	6.24	5.56	6.35
Shoulder	U3	5	6.2		6.01		5.60	
Thorax	U4	10	7.8		6.74		7.20	

Good: 6.5≦B<8.6
Fair: 4.4≦B<6.5
Marginal: 2.6≦B<4.4

Modified arm improved the over all biofidelity of SID-IIs as followings.

(1) Overall biofidelity point
Current arm : 6.24 → Modified arm : 6.35 (up 0.11 points)

(2) Thorax biofidelity point
Current arm : 6.74 → Modified arm : 7.2 (up 0.46 points)

(3) Shoulder biofidelity point
Current arm : 6.01 → Modified arm : 5.6 (down 0.41 points)