

BIOFIDELITY

1. Biofidelity Requirements

1.1 Survey of and general differences from previous side impact dummies

As of October 2003, there were five mid-sized male side impact dummies, as well as some variations thereto, available for regulatory and development use. The five dummies have different levels of biofidelity. The USDOT-SID, EuroSID-1, ES-2 and BioSID dummies have each been rated using the ISO biofidelity scale that provides classifications, as shown in Table 1^[10]. These classifications quantify how closely the dummy dynamic response matches those of a sample of human subjects, for each body region and for all body regions. The USDOT-SID has a ISO biofidelity classification of “unacceptable”, the EuroSID-1 has a classification of “marginal” and the BioSID and ES-2 have a classification of “fair.”

Table 1 – ISO biofidelity rating scale

Excellent	> 8,6 to 10
Good	> 6,5 to 8,6
Fair	> 4,4 to 6,5
Marginal	> 2,6 to 4,4
Unacceptable	0 to 2,6

As reported by Byrnes, K., et al.^[2], the US OSRP (Occupant Safety Research Partnership) conducted a series of ISO/TR 9790 tests in order to compare the biofidelity ratings of the current 50th percentile male side impact dummies USDOT-SID, EuroSID-1, ES-2 BioSID and the WorldSID. Even if not all ISO/TR 9790 tests were carried out identically with each dummy (as described in, for example, Appendix G of ^[10]), the WorldSID was the only dummy to obtain a “good” rating on the ISO biofidelity scale.

As shown in Table 2, the WorldSID achieved the best overall dummy rating and also the best single body region ratings for the head, thorax, abdomen and pelvis.

Table 2 – Biofidelity comparison of side impact dummies

	Biofidelity rating						
	Head	Neck	Shoulder	Thorax	Abdomen	Pelvis	Overall
WorldSID production version	10,0	5,6	7,1	8,3	7,8	6,1	7,6
BioSID	6,7	6,7	7,3	6,3	3,8	4,0	5,7
ES-2	5,0	4,4	5,3	5,2	2,6	5,3	4,6
EuroSID-1	5,0	7,8	7,3	5,4	0,9	1,5	4,4
USDOT-SID	0,0	2,5	0,0	3,1	4,4	2,5	2,3

Independently, the US/NHTSA (National Highway Traffic Safety Administration) evaluated the WorldSID prototype (unrevised version) together with two other side impact dummies, the ES-2 and the Hybrid III-SID to a newly developed biofidelity ranking system called Bio Rank System, as reported by Rhule, H., et al.[14].

This Bio Rank System quantifies the ability of a dummy to load a sled wall as a cadaver does (External Biofidelity) and the ability of a dummy to replicate those cadaver responses that best predict injury potential (Internal Biofidelity). The ranking is based on the ratio of the cumulative variance of the dummy response relative to the mean cadaver response and the cumulative variance of the mean cadaver response relative to the mean plus one standard deviation. That ratio expresses how well a dummy duplicates a cadaver response. Contrary to the ISO rating system, the lower the rating value the better the biofidelity.

Although still under development and not in use by the international community, the data presented by Rhule, et al., indicate that this assessment system also showed the WorldSID prototype to have the best ranking out of the three tested dummies.

In summary, compared with other, contemporary mid-sized adult male side impact dummies, the WorldSID overall ratings are better than all others. It achieves by far the best overall rating, and was the only side impact dummy as of March 2005 with an overall biofidelity rating of "good."

1.2 General

ISO/TR 9790 (1999) describes laboratory test procedures and impact response requirements suitable for assessing the lateral impact biofidelity of the head, neck, shoulder, thorax, abdomen and pelvis of crash test dummies, subcomponent test devices, and math models that are used to represent a 50th percentile adult male.

1.3 Head

Two lateral head impact tests are defined in ISO/TR 9790^[10]. Head test 1 is based on the rigid surface cadaver impacts conducted by Hodgson and Thomas^[9]. Head test 2 is based on the padded surface cadaver impacts of the Association Peugeot-Renault (APR)^[19]. Note that test 2 was not conducted since the padding specified for the test is no longer available.

An additional requirement was placed on the WorldSID head design requiring the head to meet the frontal head biofidelity as specified by Hodgson and Thomas^[9]. This test is not included in ISO/TR 9790 and is therefore not included in the biofidelity rating.

1.4 Neck

Three lateral neck bending tests are defined. Neck test 1 is based on the human volunteer data of Ewing, et al.^[8], and the requirements are based on the analysis of Wismans, et al.^[18] Neck test 2 is based on the human volunteer data of Patrick and Chou^[13]. Neck test 3 is based on the cadaver tests of the APR^[19]. To evaluate if the biofidelity requirements are met for the neck, the respective sled test environments that were used to obtain the human volunteer and/or cadaver data were to be duplicated.

1.5 Shoulder

Four lateral impact test conditions are defined for the shoulder. Shoulder test 1 is based on impactor tests conducted by the APR using unembalmed cadavers^[1].

Shoulder test 2 is based on the Ewing, et al.^[8] volunteer sled tests. Shoulder test 3 is based on the cadaver sled tests of Tarriere^[20] Shoulder test 4 is based on the cadaver sled tests of Wayne State University (WSU) as described by Irwin^{[21],[11]}.

1.6 Thorax

Six lateral thoracic impact test conditions are defined. Thorax tests 1 and 2 are based on cadaver impactor tests conducted by the Highway Safety Research Institute (HSRI) described by Eppinger, et al.^[7] and WSU described by Viano^[17]. Thorax tests 3 and 4 are based on the cadaver drop tests of the APR as described by Stalnaker, et al., and Walfisch, et al.^{[15],[22],[23]}. Thorax test 5 is based on cadaver sled tests of the University of Heidelberg described by Marcus, et al.^[12]. Thorax test 6 is based on cadaver sled tests of WSU described by Irwin, et al.^{[21],[11]}. Note that thorax test 4 was not conducted because the padding is no longer available.

1.7 Abdomen

Five lateral abdominal impact test conditions are defined. Abdomen tests 1 and 2 are based on the lateral cadaver drop tests conducted by the APR^{[23],[1]}. Abdomen tests 3 to 5 are based on cadaver sled tests of WSU^[11].

1.8 Pelvis

Thirteen lateral pelvic impact test conditions are defined. Pelvis tests 1 and 2 are based on impactor tests of ONSER described by Cesari^{[24],[4],[6]}. Pelvis tests 3 to 6 are based on free fall cadaver tests of the APR described by Tarriere^[16]. Pelvis tests 7 to 9 are based on cadaver sled tests of the University of Heidelberg described by Marcus, et al.^[12]. Pelvis tests 11 to 13 are based on cadaver sled tests of WSU described by Irwin^[11]. Note that pelvis tests 5, 6, and 9 were not conducted because the padding is no longer available.

2. Biofidelity Performance

2.1 ISO/TR 9790 ratings procedures

As found in ISO/TR 9790^[10], ISO has defined the biofidelity rating for the six WorldSID body regions as follows:

$$B_i = \frac{\sum j(V_{i,j} (\sum W_{i,j,k} R_{i,j,k}))}{\sum jV_{i,j}}$$

where

- B_i is the body region biofidelity rating,
- $V_{i,j}$ is the weighting factor for each test condition for a given body region,
- $W_{i,j,k}$ is the weighting factor for each response measurement for which a requirement is given,
- $R_{i,j,k}$ is the rating of how well a given response meets its requirement ($R_{i,j,k}$ is equal to 10 if the response meets the requirement, 5 if the response is outside but lies within one corridor width of the requirement and 0 if neither of the previous is met). Note that when a rating was determined by the WorldSID Task Group, particular emphasis was placed on the loading and peak phase of the data being considered. It is the WorldSID Task Group's understanding that this is common practice and that this procedure has been used in the determination of ratings for other dummies.
- i represents the body region,
- j represents the test condition for a given body region i ,
- k represents the response measurement for a given test condition j and a body region i .

Values for the weighting factors for the various test conditions, $V_{i,j}$, and response measurements, $W_{i,j,k}$, were determined by averaging the results of a poll of the ISO/TC22/SC12/WG5 experts and are given in Tables S.2 through S.7 of Annex S of ISO/TR 9790^[10].

The experts agreed on the following method for assigning values to $R_{i,j,k}$.

$$R_{i,j,k} = 10 \text{ If response meets requirement.}$$

$R_{i,j,k} = 5$ If response is outside requirement, but lies within one corridor width of the requirement.

$R_{i,j,k} = 0$ If neither of the above is met.

Using this method, the overall biofidelity rating, B, was to have a design target value between 0 and 10. Five classifications indicating the degree of biofidelity were established for the overall biofidelity rating. These are,

Excellent biofidelity: $8,6 \leq B \leq 10,0$

Good biofidelity: $6,5 \leq B \leq 8,6$

Fair biofidelity: $4,4 \leq B \leq 6,5$

Marginal biofidelity: $2,6 \leq B \leq 4,4$

Unacceptable biofidelity: $0,0 \leq B \leq 2,6$

Further, the WG5 experts stipulated that the overall biofidelity value, B, of a side impact dummy (or math model) had to be greater than 2,6 to be acceptable for assessing side impact occupant protection.

As described in Annex A, the objective for the WorldSID was that it would have "good" to "excellent" biofidelity.

2.2 Overall dummy

The overall WorldSID biofidelity ratings are given in Table 3.

Table 3 – Overall WorldSID biofidelity ratings

Region	Weighting	Rating
Head	7	10,0
Neck	6	5,6
Shoulder	5	7,1
Thorax	10	8,3
Abdomen	8	7,8
Pelvis	8	6,1
Overall		7,6

2.3 Head

One of the two head tests specified in ISO/TR 9790 was carried out with the WorldSID for lateral assessment. Head test 2 was not conducted, because the required padding for the test is no longer available.

Head test 1, defined in ISO/TR 9790 and according to Hodgson and Thomas^[9], is a 200 mm drop test onto a rigid surface with the head only. Targets are given for head resultant accelerations. As only test 1 could be carried out, the overall head biofidelity rating is the same as that of test 1. Head test 1 data are given in Annex A.

The biofidelity rating of the head is 10,0.

2.4 Neck

2.4.1 General

Three different sled tests were conducted to determine the lateral biofidelity of the dummy neck assembly. Neck test 2 data are from the WorldSID revised prototype. Neck test 1 and 3 are from the WorldSID pre-production dummy. All neck tests were conducted without the neck shield, since it was previously determined by Cesari et al.^[5], that the neck shield had no influence on the neck biofidelity performance. Neck test 1 through 3 data are given in Annex A.

2.4.2 Neck test 1

Neck test 1, defined in ISO/TR 9790, is a sled test based on the volunteer tests conducted by Ewing et al.^[8]. The requirements derived from these tests originate from the analysis performed by Wismans et al.^[18]. The mean sled velocity was 6,9 m/s and average sled deceleration was 7,2 G. Boundaries were given for longitudinal acceleration and displacement at T1, longitudinal and vertical head CG displacement relative to T1, the time of peak head excursion, lateral and vertical peak head acceleration, the peak lateral flexion angle and the peak twist angle.

The biofidelity rating for neck test 1 is 8,0.

2.4.2 Neck test 2

Neck test 2, defined in ISO/TR 9790, is a sled test configuration referring to the tests of Patrick and Chou^[13]. The sled velocity was 5,8 m/s and the constant deceleration level was 6,7 G. From this test, boundaries for peak flexion angle, peak forces and moments at the occipital condyles and peak head resultant acceleration were given.

The biofidelity rating for neck test 2 is 2,4.

2.4.3 Neck test 3

Neck test 3, defined in ISO/TR 9790, is the configuration established by Tarriere et al.^[16], based on a single cadaveric test with an initial velocity of 6 m/s and sled deceleration of 12,2 G. Boundaries are given for peak lateral T1 acceleration, peak lateral head CG acceleration, peak horizontal displacement of the head CG relative to the sled, peak flexion angle and peak twist angle.

The biofidelity rating for neck test 3 is 6,6.

2.4.4 Overall neck biofidelity rating

The overall neck biofidelity ratings are given in Table 4.

Table 4 – Overall neck biofidelity

	<i>j</i>	<i>V_{2,j}</i>	<i>R_{2,j}</i>
Neck test 1	1	7	8,0
Neck test 2	2	6	2,4
Neck test 3	3	3	6,6
Neck biofidelity rating		5,6	

2.5 Shoulder

2.5.1 General

All four ISO/TR 9790 shoulder tests were conducted on the WorldSID. These tests include one pendulum impact and three sled tests. The shoulder test 1 through 4 data are given in Annex A.

2.5.2 Shoulder test 1

Shoulder test 1, defined in ISO/TR 9790, involves an APR-type pendulum impacts using a 23,4 kg pendulum with a 150 mm cylindrical impact face at 4,5 m/s (Bendjellal, et al.^[11]). Targets are given for the impactor force/time history and the maximum shoulder deflection.

The biofidelity rating for shoulder test 1 is 7,1.

2.5.3 Shoulder test 2

Shoulder test 2, defined in ISO/TR 9790, is the 7,2 G sled test configuration described under neck test 1. Targets are given for peak horizontal T1 acceleration and peak horizontal T1 displacement.

The biofidelity rating for shoulder test 2 is 8,3.

2.5.4 Shoulder test 3

Shoulder test 3, defined in ISO/TR 9790, is the 12,2 G sled test configuration described under neck test 3. Targets are given for T1 accelerations.

The biofidelity rating for shoulder test 3 is 10,0.

2.5.5 Shoulder test 4

Shoulder test 4, defined in ISO/TR 9790, requirements are derived from tests performed at the Wayne State University and analysed by Irwin^[11]. The sled velocity is 8,9 m/s. Targets are given for the thorax and shoulder plate forces.

The biofidelity rating for shoulder test 4 is 5,0.

2.5.6 Overall shoulder biofidelity rating

The overall biofidelity ratings of the WorldSID shoulder are given in Table 5.

Table 5 – Overall shoulder biofidelity

	<i>j</i>	<i>V_{3,j}</i>	<i>R_{3,j}</i>
Shoulder test 1	1	6	7,1
Shoulder test 2	2	5	8,3
Shoulder test 3	3	3	10,0
Shoulder test 4	4	7	5,0
Shoulder biofidelity rating B3			7,1

2.6 Thorax

2.6.1 General

Five different tests were performed on the WorldSID thorax to determine the thorax biofidelity rating. These tests included two pendulum tests, a drop test and two sled tests. Thorax test 4 was not conducted, because the required padding is no longer available. The measurement data are given in Annex A.

2.6.2 Thorax test 1

Thorax test 1, defined in ISO/TR 9790, is a pendulum test, in which a 23,4 kg, rigid impactor with a diameter of 150 mm impacts onto the thoracic ribs, with the arms in a horizontal position, at 4,3 m/s (Eppinger, R.H., et al.^[7]). Targets are given for the pendulum force and upper spine lateral acceleration.

The biofidelity rating for thorax test 1 is 10,0.

2.6.3 Thorax test 2

Thorax test 2 is the same configuration as thorax test 1, except that the impact speed is 6,7 m/s (Viano^[17]). Targets are only given for the pendulum impact force.

The biofidelity rating for thorax test 2 is 10,0.

2.6.4 Thorax test 3

Thorax test 3, defined in ISO/TR 9790, consists of dropping the dummy laterally from a height of 1m onto a continuous, rigid plate which spans the

shoulder, thorax and abdomen regions, with a separate plate for the pelvis region. The arm is rotated 20° forward of the dummy's thoracic spine (Stalnaker^[15]). Targets are given for the thoracic plate force and peak rib deflection.

The biofidelity rating for rating for thorax test 3 is 10,0.

2.6.5 Thorax test 5

Thorax test 5, defined in ISO/TR 9790, requires a Heidelberg-type rigid wall sled impact at 6,8 m/s (Marcus^[12]). Targets are given for the thorax plate force, peak lateral upper spine acceleration, peak lateral lower spine acceleration, and peak lateral acceleration of the impacted rib.

The biofidelity rating for thorax test 5 is 5,8.

2.6.6 Thorax test 6

Thorax test 6, defined in ISO/TR 9790, is a WSU-type padded load plate wall configuration with padding of 0,10 N/mm² and 0,16 N/mm² (15 psi and 23 psi) (Cavanaugh^[3]). The dummy is seated on the sled with its arms 45° forwards from the vertical, and the sled is decelerated at an impact speed of 8,9 m/s. Targets are given for the shoulder plus thoracic plate force and the peak T12 lateral displacement relative to the sled.

The biofidelity rating for thorax test 6 is 5,0.

2.6.7 Overall thorax biofidelity rating

The overall biofidelity ratings of the WorldSID thorax are given in Table 6.

Table 6 – Summary of thorax biofidelity ratings

	<i>j</i>	<i>V_{4,j}</i>	<i>R_{4,j}</i>
Thorax test 1	1	9	10,0
Thorax test 2	2	9	10,0
Thorax test 3	3	6	10,0
Thorax test 5	5	7	5,8
Thorax test 6	6	7	5,0
Thorax biofidelity rating B4		8,3	

2.7 Abdomen

2.7.1 General

To determine the overall abdomen biofidelity of the WorldSID, four different abdominal tests were performed. These tests consist of one drop test and three sled tests. Abdomen test 2 was not conducted due to the severity of the test. The dummy's ribs bottomed out and invalidated the required data. The data are given in Annex A.

2.7.2 Abdomen test 1

Abdomen test 1, defined in ISO/TR 9790, is a lateral drop test from a height of 1 m onto a simulated armrest, which protrudes 41 mm above a continuous, rigid plate. The plate spans the shoulder and thorax regions, with a separate plate for the pelvis region. The arm is removed from the dummy (Bendjella^[1]). Targets are given for the armrest force, peak lower spine acceleration, peak impacted rib acceleration, and peak abdominal penetration.

The biofidelity rating for abdomen test 1 is 8,6.

2.7.3 Abdomen test 3

Abdomen test 3, defined in ISO/TR 9790, is a WSU-type rigid wall sled test where the sled is accelerated until it reaches a velocity of 6,8 m/s. The brakes are then applied and the dummy slides into the rigid wall (Cavanaugh^[3]). The dummy is seated on the sled with its arm at 45° forward from the vertical. A target is given for the abdominal plate force.

The biofidelity rating for abdomen test 3 is 10,0.

2.7.4 Abdomen test 4

Abdomen test 4 is the same as abdomen test 3, except that the sled velocity is 8,9 m/s (Cavanaugh^[3]). A target is given for the abdominal plate force.

The biofidelity rating for abdomen test 4 is 10,0.

2.7.5 Abdomen test 5

Abdomen test 5 is identical to abdomen test 4, except that the rigid wall is covered with paper honeycomb padding of 0,10 N/mm² and 0,16 N/mm² (15 psi and 23 psi), respectively (Cavanaugh^[3]). A target is given for the abdominal plate force.

The biofidelity rating for abdomen test 5 is 5,0.

2.7.6 Overall abdomen biofidelity rating

The overall biofidelity ratings of the WorldSID abdomen are given in Table 7.

Table 7 – Summary of abdomen biofidelity ratings

	<i>j</i>	<i>V_{5,j}</i>	<i>R_{3,j}</i>
Abdomen test 1	1	7	8,6
Abdomen test 3	3	3	10,0
Abdomen test 4	4	3	10,0
Abdomen test 5	5	7	5,0
Abdomen biofidelity rating B5		7,8	

2.8 Pelvis

2.8.1 General

Ten out of thirteen ISO/TR 9790 pelvis tests were conducted with the WorldSID. Pelvis tests 5, 6 and 9 were not conducted, as the corresponding padding was unavailable. The measurement data are given in Annex A.

2.8.2 Pelvis test 1

Pelvis test 1, defined in ISO/TR 9790, involves a rigid pendulum impact at 6 m/s. The impactor is defined as a 17,3 kg rigid impactor with a 600 mm radius of curvature and an outer diameter of 127 mm (Cesari, et al.^[24]; Cesari and Ramet^[4]; Cesari^[6]). A target is given for the pendulum force.

The biofidelity rating for pelvis test 1 is 5,0.

2.8.3 Pelvis test 2

Pelvis test 2 configuration is equivalent to pelvis test 1, but with an impact speed of 10 m/s (Cesari, et al.^[24]; Cesari and Ramet^[4]; Cesari, et al.^[6]). A target is given for the pendulum force.

The biofidelity rating for pelvis test 2 is 10,0.

2.8.4 Pelvis test 3

Pelvis test 3, defined in ISO/TR 9790, consists of dropping the dummy laterally from a height of 0,5 m onto a continuous, rigid plate which spans the shoulder, thorax and abdomen regions, with a separate plate for the pelvis region. The arm is rotated 20° forward of the dummy's thoracic spine (TARRIERE^[16]). A target is given for the peak pelvic acceleration.

The biofidelity rating for pelvis test 3 is 5,0.

2.8.5 Pelvis test 4

Pelvis test 4 is the same as pelvis test 3, but with a dropping height of 1 m. (TARRIERE, et al.^[16]). A target is given for the peak pelvis acceleration.

The biofidelity rating for pelvis test 4 is 1,7.

2.8.6 Pelvis test 7

Pelvis test 7, defined in ISO/TR 9790, requires a Heidelberg-type rigid wall sled impact at 6,8 m/s (Stalnaker et al.^[15]). Targets are given for the peak pelvic force and the peak pelvic acceleration.

The biofidelity rating for pelvis test 7 is 5,4.

2.8.7 Pelvis test 8

Pelvis test 8 is the same as pelvis test 7, but it is conducted at 8,9 m/s (Stalnaker, et al.^[15]). Only one test was conducted at this speed due to test severity. Targets are given for the peak pelvic force and the peak pelvic acceleration.

The biofidelity rating for pelvis test 8 is 7,3.

2.8.8 Pelvis test 10

Pelvis test 10, defined in ISO/TR 9790, requires a WSU-type rigid wall sled impact at 6,8 m/s (Cavanaugh, et al.^[3]). Targets are given for the pelvic plate force and the peak lateral pelvic acceleration.

The biofidelity rating for pelvis test 10 is 5,6.

2.8.9 Pelvis test 11

Pelvis test 11, defined in ISO/TR 9790, is a WSU-type rigid wall sled impact at 8,9 m/s (Cavanaugh et al.^[3]). Targets are given for the pelvic plate force and the peak lateral pelvic acceleration.

The biofidelity rating for pelvis test 11 is 5,0.

2.8.10 Pelvis test 12

Pelvis test 12, defined in ISO/TR 9790, is a WSU-type padded wall sled impact at 8,9 m/s with a padding stiffness of 0,10 N/mm² (15 psi). 200 mm padding was used to prevent the pelvis from bottoming out the padding, as previously seen with the prototype dummy. Targets are given for the pelvic plate force and the peak lateral pelvic acceleration.

The biofidelity rating for pelvis test 12 is 6,1.

2.8.11 Pelvis test 13

Pelvis test 13 is the same as pelvis test 12, but with a padding stiffness of 0,16 N/mm² (23 psi). Targets are given for the pelvic plate force and the peak lateral pelvic acceleration.

The biofidelity rating for pelvis test 13 is 5,6.

2.8.12 Overall pelvis biofidelity rating

The overall biofidelity ratings of the WorldSID pelvis are given in Table 8.

Table 8 – Overall pelvis biofidelity

	<i>j</i>	<i>V_{6,j}</i>	<i>R_{6,j}</i>
Pelvis test 1	1	8	5,0
Pelvis test 2	2	9	10,0
Pelvis test 3	3	4	5,0
Pelvis test 4	4	4	1,7
Pelvis test 7	7	8	5,4
Pelvis test 8	8	7	7,3
Pelvis test 10	10	3	5,6
Pelvis test 11	11	3	5,0
Pelvis test 12	12	3	6,1
Pelvis test 13	13	7	5,6
Pelvis biofidelity rating B6		6,1	

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ANNEX A

BIOFIDELITY TEST DATA

A.1 Head

Overall head biofidelity rating is 10,0.

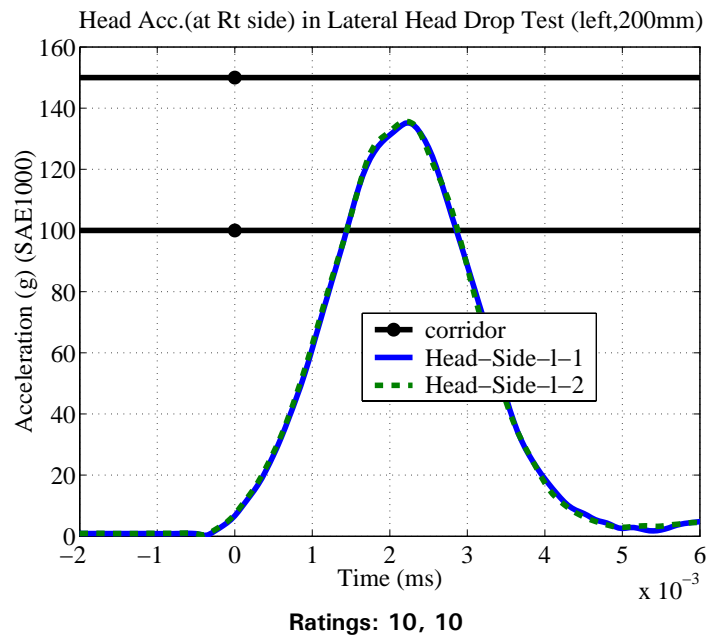


Figure A.1 – Head test 1 - 200 mm lateral head drop (right side) - resultant acceleration

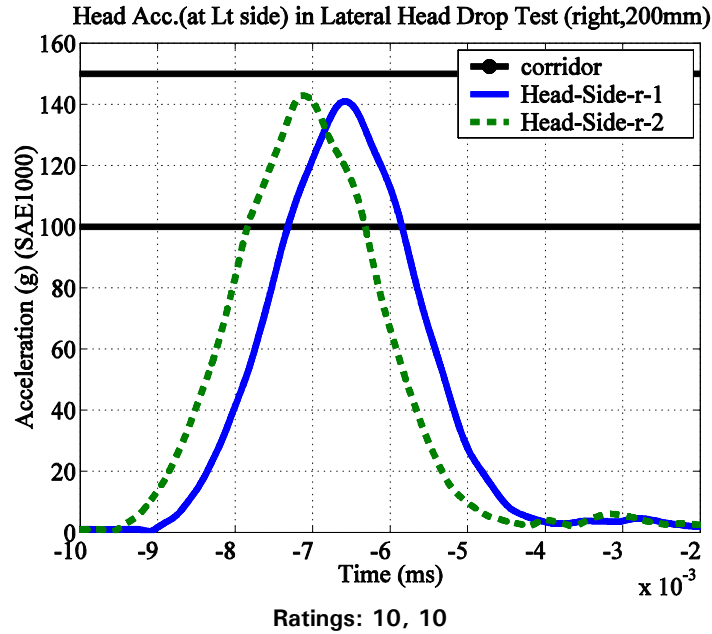


Figure A.2 – Head test 1 - 200 mm lateral head drop (left side) - resultant acceleration

Table A.1 – Head test 1 - 200 mm rigid lateral test results

Measure	Lower bound	Upper bound	Run			Weight factor	Rating
			#1	#2	Avg		
Peak resultant acceleration at a point on the non-impacted side of the head, left impact	100	150	136	136	136	9	10,0
Rating			10	10	10,0		
Peak resultant acceleration at a point on the non-impacted side of the head, right impact	100	150	142	141	142	9	
Rating			10	10	10,0		

A.2 Neck

A.2.1 Neck test 1 – 7,2 G sled test

Table A.2 – Neck test 1 - 7,2 G sled test results

Measure	Lower bound	Upper bound	Run							Weight factor	Rating
			#1	#2	#3	#4	#5	#6	Avg		
Horizontal acceleration of T1 (G) CFC180	12	18	12	12	12	11	12	11	11,7	5	8,0
Rating			10	10	10	5	10	5	8,3		
Horizontal displacement of T1 relative to sled (mm)	46	63	43	48	45	46	49	52	47,2	5	
Rating			5	10	5	10	10	10	8,3		

Measure	Lower bound	Upper bound	Run							Weight factor	Rating
			#1	#2	#3	#4	#5	#6	Avg		
Horizontal displacement of head CG T1 (mm)	130	162	130	133	132	126	125	131	129,5	8	
Rating			10	10	10	5	5	10	8,3		
Vertical displacement of head CG relative to T1 (mm)	64	94	54	60	58	56	55	58	56,8	6	
Rating			5	5	5	5	5	5	5,0		
Time of peak head excursion (sec)	0,159	0,175	0,171	0,171	0,171	0,167	0,170	0,170	0,170	5	
Rating			10	10	10	10	10	10	10,0		
Lateral acceleration of head CG (G) CFC1000	8	11	11	11	10	11	11	11	10,8	5	
Rating			10	10	10	10	10	10	10,0		
Vertical acceleration of head CG (G) CFC1000	8	10	10	11	10	9	10	9	9,8	5	
Rating			10	5	10	10	10	10	9,2		
Head flexion angle (degrees)	44	59	59	60	59	56	56	56	57,7	7	
Rating			10	5	10	10	10	10	9,2		
Head twist angle (degrees)	-45	-32	-19	-20	-20	-7	-7	-8	-13,5	4	
Rating			5	5	5	0	0	0	2,5		

A.2.2 Neck test 2 – 6,7 G sled test

Table A.3 – Neck test 2 - 6,7 G sled test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Head flexion angle (degrees)	40	50	51	49	55	51,7	7	2,4
Rating			5	10	5	6,7		
Peak moment A-P axis at OC, M_x (Nm)	40	50	30	27	29	28,7	7	
Rating			5	0	0	1,7		
Peak moment R-L axis OC, M_y (Nm)	20	30	13	12	11	12,0	3	
Rating			5	5	5	5,0		
Peak twist moment, M_z (Nm)	15	20	9	9	10	9,3	4	
Rating			0	0	5	1,7		
Peak shear force OC, F_y (N)	750	850	451	416	473	446,7	7	
Rating			0	0	0	0,0		

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Peak tension force OC, F_z (N)	350	400	561	519	573	551,0	6	
Rating			0	0	0	0,0		
Peak A-P shear force, F_x (N)	325	375	158	144	159	153,7	3	
Rating			0	0	0	0,0		
Peak resultant head acceleration (G)	18	24	16	15	17	16,0	4	
Rating			5	5	5	5,0		

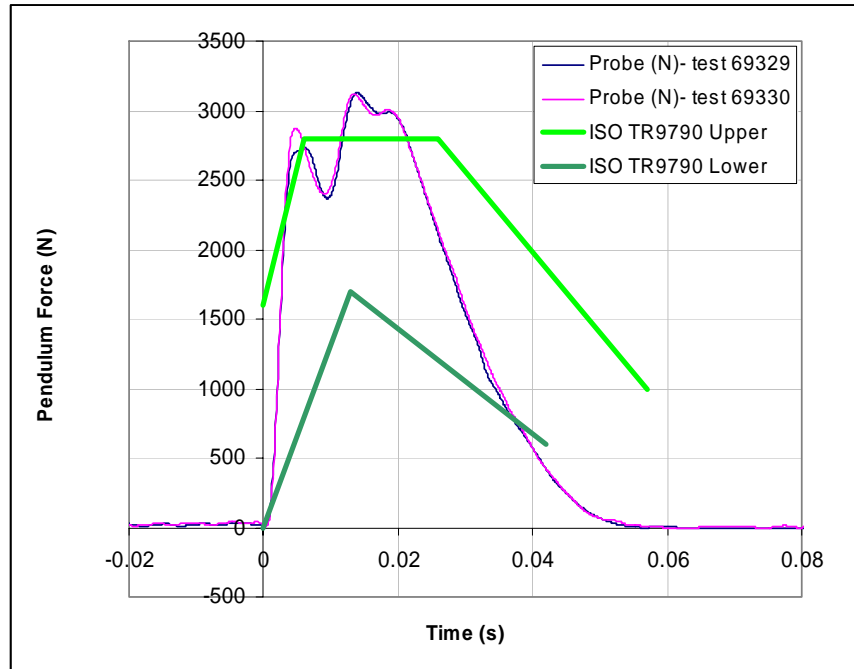
A.2.3 Neck test 3 – 12,2 G sled test

Table A.4 – Neck test 3 - 12,2 G sled test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Peak lateral acceleration of T1 (G)	17	23	19	23	20	20,7	5	6,6
Rating			10	10	10	10,0		
Peak lateral acceleration of head CG (G)	25	47	14	15	14	14,3	5	
Rating			5	5	5	5,0		
Peak horizontal displacement of head CG relative to sled (G)	185	226	188	186	190	188,0	8	
Rating			10	10	10	10,0		
Peak flexion angle (degrees)	62	75	81	83	80	81,3	7	
Rating			5	5	5	5,0		
Peak twist angle (degrees)	62	75	26	26	24	25,3	4	
Rating			0	0	0	0,0		

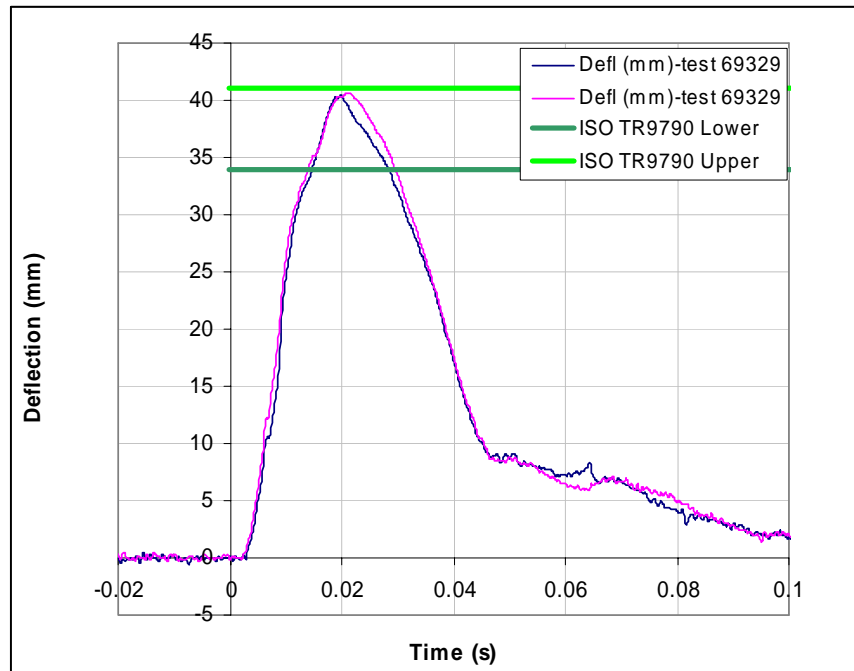
A.3 Shoulder

A.3.1 Shoulder test 1 – 4,5 m/s pendulum test



Ratings: 5, 5

Figure A.3 – Shoulder test 1 - pendulum force



Ratings: 10, 10

Figure A.4 – Shoulder test 1 - shoulder rib deflection

Table A.5 – Shoulder test 1 – 4,5 m/s pendulum test results

Measure	Lower bound	Upper bound	Run			Weight factor	Rating
			#1	#2	Avg		
Shoulder pendulum force (N)	Plot	Plot	Plot	Plot	Plot	8	7,1
Rating			5	5	5,0		
Peak shoulder deflection (mm)	34	41	40	41	40,5	6	
Rating			10	10	10,0		

A.3.2 Shoulder test 2 – 7,2 G sled test

Table A.6 – Shoulder test 2 - 7,2 G sled test results

Measure	Lower bound	Upper bound	Run							Weight factor	Rating
			#1	#2	#3	#4	#5	#6	Avg		
Horizontal acceleration T1 (G)	12	18	12	12	12	11	12	11	11,7	6	8,3
Rating			10	10	10	5	10	5	8,3		
Horizontal displacement T1 relative to sled (mm)	46	63	43	48	45	46	49	52	47,2	6	
Rating			5	10	5	10	10	10	8,3		

A.3.3 Shoulder test 3 – 12,2 G sled test

Table A.7 – Shoulder test 3 - 12,2 G sled test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Peak lateral acceleration T1 (G)	17	23	19	23	20	20,7	6	10,0
Rating			10	10	10	10,0		

A.3.4 Shoulder test 4 – 8,9 m/s padded sled test

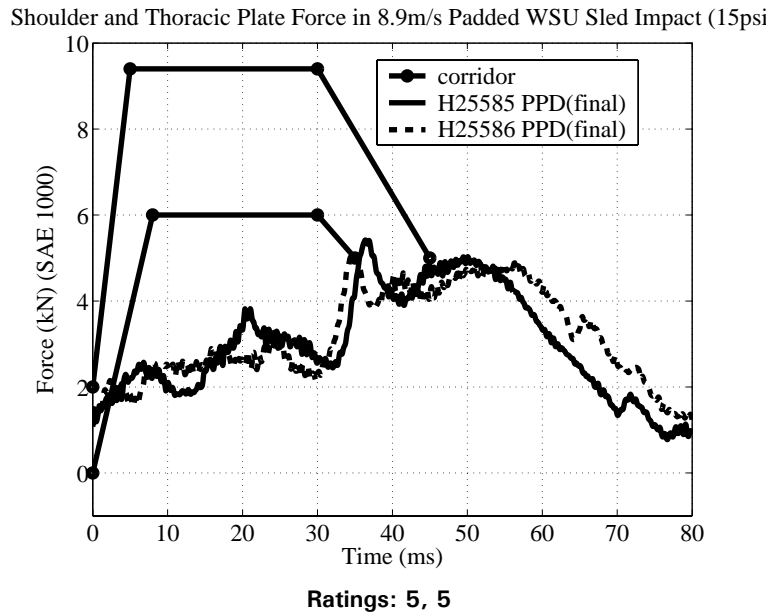


Figure A.5 – Shoulder test 4 - shoulder and thoracic plate force

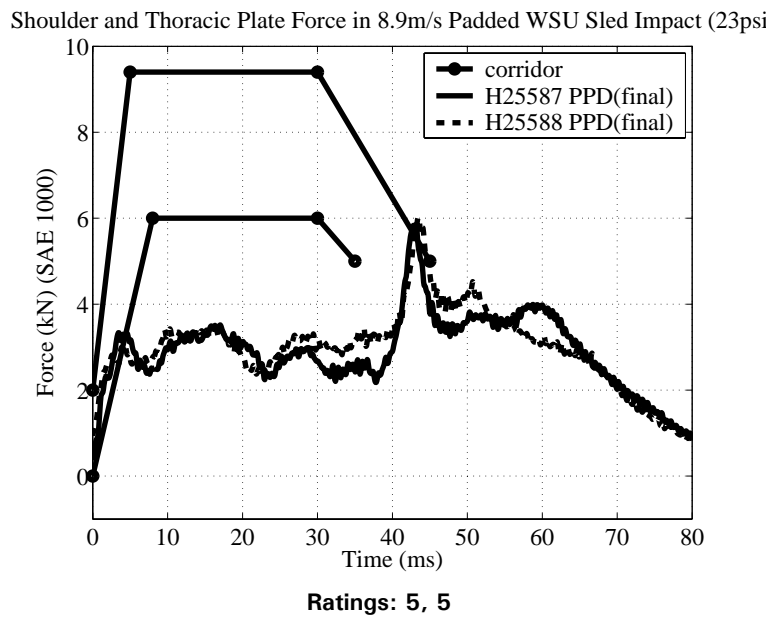


Figure A.6 – Shoulder test 4 - shoulder and thoracic plate force additional results

Table A.8 – Shoulder test 4 - 8,9 m/s padded sled test results

Measure	Lower bound	Upper bound	Run					Weight factor	Rating
			#1	#2	#3	#4	Avg		
Shoulder thorax plate force (N)	Plot	Plot	Plot	Plot	Plot	Plot	Plot	9	5,0
Rating			5	5	5	5	5,0		

A.4 Thorax

A.4.1 Thorax test 1 – 4,3 m/s pendulum test

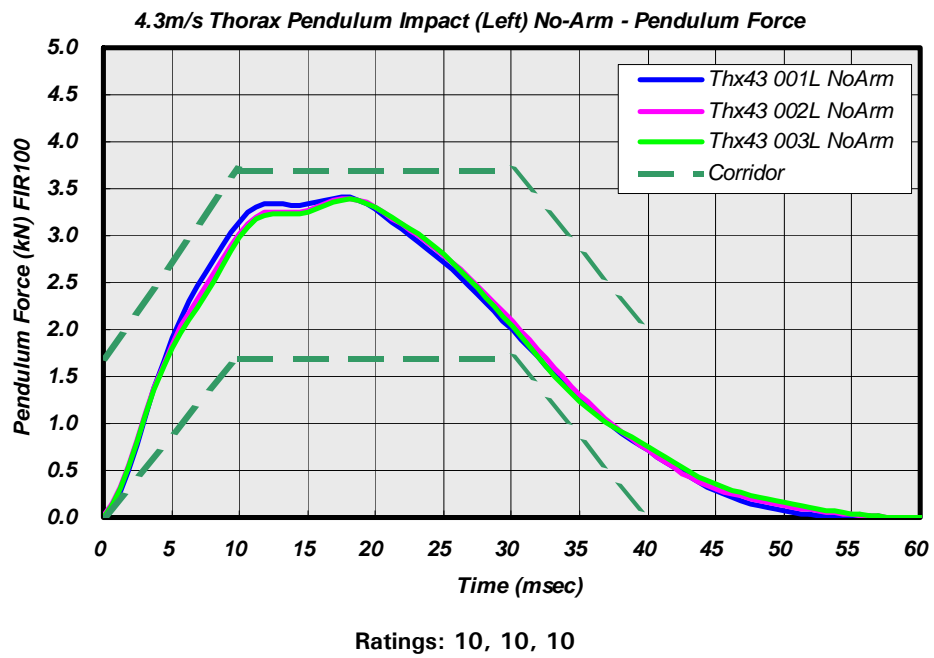


Figure A.7 – Thorax test 1 - pendulum force

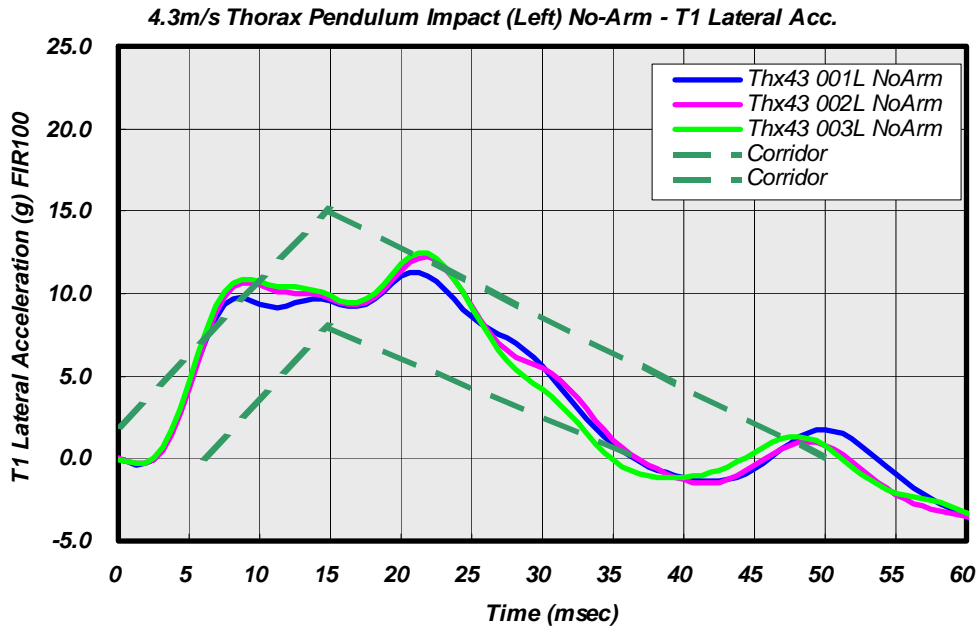
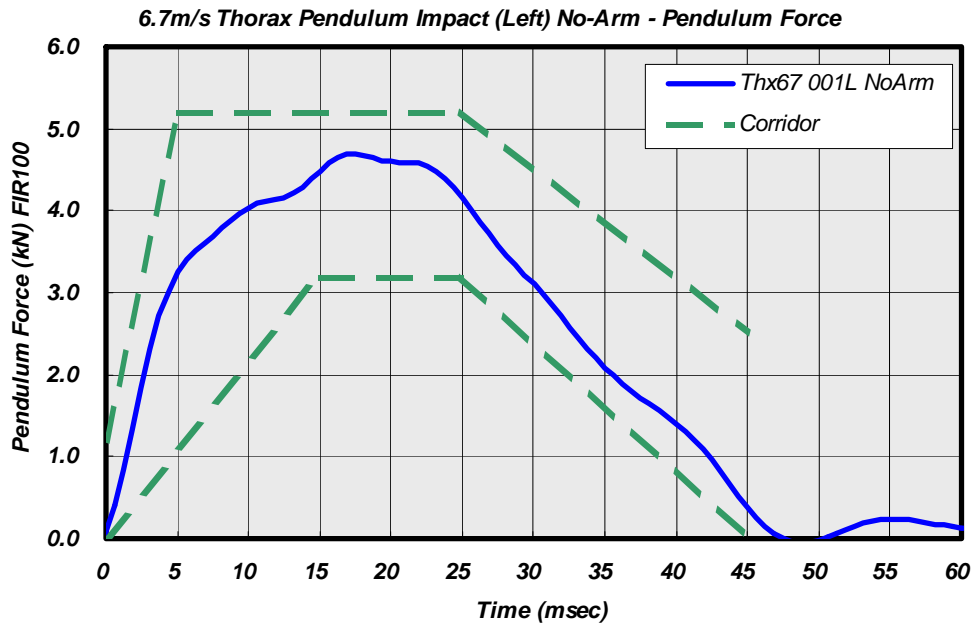


Figure A.8 – Thorax test 1 - T1 lateral acceleration

Table A.9 – Thorax test 1 - test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Pendulum force (kN)	Plot	Plot	Plot	Plot	Plot	Plot	9	10,0
Rating			10	10	10	10,0		
T1 lateral acceleration (G)	Plot	Plot	Plot	Plot	Plot	Plot	7	
Rating			10	10	10	10,0		

A.4.2 Thorax test 2 – 6,7 m/s pendulum test



Rating: 10

Figure A.9 – Thorax test 2 - pendulum force

Table A.10 – Thorax test 2 – 6,7 m/s test results

Measure	Lower bound	Upper bound	Run		Weight factor	Rating
			#1	Avg		
Pendulum force (kN)	Plot	Plot	Plot	Plot	9	10,0
Rating			10	10,0		

A.4.3 Thorax test 3 – 1 m rigid drop test

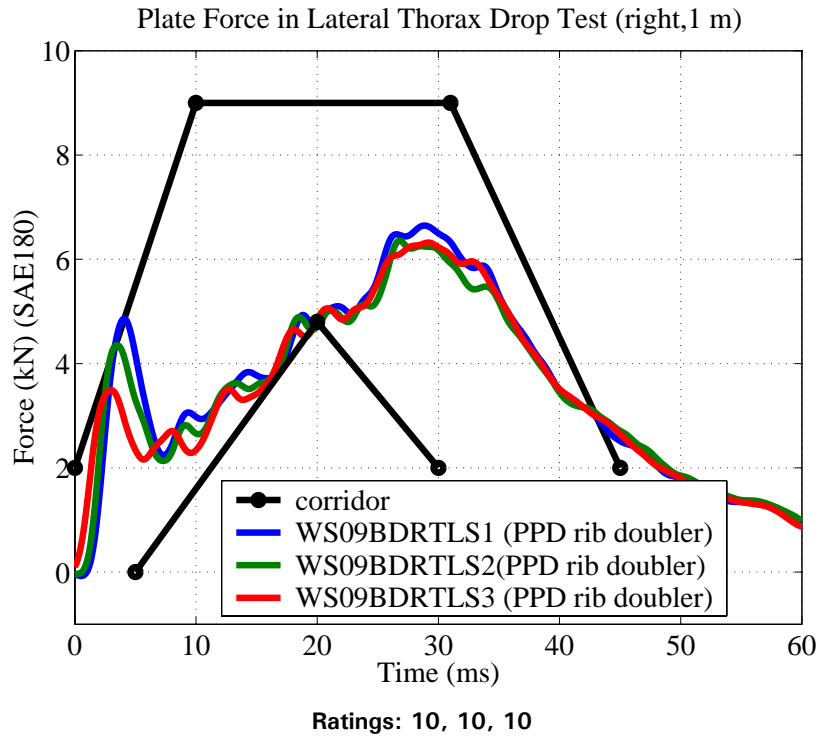


Figure A.10 – Thorax test 3 - plate force

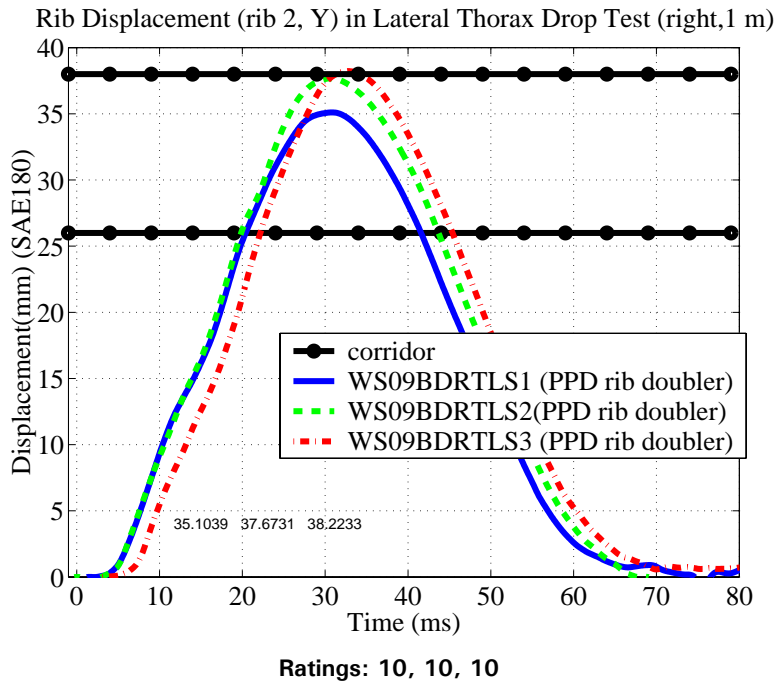


Figure A.11 – Thorax test 3 – rib displacement

Table A.11 – Thorax test 3 - 1 m rigid drop test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Thorax plate force (kN)	Plot	Plot	Plot	Plot	Plot	Plot	8	10,0
Rating			10	10	10	10,0		
Peak deflection impacted rib (mm)	26	38	35	38	38	37,0	8	
Rating			10	10	10	10,0		

A.4.4 Thorax test 4 – 2,0 m padded drop test

Not performed.

A.4.5 Thorax test 5 – 6,8 m/s rigid sled test

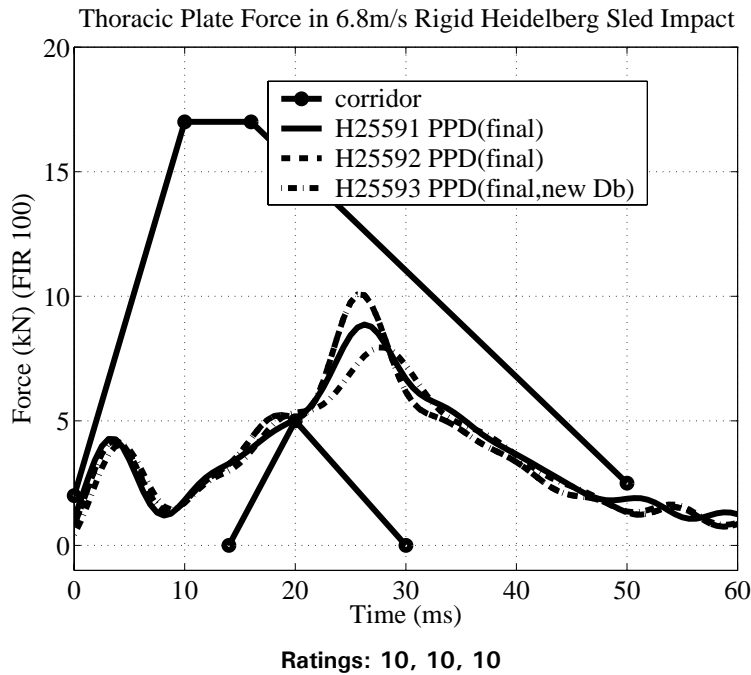


Figure A.12 – Thorax test 5 – plate force

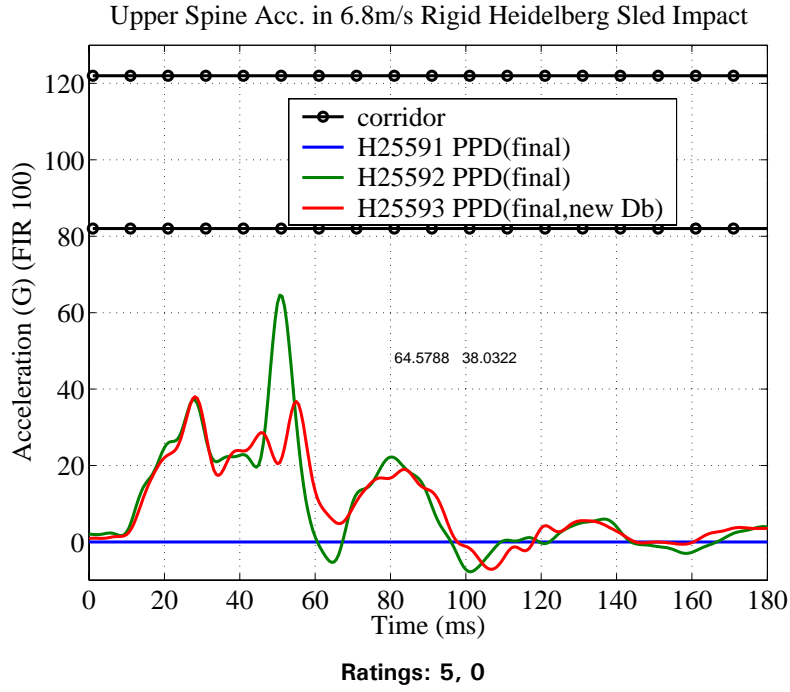


Figure A.13 — Thorax test 5 - T1 acceleration

Ratings: 5, 5, 5

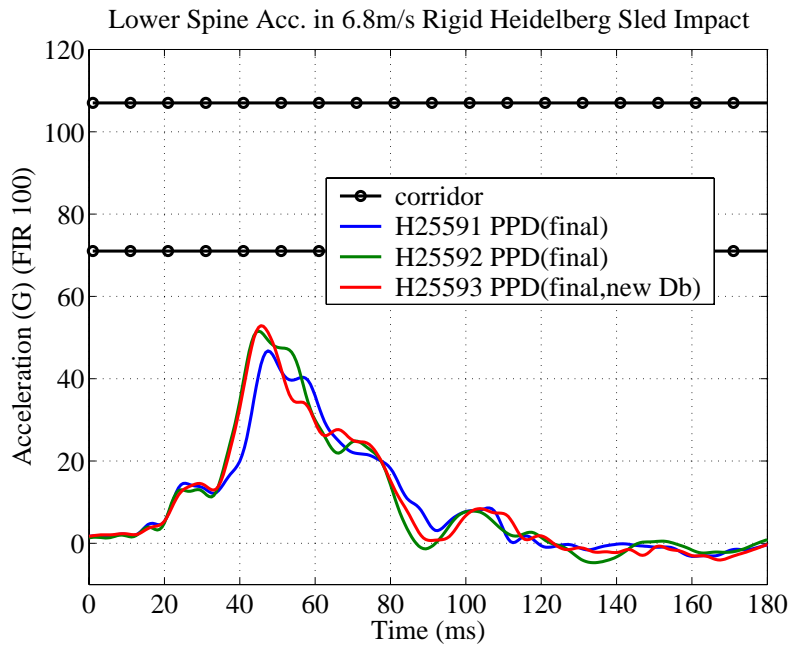


Figure A.14 — Thorax test 5 - T12 acceleration

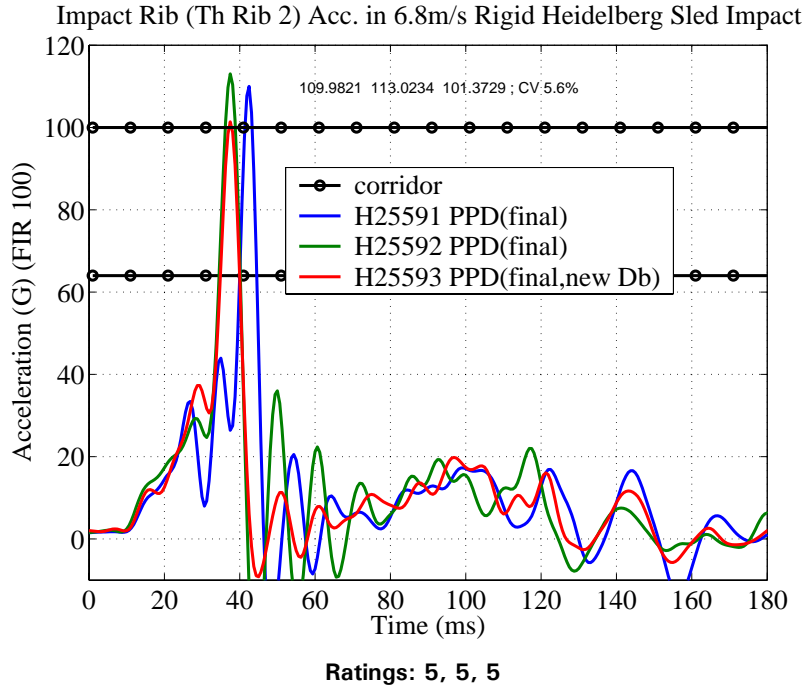


Figure A.15 — Thorax test 5 - rib acceleration

Table A.12 — Thorax test 5 - 6,8 m/s sled test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Thorax plate force (kN)	Plot	Plot	Plot	Plot	Plot	Plot	8	5,8
Rating			10	10	10	10,0		
Peak upper spine lateral acceleration (G)	82	122	N.M.	65	38	51,5	7	
Rating				5	0	2,5		
Peak lower spine lateral acceleration (G)	71	107	47	52	53	130,0	7	
Rating			5	5	5	5,0		
Peak lateral acceleration impacted rib (G)	64	100	110	113	101	108,0	6	
Rating			5	5	5	5,0		

A.4.6 Thorax test 6 – 8,9 m/s padded sled test

Shoulder and Thoracic Plate Force in 8.9m/s Padded WSU Sled Impact (15psi)

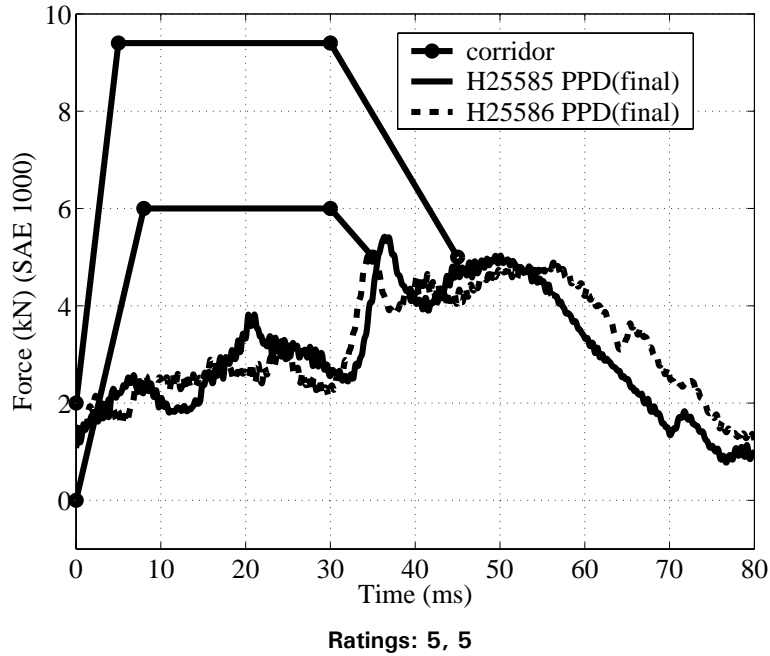


Figure A.16 – Thorax test 6 - shoulder and thoracic plate force

Shoulder and Thoracic Plate Force in 8.9m/s Padded WSU Sled Impact (23psi)

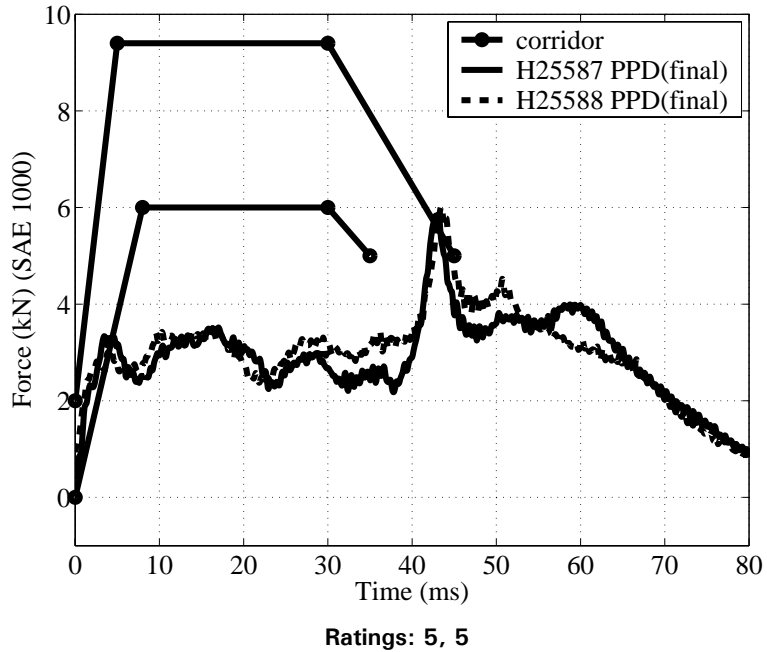


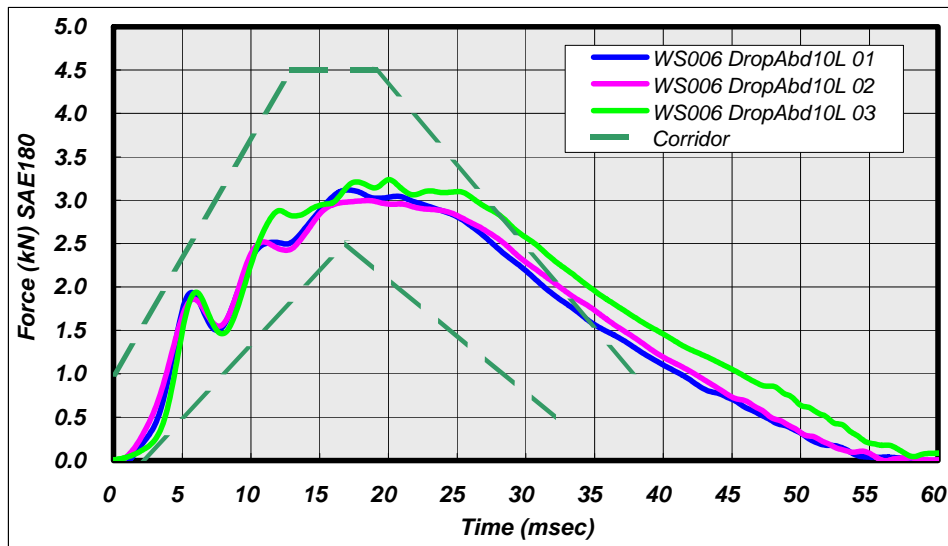
Figure A.17 – Thorax test 6 - shoulder and thoracic plate force additional results

Table A.13 – Thorax test 6 - 8,9 m/s sled test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Shoulder and thorax plate force (kN)	Plot	Plot	Plot	Plot	Plot	Plot	9	5,0
Rating			5	5	5	5,0		

A.5 Abdomen

A.5.1 Abdomen test 1 – 1,0 m drop onto rigid armrest test



Ratings: 10, 10, 10

Figure A.18 – Abdomen test 1 – armrest force

Table A.14 – Abdomen test 1 - 1 m rigid armrest test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Armrest force (kN)			See plot	See plot	See plot		9	8,6
Rating			10	10	10	10,0		
T12 lateral acceleration (G)	29	35	30	29	31	30	6	
Rating			10	10	10	10,0		
Peak acceleration of impacted rib (mm)	100	125	232	191	201	208	4	
Rating			0	0	0	0		
Abdomen penetration (mm)	41		55	55	58	56	9	
Rating			10	10	10	10,0		

A.5.2 Abdomen test 2

Abdomen test 2 is the same as test 1, except that the drop height is 2 m. Due to the severity of this test, the dummy ribs bottomed out during this test, making the data unusable.

A.5.3 Abdomen test 3 – 6,8 m/s rigid sled test

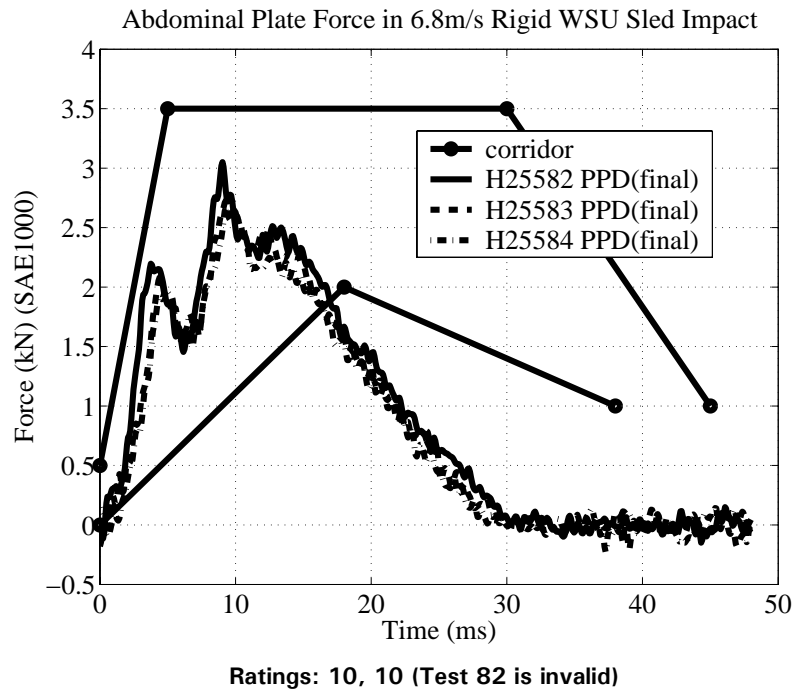


Figure A.19 – Abdomen test 3 - plate force

Table A.15 – Abdomen test 3 - 6,8 m/s plate force sled test results

Measure	Lower bound	Upper bound	Run			Weight factor	Rating
			#1	#2	Avg		
Abdomen plate force (kN)			See plot	See plot		9	10,0
Rating			10	10	10,0		

A.5.4 Abdomen test 4 – 8,9 m/s rigid sled test

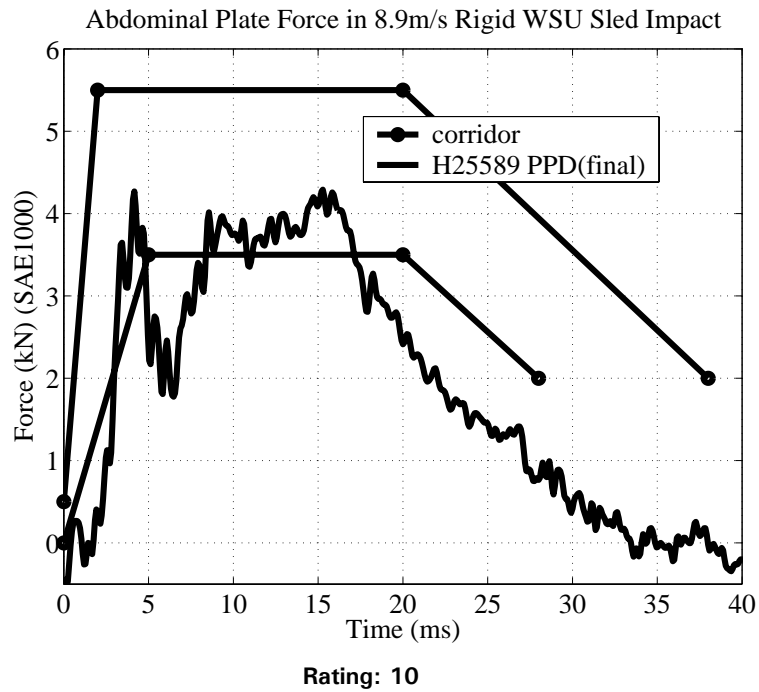


Figure A.20 – Abdomen test 4 - plate force

Table A.16 – Abdomen test 4 - 8,9 m/s rigid sled test results

Measure	Lower bound	Upper bound	Run		Weight factor	Rating
			#1	Avg		
Abdomen plate force (kN)			See plot		9	10,0
Rating			10	10,0		

A.5.5 Abdomen test 5 – 8,9 m/s padded sled test

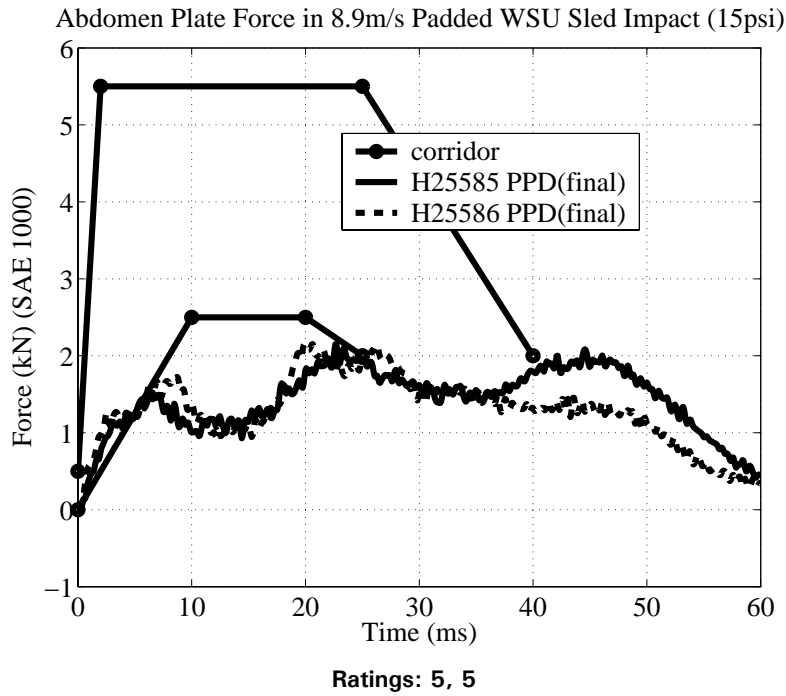


Figure A.21 – Abdomen test 5 - plate force

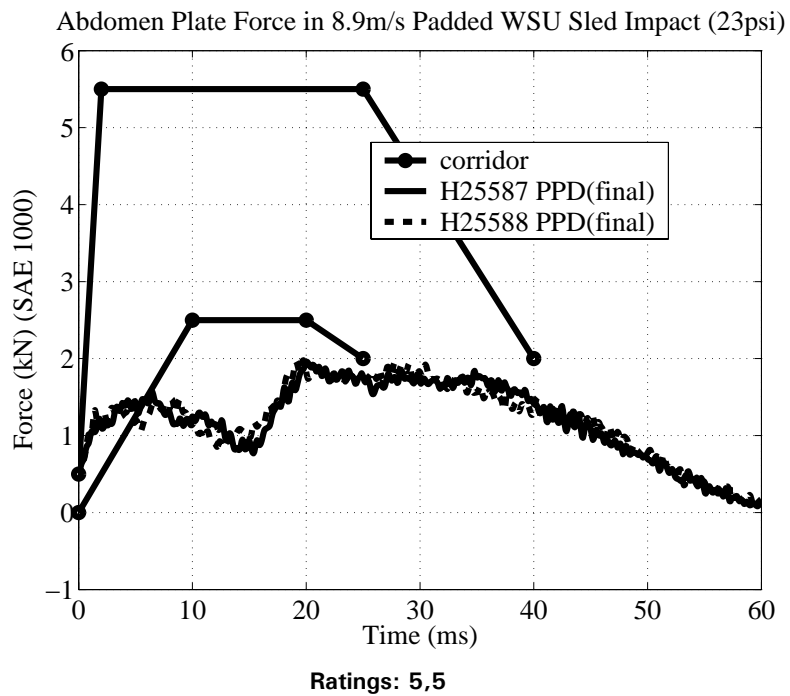


Figure A.22 – Abdomen test 5 - plate force additional results

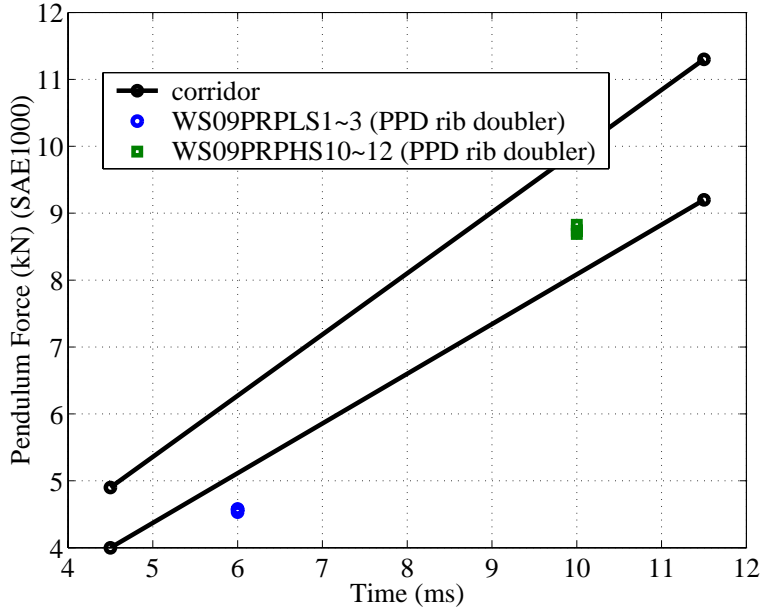
Table A.17 – Abdomen test 5 - 8,9 m/s sled test results

Measure	Lower bound	Upper bound	Run					Weight factor	Rating
			#1	#2	#3	#4	Avg		
Abdomen plate force (kN)			See plot	See plot	See plot	See plot		9	5,0
Rating			5	5	5	5	5,0		

A.6 Pelvis

A.6.1 Pelvis test 1 – 6,0 m/s pendulum test

Peak Pendulum Force in Pelvis Lateral Pendulum Test (right,6&10m/s)



Test 1 ratings: 5, 5, 5

Test 2 ratings: 10, 10, 10

Figure A.23 – Pelvis test 1 and 2 - pendulum force

Table A.18 – Pelvis test 1 – 6,0 m/s pendulum test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Pendulum force (kN)	Plot	Plot	Plot	Plot	Plot	Plot	9	5,0
Rating			5	5	5	5,0		

A.6.2 Pelvis test 2 – 10,0 m/s pendulum test

See Figure A.23.

Table A.19 – Pelvis test 2 - 10,0 m/s pendulum test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Pendulum force (kN)	Plot	Plot	Plot	Plot	Plot	Plot	9	10,0
Rating			10	10	10	10,0		

A.6.3 Pelvis test 3 – 0,5 m rigid drop test

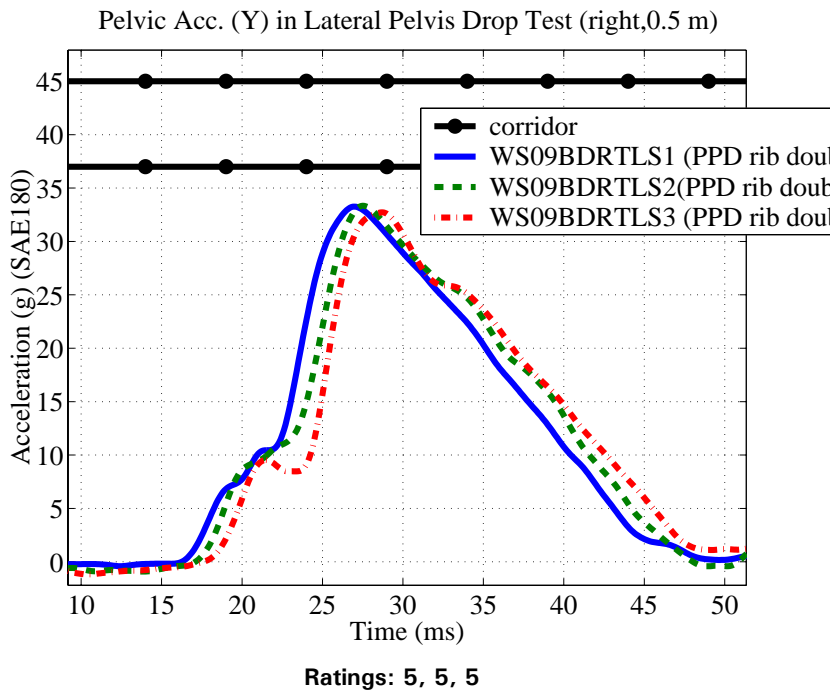


Figure A.24 – Pelvis test 3 - pelvis acceleration

Table A.20 – Pelvis test 3 - 0,5 m acceleration drop test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Peak pelvis acceleration (G)	37	45	33	33	32	32,7	7	5,0
Rating			5	5	5	5,0		

A.6.4 Pelvis test 4 – 1,0 m rigid drop test

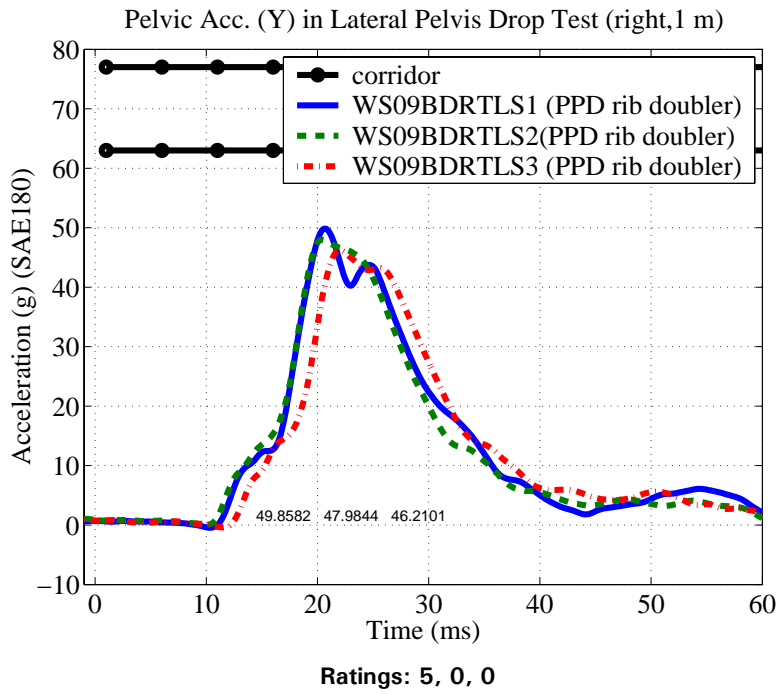


Figure A.25 – Pelvis test 4 - pelvis acceleration

Table A.21 – Pelvis test 4 – 1,0 m rigid drop test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Peak pelvis acceleration (G)	63	77	50	48	46	48,0	7	1,7
Rating			5	0	0	1,7		

A.6.5 Pelvis test 7 – 6,8 m/s rigid sled test

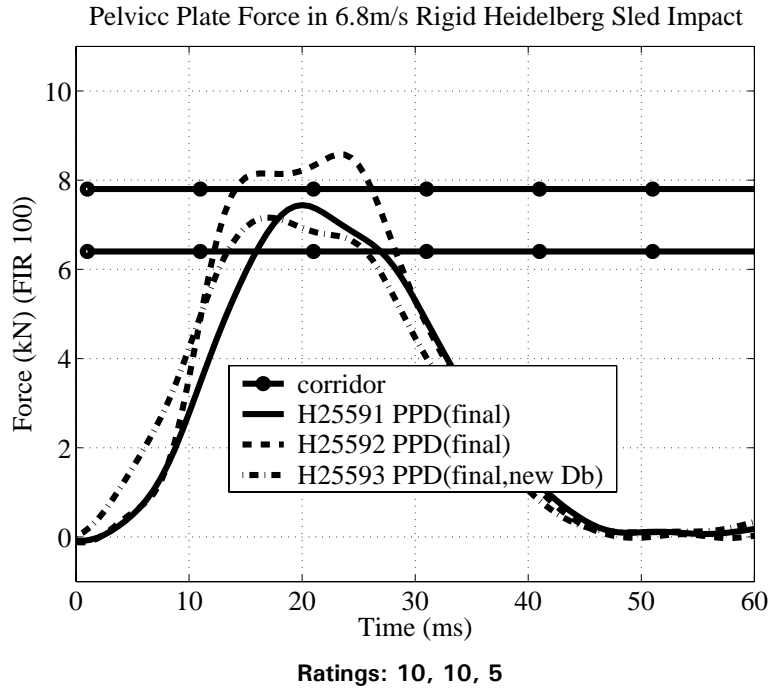


Figure A.26 – Pelvis test 7 - pelvis force

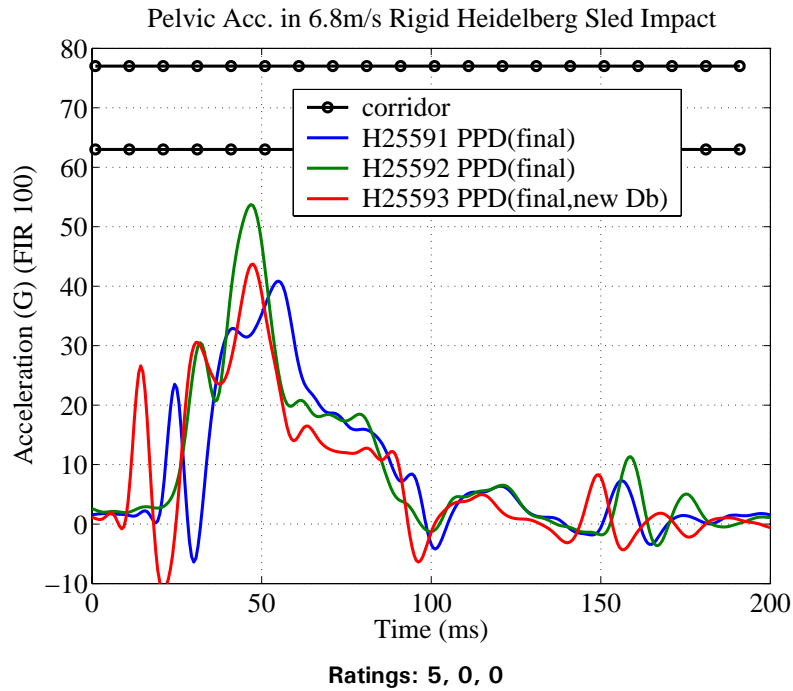


Figure A.27 – Pelvis test 7 - pelvis acceleration

Table A.22 – Pelvis test 7 - 6,8 m/s rigid sled test results

Measure	Lower bound	Upper bound	Run				Weight factor	Rating
			#1	#2	#3	Avg		
Pelvis plate force (kN)	6,4	7,8	7,4	8,6	7,2	7,7	9	5,4
Rating			10	5	10	8,3		
Peak pelvis acceleration (G)	63	77	41	54	44	46,3	7	
Rating			0	5	0	1,7		

A.6.6 Pelvis test 8 – 8,9 m/s rigid sled test

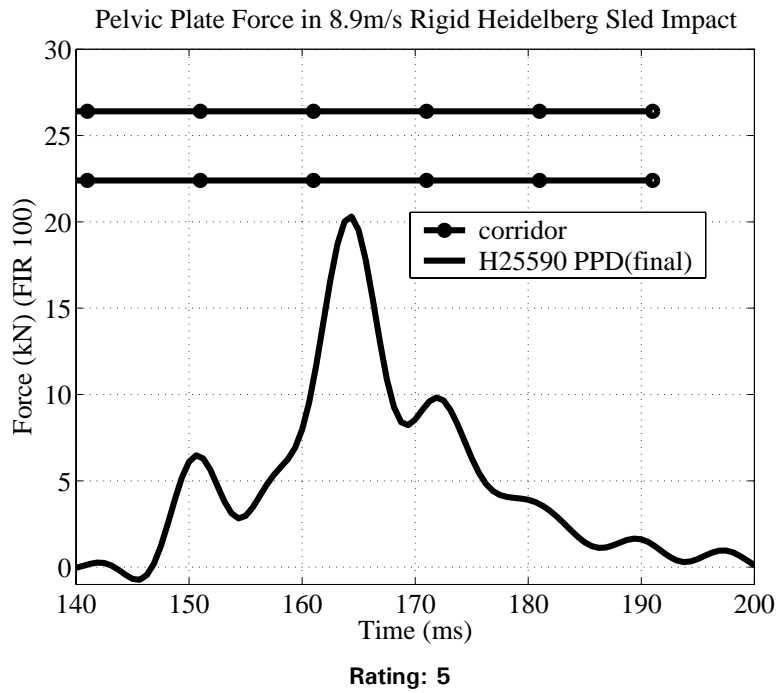


Figure A.28 – Pelvis test 8 - pelvis force

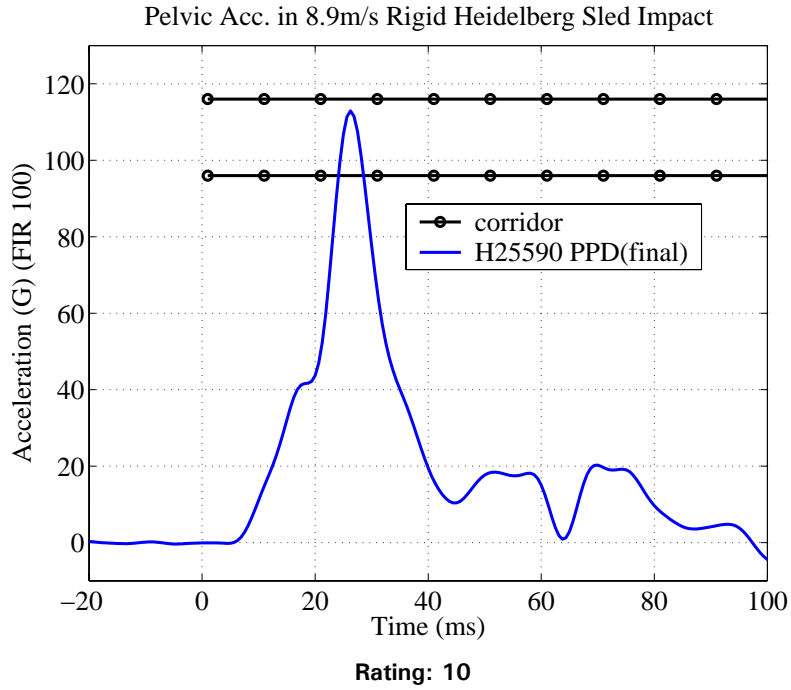


Figure A.29 – Pelvis test 8 - pelvis acceleration

Table A.23 – Pelvis test 8 - 8,9 m/s rigid sled test results

Measure	Lower bound	Upper bound	Run		Weight factor	Rating
			#1	Avg		
Pelvis plate force (kN)	22,4	26,4	20,0	20,0	8	7,3
Rating			5	5,0		
Peak pelvis acceleration (G)	96	116	113	113,0	7	
Rating			10	10,0		

A.6.7 Pelvis test 10 – 6,8 m/s Wayne State rigid sled test

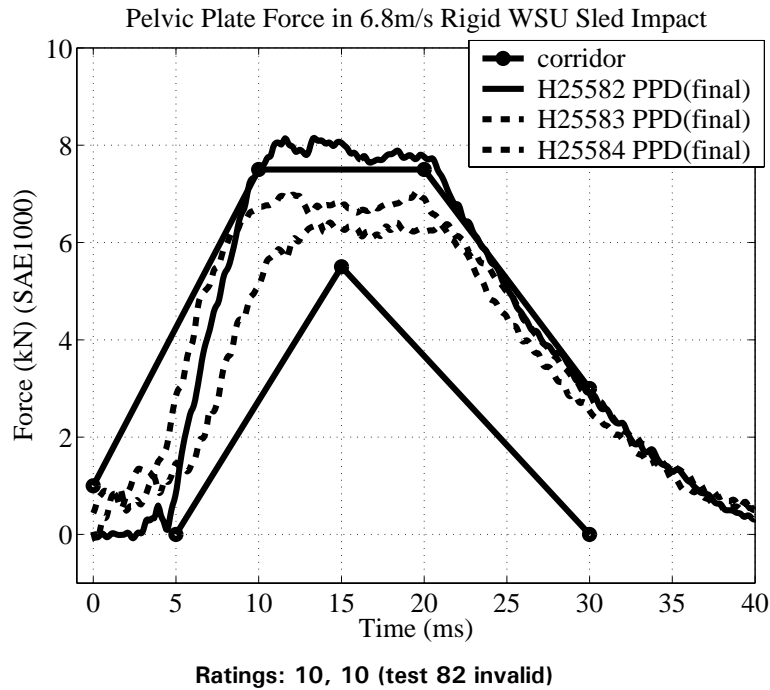


Figure A.30 – Pelvis test 10 - pelvis force

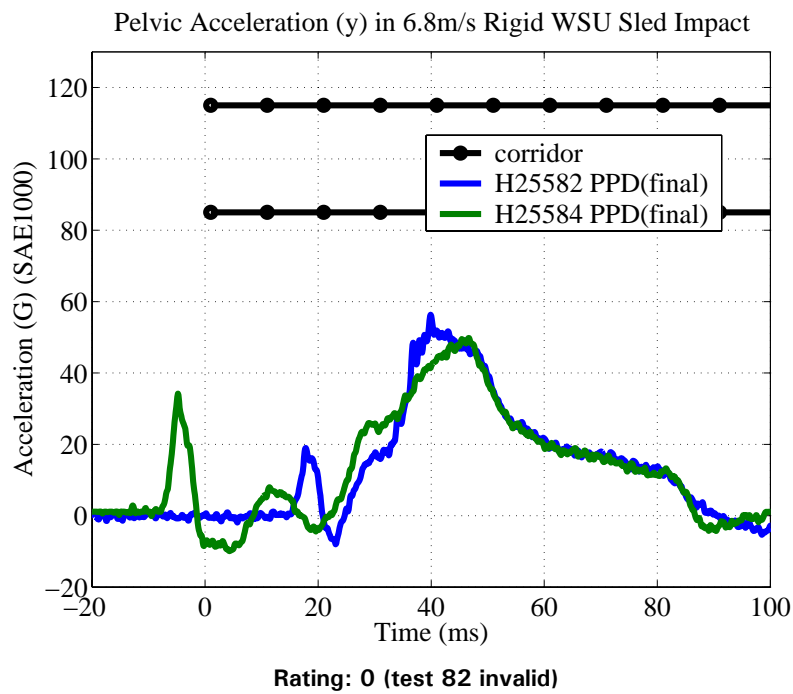


Figure A.31 – Pelvis test 10 - pelvis acceleration

Table A.24 – Pelvis test 10 - 6,8 m/s Wayne State rigid sled test results

Measure	Lower bound	Upper bound	Run			Weight factor	Rating
			#1	#2	Avg		
Pelvis plate force (kN)	Plot	Plot	Plot	Plot	Plot	9	5,6
Rating			10	10	10,0		
Peak pelvis acceleration (G)	85	115	-	50	50,0	7	
Rating			0	0	0,0		

A.6.8 Pelvis test 11 – 8,9 m/s Wayne State rigid sled test

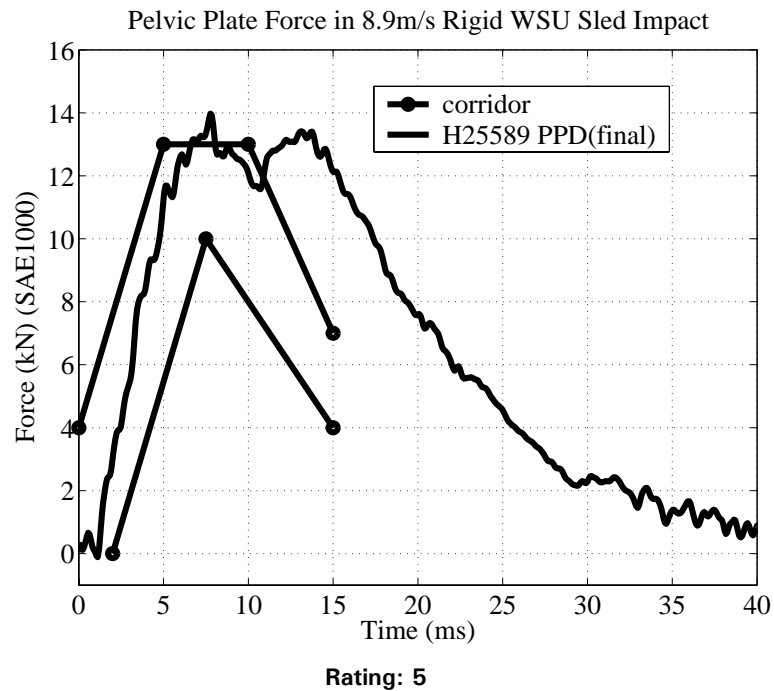


Figure A.32 – Pelvis test 11 - pelvis force

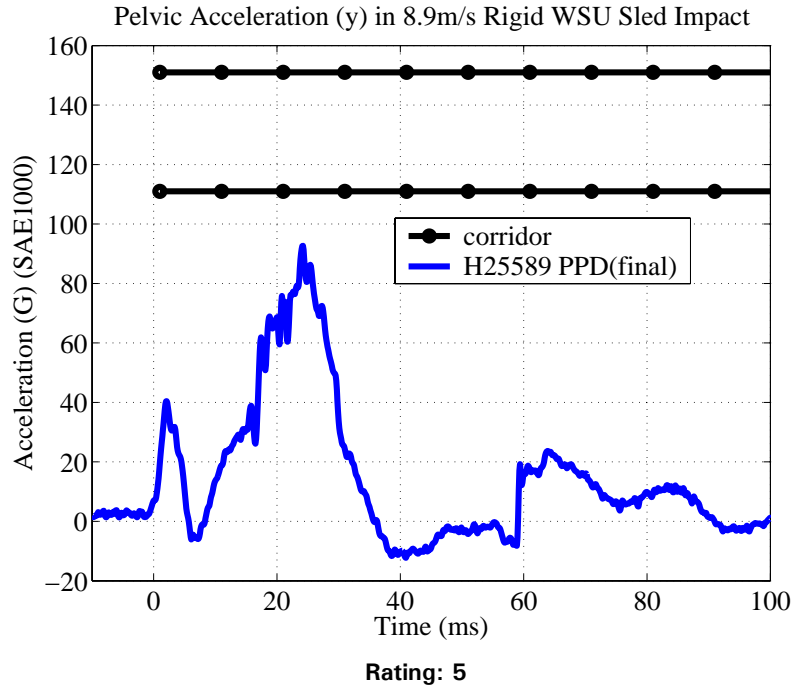


Figure A.33 – Pelvis test 11 - pelvis acceleration

Table A.25 – Pelvis test 11 – 8,9 m/s Wayne State rigid sled test results

Measure	Lower bound	Upper bound	Run		Weight factor	Rating
			#1	Avg		
Pelvis plate force (kN)	Plot	Plot	Plot	Plot	9	5,0
Rating			5	5,0		
Peak pelvis acceleration (G)	111	151	95	95,0	7	
Rating			5	5,0		

A.6.9 Pelvis test 12 – 8,9 m/s 0,1 N/mm² (15 psi) padded sled test

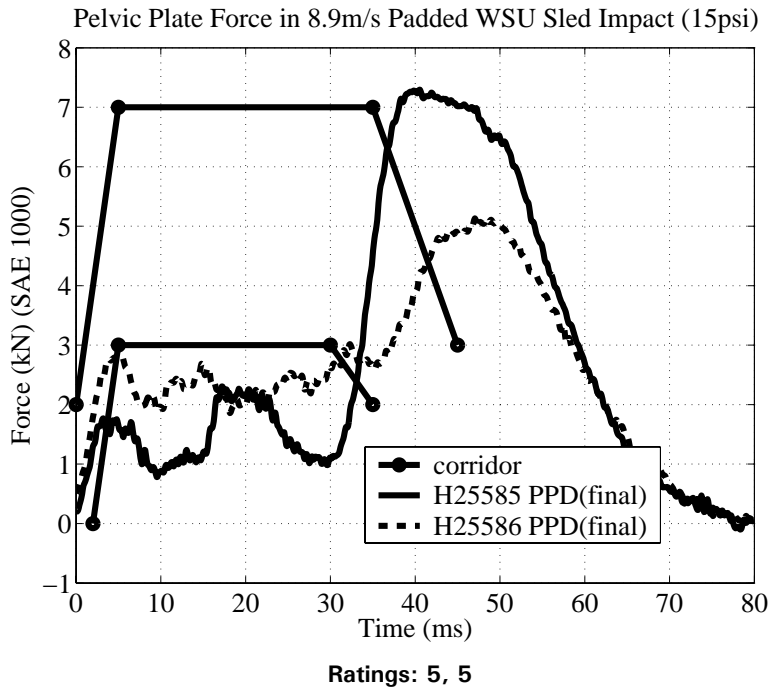


Figure A.34 – Pelvis test 12 - pelvis force

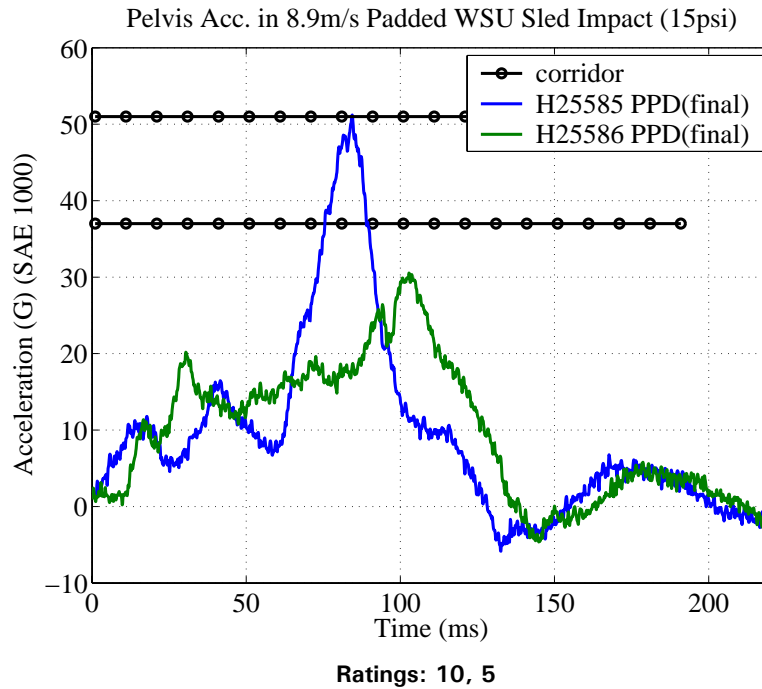


Figure A.35 – Pelvis test 12 - pelvis acceleration

Table A.26 – Pelvis test 12 – 8,9 m/s sled test results

Measure	Lower bound	Upper bound	Run			Weight factor	Rating
			#1	#2	Avg		
Pelvis plate force (kN)	Plot	Plot	Plot	Plot	Plot	9	6,1
Rating			5	5	5,0		
Peak pelvis acceleration (G)	37	51	51	31	41,0	7	
Rating			10	5	7,5		

A.6.10 Pelvis test 13 – 8,9 m/s 0,16 N/mm² (23 psi) padded sled test

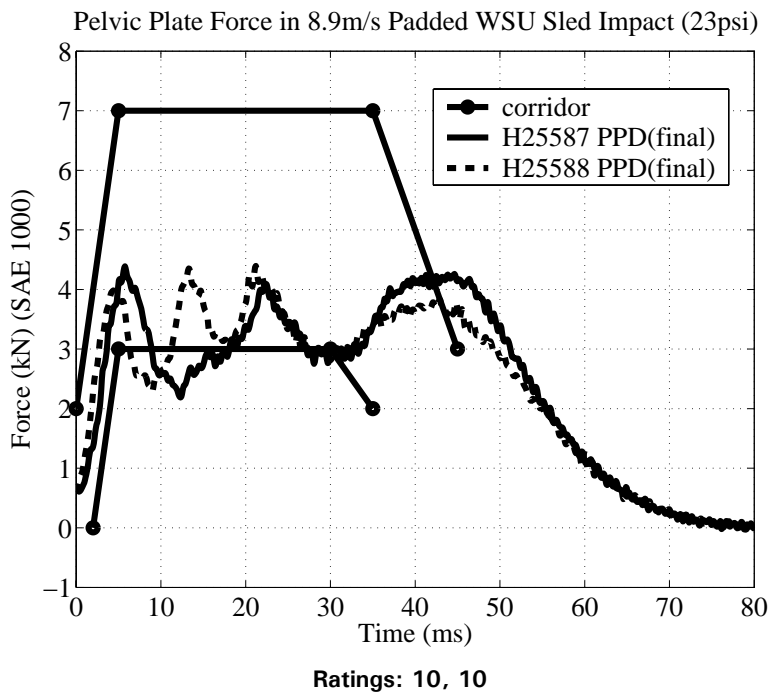


Figure A.36 – Pelvis test 13 - pelvis force

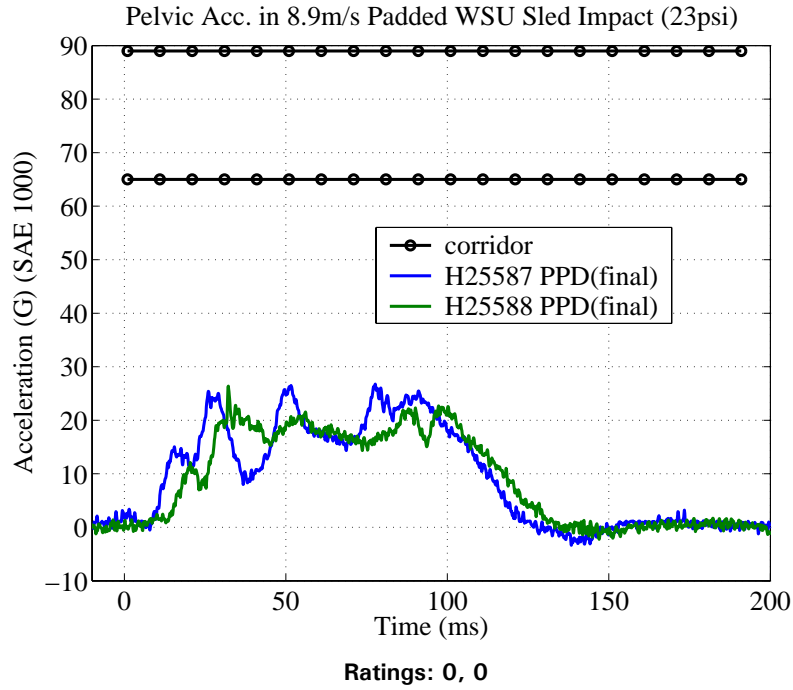


Figure A.37 – Pelvis test 13 - pelvis acceleration

Table A.27 – Pelvis test 13 – 8,9 m/s padded sled test results

Measure	Lower bound	Upper bound	Run			Weight factor	Rating
			#1	#2	Avg		
Pelvis plate force (kN)	Plot	Plot	Plot	Plot	Plot	9	5,6
Rating			10	10	10,0		
Peak pelvis acceleration (G)	65	89	27	27	27,0	7	
Rating			0	0	0,0		

A.7 Overall biofidelity rating

Table A.28 – Overall biofidelity rating

Body test number and test description	Test weighting, $V_{i,j}$	Test biofidelity
Head test 1 200 mm rigid drop	8	10,0
Head test 2 1200 mm padded drop	4	NM ^b
Head biofidelity, B1		10,0
Neck test 1 7,2 G sled impact	7	8,0
Neck test 2 6,7 G sled impact ^a	6	2,4
Neck test 3 12,2 G sled impact	3	6,6
Neck biofidelity, B2		5,6
Shoulder test 1 4,5 m/s pendulum	6	7,1
Shoulder test 2 7,2 G sled impact	5	8,3
Shoulder test 3 12,2 G sled impact	3	10,0
Shoulder test 4 8,9 m/s padded sled	7	5,0
Shoulder biofidelity, B3		7,1
Thorax test 1 4,3 m/s pendulum	9	10,0
Thorax test 2 6,7 m/s pendulum	9	10,0
Thorax test 3 1,0 m rigid drop	6	10,0
Thorax test 4 2,0 m padded drop	5	NM ^b
Thorax test 5 6,8 m/s rigid sled	7	5,8
Thorax test 6 8,9 m/s padded sled	7	5,0
Thorax biofidelity, B4		8,3
Abdomen test 1 1,0 m rigid drop	7	8,6
Abdomen test 2 2,0 m rigid drop	6	NM ^b
Abdomen test 3 6,8 m/s rigid sled	3	10,0
Abdomen test 4 8,9 m/s rigid sled	3	10,0
Abdomen test 5 8,9 m/s padded sled	7	5,0
Abdomen biofidelity, B5		7,8
Pelvis test 1 6,0 m/s pendulum impact	8	5,0
Pelvis test 2 10,0 m/s pendulum impact	9	10,0
Pelvis test 3 0,5 m rigid drop	4	5,0
Pelvis test 4 1,0 m rigid drop	4	1,7
Pelvis test 5 2,0 m padded drop	3	NM ^b
Pelvis test 6 3,0 m padded drop	5	NM ^b
Pelvis test 7 6,8 m/s rigid sled	8	5,4

Body test number and test description	Test weighting, $V_{i,j}$	Test biofidelity
Pelvis test 8 8,9 m/s rigid sled	7	7,3
Pelvis test 9 8,9 m/s padded sled	8	NM ^b
Pelvis test 10 6,8 m/s rigid sled	3	5,6
Pelvis test 11 8,9 m/s rigid sled	3	5,0
Pelvis test 12 8,9 m/s 15 psi padded sled	3	6,1
Pelvis test 13 8,9 m.s 23 psi padded sled	7	5,6
Pelvis biofidelity, B6		6,1
WorldSID overall biofidelity, B		7,6
a	Data from prototype revision 1 testing	
b	Not measured	