BIOFIDELITY OF THE WORLDSID SMALL FEMALE REVISION1 DUMMY

Andre Eggers
Britta Schnottale
Federal Highway Research Institute, BASt
Germany
Bernard Been
Kees Waagmeester
First Technology Safety Systems Europe
The Netherlands
David Hynd
Jolyon Carroll
TRL limited
United Kingdom
Luis Martínez
University Institute for Automobile Research, Polytechnic University of Madrid (UPM-INSIA)
Spain
Paper Number 09-0420

ABSTRACT

In the EC FP6 Integrated Project Advanced Protection Systems, APROSYS, the first WorldSID small female prototype was developed and evaluated by BASt, FTSS, INRETS, TRL and UPM-INSIA during 2006 and 2007. Results were presented at the ESV 2007 conference (Been *et al.*, 2007). With the prototype dummy scoring a biofidelity rating higher than 6.7 out of 10 according to ISO/TR9790, the results were very promising. Also opportunities for further development were identified by the evaluation group.

A revised prototype, Revision1, was subsequently developed in the 2007-2008 period to address comments from the evaluation group. The Revision1 dummy includes changes in the half arms and the suit (anthropometry and arm biomechanics), the thorax and abdomen ribs and sternum (rib durability), the abdomen/lumbar area and the lower legs (mass distribution). Also a two-dimensional chest deflection measurement system was developed to measure deflection in both lateral and anterior-posterior direction to improve oblique thorax loading sensitivity. Two Revision1 prototype dummies have now been evaluated by FTSS, TRL, UPM-INSIA and BASt. The updated prototype dummies were subjected to an extensive matrix of biomechanical tests, such as full body pendulum tests and lateral sled impact tests as specified by Wayne State University, Heidelberg University and Medical College of Wisconsin.

The results indicated a significant improvement of dummy biofidelity. The overall dummy biofidelity in the ISO rating system has significantly improved from 6.7 to 7.6 on a scale between 0-10. The small female WorldSID has now obtained the same biofidelity rating as the WorldSID mid size male dummy. Also repeatability improved with respect to the prototype. In conclusion the recommended updates were all executed and all successfully contributed in achieving improved performance of the dummy.

INTRODUCTION

Side impact is still one of the predominant causes of serious or fatal road accidents. A recent study analysing the national accident datasets of the UK, France and Sweden showed that side impacts typically represent 33% of all fatalities in these countries (Thomas *et al.*, 2009).

For evaluation and improvement of new and advanced occupant protection technologies anthropometric test dummies specifically designed for side impact testing have proven to be very useful. However, several different types of side impact dummies exist, which are used in various regulations and consumer tests.

The introduction of a family of worldwide harmonised side impact dummies to be used for vehicle safety development could contribute to an increased efficiency of vehicle safety development by enabling safety system designers to focus on a single set of objectives.

In a first step to address the need for worldwide harmonised side impact dummies the WorldSID 50% adult male was developed. Newland *et al.* (2005) showed, based on analysis of worldwide accident data, the importance of having also a small adult female test device for assessment of vehicle safety available. According to Newland's study done within IHRA, the proportions of male and female severely or fatally injured occupants in vehicle-to-vehicle crashes were either similar or slightly predominated by females (up to 60%) in some regions.

To address this need a prototype of a small female WorldSID was developed within the European FP6 project APROSYS to complete the family of worldwide harmonised side impact dummies with similar design, instrumentation and functional handling.

In order to accurately predict injuries of human occupants based on tests with these dummies biofidelity is crucial. The biofidelity of the WorldSID small female prototype was assessed earlier and reported by Been *et al.* (2007). The biofidelity of the prototype was already very good. Taking into account recommendations from prototype testing an updated version, the Revision1, was developed.
The objective of the study reported in this paper was to repeat the tests for biofidelity assessments and to analyse the effects of the dummy updates. The modifications, which were made based on recommendations from the prototype testing, are explained. The results of the biofidelity tests are presented and compared to the results of the prototype evaluation.

SMALL FEMAL REVISION1: DUMMY MODIFICATIONS

The dummy requirements and design specifications of the small female WorldSID prototype dummy were described in detail by Been *et al.* (2007). Therefore in this paper only modifications of Revision1 will be explained below.

Anthropometry

Recommendations were given to increase the abdomen mass and reduce the lower leg mass by the same amount of 1.2 kg total (Martínez et al., 2007). New tibia bones were installed, with the mass of each tibia reduced by 0.6 kg; the abdomen was ballasted with a high density metal lumbar bracket. Further mass increase in the thorax and abdomen was achieved with 2D IR-Traccs and the addition of damping material on the ribs. The WorldSID small female Revision1 dummy now represents the target body segment mass distribution and overall mass (see Table 1. In this table it should be noted that the difference in sub-total body segment comes from the shoe. The shoe is part of the foot and dummy and the sub-total. In the anthropometry reference the shoe is outside the sub-total an included only in the total. Further small differences may occur due to the fact that anthropometric section planes sometimes do not match dummy sub-assemblies.
The half arm length was increased by 40 mm to get closer to the human target length. However it was decided not to increase the arm length fully to the length of the human target to stay clear from the iliac wing. An arm contact on the iliac wing during testing would cause the arm to bridge between the shoulder and the iliac wing and so reducing the loads on the thorax and abdomen ribs. The total arm length from the shoulder joint to the bottom of the half arm is 240 mm. The small female anthropometric dummy target gleno-humeral joint to elbow joint distance is 255 mm.

Table 1.
Mass comparison Revision1 to target

Body segment [kg]	Target (Schneider et al. 1983)	WorldSID 5F Rev1
Head	3.70	3.66
Neck	0.60	0.54
Thorax including half arms and 2D IR-Traccs	15.23	15.81
Abdomen	1.61	1.33
Pelvis	6.98	6.98
Upper legs	11.83	11.83
Lower legs, feet & shoes	6.00	6.61
Sub Total	**45.94**	**46.75**
Suit	1.52	1.52
Pair of shoes	0.64	-
Total	**48.10**	**48.27**

Instrumentation

The major update in instrumentation was the integration of a two-dimensional chest deflection measurement system to measure deflection in both lateral and anterior-posterior direction. The calculation of deformation components in the different plane was possible by additional angular sensors in the thorax and abdomen ribs. More details on the design and performance of this 2D IR-Traccs can be found in the ESV paper by Been *et al.* (2009).
During this test series the two dummies were not fully instrumented as not enough sensors were available for full instrumentation at this stage.
The instrumentation of the WorldSID 5th female dummies as it was used in most of the tests reported in this paper is given in Table 2.

Table 2.
Instrumentation of WorldSID small female Rev1

Segment	Parameter	Nr.
Head	Acceleration ($a_{x,y,z}$)	3
Neck	Upper loads ($F_{x,y,z}$, $M_{x,y,z}$)	6
Shoulder	Loads ($F_{x,y,z}$)	3
	Deflection (δ_y)	1
Thorax/Abdomen	T1 acceleration ($a_{x,y,z}$)	3
	T12 acceleration ($a_{x,y,z}$)	3
	Rib deflection (δ_y)	5
	Rib acceleration (a_y)	5
	Rib rotation(φz)	5
Pelvis	Pubic loads (F_y)	1
	Acceleration ($a_{x,y,z}$)	3
Femur	Femoral neck load ($F_{x,y,z}$)	3
	Femur load ($F_{x,y,z}$ $M_{x,y,z}$)	6

EVALUATION METHODOLOGY

Biofidelity evaluation method

As a basis for evaluation of the biofidelity of the WorldSID 5th female Revision1 the response requirements as specified in ISO Technical Report TR9790 (ISO, 1997) for lateral biofidelity were scaled for 5th female according the formulas specified by Irwin *et al.* (2002).

To achieve similar force plate interaction with the small female dummy as the original PMHS test set up, the force plates in the sled test conditions were scaled according to the method prescribed by Ferichola *et al.* (2007). ISO Technical Report 9790 includes a large set of dynamic biofidelity performance specifications for the head, neck, shoulders, thorax, abdomen and pelvis of a 50^{th} percentile side impact dummy.

In this study a subset of the ISO test conditions was conducted, selected on the basis of the highest weighting factor. Some of the tests described in the ISO Technical Report 9790 were not performed because of a high risk of damaging the dummy.

In contrary to the prototype test, normalisation was not applied for the Revision1 tests for the assessment in ISO TR9790. Normalisation is not prescribed for ISO corridors, as the dummy is considered to perfectly represent the target anthropometry pertaining to the corridors.

In addition full body sled tests of the NHTSA configuration were conducted to evaluate the dummy against PMHS tests of Yoganandan *et al.* (2005). The NHTSA sled test conditions are not part of the ISO TR9790 biofidelity test conditions and rating system. ISO/TC22/SC12/WG5 is currently working on adopting the NHTSA sled test conditions in ISO TR9790 for the mid size male anthropometry and apply the ISO method for corridor construction to the data set. NHTSA applies a biofidelity rating using Cumulative Variance (Rhule *et al.*, 2002) on this data set. The NHTSA test conditions are part of the NHTSA biofidelity requirements to assess the response of Side Impact Dummies of the mid-size male anthropometry. Yoganandan *et al.* (2005) derived small female responses from the NHTSA sled test database by mass scaling to small female anthropometry. This data set is likely to be adopted by NHTSA for evaluation of small female side impact dummies. The data set has response corridors for external load as well as dummy internal acceleration and deflection.

The biofidelity assessment of rib deflection was done by a comparison of chest band data from the PMHS tests (Figure 2) to calculated dummy signals. The 2D deflection sensor of the small female WorldSID, 2D IR-Tracc, allows calculating the displacement of the ribs in the X-Y (transversal) plane of the dummy from the compression and rotation angle of the IR-Tracc (for details see Been *et al.*, 2009). Two parameters could be useful for assessment of rib deflection, the parameter 'Calculated Y displacement' and 'R resultant displacement' (Figure 1). As illustrated in Figure 2 the calculated Y displacement could be a good match with what was originally measured in the PMHS with the chest bands. The resultant deflection R might be an overestimation of the rib deflection with respect to the original data, getting larger with more forward or rearward displacement in the dummy's chest. For the biofidelity evaluation of the chest deflection response of the dummy, the resultant displacement and calculated lateral displacement Y were both applied for comparison with Yoganandan (2005) PMHS data.

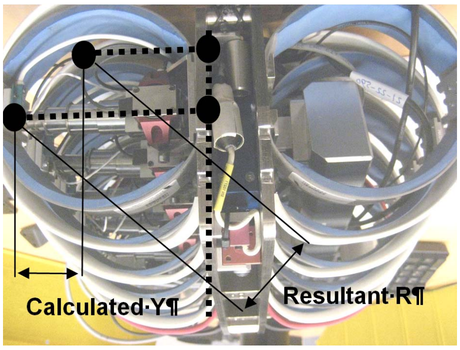


Figure 1: Deflection parameters R and Y calculated from deflection and angle measured with 2D IR-Traccs.

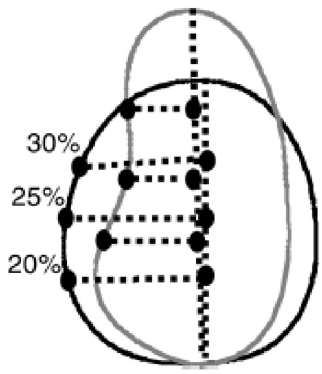


Figure 2: Computation method half-thorax deflection from PMHS testing instrumented with chest band. Source: Yoganandan, (2005).

Repeatability

ISO/TC22/SC12/WG produced a paper on how to assess repeatability and reproducibility of a dummy (ISO, 2004). Repeatability is defined as the variations in measured responses of a single dummy that is subjected to a set of identical tests. Reproducibility is defined as the variations in measured responses of two or more dummies of the same design that are subjected to sets of identical tests. The document describes the calculation methods and acceptance levels for assessing repeatability and reproducibility of a dummy design.

Requirement: Repeatability CV ≤ 7%: repeat tests with the same dummy N times, then the standard deviation (σ) divided by the average of selected measurements should not exceed 7%.
Requirement: Reproducibility CV ≤ 10%: repeat tests with different dummies, then the standard deviation divided by the average of selected measurements should not exceed 10%.

Test matrix

Like in the test programme with the prototype dummy not the complete set of ISO TR9790 tests was performed. Also some of the NHTSA sled test configurations (e.g. high velocity, thorax offset) had to be omitted due to high risk in terms of dummy damage.
Also not all test configurations reported by Been *et al.* (2007), which were done with the prototype dummy were repeated with the Revision1 dummy due to time restrictions and the need to limit the risk to the dummy. The test matrix relevant for biofidelity and repeatability evaluation of this study is provided in Table 3.

Table 3.
Test matrix WorldSID 5th Revision1 for evaluation of biofidelity and repeatability

Test type	Test configuration	No. of tests	Biofidelity assessment: Head	Shoulder	Thorax	Abdomen	Pelvis
Drop tests	200 mm rigid lateral head drop	4	x				
	376 mm forehead rigid drop	2	x				
Pendulum Tests	4.5 m/s, shoulder	3		x			
	HSRI, 4.3 m/s, lateral, thorax	3			x		
	WSU, 4.3 m/s, lateral, thorax	3			x		
	WSU, 4.3 m/s, oblique, thorax	3			x		
	WSU, 6.0 m/s, oblique, thorax	3			x		
	6.0 m/s, pelvis	4					x
	8.0 m/s, pelvis	3					x
Sled tests	WSU, 6.8 m/s, rigid wall	3				x	x
	WSU, 8.9 m/s, padded foam	3		x	x	x	x
	WSU, 8.9 m/s, paper honeycomb	3		x	x	x	x
	Heidelberg, 6.8 m/s, rigid wall	3			x		
	NHTSA/MCW, 6.7 m/s padded flat wall	5			x	x	x
	NHTSA/MCW, 6.7 m/s rigid flat wall	3			x	x	x
	NHTSA/MCW, 6.7 m/s padded pelvis offset	4			x	x	x
	NHTSA/MCW, 6.7 m/s rigid pelvis offset	3			x	x	x

RESULTS

In the following the results regarding biofidelity and repeatability will be shown per body segment.

Head

The head biofidelity was evaluated by drop testing according ISO TR9790 with 200 mm lateral drop and a 376 mm drop on the forehead. ISOTR9790 prescribes a resultant linear acceleration on the non struck side of the head on a lateral axis passing through the head centre of gravity (CG). No such instrumentation is available, as the WorldSID accelerometer is located at the head centre of gravity. The numbers given in Table 4 are obtained by calculation of the resultant linear acceleration on the non struck side of the head from the accelerations at head CG and rotational acceleration. The frontal drop test results of 2005 were slightly below the corridor. The tests were repeated with two heads of the same build level. The results are given in Table 4. Both heads now pass the frontal as well as the lateral biofidelity corridors. The prototype failed the frontal test. The overall biofidelity of the head is now 10. The results have increased about 8 g for the lateral tests and about 15 G for the frontal tests. The results show an excellent repeatability. The coefficient of variation is 2.5% or less for all accelerations.

Table 4.
Results head drop tests

Condition	Revision1 Resultant acc. [*g*] CoG	Revision1 Resultant acc. [*g*] non struck	Prototype Resultant acc. [*g*] CoG	Prototype Resultant acc. [*g*] non struck	Corridor
Lateral	127	152	120	139.5	107-161
Lateral	126	151	119	135.9	
Lateral	128	151	-	-	
Lateral	132	154	-	-	
Frontal	261	NA	244	NA	250-300
Frontal	260	NA	236	NA	

Neck

The biofidelity tests for the neck component were conducted with the prototype dummy. The neck was not changed for the Revision1 prototype and the tests were not repeated. Based on recommendations (Been *et al.*, 2007), new corridors were developed based on a new scaling method. This method and pertaining corridors shall be submitted to ISO/TC22/SC12/WG5 for consideration, however strictly speaking ISO only have published 50th percentile male response corridors (ISO, 1997).
In this report the new head-neck corridors were applied to the prototype responses. The head neck response of the Revision1 dummy may slightly have changed due to the changes in the shoulder and half arm. It is anticipated that the T1 acceleration would increase due the increased stiffness of the arm and the sternum, providing more support from the entire thorax in this test. The results are given in Table 5. The results in this table deviate from those published by Meijer *et al.* (2008). When these tests were conducted, the results of the first test were not satisfactory. The test set-up was slightly changed to obtain better shoulder interaction with the impact

panel of the sled. Therefore the results of the first test were omitted in the current report. Further the peak horizontal acceleration was rounded from 11.9 to 12, bringing the response just into the corridor. The conclusions from the reference report are taken over in this report.

From the comparison of the dummy responses and the new corridors the following dummy measures are proposed to further improve the head-neck responses:

1. The head flexion angle may be reduced by installing stiffer neck buffers in the lateral position. This will reduce the head angle and may improve the rating.
2. The neck twist response may be improved by replacing the rear square neck buffers with a circular one, which is similar to the ones used in lateral positions. The twist motion may be doubled by this measure, with a potential to approach the lower boundary of 32° and increasing the score from 0 to 5. The change will have no significant effect on the lateral response.
3. Human necks are more flexible in neck extension (backward bending) then in flexion. The frontal response has not been validated so far, but a change to the rear neck buffer will not affect the frontal response. It is recommended to assess frontal biofidelity according to Mertz OC angle moment relationship (Mertz and Patrick, 1971).

It is recommended to apply above mentioned changes and repeat neck test 1 with Revision1 updated dummy to review its response to the newly develop corridors.

Table 5.
Head-neck responses and biofidelity rating prototype dummy in new corridors

						Boundary			Ratings				Biofidelity	
Body region	Ui	Impact condition	Vij	Measurement	Wijk	Lower	Upper	Unit	test 1	test 2	test 3	Average	Impact	**Test**
Neck	6	7.2 g sled	7	Peak horizontal Acc T1	5	12	18	G		5	10	7.5	37.5	
test 1		impact		Peak hor. Displ. T1/sled	5	38	51	mm		5	5	5.0	25	
		NBDL		Peak hor. Displ. head cg/t1	8	116	145	mm		5	5	5.0	40	
				Peak vert. Displ. Head CG/T1	6	57	84	mm		10	10	10.0	60	
				Time of max head excursion	5	0.142	0.157	s		5	5	5	25	
				Peak lateral Acc head cg	5	9	12	G		10	10	10	50	
				Peak vertical Acc head cg	5	9	11	G		10	10	10	50	
				Peak flexion angle	7	44	59	deg		5	5	5	35	
				Peak twist angle	4	-32	-45	deg		0	0	0.0	0	
				Peak OC lateral bending moment	non ISO	26	43	Nm		5	5	5.0		
				Peak OC torsion twist moment	non ISO	10	17	Nm		5	5	5.0		
					50								323	**6.5**

Shoulder

The biofidelity of the shoulder response was evaluated by three pendulum tests and six WSU type sled test of two different configurations.

Figure 3 shows the impact force which is not completely inside the corridor. The shoulder deflection (Figure 4) is within the corridor for the pendulum test and also the NBDL sled test results were improved. In the WSU 8.9 m/s padded sled impact (Figure 5) the shoulder and thorax beam force is inside the corridors for two tests and in one test the response is very close to scoring 10 points.

Table 6 gives the biofidelity rating of the individual shoulder tests. Overall shoulder biofidelity has significantly improved from 5.0 to 7.4 and meets the target of ISO BR>6.5, good biofidelity.

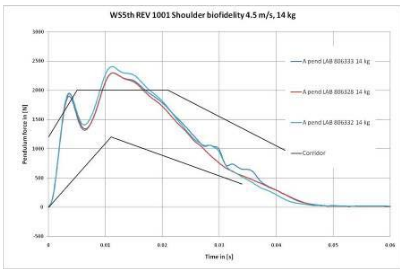


Figure 3. Shoulder impact force, 4.5 m/s, 14 kg.

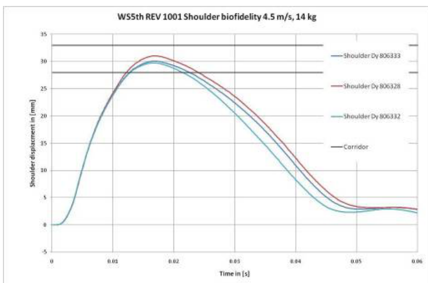


Figure 4. Shoulder deflection, 4.5 m/s, 14 kg shoulder impact.

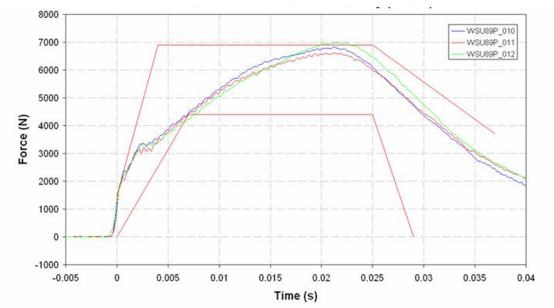


Figure 5. WSU 8.9 m/s, padded foam, shoulder and thorax forces.

Table 6.
ISO TR9790 biofidelity score for shoulder tests

Body region	Ui	Impact condition	Vij	Measurement	Wijk	Lower	Upper	Unit	test 1	test 2	test 3	Average	Impact	Test	Test condi	Body region
Shoulder	5	4.5 m/s	6	Pendulum force-time	8	force time corridor			5	5	5	5.0	40			
test 1		APR		Pendulum Force		1.2	2	kN								
		pendulum		Peak shoulder deflection	6	28	33	mm	10	10	10	10.0	60			
					14								100	**7.1**	42.9	
test 2		7.2 G sled	5	Peak horizontal Acc T1	6	15	22	G		5	10	7.5	45			
		sled		Peak hor. Displ. T1/sled	6	38	51	mm		5	5	5.0	30			
		NBDL			12								75	**6.3**	31.3	
test 4		8.9 G	7	shoulder + thoracic plate force	9	force time corridor			10	10	5	8.3	75			
		WSU sled				4.4	6.9	kN								
		23 PSI padded			9								75	**8.3**	58.3	
			18												132	**7.4**

Thorax

To assess the thorax biofidelity of the WorldSID 5th female Revision1 prototype dummy, four different pendulum and seven sled test configurations were conducted.

Thorax: Pendulum Tests - Thorax Test set-up similarly to the original WSU tests are shown in Figure 6 and Figure 7.

Figure 6 shows the force responses of the 4.3 m/s WSU lateral thorax pendulum test. The responses are close to the upper corridor limit. In the 6.0 m/s test the peak force is above the upper limit of the corridor and the duration of the response is shorter than that of the corridor (Figure 7).

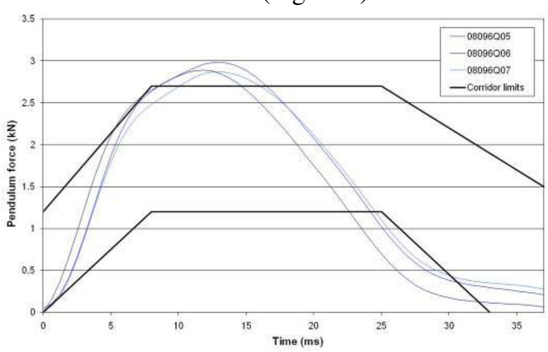


Figure 6. 4.3 m/s, 14 kg, pendulum force responses using lateral WSU setup, ISO corridor

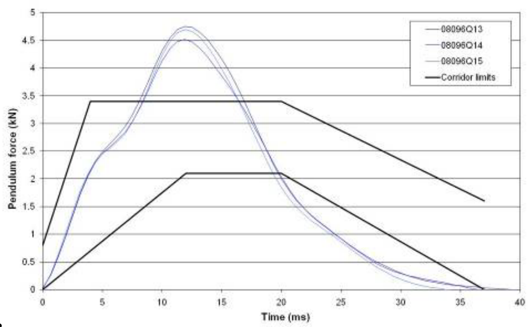


Figure 7. 6.0 m/s, 14 kg, pendulum force response, ISO corridor

Thorax: Sled Tests - Thorax plate forces from Heidelberg sled tests are shown in Figure 8 and Figure 9. Peak forces are shown in Table 7. Even though the plate force response just goes out of the corridor, the general shape better looks more similar to the corridor. However, according to the ISO rating the prototype showed a better performance. The repeatability was good in this test as the CV values in Table 7 show.

Figure 10 shows the shoulder plus thorax response from WSU sled tests along with the ISO corridors. In one test the forces were completely within the corridor, in the other two tests the signals were almost completely within the limits. Compared to the prototype tests, the biofidelity of thorax plate forces in this test configuration have been improved considerably.

Table 7.
Peak thorax plate force results

		Biofidelity target		Prototype results		Revision1 results	
		Lower limit (kN)	Upper limit (kN)	Peak values (kN)	Coefficient of variation (%)	Peak values (kN)	Coefficient of variation (%)
Thorax plate force	EEVC normalisation	7.2	12.1	7.9	4.9	10.5	4.3
				8.0		9.9	
				8.7		9.7	
	ISO normalisation	3.7	12.4	8.0	4.9	10.6	4.3
				8.1		10.0	
				8.8		9.8	

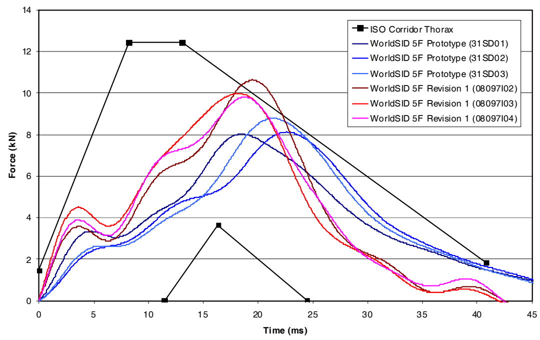


Figure 8. Heidelberg. 6.8 m/s ,Thorax force plates - ISO corridors

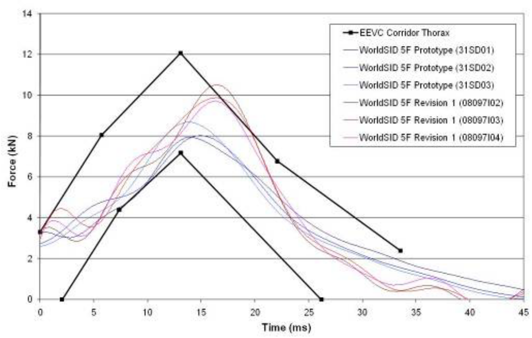


Figure 9. Heidelberg, 6.8 m/s, Thorax force plates - EEVC corridors

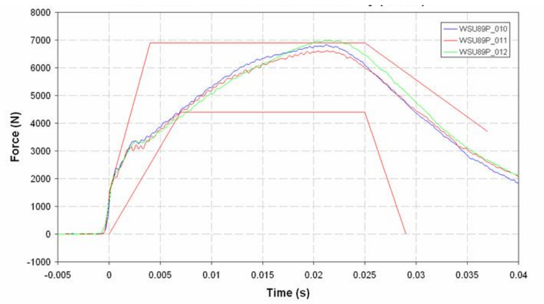


Figure 10. WSU, padded 8.9 m/s – Shoulder plus thorax beam force

Thorax: Biofidelity Rating According to ISO
The thorax biofidelity rating is given in Table 8. The thorax rating is significantly improved from 5.6 for the prototype to 6.9 for the Revision1 prototype and meets the target of ISO BR>6.5 good biofidelity. The external load responses of the Revision1 prototype dummy are generally within or just outside the upper corridors of the ISO. The ISO biofidelity rating of 6.9 for the thorax is considered to be quite good.

Thorax: Yoganadan/NHTSA Sled Tests - In the Yoganandan test series there is a variation of 4 test conditions, padded and rigid flat and offset wall and for each condition a large amount of test parameters (9) to consider (acceleration 1st and 12th vertebra and pelvis, load wall force thorax, abdomen and pelvis and deflection upper, middle and lower ribs). Therefore not all responses are shown in this report. Only a limited number of relevant responses are shown in the figures below. The biofidelity of rib deflection was evaluated as described above based on the calculated resultant and calculated lateral deflection (Figure 1).
Figure 11 to Figure 12 show the two different calculated deflection parameters for the 1st thoracic rib in the sled configuration padded flat with the PMHS corridors. In Figure 13 for comparison the measured lateral deflection of the prototype dummy in this configuration in shown.
The calculated lateral deflection (Figure 11) is close to the lower corridor which indicates only moderate biofidelity. The biofidelity in the prototype was slightly better (Figure 13). The calculated resultant deflection (Figure 12) shows the best biofidelity.
These finding would indicate that the dummy chest might be too stiff. Thus the use of the resultant rib deformation which is overestimating the real deformation could compensate the too stiff dummy chest, and finally provide a more biofidelic output.

Table 8.
Thorax biofidelity rating for Revision1 prototype

						Boundary			Ratings				Biofidelity			
Body region	Ui	Impact condition	Vij	Measurement	Wijk	Lower	Upper	Unit	test 1	test 2	test 3	Average	Impact	**Test**	Test condi	**Body region**
Thorax	10	4.3 m/s	9	Pendulum force	9	force time corridor				5	8.3	6.7	59.9			
test 1		HSRI				1.2	2.7	kN								
		pendulum		Peak T4 Y acc.	7	acc. time corridor				5	5	5.0	35			
					16	**10**	**18**	**G**					94.9	**5.9**	53.4	
test 2		6.0 m/s	9	Pendulum force	9	force time corridor				5	10	7.5	67.5			
		WSU/GML				2.1	3.4	kN								
		pendulum			9								67.5	**7.5**	67.5	
test 5		6.8 m/s	7	Thorax plate force	8	force time corridor			10	10	5	8	66.7			
		Heidelberg				3.7	12.4	kN								
		rigid sled		peak T1 Y acc.	7	100	149	G	5	0	5	3.3	23.3			
				peak T12 Y acc.	7	87	131	G	5	5	5	5.0	35			
				peak rib acc.	6	78	122	G	5	5	5	5.0	30			
					28								155	**5.5**	38.8	
test 6		8.9 m/s	7	shoulder + thoracic plate force	9	force time corridor			10	10	5	8	75			
		WSU				4.4	6.9	kN					0			
		sled		Peak lateral displacement of T12	5	65.0	88.0		10	10	10	10	50			
		23 PSI padded			14								125	**8.9**	62.5	
			32												222	**6.9**

The plots of deflection calculated parameters of the other thoracic ribs and other sled configurations are not shown in this report. However, the tendency was similar, which can also be seen in the biofidelity rating based on the cumulative variance. This was done for all configurations and all parameters and is shown at the end of the result section in Table 16.

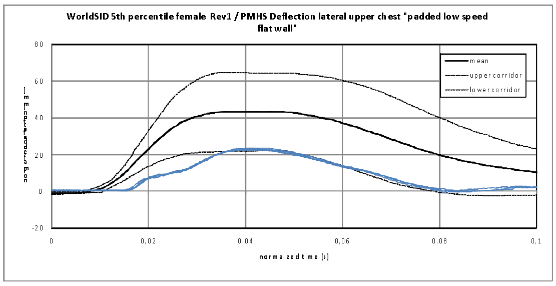


Figure 11. Padded Flat Wall 6,7 m/s; WS5F Rev1; Lateral measured deflection of 1st Thoracic rib.

Figure 12. Padded Flat Wall 6,7 m/s; WS5F Rev1; Resultant measured deflection of 1st Thoracic rib.

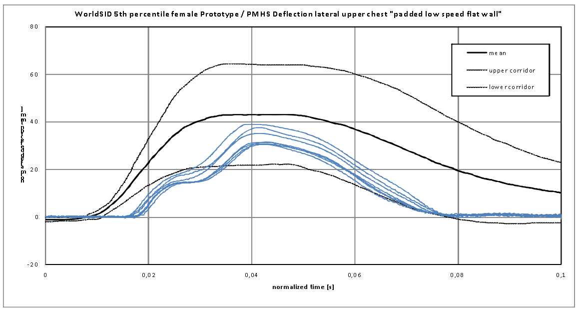


Figure 13. Padded Flat Wall 6,7 m/s; WS5F Prototype; Lateral measured deflection of 1st Thoracic rib.

The thoracic plate forces of the four different sled configurations are shown in Figure 14 to Figure 17. The forces are close to the mean PMHS curve except for the padded pelvis offset configuration where the curve is closer to the lower corridor. The results show excellent biofidelity, which improved compared to the prototype.

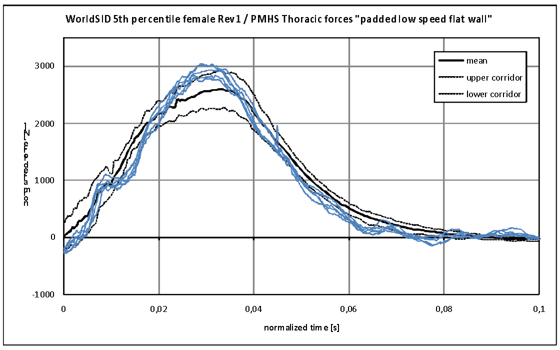


Figure 14. Padded flat, 6.8 m/s, thorax plate forces.

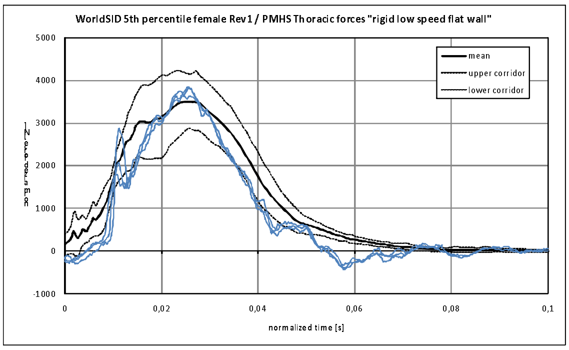


Figure 15. Rigid flat, 6.8 m/s, thorax plate forces.

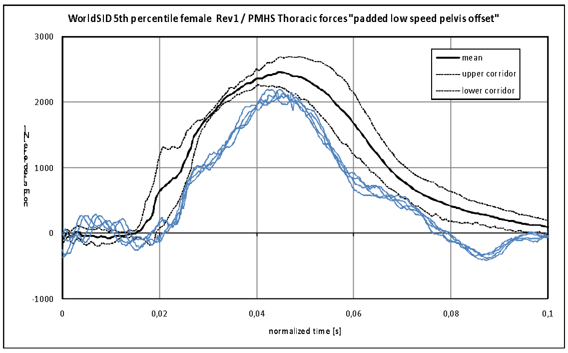


Figure 16. Padded pelvis offset, 6.8 m/s, thorax plate forces.

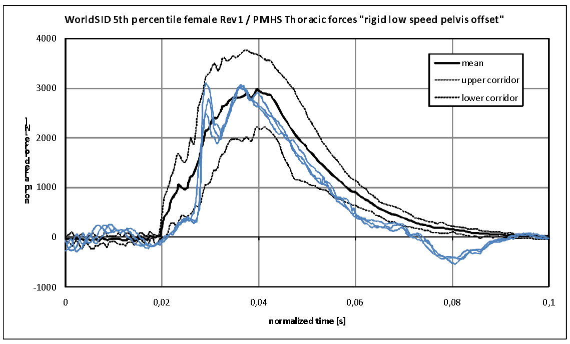


Figure 17. Rigid pelvis offset, 6.8 m/s, thorax plate forces.

Abdomen

The abdomen biofidelity for the Revision1 WorldSID 5th was evaluated based on seven different sled conditions (three WSU and four NHTSA).

Abdomen: WSU Sled Results - The results obtained in the rigid and padded tests are shown in Figure 18 and Figure 19 along with the proposed corridor. In the rigid configuration the response was too stiff and peak duration too short. This resulted in the maximum values slightly being above the upper corridor and all three curves cut the lower boundary. In the padded configuration the dummy response was in good agreement with the corridors. The dummy rigid test response lies within one corridor width out of the proposed corridor which leads to a biofidelity score of 5 according to the ISO TR9790 rating system. The padded test result lies entirely within the corridor and scores a 10.

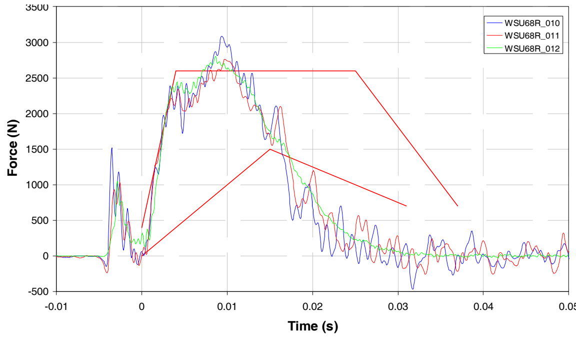


Figure 18. Abdominal forces, WSU, rigid, 6.8 m/s.

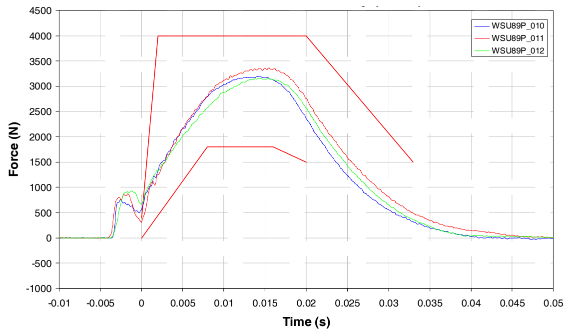


Figure 19. Abdominal forces, WSU, 8.9 m/s, padded

The overall ISO TR9790 Abdomen rating remained the same at a high level of 8.5 based on 2 out of 5 test conditions; see Table 9. The responses were slightly better than the prototype dummy, but it is not reflected in the rating.

Abdomen: NHTSA/Yoganandan Sled Tests - The plots concerning abdomen biofidelity (T12 acceleration and plate forces) are not shown here. However, the biofidelity rating is provided at the end of the result section (Table 15 to Table 17).

The responses for lower spine acceleration and abdomen force are generally close to or within the corridors, which is in good correspondence with the ISO biofidelity rating.

The load wall forces are within the corridors for all configurations showing excellent biofidelity. The biofidelity of the abdomen load wall forces was already very good for the prototype and improved further with the Revision1 dummy.

Table 9.
ISO TR9790 biofidelity score for abdomen tests based on 2 out of 5 test conditions

Body region	Ui	Impact condition	Vij	Measurement	Wijk	Boundary Lower	Upper	Unit	Ratings test 1	test 2	test 3	Average	Biofidelity Impact	Test	Test condi	Body region
Abdomen	8	6.8 m/s	3	Abdominal plate force	9	force time corridor			5	5	5	5.0	45			
test 3		WSU				1.5	2.6	kN								
		rigid sled			9								45	**5.0**	15	
test 5		8.9 m/s	7	Abdominal plate force	9	force time corridor			10	10	10	10	90			
		WSU sled				1.8	4	kN								
		23 PSI padded			9								90	**10**	70	
			10												85	**8.5**

Pelvis

The biofidelity of the small female WorldSID pelvis was extensively evaluated based on full body lateral pendulum test and sled tests of WSU, Heidelberg and NHTSA configuration.

Pelvis: Pendulum Tests - The biofidelity of pelvis impact forces has been improved (Figure 20 and Figure 21). It should be noted that these tests were conducted with a 14 kg pendulum and scaled to the required 10.1 kg pendulum mass, by applying mass scaling methods. At 6 m/s the pendulum forces are just within the lower corridor and at 8.3m/s the response moves outside the upper corridor. The 8.3m/s test was conducted using an additional pendulum accelerator with elastic bungee cord. It was not possible to run pendulum tests at higher speeds, due to limitation of the ceiling height of the building. The linear trend indicates that at 10m/s the response would still be within the 5 points boundary. Please keep in mind that the energy in this test, conducted with 14 kg pendulum at 8.3 m/s (482 J), is close to the energy of a 10.1 kg test at 10 m/s (510 J). The 8.3 m/s-14 kg test is considered to be representative for the 10.1 kg-10 m/s condition at the high end of the scale. The repeatability of the pelvis is excellent in pendulum test conditions.

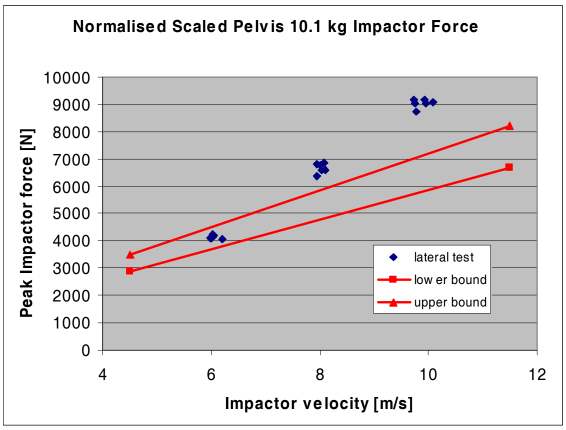
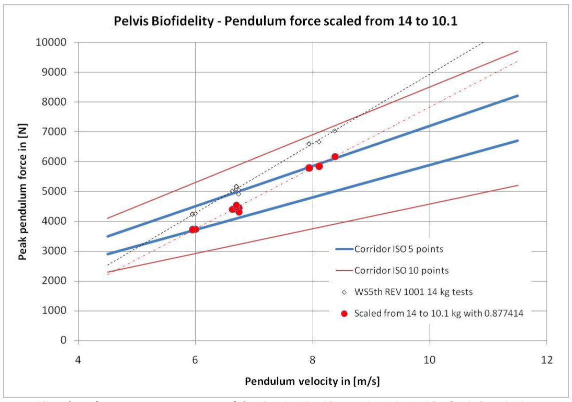


Figure 20. Prototype: Peak scaled* 10.1 kg pendulum pelvis impact force, normalised.



Scaling factor = square root of {[10.1(14+48)]/[14*(10.1+48)]}=0.877414

Figure 21. Revision1: Peak scaled* 10.1 kg pendulum pelvis impact force not normalised

Pelvis: Heidelberg Tests - Three Heidelberg conditions are applicable for the pelvis rigid sled at 6.8 and 8.9 m/s and padded 8.9 m/s sled test. The high speed tests were not conducted with the Revision1 prototype to reduce the risk of damage to the dummy and negative consequences for the completion of the test program. In the biofidelity rating the prototype responses were used for the high velocity tests, as nothing was changed in the pelvis between prototype and Revision1. The Revision1 response in the 6.8 m/s Heidelberg test was significantly stiffer than the prototype dummy (Figure 22 and Figure 23). As there were no changes to the pelvis, this is a little difficult to explain. The mass was increased in the abdomen area, but this is effectively decoupled from the pelvis by a lateral shearing lumbar. The lower legs were made lighter, but could not have influenced the pelvis responses significantly.
The repeatability of the responses from the Heidelberg sled test was very high and showed an improvement compared to the prototype (Figure 8).

Pelvis: WSU Sled Tests - Figure 24 and Figure 25 show the pelvis beam forces from the WSU sled tests. Although the forces leave the upper corridor the biofidelity has improved with respect the prototype dummy, because the peak values are lower compared to the prototype dummy.

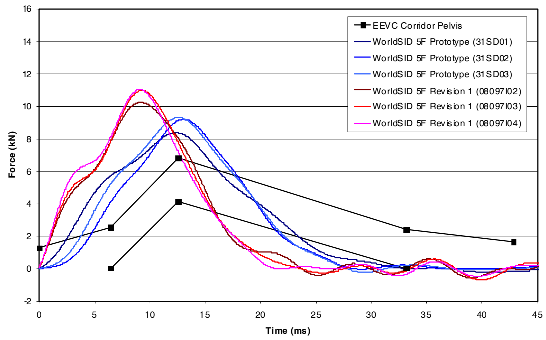


Figure 22. EEVC normalised pelvis plate force, 7.6 m/s rigid wall test condition

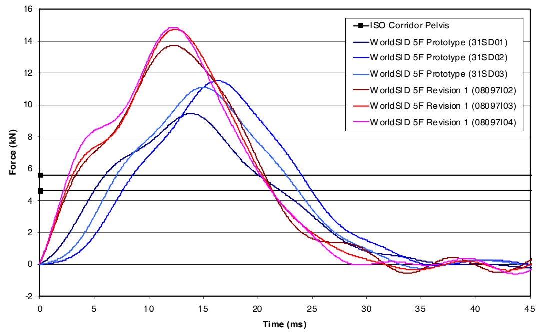


Figure 23. ISO normalised pelvis plate force, 7.6 m/s rigid wall test condition

Table 10.
Heidelberg sled test: Peak pelvis plate force results

		Biofidelity target		Prototype results		Revision1 results	
		Lower limit (kN)	Upper limit (kN)	Peak values (kN)	Coefficient of variation (%)	Peak values (kN)	Coefficient of variation (%)
Pelvis plate force	EEVC normalisation	4.1	6.8	8.4 9.2 9.3	5.6	10.3 11.0 11.0	4.0
	ISO normalisation	4.6	5.6	9.4 11.5 11.1	10.3	13.7 14.8 14.8	4.3

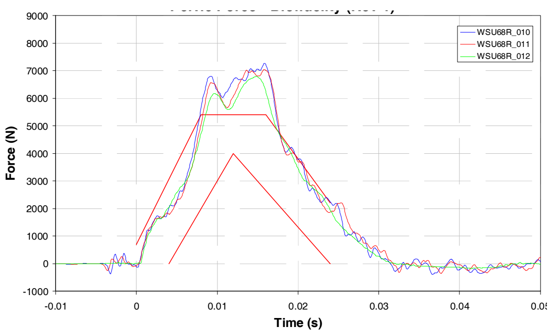


Figure 24. WSU, 6.8 m/s, rigid, ISO normalised pelvis force

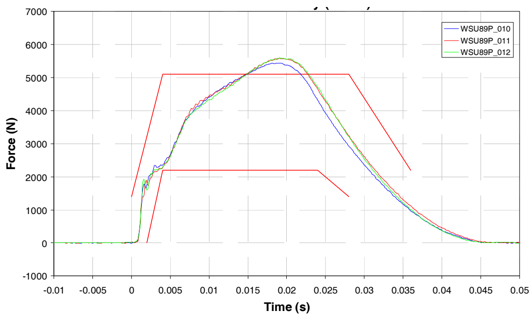


Figure 25. WSU, 8.9 m/s, padded foam, ISO normalised pelvis force

Pelvis Biofidelity Rating - The overall biofidelity pelvis responses according to the rating scheme of ISO TR9790 are summarised in Table 11.

The results of the high speed Heidelberg tests were taken over from the prototype dummy. Generally the response of the pelvis improved, except for the 6.8m/s Heidelberg test. However, in most cases the response changes were not large enough to highly increase (or diminish) the biofidelity rating of the pelvis. Nevertheless the overall pelvis biofidelity rating of the Revision1 dummy has improved with respect to the prototype from 5.6 to 6.5 and now meets the body segment target of ‘good’ biofidelity (BR ≥ 6.5).

The main contributor to the improved rating is the 10 m/s pendulum result. Please keep in mind that the score is not based on an actual test result at 10 m/s, but on the trend obtained from lower velocity tests. Also keep in mind that the energy in this test, conducted with 14 kg pendulum at 8.3 m/s (482 J), is close to the energy of a 10.1 kg test at 10 m/s (510 J). The 8.3 m/s-14 kg test is considered to be representative for the 10.1 kg-10 m/s condition. Indeed the trend of improved biofidelity is also indicated by the other test conditions. Also note that this score is based on a sub set of seven out of thirteen specified test conditions. However, the tests with the highest weighting factors were included in this sub set.

Table 11.
ISO TR9790 biofidelity score for WorldSID 5th female Revision1 pelvis tests

						Boundary			Ratings				Biofidelity			
Body region	Ui	Impact condition	Vij	Measurement	Wijk	Lower	Upper	Unit	test 1	test 2	test 3	Average	Impact	**Test**	Test condi	**Body region**
Pelvis	8	4.5 m/s	8	Pendulum force	9	2.9	3.5	kN	10	10	10	10	90			
test 1		10.14 kg impact			9								90	**10**	80	
test 2		11.5 m/s	9	Pendulum force	9	6.7	8.2	kN	5	5	5	5	45			
		10.14 kg impact			9								45	**5**	45	
test 7		6.8 m/s	8	Peak pelvic force	9	4.6	5.6	kN	0	0	0	0	0			
		Heidelberg		Peak pelvic acc.	7	78	95	G	5	5	5	5	35			
		rigid sled			16								35	**2.2**	17.5	
test 8		8.9 m/s	7	Peak pelvic force	8	16.2	19.1	kN	10	10	10	10	80			
		Heidelberg		Peak pelvic acc.	7	118	143	G	5	5	5	5	35			
		rigid sled			15								115	**7.7**	53.7	
test 9		8.9 m/s	8	Peak pelvic force	9	8.4	9.8	kN	10	10	10	10	90			
		Heidelberg		Peak pelvic acc.	8	75	93	G	5	5	5	5	40			
		padded sled			17								130	**7.6**	61.2	
test 10		6.8 m/s	3	Peak pelvic force	9	force time corridor			5	5	5	5	45			
		WSU				4	5.4	kN								
		rigid sled		Peak pelvic Y acc.	7	105	142	G	5	5	5	5	35			
					16								80	**5.0**	15	
test 13		8.9 m/s	7	Peak pelvic force	9	force time corridor			10	10	10	10	90			
		WSU				2.2	5.1	kN								
		23 PSI padded		Peak pelvic Y acc.	7	80	110	G	5	5	5	5	35			
		sled			16								125	**7.8**	54.7	
			50												327	**6.5**

Pelvis: NHTSA/Yoganandan Sled Tests - Because of the large amount of test parameters to consider not all responses are shown in this paper. Pelvis plate forces of the four tested configurations are shown in Figure 26 through Figure 30. All responses are within or close to the corridors showing increased biofidelity for all configurations. Only in the configuration rigid - pelvis offset, the forces leave the upper and lower corridor indicating a slightly worse biofidelity compared to the prototype.

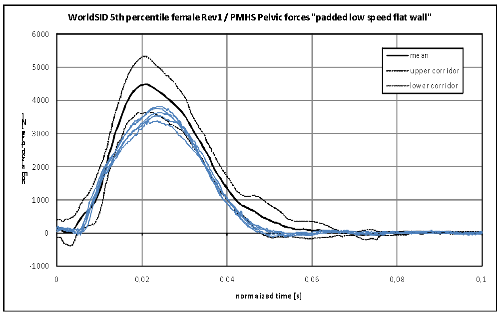


Figure 26. Revison 1, Padded, flat wall, 6.8 m/s, pelvis plate forces.

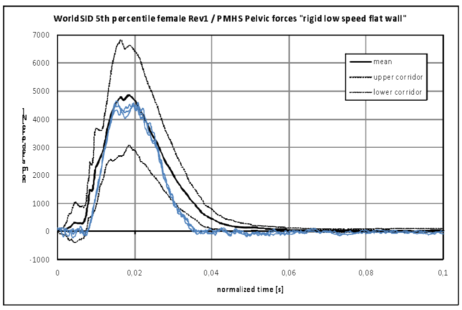


Figure 27. Figure 28: Revison 1, Rigid, flat wall, 6.8 m/s, pelvis plate forces.

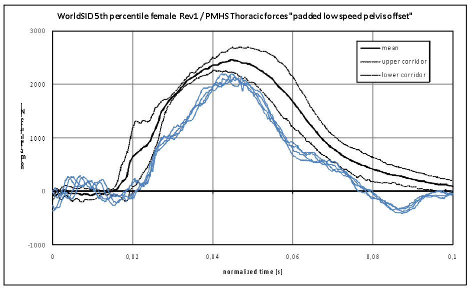


Figure 29. Revison 1, Padded, pelvis offset, 6.8 m/s, pelvis plate forces.

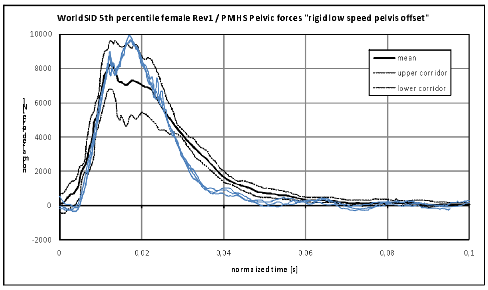


Figure 30. Revison 1, Rigid, pelvis offset, 6.8 m/s, pelvis plate forces.

Overall Biofidelity

ISO Rating - The body segment and full dummy biofidelity rating for the WorldSID 5th female prototype dummy according to the ISO TR9790 requirements (ISO, 1997) is given in Table 13. The

rating scheme used for biofidelity classification according to ISO TR9790 is given in Table 12.
The result is based on a sub-set of high weighted test conditions and is a good indication of the dummy's biofidelity. The overall Biofidelity rating is significantly improved with respect to the prototype dummy. With an overall score of 7.6 the rating of the WorldSID small female revised prototype meets the Biofidelity of her parent, the pre-production version WorldSID 50th percentile male dummy (ISO, 2004). Moreover, there are no longer definitive weak segments, as all body segments meet the target of BR ≥ 6.5.

Table 12.
ISO TR9790 biofidelity classification

Biofidelity Classification	**BR** (Calculated Biofidelity Rating)
Excellent	$8.6 \leq B < 10$
Good	$6.5 \leq B < 8.6$
Fair	$4.4 \leq B < 6.5$
Marginal	$2.6 \leq B < 4.4$
Unacceptable	$0.0 \leq B < 2.6$

Table 13.
ISO TR9790 biofidelity rating of WorldSID small female Revision1 and prototype and WorldSID mid size male pre production version

WorldSID Biofidelity rating ISO TR9790			
	Small Female		Mid size male
	Revision1	Prototype	Pre-production
Head	10	10	10
Neck	6.5	4.9	5.6
Shoulder	7.4	5	7.1
Thorax	6.9	5.6	8.3
Abdomen	8.5	8.5	7.8
Pelvis	6.5	5.6	6.1
Overall rating	7.6	6.7	7.6

EEVC Assessment - Thorax and pelvis responses from sled tests were assessed according the EEVC biofidelity corridors (Roberts *et al.*, 1991). For pelvis evaluation also responses from sled tests using a pelvis plate similar to WSU size and shape were applied to the EEVC corridors.

Thorax: The WorldSID 5th female Revision1 prototype dummy shows a good biofidelity and was improved with respect to the prototype. The thorax response was more rigid and better representing the human response; however one out of three of the test results exceeded the EEVC corridor. The high speed test was not repeated with the Revision1 prototype due to the risk at damage.

Pelvis: The Heidelberg pelvis plate responses suggest that the pelvis became stiffer with the Revision1 prototype. However no changes were made to the pelvis. In the low speed sled tests with pelvis plates of WSU shape and size the pelvis response is almost entirely within the corridor, with a little exceedence of the upper corridor. The low-speed test condition is likely to be more representative of modern vehicle door velocity and is therefore the more important requirement to meet.

NHTSA Biofidelity Rating - The results of the sled tests have been analysed and compared to the test corridors of the PMHS tests which have been conducted by the Medical College of Wisconsin (Yoganandan *et al.* 2005).

Table 14.
NHTSA Biofidelity Classification

Perfect:	BR = 0
Excellent:	BR between 0 and 1,0
Good:	BR Between 1 and 2
Moderate	2 < BR <3
Poor:	BR higher than 3

The biofidelity rating method used is the 'Cumulative Variance' by Rhule *et al.* (2002). The green shading in the table indicates that the responses were entirely within the corridor and would score excellent biofidelity; yellow and orange shadings indicate that responses are farther outside the corridor for a longer duration. Larger numbers indicate a larger deviation from the corridors.
The accelerations of lower spine and pelvis were slightly worse in the Revision prototype (Table 15). Especially the biofidelity of T12 acceleration clearly decreased in the offset tests, which should be investigated further. However, most responses were still within moderate classification.

Table 15.
Mean BR values of accelerations

		Prototype	Revision 1
Configuration	Acceleration	Mean BR values	
Padded Flat	Lower Spine (T12)	0,3	0,5
	Sacrum	2,7	3,4
Padded Pelvis Offset	Lower Spine (T12)	2,4	5,2
	Sacrum	2,3	2,8
Rigid Flat	Lower Spine (T12)	1,0	0,8
	Sacrum	3,0	4,1
Rigid Pelvis Offset	Lower Spine (T12)	1,7	3,1
	Sacrum	0,9	1,1

The chest deflections, as already mentioned above, were all improved for all test configurations, when considering the 2D IR-Tracc calculated parameter of resultant rib displacement (Table 16). Applying the parameter calculated lateral displacement for biofidelity calculation, resulted in a similar or slightly worse rating compared to the prototype.

The plate forces from the load wall are an indicator for the external biofidelity of the dummy. The NHTSA sled test results with the prototype already showed an excellent external biofidelity of the small female WorldSID (Table 17). The rating in the Revision1 tests improved even further. Now all forces show an excellent biofidelity except pelvis force in the flat padded and the thorax force in the padded pelvis offset test.

Table 16.
Mean BR values of rib deflections (Revision1 lateral and resultant deflection)

		Prototype	Revision 1	Revision 1
		Mean BR values		
	Deflection	Lateral	Lateral	Resultant
Padded Flat	Upper Chest (Thorax Rib 1)	0,8	1,1	0,6
	Mid Chest (Thorax Rib 3)	3,0	3,8	2,0
	Lower Chest (Abdomen Rib 2)	5,6	4,6	3,6
Padded Pelvis Offset	Upper Chest (Thorax Rib 1)	5,8	5,8	3,0
	Mid Chest (Thorax Rib 3)	5,8	5,4	3,5
	Lower Chest (Abdomen Rib 2)	6,2	6,0	5,5
Rigid Flat	Upper Chest (Thorax Rib 1)	1,6	3,1	1,4
	Mid Chest (Thorax Rib 3)	5,2	5,4	2,6
	Lower Chest (Abdomen Rib 2)	4,2	2,9	1,9
Rigid Pelvis Offset	Upper Chest (Thorax Rib 1)	0,6	0,5	0,3
	Mid Chest (Thorax Rib 3)	9,4	10,1	3,7
	Lower Chest (Abdomen Rib 2)	1,4	1,5	1,5

Table 17.
Mean BR values of load wall plate forces

		Prototype	Revision 1
Configuration	Plate Forces	Mean BR values	
Padded Flat	Thorax	0,4	0,9
	Abdomen	0,7	0,7
	Pelvis	0,5	1,3
Padded Pelvis Offset	Thorax	2,8	3,4
	Abdomen	0,5	0,4
	Pelvis	2,7	0,6
Rigid Flat	Thorax	1,0	0,6
	Abdomen	0,3	0,7
	Pelvis	0,4	0,2
Rigid Pelvis Offset	Thorax	0,6	0,4
	Abdomen	1,6	0,8
	Pelvis	0,5	1,0

Repeatability

Repeatability was already good for the prototype, as reported by Been *et al.* (2007). Generally for the Revision1 test houses indicated improved repeatability. A factor in improved repeatability is advanced experience of test houses in seating of the dummy and running the tests repeatably.
In almost all tests done in the test series with the Revision1 dummies an improvement of repeatability was noted. Now all responses meet the criterion of CV less than 7%. In the pendulum and drop tests CV of the majority of measured responses were even below 3% indicating an excellent repeatability.

CONCLUSIONS AND RECOMMENDATIONS

Two WorldSID small female Revision1 prototype side impact dummies were extensively evaluated and tested to verify compliance of the dummy to its requirements and to see if the changes in the revised prototype brought about the expected improvements.
The anthropometry was improved resulting in a good correspondence of the Revision1 dummy with its requirements of body segment mass distribution.
The overall dummy biofidelity in the ISO rating system has significantly improved from 6.7 to 7.6 on a scale between 0-10. The small female WorldSID has obtained the same biofidelity rating as the WorldSID mid size male dummy. The small female dummy also meets the individual body segments targets of ‘good biofidelity’. In this respect the small female dummy outclasses the 50th percentile male dummy, which does not achieve ‘good biofidelity’ for all body segments. The improved biofidelity was confirmed in the NHTSA/Yoganandan sled test conditions and rating system.
The recommendations regarding durability handling were implemented and showed an improvement in this test series. Also repeatability was improved with respect to the prototype. The repeatability generally exceeds the requirement of CV better than 7% and a CV better than 3% was achieved with pendulum and drop tests, which is considered excellent.
It can be concluded that the recommended updates were all executed and were all successful in achieving the expected outcome. The APROSYS project laid solid foundation for further activities. The WorldSID small female dummy is ready for use and further assessment by research parties and vehicle manufacturers worldwide.

Recommendations

To optimise the head-neck responses to the new targets, some measures are recommended: 1) Reduced head flexion angle by installing stiffer neck buffers in the lateral position; 2) Increase the neck twist response by replacing the rear square neck buffers with a circular ones top and bottom; 3) Assess frontal biofidelity according to Mertz OC angle moment relationship (Mertz and Patrick, 1971) Repeat the head neck tests in the NBDL sled test condition.
It is recommended that a harmonised biofidelity rating system is developed, combining benefits of various systems (EEVC, ISO and NHTSA) that have been developed. Furthermore the effect of not normalizing responses should be examined in detail.
It is recommended to improve damping material bonding, if possible.
The reliability of the IR-Traccs needs to be further improved. A further validation of the dummy oblique thorax response with available human response data is also recommended.

ACKNOWLEDGEMENTS

This work was supported through funding from: the European Commission, UK Department for Transport, the Federal Highway Research Institute (BASt) and Community of Madrid through the SEGVAUTO programme (S-0505/DPI-0329). In-dummy data acquisition system: DTS; donor sensors for 2nd dummy: ACEA. Staff of test laboratories, BASt, FTSS, TRL and UPM-INSIA.

REFERENCES

Been B.W., Meijer R., Bermond F., Bortenschlager K., Hynd D., Martinez L. and Ferichola,G. 2007. “WorldSID small female side impact dummy specifications and prototype evaluation.” Proceedings of the 20th Enhanced Safety of Vehicles (ESV) Conference, Lyon, France.

Been B.W., Waagmeester C.W., Trosseille X., Hynd. D., Carroll J. 2009.” WorldSID small female two-dimensional chest deflection sensors and sensitivity to oblique impact“. ESV 2009. Paper number: 09-0418

Ferichola G., Guerra L.J., Garcia A. 2007. “INSIA-WSU Barrier Scaling To 5th Percentile”, APROSYS Technical Report AP SP52 0055.

ISO TC22/SC12/WG 5. 2004. “Road vehicles — Design and performance specifications for the WorldSID 50th percentile male side impact dummy — Part 1: Terminology and rationale.”, ISO 15830 International Standard.

ISO.1997. “Road vehicles - anthropomorphic side impact dummy - lateral response requirements to assess the biofidelity of the dummy.” ISO TR 9790 ISO/TC22/SC12/WG5 Document N455 Rev4 May 1997

Newland, C. 2005. “International Harmonised Research Activities Side Impact Working Group Status Report.”, ESV 2005 IHRA status report on behalf of the IHRA Side Impact Working Group. conference paper 05-0460

Martínez L., Ferichola G., García A., Guerra L.J. 2007. “WorldSID 5th female prototype Anthropometry assessment”, APROSYS Technical Report AP SP52 0040-B.

Meijer R., Wisgerhof R., Wismans J., Been B.W. 2009. ‘Scaling Head-Neck Response Data And Derivation Of 5th Percentile Female Side Impact Dummy Head & Neck Response Requirements In NBDL Test Condition’, International Journal of Crashworthiness, Special Issue Advanced Protection Systems (APROSYS): Part 2.

Mertz H.J. 2004. “Calculation Methods & Acceptance Levels for Assessing Repeatability and Reproducibility (R & R)”. ISO/TC22/SC12/WG5 Document N751.

Mertz H.J., Patrick L.M. 1971. „Strength and Response of the Human Neck.” Proceedings of the 15th Stapp Car Crash Conference, pp 207-255. Society of Automotive Engineers, New York.

Rhule H., Brunner J., Bolte J., Donnelly B., Maltese M., Eppinger R. 2002. “Development of a New Biofidelity Ranking System for Anthropomorphic Test Devices.” Stapp Car Crash Journal, Vol. 46 (November 2002).

Roberts A., Lowne R., Beusenberg M. and Cesari D. 1991. “Test procedures for defining biofidelity targets for lateral impact test dummies.” 13th International Conference on Enhanced Safety of Vehicles, Paris, France: US Dept of Transport, National Highway Traffic Safety Administration, 91-S8-W-18, 956-967.

Schneider L.W., Robbins D.H, Pflüg M.A., Snyder R.G. 1983. “Development Of Anthropometrically Based Design Specifications For An Advance Adult Anthropomorphic Dummy Family.” Final Report DOT-HS-806-715 NHTSA (UMTRI).

Thomas P., Welsh R., Langerrand E., Vallet G., Otte D., Strandroth J. 2009 “Priorities for Enhanced Side Impact Protection in Regulation 95 Compliant Cars” ESV 2009. Paper number: 09-0156.

Yoganandan N. and Pintar F.A. 2005. “Deflection, Acceleration, and Force Corridors for Small Females in Side Impacts.” Traffic Injury Prevention, 6:379–386, 2005.