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Application of the NHTSA Biofidelity Ranking System to Child ATDs

K. A. Esselman, J. H. Bolte IV, H. H. Rhule, and B. R. Donnelly

ABSTRACT

The objective of this study is to apply the NHTSA Biofidelity Ranking System (Rhule et al. 2002), to child-sized side crash test dummies. This study applies the methodology of the NHTSA system and adjusts the test condition weight factors appropriately for child-sized side impact dummies. Test response corridors scaled by Irwin et al. (2002) and Van Ratingen et al. (1997) were utilized for dummy comparison. Additional adult response corridors for the shoulder were scaled using factors derived by Irwin et al. (2002) and response corridors given by Bolte et al. (2000). This ranking system quantifies the ability of a child dummy to load its environment as a cadaver does, External Biofidelity, and to replicate the scaled cadaver responses that are used to predict injury potential, Internal Biofidelity. The Q3s 3-year-old side impact dummy is used as an example in the side impact child biofidelity ranking system.

INTRODUCTION

In order to properly measure the potential for injury of children in automotive accidents, a biofidelic child ATD is needed. To evaluate biofidelity quantitatively, Rhule et al. (2002) developed a biofidelity ranking system for the side impact mid-sized male dummy. This paper addresses the need for a ranking system for child ATDs by adapting the adult ranking system using scaled adult corridors to represent child responses and adjusted test condition weights. Scaled corridors include those presented by Irwin et al. (2002), Van Ratingen (1997), and the NHTSA shoulder corridors scaled by factors also presented by Irwin.

This technical paper summarizes the methods of the NHTSA Biofidelity Ranking System (BRS) (Rhule et al., 2002) and explains how it was adapted for a 3-year-old dummy. The Q3s was utilized as a tool to apply the child dummy ranking system using data previously acquired in biofidelity testing.

METHODS

The purpose of the NHTSA BRS was to provide a quantitative and consistent way to rank dummy biofidelity for all types and sizes of dummies. The flow chart in Figure 1 shows the important components of the NHTSA BRS.

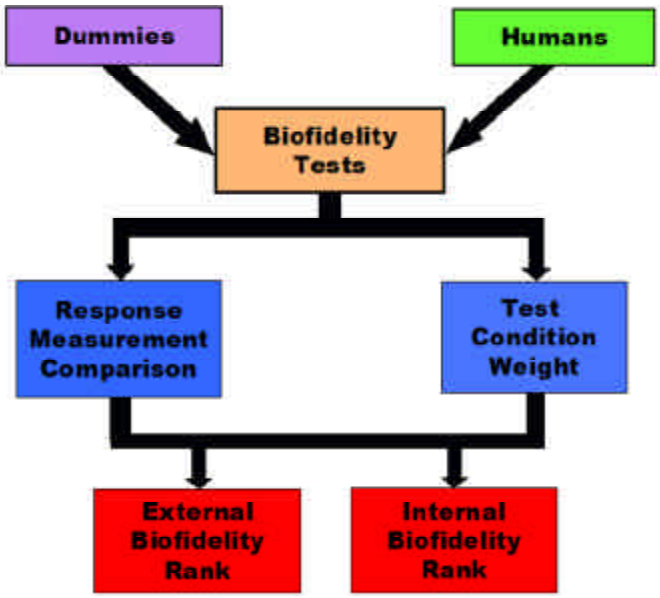

Figure 1: NHTSA Biofidelity Ranking System Flowchart

Biofidelity Tests

Over the years, several studies have provided information for the biofidelity tests used in this ranking system. Although the NHTSA adult includes specific tests for biofidelity ranking, the system does not restrict the user to these few tests. In theory, this system can be utilized with any reasonable set of biofidelity tests and adjusted by recalculating test condition weights for those specific test conditions. The dummies are then subjected to these biofidelity tests and responses measured.

In order to rank the biofidelity of a 3-year-old side impact dummy, biofidelity tests were chosen that were thought to be appropriate for a side impact child ATD. Six tests from the scaled ISO 9790 lateral biofidelity tests (Irwin et al., 2002), the NHTSA padded shoulder pendulum test (Bolte et al., 2000), and three TNO (Van Ratingen et al., 1997) scaled abdomen and pelvis tests were chosen for the child ranking system as shown in Table 1.

The biofidelity of the head was assessed using lateral head drop tests. The lateral head drop test was performed at 200 mm above the impact surface with the head suspended so that its mid-sagittal plane was at an angle of 35 ± 2 degrees from horizontal with respect to the top of the head. Acceleration was recorded at the CG of the head instead of the non-impacted side of the head as stated in ISO 9790. The results were filtered at CFC 1000 and plotted on the ISO scaled corridors.

Neck and shoulder biofidelity were assessed using the ISO 9790 Neck Test 1 /Shoulder Test 2 and Neck Test 3 /Shoulder Test 3. Five sled tests were conducted on a rigid seat fixture scaled from that defined in the test procedures. The bench height of the seat was scaled using sitting height ratios of a 3-year-old ATD to the Hybrid III 50th Male. The seat back and seating surface were adjusted to 15 degrees from vertical and the horizontal, respectively. The dummy was restrained by a 5-point seat belt used in child restraints. The right shoulder of the dummy was

placed against a wooden flat wall to support and restrict the torso. The top of the board was adjusted to a height 24-30 mm below the top of the shoulder.

Table 1. Biofidelity Test Conditions Used For The 3-Year-Old Lateral ATD Ranking System

Test Condition	Source of Tests	Source of Scaled Response Corridors	Drop Height (mm)	Impact Velocity (m/s)	Pendulum Weight (kg)	Sled Accleration Peak (G)
Head Test 1/Lateral Head Drop	ISO 9790	Irwin et al. 2002	200			
Neck Test 1 / Shoulder Test 2	ISO 9790	Irwin et al. 2002				7.2 G
Neck Test 3 / Shoulder Test 3	ISO 9790	Irwin et al. 2002				12.2 G
Shoulder Test 1	ISO 9790	Irwin et al. 2002		4.3	1.7	
NHTSA Shoulder Test	Bolte et al. 2000	Appendix A		4.3	1.7	
Thorax Test 1	ISO 9790	Irwin et al. 2002		4.3	1.7	
Thorax Test 2	ISO 9790	Irwin et al. 2002		6.7	1.7	
Abdomen Test 1	Viano et al. 1989	Van Ratingen et al. 1997		4.8	3.8	
Abdomen Test 2	Viano et al. 1989	Van Ratingen et al. 1997		6.8	3.8	
Pelvis Test 1	Viano et al. 1989	Van Ratingen et al. 1997		5.2	3.8	

The ISO 9790 Neck Test 1 and Shoulder Test 2 is based on human volunteer tests run at a pulse with a maximum acceleration of 7.2 G. The response data was compared to the scaled response corridors by Irwin et al. (2002). The ISO 9790 Neck Test 3 and Shoulder Test 3 is based on cadaver tests run at a pulse with a maximum acceleration of 12.2 G as defined in ISO 9790 (1999). The sled response data was compared to the scaled response data by Irwin et al. (2002).

In addition to the sled biofidelity tests, the ISO 9790 Shoulder Test 1 and the NHTSA Shoulder Test (Table 1) were used to assess shoulder biofidelity. The first shoulder pendulum test performed was the ISO 9790 shoulder test 1. The scaled procedures suggest testing at 4.5 ± 0.2 m/s with a 1.7 kg impactor. Scaled response corridors were provided for the 3-year-old in Irwin et al. (2002). The second shoulder test performed was the NHTSA Shoulder Pendulum Test. The NHTSA Shoulder Test is the lateral cadaver tests from Bolte et al. (2000). The procedure consisted of a pendulum test at 4.4 ± 0.2 m/s, with a two inch thick Arcel 310, 26.4 kg/m3 density foam padding attached to the face of the pendulum. A 1.7 kg pendulum was used as in the scaled procedures of the ISO Shoulder Test 1. The force vs. time response corridors from the adult cadaver data provided by Bolte were scaled for the 3-year-old by multiplying the adult cadaver data points by the scaling factors, 0.179 for force and 0.626 for time (Irwin et al. 2002). The pendulum force calculated from the acceleration channel was filtered using the CFC 180 filter and plotted on the respective corridors.

The thorax was tested using a 1.7 kg pendulum at two speeds, 4.3 ± 0.1 m/s and 6.0 ± 0.1 m/s (Table 1), both based on ISO 9790 procedures. The results were filtered using the FIR 100 filter and plotted on Irwin et al. (2002) corridors.

The abdomen was tested using procedures in Viano et al. (1989), since there is no abdomen pendulum test in ISO 9790, and scaled response corridors were provided by Van Ratingen (1997). The abdomen was impacted at a 30-degree angle forward from the frontal plane with a 3.8 kg pendulum at two speeds: 4.8 ± 0.1 m/s and 6.8 ± 0.1 m/s. The results were filtered using the FIR 100 filter and plotted on the scaled corridors.

The pelvis was tested using a 3.8 kg pendulum impacting the pelvis at 5.2 ± 0.1 m/s directly perpendicular to the hip joint as specified in Viano et al. (1989). The ISO 9790 pelvis test 1 pendulum test was not performed because a 2.27 kg pendulum was not available. The results were filtered using the FIR 100 filter and plotted on the scaled response corridors provided by Van Ratingen (1997).

Response Measurement Comparison

Scaled adult responses for the 3-year-old were adjusted to be the mean plus or minus one standard deviation as discussed in Rhule et al. (2002). The dummy and scaled human responses were compared resulting in a quantitative response measurement comparison value that was calculated using the cumulative variances of the dummy (DCV) and cadaver (CCV) as shown in Figure 2 (Rhule et al., 2002). The response measurement comparison values are achieved by calculating the variance of the dummy response compared to the mean scaled cadaver response over time.

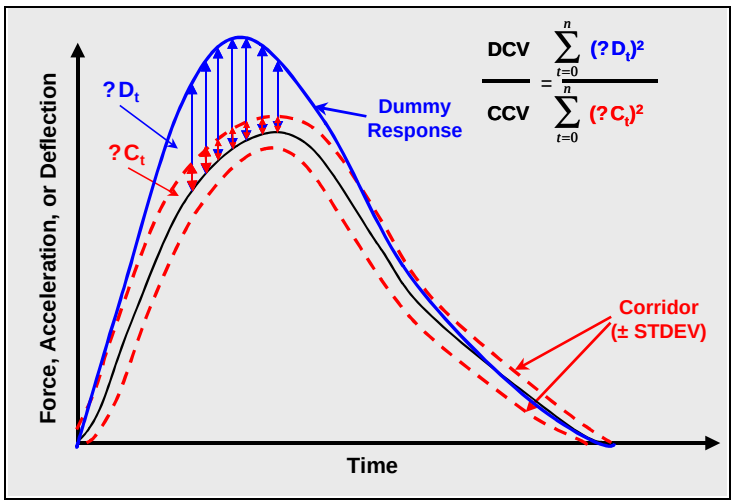

Figure 2: Response Measurement Comparison

Test Condition Weight

To give an appropriate level of importance to each biofidelity test, a test condition weight is calculated. The test condition weight (V) is calculated using Equation 1, which incorporates the number of human subjects tested (subject score) and how much alike the dummy responses are in biofidelity tests compared to standard crash tests (test relevance score).

$$V = 0.33 * (\text{subject score}) + 0.67 * (\text{test relevance}) \quad \textbf{(1)}$$

To determine the test condition weights for a 3-year-old, each of the original cadaver studies were consulted to provide the number of human subjects for the subject score. The test relevance score rates how well a biofidelity test represents a crash test. This score relies on two sources of data: crash test data and biofidelity test data utilizing the same tool or dummy. In this study, the HIII3C dummy in a Child Restraint System (CRS) was used as a tool to compare component level biofidelity tests to crash tests.

Thirteen crash test simulations were performed with the HIII3C in a CRS on a HYGE sled. These sled tests utilized acceleration pulses from Side NCAP and FMVSS 214 crash tests. For each response measurement, the data peaks from the biofidelity tests were plotted with a range of crash test peak values. The test relevance score is the ratio of the number of responses at or within the crash test data range over the total number of responses recorded. For example, in Figure 3, the HIII3C peak responses during Biofidelity Tests A and B are plotted over the range of HIII3C peak responses during Side NCAP and FMVSS simulated crash tests. Biofidelity test A would receive a test relevance score of 0.667, since two out of three responses were within the crash test data range.

Biofidelity test B would have a relevance score of 0, since no responses measured were within the range. The test relevance scores are then normalized to 10 and used in equation 1 to determine the test condition weight. Table 2 shows the test condition weights for a 3-year-old Child Biofidelity Ranking System.

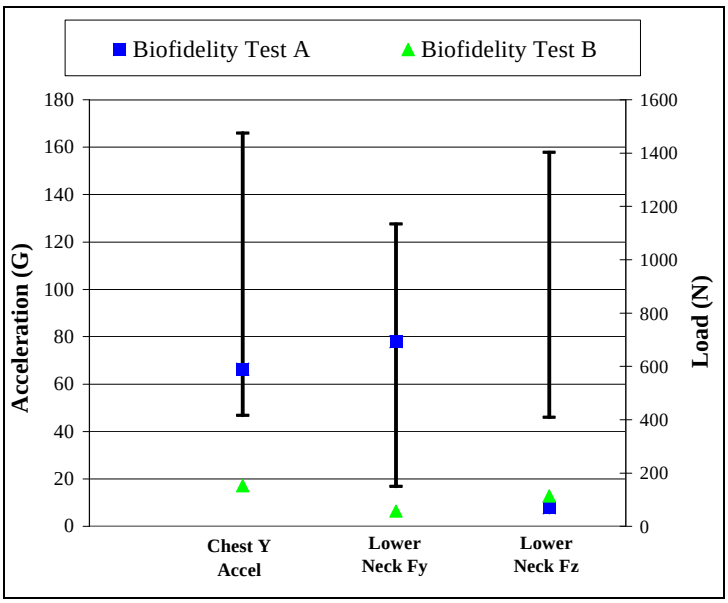

Figure 3: Test Relevance Score Comparison

Table 2. Test Condition Weights Used For A 3-Year-Old Lateral ATD

	Test Relvance Score	Normalized T.R.S.	Weighted N.T.R.S.	Subject Score	Weighted S.S.	Test Condition Weight
Head Test 1 / Lateral Head Drop	**1.0**	10	6.7	**7.0**	2.3	**9.0**
Neck Test 1 / Shoulder Test 2	**0.5**	5	3.4	**9.0**	3.0	**6.3**
Neck Test 3 / Shoulder Test 3	**0.6**	6	4.0	**1.0**	0.3	**4.4**
Shoulder Test 1	**0.6**	6	4.0	**3.0**	1.0	**5.0**
NHTSA Shoulder Test	**0.4**	4	2.7	**6.0**	2.0	**4.7**
Thorax Test 1	**0.4**	4	2.7	**7.0**	2.3	**5.0**
Thorax Test 2	**0.6**	6	4.0	**3.0**	1.0	**5.0**
Abdoment Test 1	**0.5**	5	3.4	**6.0**	2.0	**5.3**
Abdoment Test 2	**1.0**	10	6.7	**4.0**	1.3	**8.0**
Pelvis Test 1	**1.0**	10	6.7	**4.0**	1.3	**8.0**

For a different sized dummy, the test condition weights would need to be recalculated for each specific biofidelity test, since different sizes of dummies may react differently in the same test conditions. In addition, the test condition weights could be more accurately calculated using multiple dummies to determine the test relevance scores, as long as that dummy has been used in both crash tests and biofidelity tests relevant to the dummy being ranked.

Biofidelity Rank

Once the test condition weights and the response measurement comparison values are calculated, biofidelity can be calculated using the following equation:

$$B_{E,I} = \frac{\sum_{j=1}^{m}\left(V_j * \left(\frac{\sum_{k=1}^{n}\sqrt{R_{j,k}}}{n}\right)\right)}{\sum_{j=1}^{m} V_j} \qquad \textbf{(2)}$$

where:
B_E = External Biofidelity rank
B_I = Internal Biofidelity Rank
R = Response Measurement Comparison Value (DCV/CCV)
V = test condition weight
j = test condition
k = response measurement
m = number of test conditions
n = number of response measurements per test condition

Two ranks are calculated for each body region of the dummy, one to rank the dummy's ability to replicate human loading of its environment (External Biofidelity) and one to rank the human internal response in a crash (Internal Biofidelity), as shown in Figure 4. The overall external or internal biofidelity rank is the average of the corresponding biofidelity ranks found for all the body regions.

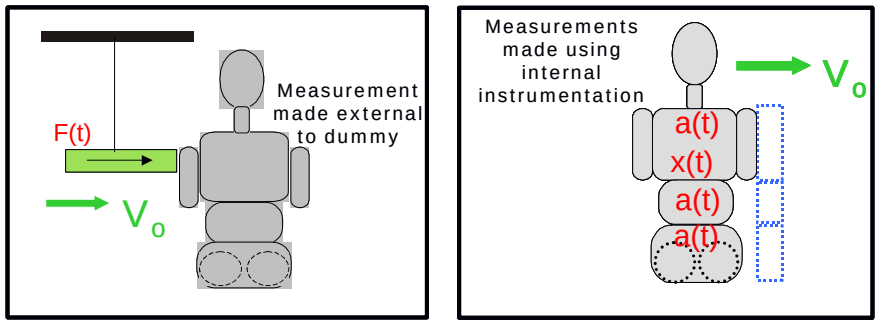

Figure 4: External (left) and Internal (right) Biofidelity Ranks are calculated for each dummy.

Each of these ranks will provide the user with a quantitative rank for each body region and the dummy as a whole. These ranks allow the designer to determine which areas of the dummy do or do not have a biofidelic response and assess how much improvement is needed for that particular region.

Rankings closest to 1 are the best biofidelic responses. The biofidelity rank for a dummy of B<2 indicates that the dummy responds most like a cadaver and is considered biofidelic (Rhule et al., 2002). Currently, that is the only classification of biofidelity available for this system.

RESULTS

To demonstrate the application of the NHTSA Biofidelity Ranking System for Child ATDs, the Q3s dummy was ranked utilizing available test data. The appendix shows the data plotted as a time series and showing the one standard deviation corridors. Table 3 shows the DCV/CCV values and the average test response measurements for each test condition used in the biofidelity ranking of the Q3s.

Due to limitations in data, only external biofidelity was calculated for the Q3s. All data collected was external measurement with exception of the head drop response, which was not included in the overall biofidelity rank since it was the only internal response. The external biofidelity ranks are summarized in Figure 5.

Table 3. **Response Measurement Averages and Biofidelity Ranks**

Body Region	Internal/ External Measurement	Test Name	Subject Score	Test Relevance Score	V	Score Parameter				Q3s	R (DCV/CCV)	Biofidelity of Body Region	Overall B
							Min	Max	Units				
Head	Internal	Head Test 1	7	10	9.0	Peak Resultant Acceleration at a Point on the Non-impacted Side of the Head	114	171	G	160	1.508	1.228	
	External	Neck Test 1	9	5	6.3	Peak Lateral Head Displacement	106	132	mm	112	1.160	2.853	2.007
						Peak Vertical Displacement of Head	99	145	mm	48	41.406		
						Peak Flexion Angle	71	95	degrees	53	25.000		
		Neck Test 3	1	6	4.3	Peak Lateral Displacement of Head CG relative to Sled			mm				
						Peak Flexion Angle	100	121	degrees	59	96.227		
Shoulder		Shoulder Test 1	3	6	5.0	Pendulum Force	0.3	0.5	kN	1.58	5.561	1.388	
		Shoulder Test 2	9	5	6.3	Peak Lateral Head Displacement	106	132	mm	112	1.160		
		NHTSA Shoulder	6	4	4.7	Pendulum Force	0.35	0.51	kN	0.4	2.267		
Thorax		Thorax Test 1	7	4	5.0	Pendulum Force	0.3	0.66	kN	0.55	0.985	1.034	
		Thorax Test 2	3	6	5.0	Pendulum Force	0.51	0.83	kN	0.67	1.083		
Abdomen		Abdomen Test 1	6	5	5.3	Pendulum Force	0.465	0.93	kN	0.9	1.612	1.304	
		Abdomen Test 2	4	10	8.0	Pendulum Force	0.93	1.395	kN	1.378	1.099		
Pelvis		Pelvis Test 1	4	10	8.0	Pendulum Force	1.15	1.84	kN	2.33	3.458	3.458	

The results in Table 3 and Figure 5 show that using the NHTSA Biofidelity Ranking System, the Q3s had an overall score of 2.0 for external biofidelity, indicating marginally acceptable biofidelity. However, the head/neck complex and the pelvis scored higher than 2.0, indicating improvement is needed in these regions.

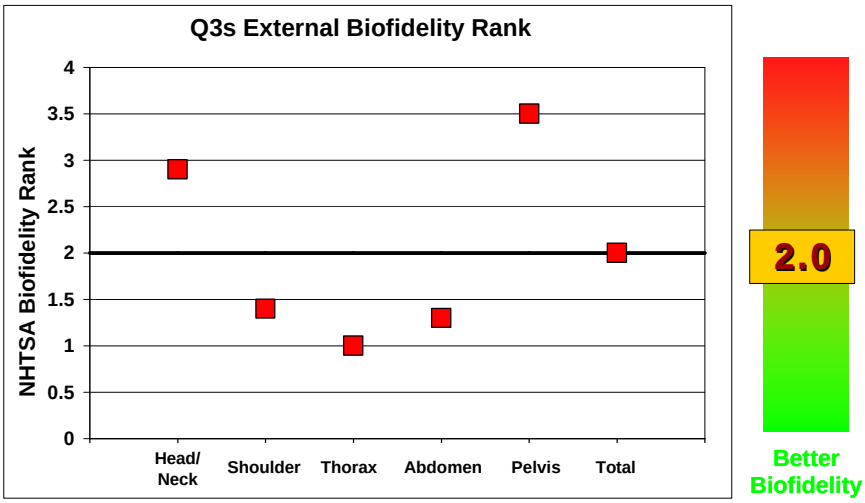

Figure 5: Preliminary Regional and Overall External Biofidelity Ranks for the Q3s

CONCLUSIONS

This paper presented an application of the NHTSA Biofidelity Ranking System for a 3-year-old child dummy. Using the methodology in the original paper by Rhule et al. (2002), any dummy of any type or size can be ranked with this system as long as the biofidelity tests selected

are appropriate and test condition weights are properly calculated for the particular dummy size being evaluated. This process must only be completed once for each size or type of dummy. Once the test condition weights are calculated for a given biofidelity test for a given dummy type and size, any available biofidelity data from these tests can be utilized to rank the dummy.

FUTURE WORK

To complete the biofidelity ranking of the Q3s, internal biofidelity ranks should be calculated using the sled tests performed by Maltese et al. (2002). The Maltese impact load wall needs to be scaled appropriately for a 3-year-old subject, and the response corridors must be generated using the factors presented by Irwin et al. (2002) to scale the adult response corridors. Test relevance scores also need to be computed for each test condition with respect to the 3-year-old as shown in this paper and used for test condition weights. Once this has been completed, any 3-year-old child ATD can be evaluated using the biofidelity test conditions used in this system for a quantitative comparison and rank.

Additional work to validate the system is planned. Once the Q3s is tested in crash environments, the response data can be compared to the responses of the biofidelity tests to calculated test relevance scores using the Q3s as a tool. Then, more accurate scores can be calculated by averaging the scores of the HIII3C and the Q3s.

ACKNOWLEDGEMENTS

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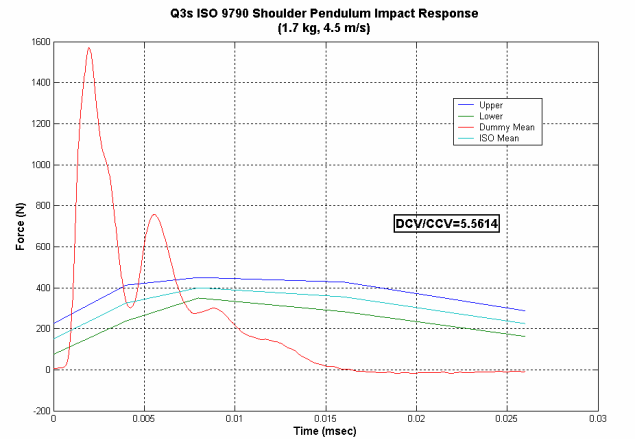
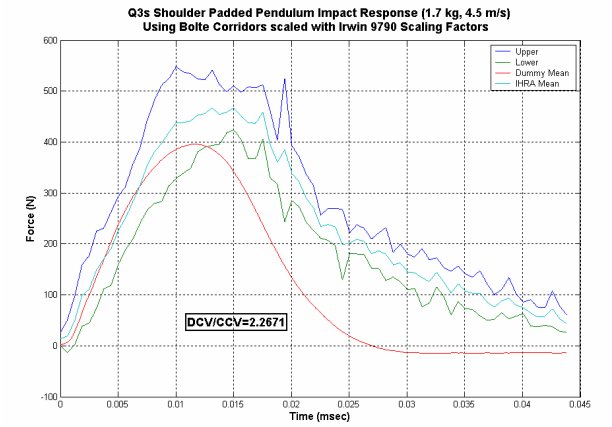
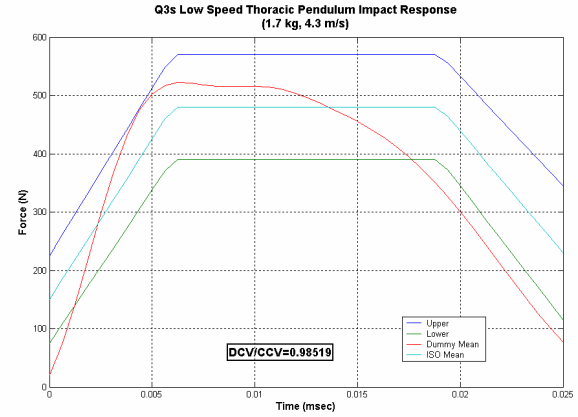
APPENDIX



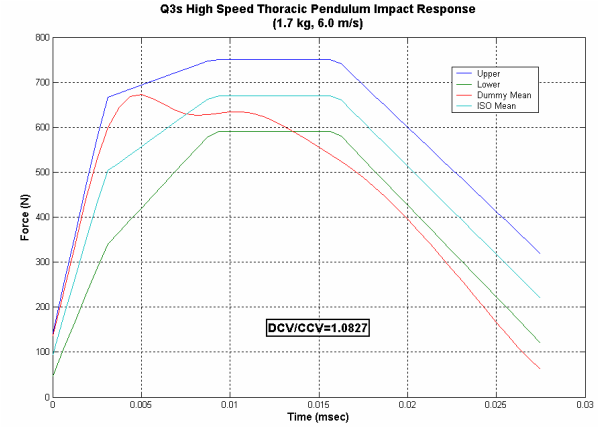
A-1. ISO Shoulder Test 1



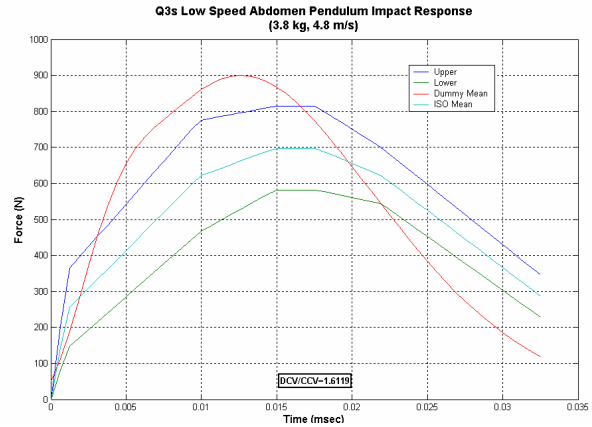
A-2. NHTSA Shoulder Test



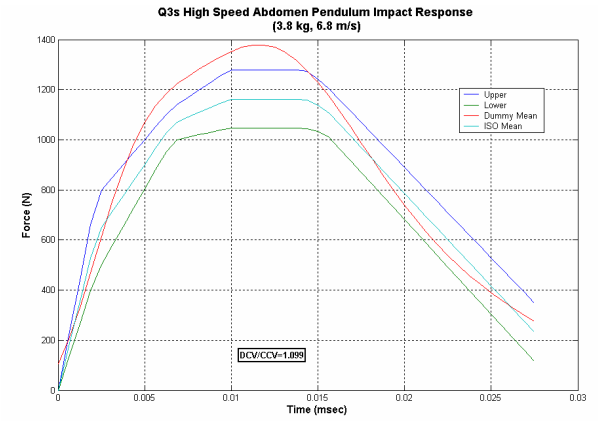
A-3. Thorax Test 1



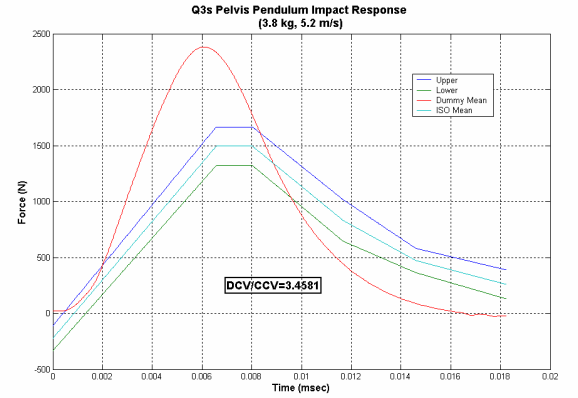
A-4. Thorax Test 2



A-5. Abdomen Test 1



A-6. Abdomen Test 2



A-7. Pelvis Test 1

DISCUSSION

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PRESENTER: ***Kelli Esselman, Transportation Research Center, Inc.***

QUESTION: *Guy Nusholtz, Daimler/Chrysler*
The first question is, has to do with the results of data that you may not have reported...[tape ends]

ANSWER: Yes. We have just done the component tests, such as head drops and the pendulum test that I presented today.

Q: Alright. If it's a fundamental property, it should show up in the head-drop test because that's gonna put a frequency component, or a power component high enough to excite the resonance. So if it didn't occur--Or, do you know whether it occurred or not?

A: We didn't see any abnormal responses in the head-drop test. But like I said, I believe most of the ringing came in out-of-position tests. So right now, we have nothing to compare that to.

Q: Well, they did come in, but it's a physical phenomenon. It's not attached to--You know, if you put a certain type of input, you should get the ringing. And my guess is that if you didn't see it, then it's gone.

A: Right, and they did redesign the head so the Q3S head is different than the original Q3.

Q: You had some data with regard to the Hybrid III. Did you look at comparing the Hybrid III in site impact to the Q3?

A: I don't see why that you would try and test for biofidelity of a frontal dummy. First of all, I think that's a little unfair to the dummy, putting it through side impact tests. Now, the Hybrid 3-C information that we do have in this, in the crash test and in the--Let me just get this here. What we did here with the test condition weights, what it was based on here was the crash test data. There's no crash test data with the Q3S. So what we had to do is use Hybrid III as a gage. Now, none of the--Biofidelity has nothing to do with the test condition weight; it's just comparing the responses of what happened in natural crashes versus what happens in the biofidelity tests. So, just because we used the Hybrid 3-C in this to validate the test condition weights doesn't necessarily mean that it's gonna get a good rank, as far as side. And no, we did not rank the Hybrid 3-Cs in the side, side impact.

Q: Even though it may, theoretically, it's not a fair comparison, the Hybrid III is still used in side impact evaluation. That's the primary reason. So if you're going to--It's sort of a standard right now. If you're gonna evaluate the Q3, then it makes sense to compare it against the standard that we use right even though it wasn't designed for side impact.

A: Well, I guess--I guess I could add a little input there. We did test the Hybrid 3-C in some side impact conditions, and there were some problems with the Hybrid 3-C. And as far as the ranking and the numbers that we would get, I don't think the Hybrid 3-C would even get close to what the Q3 has provided for us in the side.

Q: So, you do have some, some level--not a strong level, but some level of comparison.

A: Right. Just, I didn't do anything with the ranking system because we were ranking strictly the Q3S, due to fairness and side impact conditions.

Q: Due to fairness? Side impacts are never fair.

A: I'm just saying--No. I'm just saying that the Q3S is a side-impact dummy. The Hybrid 3-C is a frontal dummy. And if you test the frontal dummy necessarily in a side impact condition, you wouldn't really expect it to act biofidelically in a side impact condition.

Q: No, that's also correct, but it doesn't mean it won't. Thank you.

A: Thank you.