# COMPARISON OF WORLDSID AND ES-2RE BIOFIDELITY USING AN UPDATED BIOFIDELITY RANKING SYSTEM

**Heather Rhule**
**Kevin Moorhouse**
**Bruce Donnelly**
National Highway Traffic Safety Administration
United States
**Jim Stricklin**
Transportation Research Center Inc.
United States
Paper Number 09-0563

## ABSTRACT

In 2002 the biofidelity of the SID-HIII, ES-2 and prototype WorldSID side impact dummies were compared using a new Biofidelity Ranking System (BRS or BioRank) [Rhule, 2002]. The current study introduces updates made to the BRS and assesses the biofidelity of the ES-2re and the latest WorldSID side impact dummies. Approximately twelve drop tests, ninety pendulum tests and forty sled tests with a dual-occupant buck were performed with the ES-2re and WorldSID dummies, including lateral and oblique shoulder impactor tests [Bolte, 2003]; lateral and oblique thorax impactor tests [Shaw, 2006]; five Maltese sled tests [Maltese, 2002]; and several drop, pendulum and sled tests from ISO 9790 [ISO, 1999]. Test condition weight factors used previously have been eliminated in the updated BRS, giving all test conditions equal value. A scale for quality of the biofidelity ranking value, B, is demonstrated by comparing individual human subject responses to response targets and generating individual cadaver B values for both External and Internal Biofidelity. Having a scale of B values for the subject responses used to create the target response will give the user a metric for understanding the quality of a dummy's biofidelity. Finally, the sensitivity of the biofidelity ranking value, B, is illustrated using data from repeated tests on multiple WorldSID dummies. The sensitivity analysis will help the user understand if the biofidelity of two (or more) dummies is similar or different. This recent data and updated BRS show that the WorldSID dummy exhibits improved overall biofidelity over the ES-2re. Results of the updated BRS show that the WorldSID and ES-2re demonstrated Internal Biofidelity values of 1.2 and 1.7, respectively; the WorldSID demonstrated an External Biofidelity score of 2.2 while the ES-2re demonstrated an External Biofidelity score of 2.8.

## INTRODUCTION

In 2002 a new Biofidelity Ranking System (BRS) was introduced and used to compare the biofidelity of the SID-HIII, ES-2 and prototype WorldSID side impact dummies [Rhule, 2002]. Since then the BRS has been used to evaluate several side impact dummies and has received constructive critique from the biomechanics community [Irwin, 2003]. Criticisms included use of less biofidelic dummies for evaluation of the relevance of test conditions and assignment of test condition weights, a desire for further explanation of the meaning of the biofidelity "B" values, and lack of analysis of the sensitivity of the B values. This paper addresses each of these concerns by eliminating test condition weights from the updated BRS, providing further analysis of the statistical meaning of the B values and a scale for interpreting the quality of biofidelity from the B values, as well as providing analysis of the significant difference between two B values. This paper discusses the updates that have been made to the Biofidelity Ranking System and presents results of its application to recent test data from two side impact dummies, the ES-2re and the current production WorldSID dummy.

The evaluation and modification of the WorldSID dummy has been accomplished with the collaboration and support of the WorldSID Organization. Recent changes to the dummy include relocating the pelvis data acquisition docking station, a change in rib damping material and a change in IRTRACC mounting range-of-motion.

## BACKGROUND

The purpose of the Biofidelity Ranking System is to objectively quantify response differences between human subjects and crash test dummies to evaluate how well a dummy replicates the behavior and response of a human. In order to evaluate a dummy's biofidelity, it must be subjected to a set of tests that have associated human subject response targets (also referred to as biofidelity corridors). The set of tests and response measurements (and associated human response targets) to be used for evaluating biofidelity are selected by the analyst prior to utilizing the objective BRS and will affect results.

The fundamental nature of the Biofidelity Ranking System lies in the comparison of each dummy response to its corresponding mean human subject response. The Response Measurement Comparison Value (R) for each required measurement is calculated as a ratio of the cumulative variance of the dummy response relative to the mean cadaver response (DCV) over the cumulative variance of the mean cadaver response relative to the mean plus one standard deviation (CCV), as described in Rhule et al, 2002. A lower DCV/CCV ratio indicates a closer dummy response relative to that of the mean cadaver, and better dummy biofidelity.

The BRS calculates ranks for External Biofidelity and Internal Biofidelity by first calculating the DCV/CCV ratio (R) for each response measurement and then taking its square root; then those values are averaged for various test conditions and then for various body regions. External Biofidelity describes the ability of a dummy to replicate human loading of a test environment. Signals which measure the response of the test environment due to its interaction with the dummy (or human subject) are used to calculate External Biofidelity ranks. Internal Biofidelity describes the ability of a dummy to duplicate the responses of human subjects. Signals which measure the response of the dummy (or human subject) due to its interaction with the test environment are used to calculate Internal Biofidelity ranks.

## UPDATES TO THE BIOFIDELITY RANKING SYSTEM

Over the last several years the Biofidelity Ranking System has been used to evaluate the biofidelity of many dummies. As with any state of the art system evolution is inevitable. As a result of its development, the following updates have been incorporated into the evaluation of side impact dummy biofidelity using the BRS.

### Test Condition Weights Removed

The Test Condition Weights included in the original BRS were based on a combination of 1) the number of subjects used to create the human subject response target (Subject Score) and 2) how well the biofidelity test represented the intended crash environment (Test Relevance Score). The equation to calculate the Test Condition Weights subjectively added one-third of the Subject Score to two-thirds of the Test Relevance Score.

The Test Relevance Score indicates how well each biofidelity test represents regulatory-type crash tests. The biofidelity tests whose dummy responses are equal to or less than the dummy response in crash tests receive higher Test Relevance Scores. Some in the biomechanics community argued that the dummies used (SID-HIII and ES-2) to evaluate the relevance of the biofidelity tests were not very biofidelic, which invalidated the Test Condition Weights.

The assessment of subject sample size and test relevance in this paper was performed during the data selection process and is not part of the completely objective BRS. The Test Condition Weights have been eliminated from the BRS. All tests used for evaluating dummy biofidelity are now of equal value.

### Biofidelity Rank Calculation

Without the Test Condition Weights, the equation for calculating the biofidelity ranks is different from that presented in 2002. In the updated BRS, External and Internal Biofidelity ranks are calculated according to Equation 1. The External and Internal Biofidelity ranks are each made up of an average of ranks from each body region (*i* in Equation 1). The body regions include the head, neck, shoulder, thorax, abdomen and pelvis. Each body region rank is made up of an average of ranks from each corresponding test condition (*j* in Equation 1). Each test condition rank (for a given body region) is made up of an average of the square root of the response measurement comparison values (*R* in Equation 1) for each measurement required (*k* in Equation 1) for that test condition. Figure 1 illustrates the sequence of averages that result in the External (or Internal) Biofidelity ranks.

## INTERPRETING THE BIOFIDELITY VALUES

What do the biofidelity values (B-values) mean? Albeit a lower value of B indicates better biofidelity, but what do the numbers represent? How different do the numbers have to be to indicate a significant difference in biofidelity?

$$B = \frac{\sum_{i=1}^{l}\left(\frac{\sum_{j=1}^{m}\left(\frac{\sum_{k=1}^{n}\sqrt{R_{i,j,k}}}{n}\right)}{m}\right)}{l} \qquad (1).$$

where

$B$= biofidelity rank, either External or Internal
$R$ = Response Measurement Comparison Value
$i$ = body region
$j$ = test condition
$k$ = response measurement
$l$ = number of body regions
$m$ = number of test conditions
$n$ = number of response measurements per test condition

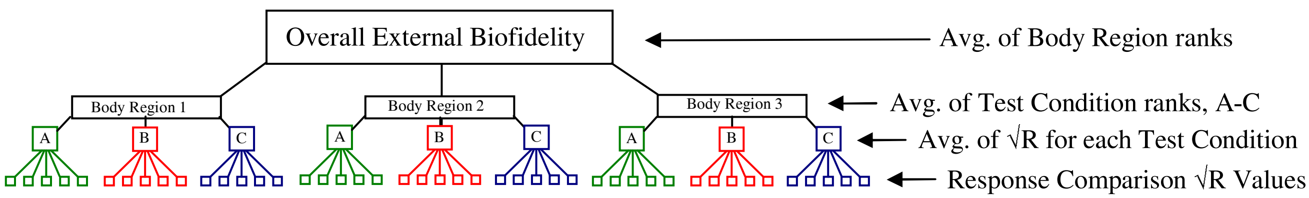


**Figure 1. Schematic showing the sequence for averaging √R values.**

**B-value Scale**

It is important to understand what a BioRank score actually means. For any given response measurement in a biofidelity test, a DCV/CCV ratio, or R value, is calculated and its square root is taken so that it represents multiples of a cumulative standard deviation. A value of $\sqrt{R} < 1$ would indicate that the dummy response is less than one cumulative standard deviation different from the cadaver mean response for that set of cadaver test data. Similarly, a value of $\sqrt{R} < 2$ would indicate that the dummy response is within two cumulative standard deviations of the cadaver mean and a value of $\sqrt{R} < 3$ indicates the dummy is within three cumulative standard deviations of the cadaver mean response. This assumes that the cadaver data set is a representative sample of the cadaver population and is normally distributed. Because cadaver sample size is usually rather small and the variation in the cadaver data set is due to both natural human variation as well as test-to-test variation, there is no guarantee that this assumption is valid.

A methodology for developing a scale for the BioRank was developed by Rhule [Rhule 2002]. In that study a set of external cadaver responses was analyzed by comparing one cadaver from the set of cadavers to the mean and standard deviation of the remaining cadavers in the set. This approach is analogous to comparing a dummy response to a cadaver mean and standard deviation but calculates a $\sqrt{R}$ value for each cadaver in the data set and allows for the assessment of the distribution statistics for the sample of cadaver responses. If the cadaver data is normally distributed then it is reasonable to use values of $\sqrt{R}$ = 1, 2 and 3, etc., as measures of dummy similarity to the cadaver mean response. For a value of $\sqrt{R} < 1$ the dummy would be as similar to the mean response as 68% of cadavers, $1 < \sqrt{R} \leq 2$ would be as similar to the mean response as the next 27% of cadavers, $2 < \sqrt{R} \leq 3$ would be as similar as the next 4% of cadavers, and $\sqrt{R} > 3$ would only be as similar as 1% of cadavers. This basic approach was used again to evaluate the distribution of cadaver responses for additional channels of both external and internal responses for the Maltese data [Maltese, 2002] and the Shaw data [Shaw, 2006].

This more extensive analysis has a few differences from the analysis presented in Rhule's 2002 study. In both studies the Maltese data for the padded high-speed flat wall sled tests (PHF) were used because there were seven subjects tested under that condition and this provided a reasonably large sample size. After the publication of the 2002 paper, Maltese re-analyzed his data and made it available on the NHTSA website. This re-analysis included phase shifting of the data to minimize the cumulative variance with the idea of eliminating time shifts due to subject "fatness" and "thinness". This phase-shift corrected data was used in the analysis presented here. In addition to analyzing external data for thorax, abdomen and pelvis load force, the internal responses for chest-band deflection and lower spine acceleration were also analyzed. In this study the Shaw pendulum test data was also analyzed which included seven subjects (Note: the force data was re-analyzed for this paper due to an error in the inertial mass of the impactor). For this data the external pendulum force in both lateral and oblique tests were analyzed as well as the internal chest-band deflection.

The results for the analysis of the $\sqrt{R}$ values for the selected test data from Maltese and Shaw are shown in Table 1. Note that the subject identification numbers for the subjects are also presented in the table. The Maltese sled data for padded high-speed flat wall tests was analyzed for the thorax, abdomen and pelvis load forces, for the upper and middle chest-band deflection and the lower spine y acceleration. The results of Table 1 show that although the $\sqrt{R}$ values vary, the average values for each channel are approximately 1.0 and a dummy with a *B*-value of ≤1.0 has a response that is less than or equal to one cumulative standard deviation different from the mean cadaver response. This is true for both external measures and internal measures. The Shaw data from lower energy pendulum tests in lateral and oblique impacts was analyzed for external force and for internal chest-band deflection. The results of Table 1 show that, similar to the Maltese data, the Shaw data has values of $\sqrt{R}$ that average approximately 1.0 and that a dummy with a *B*-value of ≤1.0 has a response that is less than or equal to one cumulative standard deviation different from the mean cadaver response. A set of $\chi^2$ goodness-of-fit tests on the channels shown in Table 1 indicate that eight of the twelve channels do not reject the hypothesis that they are from a normal distribution at the $\alpha = 0.05$ level [Mathworks, 2008]. Although there are only seven subjects, this provides some limited confidence that the cadaver data is normally distributed.

This analysis provides support for a biofidelity ranking metric as shown in Table 2. This scoring metric is continuous and directly related to the normal distribution statistics of multiples of standard deviation. This metric can also be used to compare and contrast the responses of different dummies to a cadaver data set and, without too much risk, to compare different dummies and different cadaver data sets so long as the assumption of a normal distribution within the cadaver populations is valid.

**Table 1.**
**$\sqrt{R}$ values for selected cadaver to cadaver mean response data**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Maltese Data | | | | | | | | |
| | 3320 | 3321 | 3323 | 3580 | 3581 | 3586 | 3589 | Channel Average |
| PHF Thorax Force-external | 1.16 | 1.03 | 1.97 | 0.55 | 0.92 | 1.21 | 0.55 | 1.06 |
| PHF Abdomen Force-external | 0.75 | 0.75 | 1.27 | 0.77 | 1.39 | 0.84 | 1.67 | 1.06 |
| PHF Pelvis Force-external | 0.75 | 1.19 | 1.07 | 1.03 | 1.05 | 0.79 | 1.61 | 1.07 |
| Total External Average | | | | | | | | 1.06 |
| PHF Lower Spine-internal | 0.63 | 2.29 | 1.14 | 0.68 | 0.93 | 0.63 | 1.13 | 1.06 |
| PHF Upper Chest Half Deflection-internal | 2.67 | 0.43 | 0.41 | 1.45 | 1.26 | 0.44 | 0.55 | 1.03 |
| PHF Lower Chest Half Deflection-internal | 1.19 | 1.14 | 0.36 | 1.27 | 1.11 | 1.55 | 0.74 | 1.05 |
| Total Internal Average | | | | | | | | 1.05 |
| Shaw Data | | | | | | | | |
| | 503 | 504 | 505 | 506 | 507 | 601 | 602 | |
| Lateral Force-external | 1.41 | 0.80 | 1.01 | 1.16 | 0.47 | 0.80 | 1.75 | 1.06 |
| Oblique Force-external | 0.98 | 1.21 | 1.92 | 0.42 | 1.37 | 0.95 | 0.43 | 1.04 |
| Total External Average | | | | | | | | 1.05 |
| Lateral Deflection-internal | 0.43 | 0.31 | 0.33 | 1.23 | 1.02 | 1.34 | 2.46 | 1.02 |
| Oblique Deflection-internal | 0.72 | 1.92 | 2.53 | 0.47 | 0.50 | 0.63 | 0.44 | 1.03 |
| Total Internal Average | | | | | | | | 1.02 |

**Table 2.**
**Biofidelity Scale**

| | |
|---|---|
| $B \leq 1$ | within one standard deviation of the mean cadaver response |
| $1 < B \leq 2$ | between one and two standard deviations of the mean cadaver response |
| $2 < B \leq 3$ | between two and three standard deviations of the mean cadaver response |
| $B > 3$ | more than three standard deviations from the mean cadaver response |

**B-value Sensitivity**

It is important to know the sensitivity of the B-value with respect to the response of the post-mortem human subjects (PMHS) to which it is being compared. This is especially important if two different dummies, such as the WorldSID and the ES-2re, are being compared to the same PMHS data set and the resulting B-values for the two dummies are similar but not exactly the same – is the difference significant? Stated a different way, if two dummies have B-values separated by a small amount, such as $\Delta B = 0.2$ for example, is one actually more biofidelic than the other?

The sensitivity of the B-values can be assessed by studying the B-values calculated separately for two of the same dummy type, i.e., reproducible dummies, compared to the same PMHS data set. In this study two different WorldSID dummies that have been assessed for reproducibility and found not to be significantly different in response were subjected to multiple identical sled tests in several different configurations. The dummy responses from the repeat sled tests were used to calculate mean $\sqrt{R}$ values for each dummy in each response. In Table 3, Dummy Responses 1-22 show the mean $\sqrt{R}$ values for Dummies 1 and 2 for internal and external thorax, abdomen and pelvis measurements. A set of paired differences were then created from the mean $\sqrt{R}$ values from each configuration, and the mean and standard deviation were calculated. A critical value of difference in $\sqrt{R}$ value was calculated using the two-tailed t-statistic for the means of paired differences and a value of $p = 0.05$. The standard deviation for paired differences is

$$S_d^2 = \frac{\sum (d_i - \bar{d})^2}{n-1}$$

where $S_d$ = standard deviation of paired differences
$n$ = sample size
$d_i$ = differences between paired values
$\bar{d}$ = the mean of the differences.

The critical value is found by manipulating the equation for the t-statistic for paired observations,

$$d_0 = \bar{d} - t \cdot S_d / \sqrt{n}$$

where $d_0$ = critical value of difference
$t$ = the t-statistic for p=0.05 and (n-1) DOF

From this analysis we can infer that a difference larger than this critical value indicates that the biofidelity of the two dummies is not the same. Therefore, the critical difference in the B value of two dummy responses is given by:

$$\Delta B = \bar{d} - d_0$$

For the two WorldSID dummies being used as an example, Table 3 shows the means of the paired differences for each body region, the standard deviations of the paired differences, the resulting critical values of difference, $d_0$, and the critical values for $\Delta B$.

The $\Delta B$ values in the last row of Table 3 range from 0.13 to 0.27 with an average value of 0.20. The internal $\Delta B$ values range from 0.13 to 0.18 with an average of 0.15 and the external $\Delta B$ values range from 0.19 to 0.27 with an average of 0.24. This indicates that for the two WorldSID dummies exposed to a set of sled tests, the sensitivity of the B-value is approximately 0.15 for internal biofidelity and 0.24 for external biofidelity with an overall average sensitivity of 0.20.

This exercise indicates that B-values that are less than or equal to 0.2 different, $\Delta B \leq 0.2$, are not significantly different and the biofidelity of two dummies or body regions being compared is essentially the same. This analysis is not a rigorous proof and to be accurate, this analysis would have to be repeated for each case; however, it serves as a general guideline for evaluating the biofidelity results for two dummies or two body regions.

**Table 3.**
**Sensitivity results for mean √R and corresponding ΔB**

| Region | Thorax | | | | | | Abdomen | | | | | | Pelvis | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Internal | | | External | | | Internal | | | External | | | Internal | | | External | | | |
| Dummy | 1 | 2 | Diff | 1 | 2 | Diff | 1 | 2 | Diff | 1 | 2 | Diff | 1 | 2 | Diff | 1 | 2 | Diff | |
| Response Measurements | | | | | | | | | | | | | | | | | | | |
| 1 | 6.200 | 5.857 | 0.343 | 1.300 | 1.200 | 0.100 | 2.673 | 2.817 | 0.143 | 0.657 | 0.543 | 0.113 | 1.560 | 1.490 | 0.070 | 6.971 | 6.543 | 0.429 | |
| 2 | 3.844 | 4.178 | 0.333 | 3.260 | 3.220 | 0.040 | 1.577 | 1.697 | 0.120 | 1.890 | 1.330 | 0.560 | 2.273 | 1.897 | 0.377 | 1.807 | 1.717 | 0.090 | |
| 3 | 0.388 | 1.000 | 0.612 | 4.550 | 3.870 | 0.680 | 1.550 | 2.000 | 0.450 | 0.860 | 1.020 | 0.160 | 1.240 | 1.080 | 0.160 | 2.473 | 1.790 | 0.683 | |
| 4 | 2.277 | 2.360 | 0.083 | 3.640 | 3.970 | 0.330 | 2.830 | 2.750 | 0.080 | 3.600 | 3.820 | 0.220 | 1.890 | 1.990 | 0.100 | 4.050 | 4.070 | 0.020 | |
| 5 | 1.623 | 1.687 | 0.063 | 5.620 | 5.560 | 0.060 | 2.810 | 2.960 | 0.150 | 3.000 | 2.660 | 0.340 | 1.340 | 1.180 | 0.160 | 1.480 | 1.720 | 0.240 | |
| 6 | 1.477 | 1.743 | 0.267 | 2.800 | 2.330 | 0.470 | | | | 1.683 | 1.747 | 0.063 | | | | 3.950 | 3.590 | 0.360 | |
| 7 | 1.903 | 2.033 | 0.130 | | | | | | | | | | | | | | | | |
| 8 | 1.307 | 1.243 | 0.063 | | | | | | | | | | | | | | | | |
| 9 | 1.357 | 1.313 | 0.043 | | | | | | | | | | | | | | | | |
| 10 | 0.703 | 0.727 | 0.023 | | | | | | | | | | | | | | | | |
| 11 | 0.687 | 0.917 | 0.230 | | | | | | | | | | | | | | | | |
| 12 | 1.820 | 3.140 | 1.320 | | | | | | | | | | | | | | | | |
| 13 | 1.260 | 1.570 | 0.310 | | | | | | | | | | | | | | | | |
| 14 | 0.790 | 0.540 | 0.250 | | | | | | | | | | | | | | | | |
| 15 | 1.790 | 1.800 | 0.010 | | | | | | | | | | | | | | | | |
| 16 | 4.500 | 4.270 | 0.230 | | | | | | | | | | | | | | | | |
| 17 | 2.760 | 2.670 | 0.090 | | | | | | | | | | | | | | | | |
| 18 | 4.610 | 4.590 | 0.020 | | | | | | | | | | | | | | | | |
| 19 | 0.880 | 0.750 | 0.130 | | | | | | | | | | | | | | | | |
| 20 | 0.900 | 0.940 | 0.040 | | | | | | | | | | | | | | | | |
| 21 | 0.430 | 0.530 | 0.100 | | | | | | | | | | | | | | | | |
| 22 | 0.440 | 0.480 | 0.040 | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| Mean | | | 0.215 | | | 0.280 | | | 0.189 | | | 0.243 | | | 0.173 | | | 0.304 | |
| S | | | 0.288 | | | 0.260 | | | 0.149 | | | 0.182 | | | 0.120 | | | 0.242 | |
| do | | | 0.088 | | | 0.008 | | | 0.004 | | | 0.051 | | | 0.024 | | | 0.050 | Mean |
| Delta B | | | 0.13 | | | 0.27 | | | 0.18 | | | 0.19 | | | 0.15 | | | 0.25 | 0.197 |

## DUMMY BIOFIDELITY COMPARISON

Several drop, pendulum and sled tests were conducted with the ES-2re and production WorldSID dummies in order to assess and compare their biofidelity utilizing the updated Biofidelity Ranking System.

### Selected Tests and Response Measurements

The tests selected for biofidelity evaluation, as well as which response measurements are to be used, are entirely up to the user and should be considered carefully because they will have a significant impact on the biofidelity results.

Ideally, the more response measurements and test conditions utilized for biofidelity evaluation, the better and more well-rounded the evaluation will be. However, sometimes including all possible response measurements and test conditions is not feasible. In addition, if only one body region is to be assessed, only those associated response measurements and test conditions are necessary for evaluation.

When assessing a dummy's whole-body biofidelity, rather than just one body region, each body region would ideally have the same number of test conditions and response measurements so that each body region has equal representation in the overall biofidelity rank, which is an average of the body region ranks. It is important to recognize the effect of various measurements, test conditions and body regions on biofidelity ranks since some body regions may have more test conditions than others and some test conditions may have more response measurements than others. In addition, it is possible for a body region of one dummy to have better biofidelity than that of another dummy, but have a worse overall biofidelity rank. For this reason, body region ranks should be considered carefully along with the overall biofidelity ranks.

Some of the tests used to compare dummy biofidelity in the 2002 paper were removed for the current study and other tests have been added. Tests that were removed include ISO 9790 Shoulder Test 1 and Maltese's High Speed Rigid Flat Wall sled test. ISO's Shoulder Test 1 was removed because a definition of time zero could not be obtained and the response corridor was generated from both oblique and lateral data rather than just lateral or just oblique. The Maltese test was removed because the test condition was deemed too severe.

Tests that were added include 15° and 30° oblique shoulder [Bolte] and 30° oblique thorax [Shaw] pendulum tests so that responses in the oblique direction could be evaluated. However, displacement in the oblique shoulder tests was not used because appropriate measurements were difficult to obtain using video. In addition, Shaw's lateral thorax pendulum test was included in order to add the thorax force and deflection measurements in a lower speed pendulum test to the array of response measurements. ISO's Pelvis Test 1 was added to include a localized impact to the pelvis region. ISO's 6.8 m/s Heidelberg and 6.8 m/s Wayne State sled tests were added to include additional full-body sled tests.

Additional tests were considered for use in the current study but were not selected due to unavailability of test materials that replicate those of the original human subject studies.

In the original BRS presented in 2002, the internal ranks were calculated only from signals used in injury criteria. Internal ranks are calculated here using as many internal responses for which there are matching human subject response targets. Additional signals are used for biofidelity evaluation because ideally, a dummy would respond in every way like a human.

The set of tests and response measurements selected for comparing the ES-2re and WorldSID biofidelity in this paper (Table 4.) is quite comprehensive considering the fact that human subject data for this particular application is not vast.

**Adjusted Targets**

In order for the Biofidelity Ranking System to result in meaningful, quantitative comparisons, it is important that the human response targets for the measurements and tests selected for comparison consist of a common statistical definition. In the BRS, the denominator of the DCV/CCV ratio is the cumulative squared difference of the cadaver mean to the cadaver mean plus one standard deviation. For the tests selected for inclusion in this study that had some other definition for the human response target, an adjusted human response target was established.

Table 5 and Table 6 list the tests and response measurements, the reference response corridor, the method for establishing the adjusted target shown, the size assumption of the reference corridor, and the starting and ending points for the DCV/CCV calculation. It is recognized that these adjustments will have an effect on the results of the BRS ranks.

**Table 4.**
**Test conditions and response measurements for biofidelity evaluation of the ES-2re and WorldSID dummies**

| Test Type | Reference | Test Description | Measurement |
|---|---|---|---|
| Pendulum | Bolte | 4.4 m/s Lateral Pendulum Impact | Pendulum Force |
| | | | Shoulder Y-axis Displacement |
| | | 4.4 m/s 15º Pendulum Impact | Pendulum Y-axis Force |
| | | | Pendulum X-axis Force |
| | | 4.4 m/s 30º Pendulum Impact | Pendulum Y-axis Force |
| | | | Pendulum X-axis Force |
| | Shaw | 2.5 m/s Lateral Pendulum Impact | Pendulum Force |
| | | | Thorax Displacement |
| | | 2.5 m/s 30º Pendulum Impact | Pendulum Force |
| | | | Thorax Displacement |
| Drop | ISO 9790 | Head Test 1:<br>200 mm Rigid Lateral Head Drop | Peak Resultant Head Acceleration<br>on opposite side of head* |
| Pendulum | | Thorax Test 1:<br>4.3 m/s Pendulum Impact | T-1 Lateral Acceleration |
| | | | Pendulum Force |
| | | Pelvis Test 1:<br>6 m/s Lateral Pendulum Impact | Peak Pendulum Force |
| Sled | | Neck Test 1:<br>7.2 g Sled Test | Peak Horizontal Displacement of<br>Head cg Relative to T-1 |
| | | | Peak Vert. Displacement of<br>Head cg Relative to T-1 |
| | | | Peak Flexion Angle |
| | | Neck Test 3:<br>12.2 g Sled Test | Peak Horizontal Displacement of<br>Head cg Relative to Sled |
| | | | Peak Flexion Angle |
| | | Shoulder Test 2:<br>7.2 g Sled Test | Peak Horizontal Displacement of<br>T-1 Relative to Sled |
| | | Thorax Test 5 & Pelvis Test 7:<br>6.8 m/s Heidelberg Sled | Thorax Plate Force |
| | | | Peak Lateral Acceleration of T-1 |
| | | | Peak Lateral Acceleration of T-12 |
| | | | Peak Lateral Acceleration of the Impacted Rib |
| | | | Peak Pelvis Plate Force |
| | | | Peak Pelvis Lateral Acceleration |
| | | Abdomen Test 3 & Pelvis Test 10:<br>6.8 m/s Wayne State Sled | Abdomen Plate Force |
| | | | Pelvis Plate Force |
| | | | Peak Pelvis Lateral Acceleration |
| | Maltese | 6.7 m/s Padded Flat Wall<br>6.7 m/s Rigid Flat Wall<br>6.7 m/s Rigid Abdomen Offset<br>6.7 m/s Rigid Pelvis Offset<br>8.9 m/s Padded Flat Wall | Thorax Plate Force |
| | | | T-1 Lateral Acceleration |
| | | | T-12 Lateral Acceleration |
| | | | Upper Thoracic Lateral Deflection |
| | | | Lower Thoracic Lateral Deflection |
| | | | Abdomen Plate Force |
| | | | Mid-Abdominal Deflection |
| | | | Pelvis Plate Force |
| | | | Pelvis Lateral Acceleration |

*Dummy measurements were located at the center of gravity location in the head

**Table 5.**
**Adjusted time series response targets**

| ISO 9790 Test Name | Thorax Test 1 | | Thorax Test 5 | Abdomen Test 3 | Pelvis Test 10 |
|---|---|---|---|---|---|
| Channel Name | T1 Lateral Acceleration vs. Time | Pendulum Force vs. Time | Thorax Plate Force vs. Time | Abdomen Plate Force vs. Time | Pelvis Plate Force vs. Time |
| Reference PMHS Corridor Used | Irwin's [Irwin, 2008] draft proposed corridor | Irwin's [Irwin, 2008]draft proposed corridor | Petitjean's [Petitjean, 2008] draft corridor | ISO 9790 | ISO 9790 |
| Steps to Follow To Generate Mean and Standard. Deviation Targets | Extend lower corridor line from 8 ms to 0 ms. Extend lower corridor from 35 to 50 ms matching slope of upper corridor. | Remove 700 N from plateau of upper and lower corridors. Extend lower corridor line from 5 ms to 0 ms. Extend lower corridor from 30 ms to 45 ms matching slope of upper corridor. | Extend lower corridor line from 10 ms to 0 ms. Extend lower corridor from 38 to 55 ms matching slope of upper corridor. | Leave ISO corridor as-is, except extend lower corridor from 38 to 45 ms, matching slope of upper corridor. | Leave ISO corridor as-is. |
| Assumption of Reference Corridor Size | mean +/- 2 SD | mean +/- 2 SD | mean +/- 3 SD | mean +/- 1 SD | mean +/- 1 SD |
| DCV/CCV Calculation Start Point | Time zero | Time zero | Time zero | Time zero | Time zero |
| DCV/CCV Calculation End Point | When corridor mean reaches 10% of its max (1.24 g) | 45 ms; doesn't go down to 10% of mean | When corridor mean reaches 10% of its max (0.931 kN) | 45 ms; doesn't go down to 10% of mean | 30 ms; doesn't go down to 10% of mean |

**Table 6.**
**Adjusted peak value response targets**

| ISO 9790 Test Name | Channel Name | ISO 9790 Lower Bound | ISO 9790 Upper Bound | Size Assumption of Reference Corridor | BRS Lower Bound | BRS Upper Bound |
|---|---|---|---|---|---|---|
| Thorax Test 5 | Peak lateral acceleration of the upper spine | 82 g | 122 g | mean +/- 2 SD | 92 g | 113 g |
| | Peak lateral acceleration of the lower spine | 71 g | 107 g | | 80 g | 98 g |
| | Peak lateral acceleration of the impacted rib | 64 g | 100 g | | 74 g | 91 g |
| Pelvis Test 1 | Peak pendulum force | 5.11 kN | 6.27 kN | mean +/- 1 SD | 5.11 kN | 6.27 kN |
| Pelvis Test 7 | Peak pelvic plate force | 6.4 kN | 7.8 kN | mean +/- 1 SD | 6.4 kN | 7.8 kN |
| | Peak lateral pelvic acceleration | 63 g | 77 g | mean +/- 1 SD | 63 g | 77 g |
| Pelvis Test 10 | Peak lateral pelvic acceleration | 85 g | 115 g | mean +/- 2 SD | 93 g | 108 g |

## Time Zero

In order to properly evaluate dummy biofidelity, it is important to define time zero, or the start of the event. If the condition of the test is such that it results in a steep increase in response over a short amount of time, but time zero is undefined, assessing whether a dummy responds similarly in time to the human will be difficult. In the case that time zero is not defined by the author of the human subject response data, a time zero definition must be established so that the dummy and human subject response target data can be located in time consistently.

Table 7 indicates the definition of time zero for each response measurement and test condition selected, as well as how the time zero definition was established.

**Table 7.**
**Filter classes and time zero definitions**

| Test Description | Data Channel | Filter | Time Zero Definition |
|---|---|---|---|
| ISO 9790 Head Test 1 | Peak Head Resultant Acceleration | CFC 1000 | n/a |
| ISO 9790 Neck Test 1 | All Data | Video | n/a |
| ISO 9790 Shoulder Test 2 | | | n/a |
| ISO 9790 Neck Test 3 | All Data | Video | n/a |
| NHTSA (Bolte) Shoulder Tests | Pendulum Force | CFC 180 | Time of contact between pendulum and subject |
| | Shoulder Displacement | Video | |
| ISO 9790 Thorax Test 1 | Pendulum Force | FIR 100 | Last zero crossing before maximum* |
| | T-1 Lateral Acceleration | FIR 100 | |
| NHTSA (Shaw) Thorax Tests | Pendulum Force | CFC 600 | Time of contact between pendulum and subject |
| | Thorax Deflection | CFC 1000 | |
| ISO 9790 Thorax Test 5 | Thorax Plate Force | CFC 1000 | 5% of peak of thorax plate force is time zero (assuming thorax plate is first contact) |
| | Peak T-1 Lateral Acceleration | FIR 100 | n/a |
| | Peak T-12 Lateral Acceleration | FIR 100 | n/a |
| | Peak Impacted Rib Lateral Acceleration | FIR 100 | n/a |
| ISO 9790 Pelvis Test 7 | Peak Pelvis Plate Force | FIR 100 | n/a |
| | Peak Pelvis Lateral Acceleration | FIR 100 | n/a |
| ISO 9790 Abdomen Test 3 | Abdomen Plate Force | CFC 1000 | Last zero crossing before maximum* |
| ISO 9790 Pelvis Test 10 | Pelvis Plate Force | CFC 1000 | Last zero crossing before maximum* |
| | Peak Pelvis Lateral Acceleration | CFC 1000 | n/a |
| ISO 9790 Pelvis Test 1 | Peak Pendulum Force | CFC 1000 | n/a |
| NHTSA (Maltese) Sled Tests | Thorax, Abdomen and Pelvis Plate Forces | CFC 1000 | See Note |
| | T-1 Lateral Acceleration | CFC 180 | |
| | T-12 Lateral Acceleration | CFC 180 | |
| | Upper Thoracic Lateral Deflection | CFC 600 | |
| | Lower Thoracic Lateral Deflection | CFC 600 | |

* Indicates that no time zero definition was given in the original work, and an assumption was made here based on figures shown in ISO 9790.

Note: For flat wall tests, time-zero is determined by initiation of arm contact on the thoracic load plate. In pelvic and abdominal offset tests, time-zero is coincident with specimen contact with the offset load plate. Contact with the load plate is determined by finding the first point in time on the load wall force-time history where the load exceeds 200 N and then incrementing backward to find the point in time where the force-time history crosses zero load (zero-crossing load). The time of occurrence of the zero-crossing load is taken to be the start of the impact event for **all** recorded signals.

**Data Processing**

Another vital element of evaluating dummy biofidelity is processing the dummy data identically to that of the human subjects, including setting time zero and filtering. In order to duplicate an exact biofidelity ranking number using the BRS, updated or not, the sequence of steps taken is also important. In the updated BRS, all of the transducer data from the dummy tests were recorded according to the digital data sampling requirements of SAE J211-1 [SAE, 2003]. For the data that was determined using video analysis, digital video cameras with a recording rate of 1000 frames-per-second were used. Following acquisition, all transducer data were processed in software as follows:

1. Any pre-test data channel bias was removed.
2. Sled wall body region force plate (e.g. Thorax Plate, Pelvis Plate) loads were calculated by summing the individual load cells used at each force plate location. Since the force plate load cells are recorded at SAE J211 Channel Filter Class (CFC) 1000 by the sled data acquisition system, the load cell channels were summed at CFC 1000.
3. The data channels were digitally filtered using the same filter specification used for the human subject biofidelity corridor data. The filter specifications are shown in Table 7.
4. Time zero was set as defined for the human subject data, also shown in Table 7.
5. Since all of the biofidelity corridors are positive polarity, negative polarity data channels were inverted to be positive.
6. The data channels were sub-sampled to match the sample rate of the human subject response target data.
7. The data channels were truncated to match the length of the response targets, shown in Table 5.
8. The $\sqrt{R}$ values were calculated.

**RESULTS**

Table 8 shows the External and Internal Biofidelity ranks achieved when the updated BRS is applied to recent test data with the two dummies. Table 8 includes External and Internal ranks for each dummy for each body region as well as overall ranks. In addition, Table 8 shows overall Internal biofidelity ranks without the abdomen body region.

**Table 8.**
**External and internal biofidelity ranks for WorldSID and ES-2re**

| Body Region | External Biofidelity | | Internal Biofidelity | |
|---|---|---|---|---|
| | WorldSID | ES-2re | WorldSID | ES-2re |
| Head | | | 0.3 | 1.0 |
| Neck | | | 0.8 | 2.2 |
| Shoulder | 1.0 | 2.1 | 0.9 | 1.3 |
| Thorax | 3.2 | 3.1 | 2.0 | 2.4 |
| Abdomen | 1.9 | 2.7 | 2.4 | n/a |
| Pelvis | 2.7 | 3.5 | 1.8 | 1.5 |
| Overall (with Abdomen) | 2.2 | 2.8 | 1.4 | - |
| Overall (without Abdomen) | - | - | 1.2 | 1.7 |

**DISCUSSION**

**External Biofidelity of WorldSID vs. ES-2re**

As shown in Table 8, the WorldSID dummy received an overall external BioRank score of 2.2 versus the ES-2re's overall score of 2.8. The WorldSID ranked better than the ES-2re in all body regions except the thorax where both dummies received equivalent ranks with scores of 3.2 and 3.1, respectively. The external thorax assessment consists of thorax plate force responses from the NHTSA [Maltese, 2002] and Heidelberg [ISO 1999] sled test conditions and pendulum force responses from the ISO 9790 Thorax Test 1 and the NHTSA [Shaw, 2006] 2.5 m/s lateral and oblique thorax test conditions. As shown in Figure 2, both dummies performed well in the Heidelberg sled test, which would be expected since this test was used as a performance criterion for the development of both dummies. Neither dummy performed as well in the NHTSA [Maltese, 2002] sled test conditions as shown in the plots of Figure 3, Figure 4, and Figure 5. Figure 5 shows how the vertical linkage of human body regions is important, especially the phasing among them. Specifically, as shown in Figure 5, the thorax load wall is loaded earlier by the dummies than by the human subjects. Both the ES-2re and WorldSID need improvement regarding the timing of the thorax response in such a loading condition; however, the magnitude of the ES-2re response is much closer to the mean human response than is that of the WorldSID.

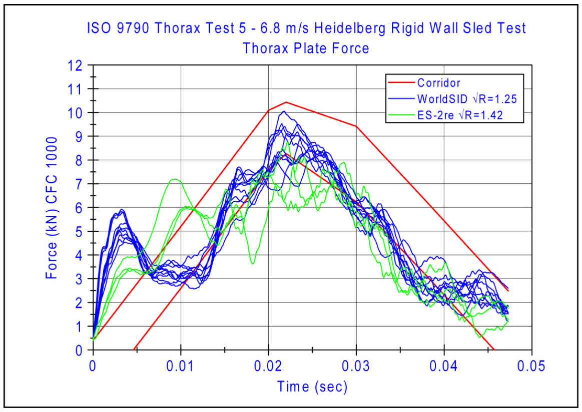


**Figure 2. Thorax plate force from ISO 9790 Thorax Test 5.**

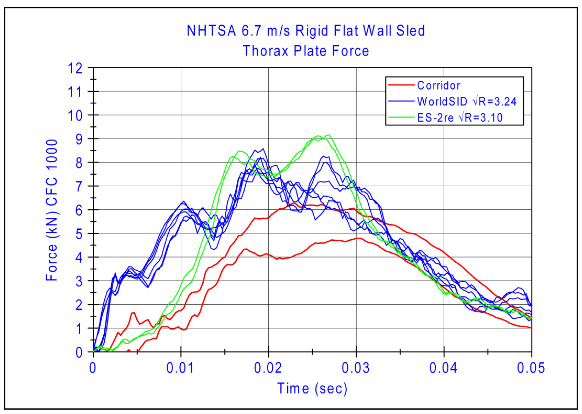


**Figure 3. Thorax plate force from Maltese Rigid Low-Speed Flat Wall Sled Test.**

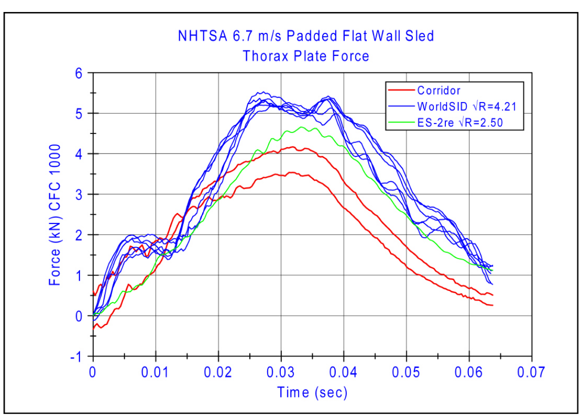


**Figure 4. Thorax plate force from Maltese Padded Low-Speed Flat Wall Sled Test.**

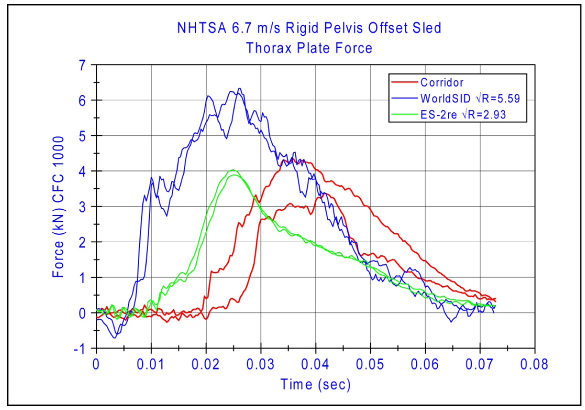


**Figure 5. Thorax plate force from Maltese Rigid Low-Speed Pelvis Offset Sled Test.**

**Internal Biofidelity of WorldSID vs. ES-2re**

As shown in Table 8, excluding the abdominal ranking for a direct and fair comparison, the WorldSID dummy received an overall internal BioRank score of 1.2 versus the ES-2re's overall score of 1.7. When the abdominal rank is included, the WorldSID receives a BioRank score of 1.4. The WorldSID dummy ranked well in all body regions except the abdominal region which received a score of 2.4. Since internal abdomen biofidelity is based on abdominal deflection response targets, the ES-2re is not ranked in this category. The ES-2re ranked well in all body regions except for the neck and thorax regions where it received scores of 2.2 and 2.4, respectively. Figure 6 shows data for the lower thoracic rib deflection from the NHTSA [Maltese, 2002] Rigid Abdomen Offset test where the WorldSID had a √R of 0.7 and the ES-2re, 1.9. The difference in responses is suspected to be a result of the offset abdomen plate engaging the lower thoracic region of the human subject and WorldSID dummy while engaging below the thoracic region of the ES-2re dummy due to its higher seated stature.

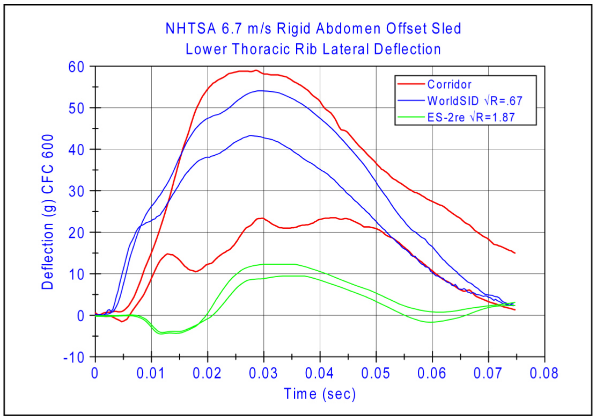


**Figure 6. Lower thoracic rib deflection from Maltese Rigid Low-Speed Abdomen Offset Sled Test.**

**Design Differences Between the WorldSID and ES-2re**

**Head -** The ES-2re head is based on the Hybrid III 50th percentile head and consists of a cast aluminum skull covered with a removable vinyl skin. The WorldSID head assembly uses a molded polyurethane skull with a bonded vinyl skin. Although the head assemblies are significantly different in design, the ES-2re and WorldSID dummies received similar internal head BioRank scores of 1.0 and 0.3, respectively.

**Neck -** With the exception of fore/aft tuning buffers in the WorldSID neck, which were modified to better tune the WorldSID's flexion /extension response, the ES-2re and WorldSID dummies use the same neck design. Although the neck designs are similar, the dummies ranked differently with the WorldSID receiving an internal score of 0.8 and the ES-2re receiving a score of 2.2. There are other factors that may account for the difference in neck biofidelity scores. The necks are ranked using ISO 9790 Neck Test 1 and Neck Test 3 which are restrained occupant sled tests. Since the dummies are restrained against a wall in these tests, differences in shoulder and thorax responses could influence the results. Also, the WorldSID head has a slightly higher mass than the ES-2re head which could have some effect on head translation. Another unknown but potential difference is in the methodologies used to perform the video data acquisition and analysis.

**Shoulder -** There are significant differences between ES-2re and WorldSID shoulder designs. The ES-2re shoulder consists of two pivoting clavicles guided between two shoulder plates that limit their movement to one plane. The clavicles are held in their neutral position by elastic cords. Shoulder deflection occurs by pivoting the clavicle from the neutral position forward in an arcing motion, resulting in both anterior and medial shoulder deflection. The ES-2re shoulder cannot deflect in the purely lateral direction or pivot rearward. The WorldSID torso, including the shoulder, consists of six rib assemblies: one shoulder, three thoracic and two abdominal. Each rib assembly consists of two inner rib bands (one on each side of the thorax) and an outer rib band that defines the torso's shape. Each outer rib band is fastened to the spine box at the rear and to a plastic sternum at the front. The inner rib bands have a bonded damping material to tune the rib response for each specific body region. The design of the WorldSID ribs allows a purely lateral deflection as well as some capability of forward and rearward deflection under oblique loading.

The ES-2re has no instrumentation for measuring shoulder deflection while each of the WorldSID ribs is instrumented with an IRTRACC on the impact side of the dummy for measuring lateral deflection only.

The 4.4 m/s lateral and oblique pendulum impact tests resulted in unrealistic shoulder deflections in both the ES-2re and WorldSID dummies. The human subject shoulders deflected medially in pure lateral impacts and posteriorly and medially, with decreased stiffness, during anterolateral impacts [Bolte 2000, Bolte 2003]. The WorldSID force response was similar to that of the human subjects resulting in an external shoulder biofidelity score of 1.0. Due to the location of pendulum impact on the WorldSID's shoulder, the pendulum tended to deflect upward, pushing the shoulder rib downward. Although this motion is not consistent with that of the human subjects the WorldSID rank for shoulder internal biofidelity, based on only the lateral deflection, is 0.9. The inability of the ES-2re clavicle to deflect posteriorly resulted in the shoulder response becoming stiffer when the loading moved from the lateral to the anterolateral direction resulting in an external biofidelity score of 2.1. The ES-2re clavicle exhibited a tendency for forward rotation, even during anterolateral impacts. Although this motion is also not consistent with that of the human subjects the ES-2re dummy rank for shoulder internal biofidelity is 1.3. The reasonably good ranks for dummy shoulder kinematics that do not simulate the human kinematics result from incomplete displacement data from the human subjects, allowing limited comparison with the dummies.

**Thorax** - The ES-2re thoracic region consists of three rib modules. Each of the three rib modules is comprised of a steel rib bow covered with flesh-simulating foam. A linear guide assembly attaches between the impact and non-impact side of the rib and limits the deflection to purely lateral. In parallel with the linear guide assembly is a hydraulic damper. A spring inside the linear guide assembly is used to tune the performance of the modules. A potentiometer is installed in each rib module to measure deflection. The WorldSID thoracic region consists of three rib band assemblies as described in the shoulder section, having the same lateral and oblique deflection capabilities. The thoracic biofidelity of the WorldSID and ES-2re are nearly the same with external ranks of 3.2 and 3.1 and internal ranks of 2.0 and 2.4, respectively. With the exception of the NHTSA [Shaw, 2006] 2.5 m/s 30° pendulum impact test, all of the thorax biofidelity tests provide only lateral inputs to the dummy. Therefore, differences in oblique thorax response capabilities between the two dummies are not highlighted. Both dummies demonstrated scores indicative of needing improvement for the pendulum force response measurement of the oblique pendulum impact test (WorldSID 4.1, ES-2re 5.7). In the lateral impacts, both dummies achieve lower (i.e., better) scores for the ISO tests, but higher (i.e., worse) scores for the Shaw and Maltese tests. This is likely due to the fact that the Shaw and Maltese data is relatively new and the ISO data was used as design criteria for both dummies.

**Abdomen** – The WorldSID abdomen is represented by "rib" structures as discussed previously and measures abdominal deflection with IRTRACCs. The ES-2re abdominal region consists of a foam-covered cast aluminum drum positioned around the lumbar spine. There are three load cells attached to the drum to measure the force between the drum and the foam covering. There is no instrumentation for measuring abdominal deflection. Since the internal abdominal biofidelity response targets are based on abdomen deflection, the ES-2re could not be rated for internal abdomen biofidelity; however, the WorldSID only scored a 2.4. External biofidelity scores were 1.9 and 2.7 for the WorldSID and ES-2re, respectively.

**Pelvis** - The ES-2re and WorldSID dummies have pelvis structures consisting of a central sacrum block and two polyurethane iliac wings that are joined at the pubic symphysis by a load cell. The WorldSID pubic symphysis load cell is coupled to the iliac wings using rubber bushings while the ES-2re uses aluminum bushings. The WorldSID pelvis design exhibited a less rigid response than the ES-2re pelvis resulting in external pelvis biofidelity scores of 2.7 and 3.5, respectively. In spite of the stiffer ES-2re pelvis the internal biofidelity score of 1.5 was slightly better than the WorldSID at 1.8.

## CONCLUSIONS

The Biofidelity Ranking System (BRS) has been updated and used to assess the biofidelity of the WorldSID and the ES-2re side impact dummies.

- The subjective decision as to what test data are included in the biofidelity ranking of a dummy is made before the application of the objective BRS.
- The various tests selected for use in the BRS are no longer weighted – each test condition receives the same weight if it is included by the analyst in the BRS. Care should be taken to assure that the tests selected represent an appropriate assessment of the dummy biofidelity based on test severity, body region distribution and data reliability.
- A scale of biofidelity has been established for B values based on the number of standard deviations from the mean cadaver responses.
- A sensitivity analysis of $\sqrt{R}$ values indicates that two B value ranks with a difference of 0.2 or less are not significantly different.
- The WorldSID received an overall internal biofidelity rank of 1.2 and the ES-2re received an overall internal biofidelity rank of 1.7.
- The WorldSID received an overall external biofidelity rank of 2.2 and the ES-2re received an overall external biofidelity rank of 2.8.
- This biofidelity evaluation using the updated BRS indicates good biofidelity for this improved version of the WorldSID dummy.

## REFERENCES

Bolte, IV,J.H., Hines, M.H., McFadden, J.D., and Saul, R.A. (2000) Shoulder Response Characteristics and Injury Due to Lateral Glenohumeral Joint Impacts. Stapp Car Crash Journal 44: 261-280. Society of Automotive Engineers, Warrendale, PA.

Bolte, IV,J.H., Hines, M.H., Herriott, R.G., McFadden, J.D., and Donnelly, B.R. (2003) Shoulder Impact Response and Injury Due to Lateral and Oblique Loading . Stapp Car Crash Journal 47: 35-53. Society of Automotive Engineers, Warrendale, PA.

Hodgson, V.R. and Thomas, L.M. (1975) Head Impact Response. Vehicle Research Institute Report – VRI 7.2. Society of Automotive Engineers.

Irwin, A., Sutterfield, A., Hsu, T., Kim, A., Mertz, H., Rouhana, S., Scherer, R. (2005) Side Impact Response Corridors for the Rigid Flat-Wall and Offset-Wall Side Impact Tests of NHTSA Using the ISO Method of Corridor Development. Stapp Car Crash Journal. 49:423-456.

Irwin, A. (June 2008) Personal communication.

ISO (1999) Technical Report 9790: Road Vehicles – Anthropomorphic Side Impact Dummy – Lateral Impact Response Requirements to Assess the Biofidelity of the Dummy.

Maltese, M.R., Eppinger, R.H., Rhule, H.H., Donnelly, B., Pintar, F.A. and Yoganandan, N. (2002) Response Corridors of Human Surrogates In Lateral Impacts. Stapp Car Crash Journal 46: 321-351.

Mathworks, Inc. Matlab version 7.7.0.471 (R2008b), September 17, 2008.

Morgan, R.M., Marcus, J.H., and Eppinger, R.H. (1986) Side Impact – The Biofidelity of NHTSA's Proposed ATD and Efficacy of TTI. Proc. 30th Stapp Car Crash Conference, pp. 27-40. Society of Automotive Engineers, Warrendale, PA.

Petitjean, A. (June 2008) Personal communication.

Rhule, H.H., Maltese, M.R., Donnelly, B.R., Eppinger, R.H., Brunner, J.K., and Bolte, J.H.IV. (2002) Development of a New Biofidelity Ranking System for Anthropomorphic Test Devices. Stapp Car Crash Journal 46: 477-512.

SAE. (2003) Surface Vehicle Recommended Practice, SAE J211-1, Rev. Dec. 2003. Society of Automotive Engineers, Warrendale, PA.

Shaw, J.M., Herriott, R.G., McFadden, J.D., Donnelly, B.R., Bolte, IV,J.H. (2006) Oblique and Lateral Impact Response of the PMHS Thorax. Stapp Car Crash Journal 50: 147-167.

**APPENDIX A. SQUARE ROOT OF R VALUES FOR EACH RESPONSE MEASUREMENT USED TO EVALUATE THE BIOFIDELITY OF THE ES-2re AND WORLDSID DUMMIES USING THE UPDATED BRS**

| | Test Type | DROP | SLED | | | PENDULUM | | | | | | | SLED | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Measurement | Dummy | ISO 9790 Head Test 1 | ISO 9790 Neck Test 1 | ISO 9790 Neck Test 3 | ISO 9790 Shoulder Test 2 | Bolte Lateral Shoulder | Bolte 15º Shoulder | Bolte 30º Shoulder | ISO 9790 Thorax Test 1 | Shaw Lateral Thorax | Shaw 30º Thorax | ISO 9790 Pelvis Test 1 | ISO 9790 6.8 m/s Heidelberg | ISO 9790 6.8 m/s Wayne State | Maltese 6.7 m/s Rigid Flat Wall | Maltese 6.7 m/s Padded Flat Wall | Maltese 6.7 m/s Rigid Abdomen Offset | Maltese 6.7 m/s Rigid Pelvis Offset | Maltese 8.9 m/s Padded Flat Wall |
| Peak Resultant Head Acceleration | WSID | 0.33 | | | | | | | | | | | | | | | | | |
| | ES-2re | 1.02 | | | | | | | | | | | | | | | | | |
| Peak Horiz. Disp. of Head cg Relative to T-1 | WSID | | 1.22 | | | | | | | | | | | | | | | | |
| | ES-2re | | 3.25 | | | | | | | | | | | | | | | | |
| Peak Vert. Disp. of Head cg Relative to T-1 | WSID | | 1.22 | | | | | | | | | | | | | | | | |
| | ES-2re | | 2.49 | | | | | | | | | | | | | | | | |
| Peak Flexion Angle | WSID | | 0.40 | 1.15 | | | | | | | | | | | | | | | |
| | ES-2re | | 1.00 | 2.85 | | | | | | | | | | | | | | | |
| Peak Horiz. Disp. of Head cg Relative to Sled | WSID | | | 0.25 | | | | | | | | | | | | | | | |
| | ES-2re | | | 1.59 | | | | | | | | | | | | | | | |
| Pendulum Force | WSID | | | | | 0.87 | | | 1.27 | 2.94 | 4.13 | | | | | | | | |
| | ES-2re | | | | | 1.10 | | | 2.29 | 2.52 | 5.71 | | | | | | | | |
| Pendulum Y-axis Force | WSID | | | | | | 1.26 | 0.54 | | | | | | | | | | | |
| | ES-2re | | | | | | 2.96 | 3.44 | | | | | | | | | | | |
| Pendulum X-axis Force | WSID | | | | | | 0.84 | 1.59 | | | | | | | | | | | |
| | ES-2re | | | | | | 1.96 | 1.83 | | | | | | | | | | | |
| Peak Horiz. Disp. of T-1 Relative to Sled | WSID | | | | 0.24 | | | | | | | | | | | | | | |
| | ES-2re | | | | 1.47 | | | | | | | | | | | | | | |
| Shoulder Y-axis Displacement | WSID | | | | | 1.55 | | | | | | | | | | | | | |
| | ES-2re | | | | | 1.11 | | | | | | | | | | | | | |
| Thorax Plate Force | WSID | | | | | | | | | | | | 1.25 | | 3.24 | 4.21 | 3.81 | 5.59 | 2.57 |
| | ES-2re | | | | | | | | | | | | 1.42 | | 3.10 | 2.50 | 4.22 | 2.93 | 2.83 |
| T-1 Lateral Acceleration | WSID | | | | | | | | 1.66 | | | | | | 2.32 | 1.28 | 2.48 | 1.80 | 0.82 |
| | ES-2re | | | | | | | | 2.64 | | | | | | 1.50 | 1.31 | 3.30 | 1.59 | 1.23 |
| Thorax Displacement | WSID | | | | | | | | | 1.54 | 3.17 | | | | | | | | |
| | ES-2re | | | | | | | | | 1.22 | 3.32 | | | | | | | | |
| Peak T-1 Lateral Acceleration | WSID | | | | | | | | | | | | 6.03 | | | | | | |
| | ES-2re | | | | | | | | | | | | 6.86 | | | | | | |
| Peak T-12 Lateral Acceleration | WSID | | | | | | | | | | | | 4.01 | | | | | | |
| | ES-2re | | | | | | | | | | | | 4.22 | | | | | | |
| Peak Lateral Accel. of Impacted Rib | WSID | | | | | | | | | | | | 0.70 | | | | | | |
| | ES-2re | | | | | | | | | | | | 2.95 | | | | | | |
| T-12 Lateral Acceleration | WSID | | | | | | | | | | | | | | 1.66 | 1.34 | 1.42 | 4.39 | 0.92 |
| | ES-2re | | | | | | | | | | | | | | 1.54 | 1.27 | 3.15 | 4.03 | 0.94 |
| Upper Thoracic Lateral Deflection | WSID | | | | | | | | | | | | | | 1.61 | 0.72 | | 2.72 | 0.48 |
| | ES-2re | | | | | | | | | | | | | | 2.34 | 0.90 | | 2.18 | 0.93 |
| Lower Thoracic Lateral Deflection | WSID | | | | | | | | | | | | | | 1.97 | 0.81 | 0.67 | 4.60 | 0.46 |
| | ES-2re | | | | | | | | | | | | | | 2.00 | 1.01 | 1.87 | 4.73 | 0.77 |
| Abdomen Plate Force | WSID | | | | | | | | | | | | | 1.72 | 0.60 | 1.61 | 0.94 | 3.71 | 2.83 |
| | ES-2re | | | | | | | | | | | | | 2.08 | 0.58 | 1.05 | 5.28 | 3.95 | 3.24 |
| Mid-Abdominal Deflection | WSID | | | | | | | | | | | | | | 2.75 | 1.64 | 1.78 | 2.79 | 2.89 |
| | ES-2re | | | | | | | | | | | | | | n/a | n/a | n/a | n/a | n/a |
| Peak Pendulum Force | WSID | | | | | | | | | | | 0.23 | | | | | | | |
| | ES-2re | | | | | | | | | | | 5.39 | | | | | | | |
| Peak Pelvis Plate Force | WSID | | | | | | | | | | | | 6.76 | | | | | | |
| | ES-2re | | | | | | | | | | | | 7.89 | | | | | | |
| Pelvis Plate Force | WSID | | | | | | | | | | | | | 1.61 | 1.77 | 2.13 | 4.06 | 1.60 | 3.77 |
| | ES-2re | | | | | | | | | | | | | 1.63 | 2.44 | 2.13 | 2.14 | 1.49 | 4.82 |
| Peak Pelvis Lateral Acceleration | WSID | | | | | | | | | | | | 0.35 | 3.98 | | | | | |
| | ES-2re | | | | | | | | | | | | 1.50 | 1.00 | | | | | |
| Pelvis Lateral Acceleration | WSID | | | | | | | | | | | | | | 1.53 | 2.09 | 1.16 | 1.94 | 1.26 |
| | ES-2re | | | | | | | | | | | | | | 1.72 | 1.69 | 1.09 | 2.62 | 1.09 |

Internal Head Values
Internal Neck Values
External Shoulder Values
Internal Shoulder Values
External Thorax Values
Internal Thorax Values
Ext Abdomen Values
Int Abdomen Values
External Pelvis Values
Internal Pelvis Values

| Final Ranks: | | Head | Neck | Shoulder | Thorax | Abdomen | Pelvis | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **EXTERNAL** | **WSID** | | | **1.0** | **3.2** | **1.9** | **2.7** | **Overall** | **2.2** | | |
| | **ES-2re** | | | **2.1** | **3.1** | **2.7** | **3.5** | | **2.8** | | |
| **INTERNAL** | **WSID** | **0.3** | **0.8** | **0.9** | **2.0** | **2.4** | **1.8** | **Overall w/abd** | **1.4** | **Overall w/o abd** | **1.2** |
| | **ES-2re** | **1.0** | **2.2** | **1.3** | **2.4** | **N/A** | **1.5** | | **n/a** | | **1.7** |