EVALUATION OF THE 95TH PERCENTILE HIII LARGE MALE DUMMY

Joshua Shaw
Transportation Research Center Inc.
Edward Probst
Bruce Donnelly
NHTSA – VRTC
United States
Paper Number 07-0228

ABSTRACT

This study summarizes results from a preliminary evaluation of the Hybrid III Large Male Dummy. The paper reviews the dimensions, certification test responses, durability, and repeatability and reproducibility of two Hybrid III 95th Percentile Large Male dummies, each produced by a different manufacturer. Response data from multiple repeats of the proposed Calibration and Inspection Test Procedure sections from the SAE Draft of the "User's Manual for the HIII 95th Large Male Test Dummy" (SAE, 2003) are used as the basis for the analysis. An overview of the test methodologies employed is presented as well as an assessment of the compliance with the proposed certification specifications, durability at high energy test levels and repeatability and reproducibility. Besides employing the typical repeatability measures of traditionally-calculated coefficients of variation, a new technique is proposed and discussed involving a time-variant method of calculating coefficients of variation.

INTRODUCTION

The first anthropomorphic representation of a large male was developed by the Sierra Engineering Company in the late 1940's and early 1950's under contract to the U.S. Air Force. This 95th percentile anthropomorphic test device (ATD) known as "Sierra Sam," was primarily used for early aerospace and high altitude parachute experimentation. With the development of more biofidelic ATDs in the 1970's and early 1980's, such as GM's Hybrid generation of 50th percentile dummies, a foundation was established for the creation of a "family" of these advanced dummies.

In 1987 the Center for Disease Control (CDC) awarded a grant to the Ohio State University for the development of this Hybrid III (HIII) family of dummies. The SAE formed a task group of industry, government, and academic biomechanics experts to support this work through the generation of geometric and mass scale factors. These factors were applied to the HIII 50th percentile male specifications to develop dimensional, weight and impact performance requirements for 5th and 95th percentile HIII dummies.

Although the HIII 5th percentile small female is currently regulated by the Code of Federal Regulations, Title 49, Part 572, the 95th Percentile Large Male is not; albeit a 95th surrogate is referenced in FMVSS No. 202 governing head restraints.

The purpose of this evaluation is to support a future Federalization process by conducting a thorough inspection of component and full-dummy external dimensions of two HIII 95th large male dummies from different ATD suppliers. In addition, preliminary evaluations of the repeatability and reproducibility (R & R) and laboratory durability of each dummy are also performed.

Two draft documents currently being developed by the SAE Dummy Test and Evaluation Subcommittee are used as templates for the experimental aspects of this investigation. A draft version of the SAE Engineering Drawing Package (SAE EA 32) is used as the basis for a common dimensional and weight inspection of both dummies. The R & R test plan is based upon multiple repeats of the major certification tests enumerated in the SAE draft of the "Users Manual for the HIII 95th Large Male Test Dummy" (SAE, 2003). The durability assessment is developed by scaling the certification tests to energy levels associated with proposed injury levels for the large male.

For the purposes of this project two dummies were purchased from two manufacturers, one from Denton ATD (DATD) and one from First Technology Safety Systems (FTSS). Dummy #077 is from DATD and dummy #226 is from FTSS.

METHODS

Inspection

The drawing review process involves examining all of the engineering drawings for clarity and accuracy. These drawings are checked both by comparing the physical part dimensions to the drawing dimensions as well as by comparison to the contents of other federally regulated dummies, such as the HIII 50th percentile male dummy. The inspection process is a

physical check of the dummy components in both segment weights and external dimensions. This can also include the inspection of individual part dimensions to the corresponding drawing(s). The segment weights and external dimensions of each dummy are listed in the Results section along with the specification.

Certification Testing

The certification tests utilized to determine the repeatability and reproducibility of the HIII 95th Large Male dummy are those as specified in the SAE User's Manual. These types of tests are the same as those specified for the 50th percentile Hybrid III dummy, but the dynamic response requirements have been scaled (Mertz, 1989) for a large male dummy based on geometric similitude. The tests specified by the User's Manual include frontal thorax impact, frontal neck flexion and extension tests, knee impact, and knee slider impact.

Head Drop Certification Test - Head drop certification tests are conducted by dropping an isolated head from a height of 376 mm onto a 50.8 mm thick steel plate and measuring the triaxial acceleration at the center of gravity (CG) of the head. The resultant acceleration is calculated from the filtered acceleration time histories and according to the SAE User's Manual should be between 220 – 265 g at peak and the lateral acceleration (Y axis) should be less than 15 g in either direction (positive or negative Y axis). Mertz et. al. (1989) specifies the same acceleration range for the head drop.

Neck Flexion Certification Test - The neck flexion and extension tests are conducted using a pendulum to which the neck and head are attached. The pendulum is released from a given height to produce a desired velocity at the bottom of the swing arc. As it reaches the bottom vertical position it is arrested by an energy absorbing component. Although the pendulum arm motion stops, the inertia of the head causes the neck to flex in relation to the pendulum. A six axis upper neck load cell was used to record the forces and moments generated about the occipital condyle (OC) joint while two rotary potentiometers and a connecting rod are used to determine the angle of the head in relation to the pendulum, which represents the torso. This angle is known as D-plane rotation.

The SAE User's Manual specifies an impact velocity of 6.89 – 7.13 m/s at the pendulum CG and a pulse profile measured by the integrated pendulum acceleration, to define the energy absorbing

component. Mertz et. al. (1989) also specifies a corridor for the neck flexion response. The corridor coordinates are shown in Table 1.

Table 1.
Mertz et. al. OC moment versus D-plane angle neck flexion corridor

Upper Boundary Coordinates		Lower Boundary Coordinates	
Moment [Nm]	Rotation [deg]	Moment [Nm]	Rotation [deg]
0	0	0	34
83	14	37	53
83	43	120	73
120	64	258	77
258	68		

Neck Extension Certification Test - The SAE User's Manual specifies an impact velocity of 5.90 – 6.19 m/s at the pendulum CG and a pulse profile as measured by the integrated pendulum acceleration. Mertz et. al. (1989) also specifies a corridor for the neck extension response. The corridor coordinates are shown in Table 2.

Table 2.
Mertz et. al. OC moment versus D-plane angle neck extension corridor

Upper Boundary Coordinates		Lower Boundary Coordinates	
Moment [Nm]	Rotation [deg]	Moment [Nm]	Rotation [deg]
0	0	0	-48
-42	-19	-11	-77
-42	-58	-92	-92
-65	-77		
-92	-82		

Thorax Certification Test - The thorax certification test is a frontal impact to the dummy chest centered midsternally with a 23.36 kg pendulum traveling at a velocity of 6.71 +/- 0.12 m/s at impact. In addition to the peak response requirements stated in the SAE User's Manual, Mertz et. al. specify a force versus deflection corridor (Table 3) for the entire impact.

Knee Impact Certification Test - Knee impacts are administered at velocities between 2.07 – 2.13 m/s by a 5-kg pendulum to the knee of a flexed lower extremity. It was assumed that both knees of the same dummy are the same and therefore only one knee from each dummy is compared.

Table 3.
Mertz et. al. force versus deflection thorax corridor

Upper Boundary Coordinates		Lower Boundary Coordinates	
Force [kN]	Deflection [mm]	Force [kN]	Deflection [mm]
4.85	6.6	3.65	6.6
5.07	26.4	3.78	2.64
5.34	39.6	3.96	3.96
6.05	64.8	4.45	6.07
4.94	80.8	3.47	6.35
3.47	85.9	0.98	5.41
0.98	76.7		

Knee Slider Certification Test - The knee slider certification test was conducted in nearly the same manner as the knee impact test. However, the lower portion of the leg is removed and an impact fixture is attached to the knee slider. A 12-kg pendulum strikes the fixture at velocities between 2.70 – 2.80 m/s. Rather than the SAE specified deflection response, Mertz et. al. specified a stiffness corridor, 137 – 187 N/mm.

Repeatability and Reproducibility

In the traditional method for assessing the repeatability and reproducibility of a dummy design, a test is repeated a number of times and the average, standard deviation, and coefficient of variation (CV) of the peak of the response parameters are quantified. Accepted practice is that a CV between 0 – 5% is Excellent, 5 – 8% is Good, 8 – 10% is Acceptable, and > 10% is Unacceptable (Rhule 2005). Once a dummy response is shown to be repeatable (by displaying an acceptable or better CV), the reproducibility is assessed by combining the results from all tests of all dummies and applying the same standard for CV. This approach has several shortcomings and a modified approach will be followed in this study.

The traditional approach for assessing dummy repeatability, as described above, has been to test a dummy several times, in identical configurations, and to calculate the CV at the maximum points of a relevant response parameter. This approach assesses the dummy response at the point in time at which most certification criteria are established, e.g., maximum chest force or maximum neck rotation. The drawback to this approach is that the dummy response is a time history and the time at which the maximum value occurs, as well as the overall shape

of the response, is important. When comparing maximum response values from repeat tests the values may not be occurring at the same point in time and a small or large CV may not actually be a valid assessment of repeatability. Further, it may be that the maximum values are the only point in time at which the dummy responses are similar and the repeatability is actually poor at all other points in time. In this study of the 95th percentile male dummy an assessment of repeatability will be made over a portion of the response time history.

A set of six force versus time response curves from the thorax certification tests conducted on dummy 077 are shown in Figure 1.
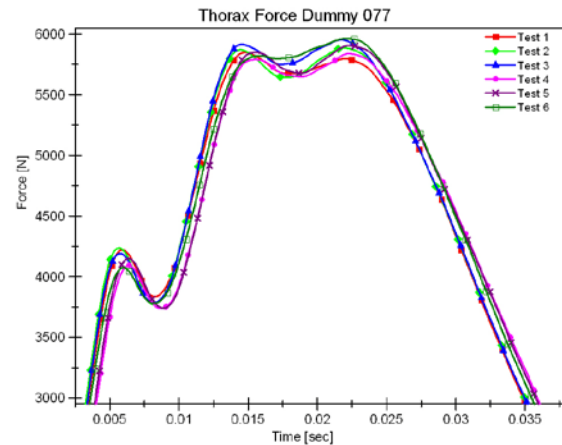

Figure 1. Central portion of force versus time response for certification tests conducted on dummy 077.

It can be seen that the curves are all quite similar but that there are slight differences in magnitude and timing of peaks, e.g., Test 1 curve versus Test 2 curve. A mean force versus time curve can be generated from these six digitized curves by averaging the force values at each time increment. Similarly, a standard deviation and a coefficient of variation for the six responses can also be generated at each time increment. At the maximum mean force (0.0221 seconds) the CV is 1.1%; however, at another point in time near the maximum mean force (0.0157 seconds) the CV is 0.5%; less than half. For the portion of the curve that is above half of the maximum value (i.e., all data above 50% of the peak value of the mean curve), the central portion of the response data, the CV varies from 0.5% to 8.5% with an average CV of 2.2%. Although the majority of these CV values are below the accepted standard of 5%, indicating very good repeatability, the CV calculated in the traditional manner (1.1%, see Table

13) is not representative of the CVs over the central portion of the curve.

If it is assumed that the important part of a response curve is the central portion of the curve, a confidence interval band can be drawn around the mean based on the sample response curves obtained from the six tests. It can be stated that we are 90% confident that the true mean lies within a confidence interval estimated from the sample responses we have. The equation for calculating a confidence interval (CI) is (Bendat, 2000):

$$CI = \mu \pm \frac{S(t_{\alpha/2})}{\sqrt{N}} \qquad (1)$$

where S = the unbiased sample standard deviation as a function of time

μ = the sample mean value as a function of time

N = the number of tests

$t_{\alpha/2}$ = the two-tailed t-statistic for 90% = 2.015.

Thus, the confidence interval band (CI$_B$) (the projected range of mean variation about the sample mean) can be defined as:

$$CI_B = 2 * \frac{S(t_{\alpha/2})}{\sqrt{N}} \qquad (2)$$

It can be stated that one half of the confidence interval band divided by the sample mean is analogous to the CV

$$\frac{CI_B}{2\mu} = \frac{S(t_{\alpha/2})}{\mu\sqrt{N}} = \frac{CV(t_{\alpha/2})}{\sqrt{N}} \qquad (3)$$

Note that the unbiased standard deviation has a denominator of N-1 whereas the biased standard deviation, with a denominator of N, is normally used in the traditional CV calculation ([N/(N-1)]=1.09 times the biased CV yields the unbiased CV for N=6). If the "excellent" value of CV=5% is used in the calculation, the 90% confidence interval is ±4.5% of the sample mean, as shown below.

$$\frac{CI_B}{2} = \frac{1.09CV(t_{\alpha/2})}{\sqrt{N}}$$
$$= \frac{1.09(0.05)(2.015)\mu}{\sqrt{6}} = 0.045\mu \qquad (4)$$

In other words, if the sample response data has a CV of 5%, we can be 90% confident that the true mean

lies within a ±5% corridor (actually 4.5%) of the mean. Practically speaking, it is 90% certain that the calculated mean is a good estimate of the true response. Similarly, if the sample response data has a CV of 10%, we can be 90% confident that the true mean lies within a ±10% corridor (actually 9%) of the mean. This analysis makes the usual assumptions of statistical independence and a normal distribution of response data. It must be noted that the number of repeat tests in this example was limited by practical considerations to N=6.

In this study repeatability will be assessed by calculating the CV at all points in the time history of the central portion and averaging all of these values to obtain a representative CV for that portion. If the average CV is below 5% the repeatability will be considered to be excellent.

Dummy to dummy reproducibility, where each dummy has already been shown to be repeatable, is assessed with a comparison of means by the Student t-test. A null hypothesis is selected stating that the average of the absolute value of the paired differences between the two dummy means is greater than 10% of the mean of the means. We will test this hypothesis using the one-tailed T statistic tested against the Student t-value at the 10% probability level (α = 0.05). The degrees of freedom will be the number of pairs, which is large and can be considered as infinity when using the table of t-values. The test statistic uses the standard error for the paired differences.

$$T = \frac{\sum\limits_{i=1}^{d}\left[(0.1)(\mu) - |\mu_{1i} - \mu_{2i}|\right]}{(S_d)(\sqrt{d})} \qquad (5)$$

Where μ_1 and μ_2 are the sample means

μ = the mean of the means

d = the number of pairs of data points

S_d = the standard deviation of the differences.

If the test statistic is larger than the t-value of 1.282 the null hypothesis is rejected and we can assume the responses from the two dummies are from the same population and can be combined. If the two sets of data are likely from the same population, it is reasonable to calculate a mean from all of the data for the dummy and apply the same procedure as was discussed previously for repeatability. In the case of reproducibility we will apply the more liberal 10% standard of acceptable reproducibility. If the two

dummies are significantly different, i.e., if the null hypothesis is not rejected, then the dummies are not reproducible.

Durability

To determine the durability of a dummy component, the input is incrementally increased to levels above the standard certification tests and the component inspected between test intervals. All dummies are designed and created with the intention of being used in a situation that could potentially cause injury to a human. Dummies are routinely subjected to events at or near the injury level in actual crash testing. Therefore it is necessary to have a dummy that is durable up to and beyond the injury levels that have been identified.

Injury levels for the 95th Male dummy were either determined from the corridors in Mertz (1989) or by scaling the injury values for the Hybrid III 50th Male listed in 49 CFR 571.208 up to the 95th Male using the scale factors listed in Mertz. It should be noted that the values employed are <u>not</u> the Injury Assessment Reference Values that would accompany a Final Rule for the 95th percentile dummy. Rather they are simply values used to determine an upper level that the durability testing should attempt to reach. The injury values that were determined to be sufficient for this testing are listed in Table 4.

Table 4.
Assumed injury levels for 95th Male dummy

Body Segment	50th Male Injury Level	95th Male Injury Level	95th Value Source
Head	HIC$_{36}$ 1000	HIC$_{36}$ 1000	49 CFR 571.208
Neck Flexion	OC Moment 190 Nm	OC Moment 258 Nm	Assumed Mertz (1989)
	$\Theta = 80°$	$\Theta = 77°$	Assumed Mertz (1989)
Neck Extension	OC Moment 57 Nm	OC Moment 92 Nm	Assumed Mertz (1989)
	$\Theta = 95°$	$\Theta = 92°$	Assumed Mertz (1989)
Thorax	Deflection = 76 mm	Deflection = 79 mm	49 CFR 571.208
	Force = 5.43 kN	Force = 6.05 kN	49 CFR 571.208
Knee	Force = 10 kN	Force = 12.7 kN	49 CFR 571.208

The data from Table 4 was then used to determine the inputs for durability testing. Rhule et. al. (2005) simply increased the input energy by a nominal 30%. Doing this however did not guarantee that a test type would result in a response at or exceeding the injury values. For the current study the outputs were used in a variety of engineering relations to determine the inputs required to produce a desired response. For example, to achieve the thorax injury level of a force of 6.05 kN and a deflection of 79 mm, the 23.4 kg pendulum mass must impact the dummy chest at some as-yet-unknown velocity. Conducting an energy balance calculation that relates the work done to the input energy, the input velocity can be determined. The specific approach for each test type is described below.

<u>Head Drop</u> - The Head Injury Criteria (HIC$_{36}$) is specified at 1000 for both the 5th percentile small female and the 50th percentile male dummies (49 CFR 571.208), therefore there was no reason to change the injury level for the larger 95th percentile dummy. HIC$_{36}$ was calculated for several of the certification tests completed prior and it was noted that the values obtained were nearly at 1000. As a result the maximum head drop distance was increased to the greatest height that the in-house drop fixture would allow to achieve HIC$_{36}$ results above 1000. The head was then dropped from the standard certification test height (376 mm), an intermediate height (415 mm), and the highest height (450 mm).

<u>Neck Flexion</u> - Injury values for neck flexion were derived from the corridors specified in Mertz (1989). The angle and moment were then used in an energy calculation to determine the input kinetic energy and thus the input pendulum velocity. It was assumed that the input translational kinetic energy would be converted to the output rotational work in this test type. Before the injury level velocity was determined a nominal loss term was calculated from the certification test averages so that losses could be approximated in the higher energy tests. For example, the average input velocity was 6.99 m/s and the average moment and rotation were 125 Nm and 61°, respectively. Solving the energy equation for the loss portion gives

$$Loss = \frac{1}{2}mv^2 - M\theta \qquad (6)$$

where m is the mass of the head and neck (6.65 kg), M is the moment, and θ the rotation,

$$Loss = \frac{1}{2}6.65kg*\left(6.99\frac{m}{s}\right)^2 - 125Nm*1.06radians \quad (7)$$

which equals a loss of 30.1 joules. Now if Equation 6 is algebraically manipulated to solve for velocity and the injury level values and the loss term are input, it becomes

$$v = \sqrt{\frac{2}{m}\left(M\theta + Loss\right)} \quad (8)$$

$$v = \sqrt{\frac{2}{6.65kg}\left(258Nm*1.34rad + 30.1J\right)} \quad (9)$$

The velocity required to produce the injury level is 10.6 m/s. Therefore the neck flexion tests would be performed at the certification test velocity (6.99 m/s), at an intermediate level (8.80 m/s), and at the injury producing level (10.6 m/s). Unfortunately, the equipment available could only reach heights capable of producing a 7.50 m/s impact velocity. It was decided to test at the certification velocity (6.99 m/s), an intermediate velocity (7.25 m/s), and the upper limit of the equipment (7.50 m/s).

Neck Extension - The same activity was completed for the neck extension test to determine the input required to produce an injury event in the dummy. The injury values for extension were also assumed from the corridors specified in Mertz (1989). Equation 6 was used again to determine the nominal loss in a standard neck extension certification test. The average velocity for these tests was 5.99 m/s and the average moment and rotation were 67.4 Nm and 79.0°, respectively. Solving Equation 6 with these inputs gives,

$$Loss = \frac{1}{2}6.65kg*\left(5.99\frac{m}{s}\right)^2 - 67.4Nm*1.38radians \quad (10)$$

where the loss equals 26.3 joules. Similar to the neck flexion test, the injury level inputs and the loss term are used in Equation 8 to determine the velocity that would cause an injury reading

$$v = \sqrt{\frac{2}{6.65kg}\left(92Nm*1.61rad + 26.3J\right)} \quad (11)$$

the required velocity was 7.24 m/s. This velocity was attainable and the dummy necks were tested at the certification velocity (5.99 m/s), an intermediate level (6.60 m/s), and the injury level (7.24 m/s).

Thorax - The determination of the input energy for the thorax impact test to achieve injury level was similar to that of the neck flexion and extension. For this test however, the input kinetic energy was related to the linear work output. Also similar was the calculation of the nominal energy loss in the certification tests. Using the average impact velocity, peak force, and peak deflection, the loss was calculated as follows

$$Loss = \frac{1}{2}mv^2 - Fd \quad (12)$$

where m = 23.36 kg and v, F, and d are the averages from Table 10 to give

$$Loss = \frac{1}{2}23.36kg*\left(6.75\frac{m}{s}\right)^2 - 5.79kN*67.7mm \quad (13)$$

which results in a nominal loss of 140 joules. Equation 12 is algebraically manipulated to solve for velocity

$$v = \sqrt{\frac{2}{m}\left(Fd + Loss\right)} \quad (14)$$

and the injury level parameters are used to determine the velocity required

$$v = \sqrt{\frac{2}{23.36kg}\left(6.05kN*79mm + 140J\right)} \quad (15)$$

which is 7.27 m/s. The in-house equipment had the ability to conduct impacts at greater speeds and therefore it was decided to test at the maximum velocity the equipment could produce. The thoraces of the dummies were tested at the certification velocity (6.75 m/s), an intermediate velocity (7.50 m/s) which is near the injury level, and at the highest velocity attainable (8.33 m/s).

Knee Impact - The knee impact test does not measure a deflection, but rather just a force. Instead of balancing the energy to determine the injury level input, the velocity requirement was found using conservation of linear momentum

$$mv_f - mv_i = \int Fdt + Loss \quad (16)$$

where m is the mass of the pendulum and v_f is approximately 0.73 m/s in the opposite direction after the impact. The loss was accounted for in the standard certification test as follows

$$Loss = m(v_f - v_i) - \int F dt \qquad (17)$$

$$Loss = 5kg\left(-0.73\frac{m}{s} - 2.10\frac{m}{s}\right) - .5(.00475s)(-6451N) \qquad (18)$$

and found to be 1.98 kgm/s. The impulse was approximated by integrating a triangular waveform with a height equivalent to the average peak force and a base equivalent to the duration of the force pulse from the certification tests. Now solving Equation 16 for v_i to obtain the injury level output gives

$$mv_i = mv_f - \int F dt - Loss \qquad (19)$$

with the final, or rebound, velocity being a product of the input velocity. Therefore, the coefficient of restitution, 'e', was calculated from the certification parameters such that

$$e = \frac{mv_f}{mv_i} = \frac{0.73\,m/s}{2.10\,m/s} = 0.35 \qquad (20)$$

which makes Equation 19 become

$$mv_i - mev_i = -\int F dt - Loss \qquad (21)$$

$$v_i = \frac{-\int F dt - Loss}{m(1-e)} \qquad (22)$$

Substituting the calculated loss, the desired force value and the mass into this equation allows for the determination of the velocity required to produce the injury level force response. The duration of the force response was assumed to be equivalent to that of the certification tests. Thus

$$v_i = \frac{-.5 * .00475s * (-12700N) - 1.17 kgm/s}{5kg(1 - 0.35)} \qquad (23)$$

results in a velocity of 8.89 m/s. This velocity is greater than the highest velocities attainable on the knee impact fixture. Therefore the equation was

solved using a different mass, indicating a different pendulum to be used. The decision was made to use the 12 kg pendulum that was specified for the knee slider tests, rather than the standard 5 kg impactor, to reduce the required velocity. Solving Equation 23 again with a higher mass results in a velocity of 3.70 m/s, a value much more reasonably attained. Since the test velocity was to be incrementally increased from the certification velocity, it was decided to use the larger mass for all of the durability impacts rather than switching part of the way through the test plan.

Therefore, the certification test velocity would have to be reduced to account for the larger mass. The velocity was scaled based on kinetic energy from the 5 kg, 2.10 m/s impact to the 12 kg impact. This resulted in a 1.36 m/s impact required to maintain the input kinetic energy requirement. The knee impact test velocity was incremented up to the injury level similar to the other tests. The adjusted certification test velocity was completed first (1.36 m/s), then an intermediate velocity (2.53 m/s), and then the velocity required to produce injury (3.70 m/s).

RESULTS

Inspection
The inspection of each dummy yielded a positive result. The weights for all segments of both dummies were within the specifications. The majority of the external dimensions were within the specification for both dummies, however the 'hip pivot from backline' and the 'head circumference' were outside of the specification on dummy 226. The 'reference location for chest circumference' was also slightly high for both dummies. The measurements for both dummies can be seen in Tables 5 and 6 and Figure 2.

Certification Testing

Head Drop Test – The results for the head drop certification test are listed in Table 7 and the response time histories are shown in Figures 3 and 4 along with the SAE and Mertz corridors. The head resultants for dummy 226 were at the top bound of the corridor while the resultants for dummy 077 were just slightly higher than the top bound of the corridor. Dummy 226 had essentially no differences in phase while dummy 077 had slight differences. Both dummies had nearly the same duration for the impacts.

Neck Flexion – The results for the neck flexion certification test are listed in Table 8 and the response time histories are shown in Figures 5 and 6 along

with the SAE and Mertz corridors. The neck flexion responses were similar for each dummy but were just short of the corridor. Dummy 077 had three of the six tests enter the corridor but dummy 226 only had one test enter the corridor. Dummy 226 only obtained one value for the OC Moment within the rotation interval and, as a result, an average, standard deviation, and CV could not be calculated. Subsequently a CV could not be calculated for reproducibility for this parameter. All of the tests on both dummies did however match the Mertz corridor fairly well, with the peak portion being the exception.

Neck Extension – The results for the neck extension certification test are listed in Table 9 and the response time histories are shown in Figures 7 and 8 along with the SAE and Mertz corridors. The neck extension responses were quite similar but again were just short of being within the corridor. None of the tests for either dummy entered the SAE corridor. Five of the six tests on dummy 077 produced a rotation that was within the specification, but all were below the minimum OC Moment. This resulted in an average, standard deviation, and CV to be calculated, but the average was below the lower bound of the OC Moment specification. None of the tests on dummy 226 produced enough rotation to meet the specification, thus the OC Moment parameter does not have an associated average, standard deviation, or CV. Likewise, a CV for reproducibility could not be calculated for the OC Moment parameter. The majority of the tests on dummy 077 matched the Mertz corridor while most of the tests on dummy 226 did not match the corridor, specifically in the peak region.

Thorax – The results for the thorax impact certification test are listed in Table 10 and the response time histories are shown in Figures 9 and 10 along with the SAE and Mertz corridors. The thorax impact responses were excellent and nearly all were within the corridor. Five of the six tests on dummy 077 and six of six tests on dummy 226 were within the SAE corridor. In addition, all of the tests matched the Mertz corridor very well.

Knee Impact – The results for the knee impact certification test are listed in Table 11 and the response time histories are shown in Figures 11 and 12 along with the SAE and Mertz corridors. The knee impact responses for both dummies were all within the SAE corridor, but most were higher than the Mertz corridor. All of the test results on dummy 226 were within the SAE corridor but all were higher than the Mertz corridor. Five of the six tests on dummy 077 were above the Mertz corridor but all were within the SAE corridor. There were some slight variations in phase for each of the dummies.

Knee Slider – The results for the knee slider certification test are listed in Table 12 and the response time histories are shown in Figures 13 through 16, along with the SAE and Mertz corridors. Nearly all of the knee slider deflections were within the SAE corridor and all very similar. Six of six tests on dummy 077 and five of six tests on dummy 226 were within the deflection corridor. All of the tests for each dummy were similar in shape and phase for the deflection responses. The knee stiffness for dummy 077 matched the Mertz corridor slightly better than dummy 226. The majority of the stiffness response for dummy 077 matched the slope of the Mertz corridors while the loading portion of the stiffness response of dummy 226 did not match the Mertz corridor.

Repeatability and Reproducibility

The traditional CV based on peak values and the time-based average CV were calculated in the manner described previously for each of the response parameters from the certification tests. If both of the dummies were repeatable, the time-based means were then compared using the t-test. If the two means were from the same population the twelve responses from both dummies were used to calculate a single time-based mean and the average CV for both dummies was calculated to assess reproducibility. If the two dummies were found to be from different populations they are considered not reproducible.

All of the repeatability and reproducibility CVs are presented in Table 13. Under the heading of Repeatability the time-based average CV and the traditional peak CV are shown. Under the heading of Reproducibility the t-statistic, the time-based average CV, and the traditional peak CV are shown. If the t-test indicated the two dummies were not from the same population the average CV was not calculated because the dummies were not reproducible. The traditional CV for peak values is presented in parenthesis although the merit of these CV values is questionable since the two dummies were found to be from different populations.

Table 5.
Dummy segment specification and actual weights

Segment Weight	Part #	Specification [kg]			Dummy 226	Dummy 077
Head Assembly	880995-1100	4.94	+/-	0.05	4.92	4.94
Neck Assembly	880995-1250	1.68	+/-	0.05	1.69	1.72
Upper Torso Assembly	880995-1300	22.3	+/-	0.36	22.0	22.5
Lower Torso Assembly	880995-1450	30.3	+/-	0.36	30.4	30.0
Upper Arm, Left	880995-700	2.81	+/-	0.09	2.79	2.83
Upper Arm, Right	880995-700	2.81	+/-	0.09	2.82	2.81
Lower Arm, Left	880995-732	2.06	+/-	0.05	2.05	2.05
Lower Arm, Right	880995-732	2.06	+/-	0.05	2.06	2.06
Hand, Left	78051-208	0.57	+/-	0.05	0.55	0.56
Hand, Right	78051-209	0.57	+/-	0.05	0.53	0.54
Upper Leg, Left	880995-1513	8.21	+/-	0.09	8.20	8.17
Upper Leg, Right	880995-1514	8.21	+/-	0.09	8.16	8.16
Lower Leg, Left	880995-1513	5.75	+/-	0.09	5.81	5.83
Lower Leg, Right	880995-1514	5.75	+/-	0.09	5.80	5.82
Foot, Left	880995-1600	1.59	+/-	0.07	1.58	1.61
Foot, Right	880995-1601	1.59	+/-	0.07	1.53	1.61
TOTAL WEIGHT		101	+/-	1.63	101	101
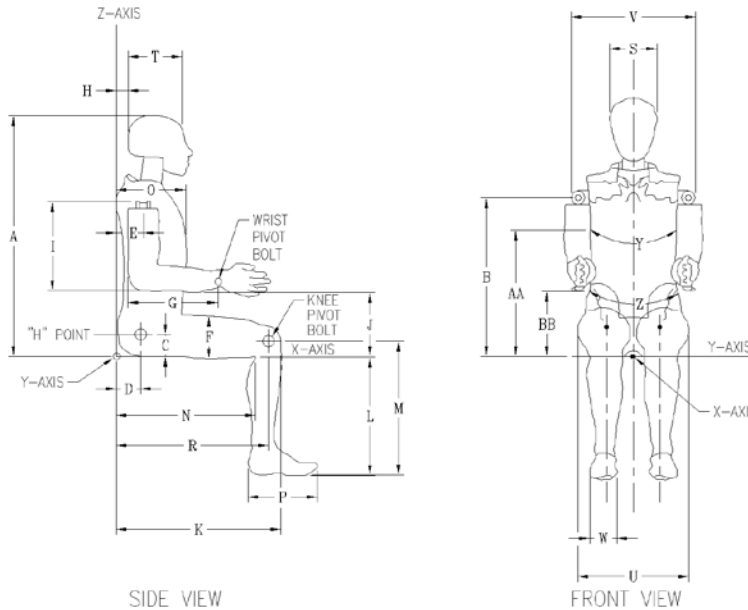
Figure 2. Reference diagram for dummy external dimensions listed in Table 6.

Table 6.
Dummy external dimension specification and actual measurements

External Dimension	Key	Specification [mm]			Dummy 226	Dummy 077
Total Sitting Height	A	919	+/-	15	921	927
Shoulder Pivot Height	B	536	+/-	15	532	541
Hip Pivot Height	C	102	+/-	5	94	97
Hip Pivot from Backline	D	155	+/-	5	142	152
Shoulder Pivot from Backline	E	91	+/-	5	97	93
Thigh Clearance	F	168	+/-	8	168	173
Back of Elbow to Wrist Pivot	G	310	+/-	8	311	312
Head Back from Backline	H	89	+/-	3	89	89
Shoulder to Elbow Length	I	363	+/-	10	356	353
Elbow Rest Height	J	213	+/-	10	210	216
Buttock to Knee Length	K	648	+/-	13	643	648
Popliteal Height	L	470	+/-	13	470	470
Knee Pivot to Floor Height	M	533	+/-	13	523	533
Buttock Popliteal Length	N	503	+/-	13	503	503
Chest Depth	O	246	+/-	8	246	246
Foot Length	P	264	+/-	8	269	264
Buttock to Knee Length	R	579	+/-	13	577	579
Head Breadth	S	155	+/-	5	160	156
Head Depth	T	196	+/-	5	201	199
Hip Breath	U	404	+/-	10	409	403
Shoulder Breath	V	475	+/-	10	472	475
Foot Breath	W	99	+/-	8	101	99
Head Circumference	X	572	+/-	5	584	574
Chest Circumference with Jacket	Y	1135	+/-	20	1130	1146
Waist Circumference	Z	1008	+/-	20	988	988
Reference Location for Chest Circumference	AA	483	+/-	5	508	508
Reference Location for waist Circumference	BB	203	+/-	5	203	203

Table 7.
Head drop certification test results for R&R

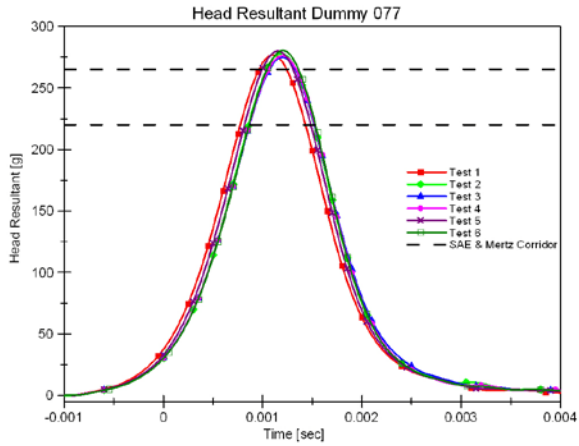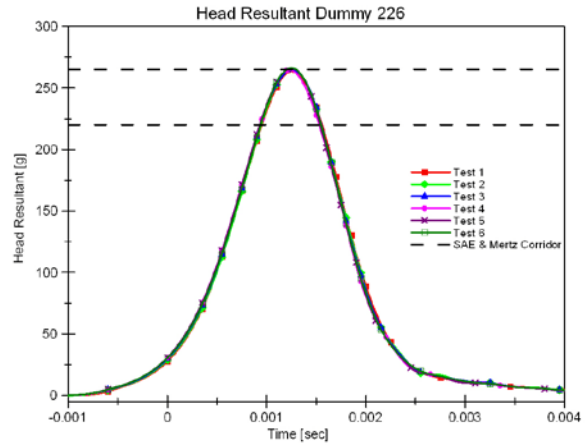| Dummy No.	Maximum Resultant Acceleration	
	220 – 265 g	
077	Average	278
	Std Dev	1.99
	%CV	0.72
226	Average	265
	Std Dev	1.03
	%CV	0.39
Both	Average	271
	Std Dev	6.95
	%CV	2.56

Figure 3. Dummy 077 head drop response.

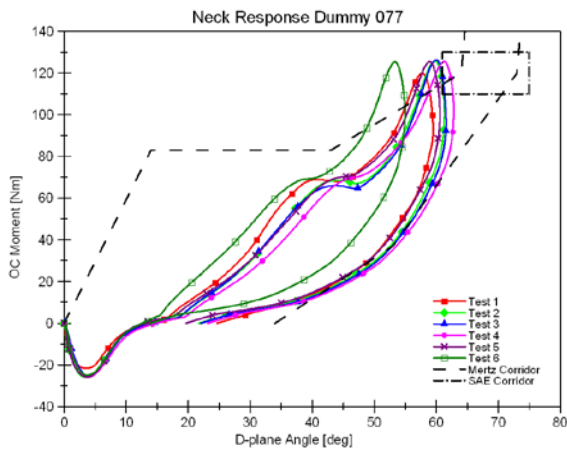**Figure 4. Dummy 226 head drop response.**

Figure 5. Dummy 077 neck flexion response.
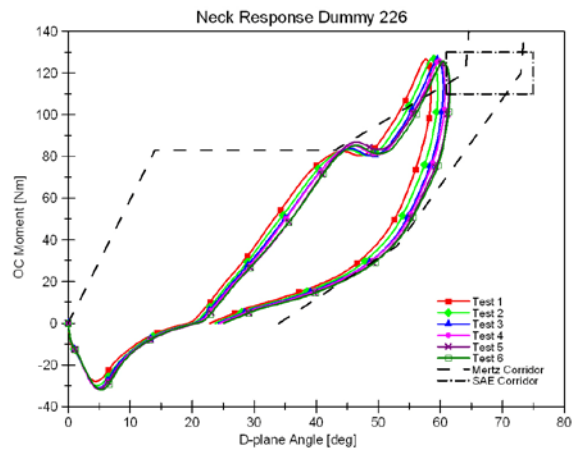

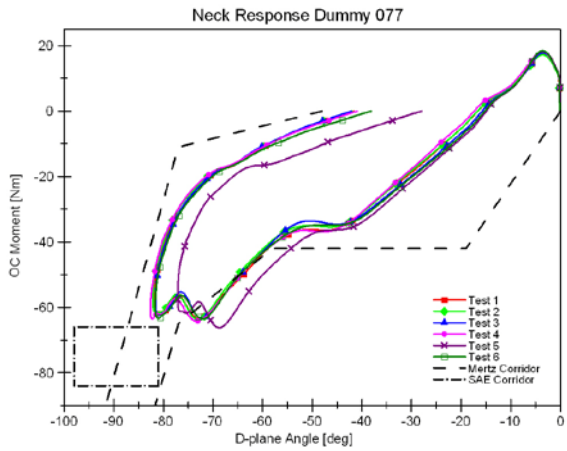**Figure 6. Dummy 226 neck flexion response.**

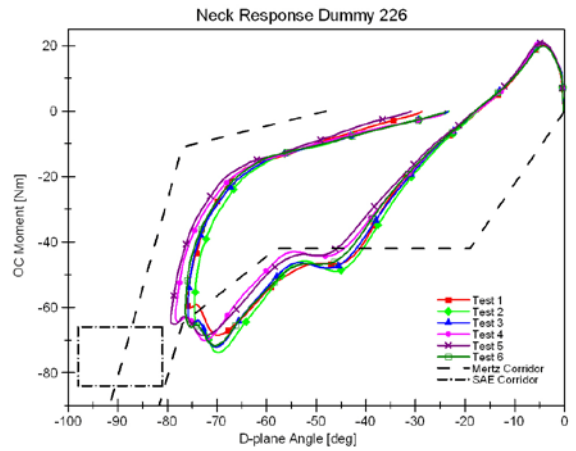**Figure 7. Dummy 077 neck extension response.**

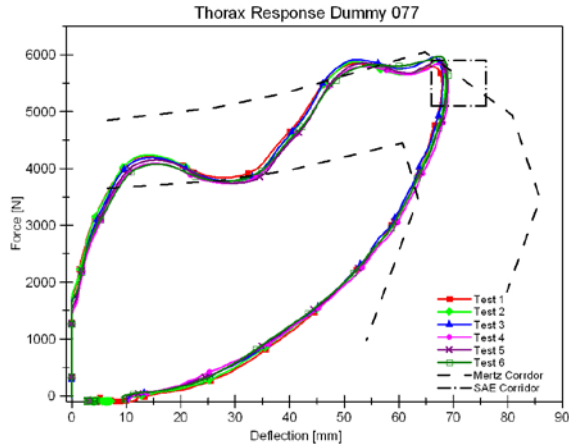

Figure 8. Dummy 226 neck extension response.
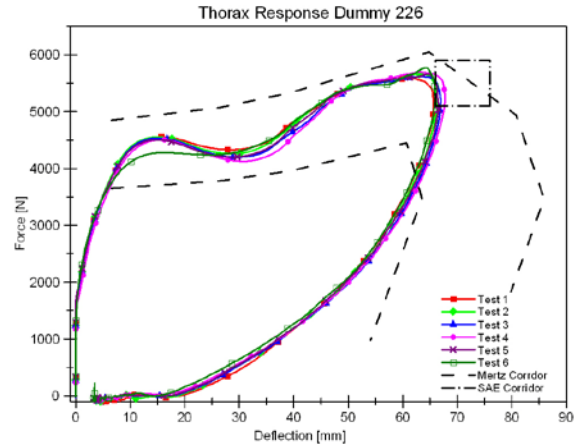
Figure 9. Dummy 077 thorax impact response.

Figure 10. Dummy 226 thorax impact response.

Table 8. Neck flexion certification test results for R&R

	Impact Velocity	Pendulum Velocity Profile			Peak D-Plane Rotation	OC Moment Peak in Rotation Interval	OC Moment 10 Nm Decay	Peak OC Moment
	m/s	m/s @ 10ms	m/s @ 20ms	m/s @ 30ms	deg	Nm	ms	Nm
	6.89-7.13	**2.2-2.7**	**4.0-5.0**	**5.7-6.9**	**61-75**	**110-130**	**77-97**	
Dummy 077								
Average	6.99	2.44	4.60	6.62	62.1	123	80.3	123
Std Dev	0.00	0.01	0.03	0.04	4.60	6.31	0.35	5.72
CV %	0.00	0.56	0.75	0.60	7.40	5.13	0.44	4.63
Dummy 226								
Average	6.99	2.50	4.62	6.53	59.9	N/A	79.7	126
Std Dev	0.00	0.03	0.03	0.03	1.37	N/A	0.44	0.95
CV %	0.00	1.31	0.74	0.48	2.29	N/A	0.55	0.75
Both								
Average	6.99	2.47	4.61	6.58	61.0	N/A	80.0	125
Std Dev	0.00	0.04	0.03	0.06	3.43	N/A	0.47	4.22
CV %	0.00	1.54	0.76	0.85	5.63	N/A	0.59	3.38

Table 9.
Neck extension certification test results for R&R

	Impact Velocity	Pendulum Velocity Profile			Peak D-Plane Rotation	OC Moment Peak in Rotation Interval	OC Moment 10 Nm Decay	Peak OC Moment
	m/s	m/s @ 10ms	m/s @ 20ms	m/s @ 30ms	deg	Nm	ms	Nm
	5.95-6.91	1.8-2.2	3.2-4.2	4.8-5.8	81-98	66-84	100-120	
Dummy 077								
Average	5.96	1.93	3.69	5.32	81.2	62.5	106	64.1
Std Dev	0.02	0.02	0.03	0.05	2.02	0.90	1.48	1.10
CV %	0.41	1.22	0.74	1.01	2.49	1.45	1.39	1.72
Dummy 226								
Average	6.01	1.94	3.71	5.35	76.8	N/A	104	70.8
Std Dev	0.00	0.06	0.04	0.04	1.75	N/A	1.11	2.13
CV %	0.00	2.88	1.11	0.77	2.28	N/A	1.08	3.01
Both								
Average	5.99	1.93	3.70	5.33	79.0	N/A	105	67.4
Std Dev	0.03	0.04	0.03	0.05	2.91	N/A	1.80	3.89
CV %	0.52	2.13	0.92	0.90	3.69	N/A	1.72	5.77

Table 10.
Thorax certification test results for R&R

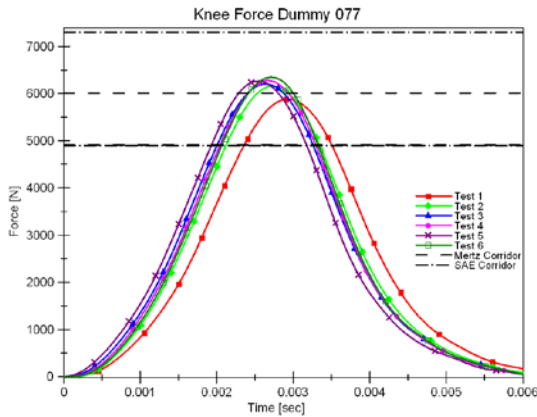|	Impact Velocity	Chest D_{max}	F_{max} in Defl Corridor	Hysteresis	F_{max}
	m/s	mm	kN	%	kN
	6.59 - 6.83	66.0 - 76.0	5.10 - 5.91	69 - 85	
Dummy 077					
Average	6.75	68.6	5.89	71.7	5.90
Std Dev	0.04	0.47	0.06	0.82	0.05
CV %	0.53	0.68	1.06	1.14	0.84
Dummy 226					
Average	6.75	66.8	5.56	73.7	5.68
Std Dev	0.01	0.74	0.10	0.52	0.05
CV %	0.15	1.11	1.86	0.70	0.90
Both					
Average	6.75	67.7	5.74	72.7	5.79
Std Dev	0.02	1.10	0.19	1.23	0.12
CV %	0.35	1.62	3.33	1.69	2.15

Figure 11. Dummy 077 knee impact force response.
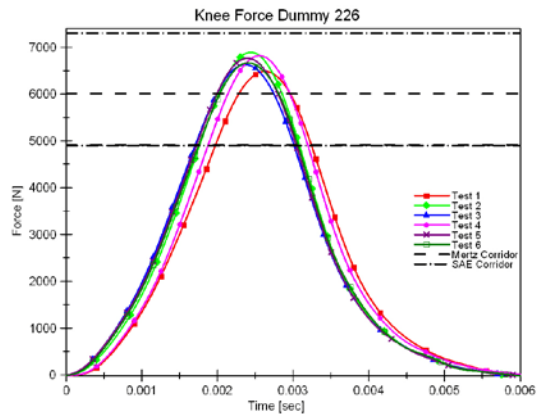
Figure 12. Dummy 226 knee impact force response.

Table 12.
Knee slider certification test results for R&R

	Velocity	Knee Slider	Pendulum Force
	m/S	mm	N
	2.7 - 2.8	15.0-18.3	
Dummy 077			
Average	2.75	17.6	3710
Std Dev	0.02	0.18	86.7
%CV	0.66	1.04	2.34
Dummy 226			
Average	2.73	15.3	3920
Std Dev	0.00	0.42	36.3
%CV	0.00	2.74	0.93
Both			
Average	2.74	16.4	3810
Std Dev	0.02	1.22	129
%CV	0.62	7.39	3.38
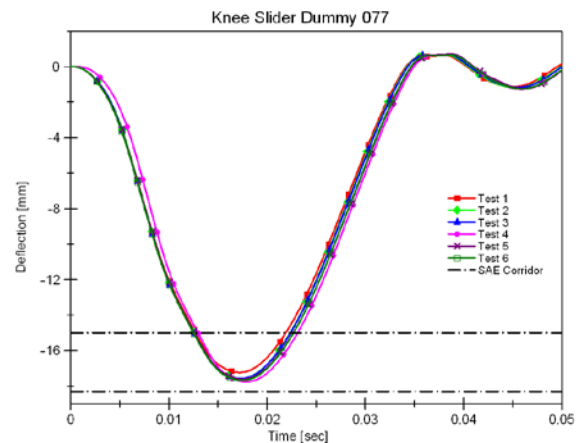
Figure 13. Dummy 077 knee slider deflection response.

Table 11.
Knee impact certification test results for R&R

	Velocity	Pendulum Force
	m/S	N
	2.07 - 2.13	4900 - 7300
Dummy 077		
Average	2.10	6190
Std Dev	0.02	166
CV %	0.78	2.68
Dummy 226		
Average	2.10	6710
Std Dev	0.00	148
CV %	0.17	2.20
Both		
Average	2.10	6450
Std Dev	0.01	309
CV %	0.54	4.80
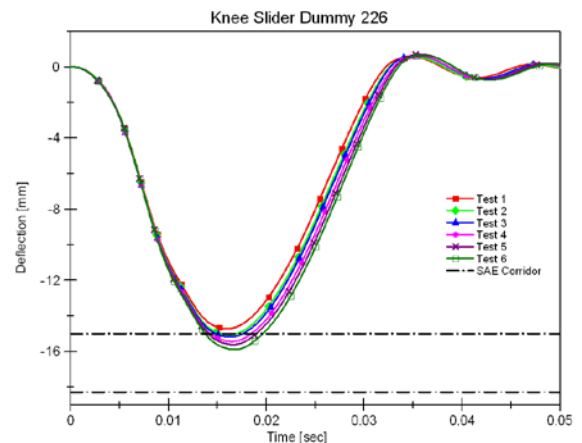
Figure 14. Dummy 226 knee slider deflection response.
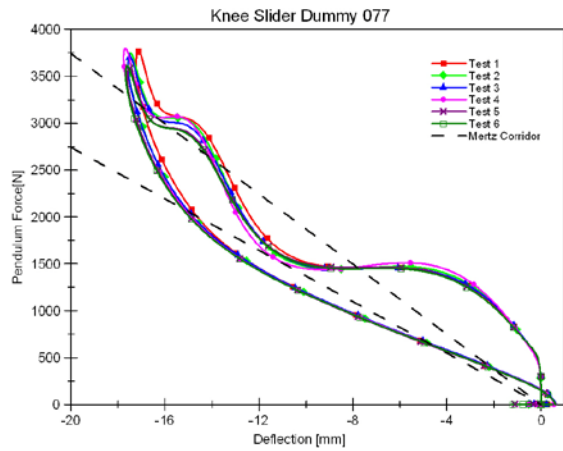
Figure 15. Dummy 077 knee slider stiffness response.

Figure 16. Dummy 226 knee slider stiffness response.

Figure 17. Head drop response for both dummies at increasing drop heights.
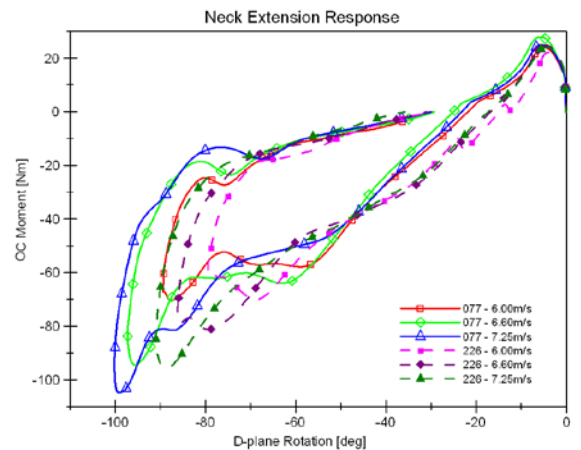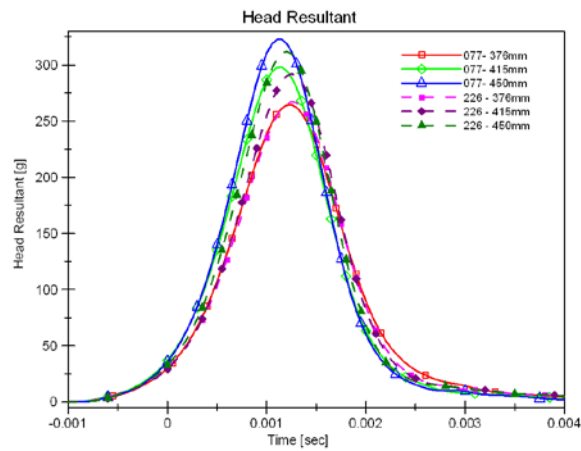

Figure 18. Neck flexion response for both dummies at increasing pendulum velocities.

Figure 19. Neck extension response for both dummies at increasing pendulum velocities.
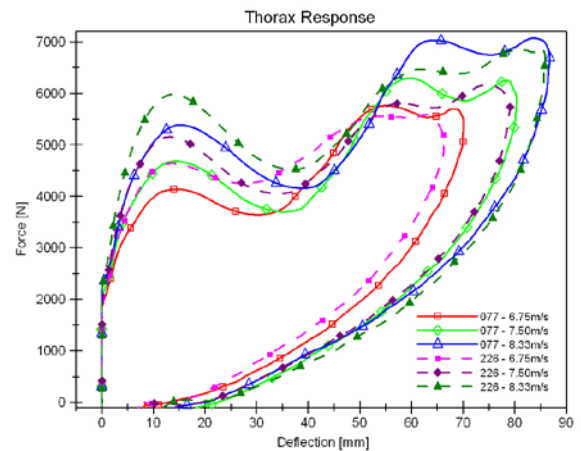

Figure 20. Thorax response for both dummies at increasing pendulum velocities.
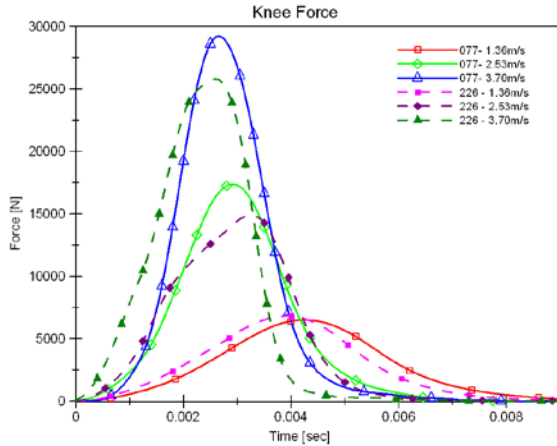
Figure 21. Knee response for both dummies at increasing 12 kg pendulum velocities.

DISCUSSION

Certification Testing

For the majority of the certification test types conducted the responses fit within the proposed SAE corridor. The tests that did not result in a response that was inside the corridor could easily be made to fit the corridor with a slight adjustment of the corridor bounds. For example, the head drop test could have the response corridor increased by 20g's and then all of the tests that were conducted would be contained within the allowable region. Likewise, the neck flexion response corridor could be moved so that the moment requirement is held the same, but the rotation requirement reduced by 7 – 10 degrees and all responses would fall within the corridor. The neck extension corridor would have to be reduced both in terms of moment, 6 Nm, and rotation, 6 – 7 deg, so that all of the responses would fall within the corridor. The thorax and knee impact tests already fall within the corridor and would not necessitate a change. However, the knee slider deflection corridor could be reduced by 2 mm and all of the responses would be within the specification.

Repeatability and Reproducibility

In most instances the traditional approach to CV provides a lower value indicating a better repeatability or reproducibility than does the time-based average CV. This is illustrated by the knee impact force response CVs. The traditional approach results in a CV of 2.7% and 2.2% for dummy 077 and 226, respectively, while the time-based average CV results in a CV of 9.2% and 7.8% for dummy 077 and

226, respectively, nearly four times higher. This result can be explained by examining Figure 22. The six force versus time curves are relatively similar in shape, duration, and especially peak values which translates into an excellent CV value from the traditional approach. However a distinct difference in phase can be observed among the test results which is attributed to the knee itself and not the test setup (time zero defined by electrical contact switch).
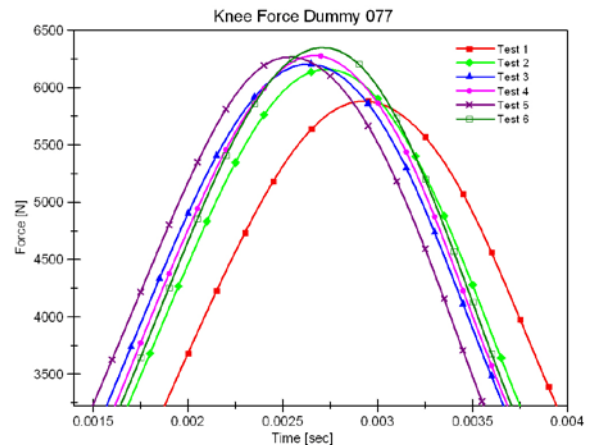

Figure 22. Knee force versus time histories near peak for dummy 077.

Figure 23 shows the time-based average curve and plus and minus one standard deviation curves for the same six knee force responses. It can be seen that the standard deviation at the peak of the curves is smaller than at other times. Further, it can be seen that the standard deviation on the sloped sections of the curve is essentially constant. This is due to the phase shift among the curves seen in Figure 22. As a result of this situation the CV (standard deviation divided by the mean) increases as the mean value decreases and the time-based average CV is larger than the CV at the peak.
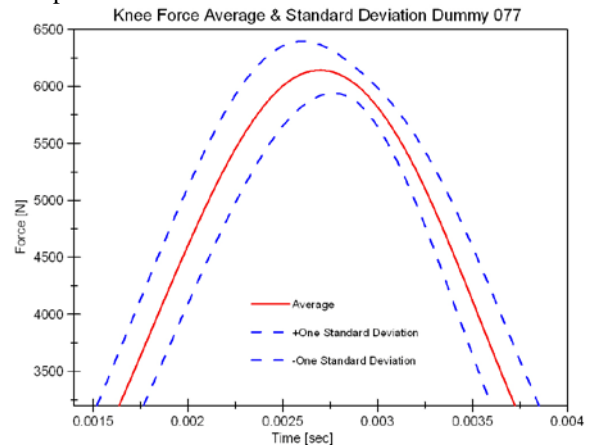

Figure 23. Knee force versus time mean and standard deviation.

Although the knee force responses for the two dummies were both repeatable, the t-test indicates that they are not reproducible. A look at the knee force response curves of Figures 11 and 12 indicate that the two dummy knees are quite different in both magnitude and timing. The traditional CV, as shown in Table 13, is 4.8% whereas the time based average CV is 13% (not shown) which is larger than the acceptable level of 10% for reproducibility. The time-based average CV methodology is better able to identify the fact that the knee force responses are not reproducible.

Table 13.
Time series CV and peak CV comparison along with t-statistic for repeatability and reproducibility

	Repeatability			Reproducibility	
	CV Avg	CV peaks	T statistic	CV Avg	CV peaks
Head 077	4.93	0.72	2.45	6.28	2.56
Head 226	1.31	0.39			
Neck Flx Angle 077	5.77	7.40	151	4.65	5.63
Neck Flx Angle 226	2.47	2.29			
Neck Flx Mom 077	2.58	4.63	11.3	5.08	3.38
Neck Flx Mom 226	1.96	0.75			
Neck Ext Angle 077	3.53	2.49	2.91	5.94	3.69
Neck Ext Angle 226	2.76	2.28			
Neck Ext Mom 077	2.32	1.72	-17.0		(5.77)
Neck Ext Mom 226	4.12	3.01			
Thorax Force 077	2.19	0.84	56.2	3.10	2.15
Thorax Force 226	1.81	0.90			
Thorax Defl 077	1.63	0.68	17.9	1.97	1.62
Thorax Defl 226	1.58	1.11			
Knee Impact 077	9.18	2.68	-7.37		(4.80)
Knee Impact 226	7.80	2.20			
Knee Slider Defl 077	2.20	1.04	-19.0		(7.39)
Knee Slider Defl 226	3.82	2.74			
Knee Slider Force 077	3.52	2.30	-16.4		(3.38)
Knee Slider Force 226	3.50	0.93			

Coefficient of Variation <= 5%
Coefficient of Variation > 5% <= 10%
CV for dummies from different populations (#)

Considering the other body components of these dummies that were found to be not reproducible (knee slider force and deflection and neck extension moment) the time-based average CVs (9%, 9%, 8%, respectively) are larger than the traditional CVs but the values are within the acceptable limit of 10%. This indicates that merely averaging all of the data and calculating a CV without performing the t-test does not identify non-reproducibility; the t-test is required.

CONCLUSIONS

When evaluating the averages of six repeats of the various certification tests for each dummy, it can be seen that neither dummy fully complies with the proposed SAE certification requirements. Dummy 077 does not certify with respect to the head drop requirements while dummy 226 does not certify with respect to the peak D-plane angular requirements for either neck flexion or extension. However, if the certification specifications were to be adjusted both dummies could meet the revised specifications. Because the certification specifications were based on scaled 50th percentile male specifications it is

reasonable to adjust the specifications to fit the dummies so long as the dummies being evaluated are reproducible. It is to be expected that design and fabrication variances would result in a 95th sized dummy that is not a perfectly scaled replica of the 50th sized dummy.

Traditional methods of calculating repeatability CV values (CV peak method) show both dummies, individually, provide good or excellent response CVs for all of the certification tests. A proposed method of calculating a time-based CV (CV average method) also shows the CVs for both dummies to range from good to excellent although the time-based method appears to be more demanding.

The reproducibility CV is good to excellent for all certification test responses when looking at the combined data from both dummies using the traditional method of calculating CV. However, when using hypothesis testing of the time-based responses to study the reproducibility of the two dummies, the Neck Extension Moment, Knee Impact, Knee Slider Deflection, and Knee Slider Force are shown to be statistically different. If the two dummies are not from the same population the pooling of all responses from both dummies in order to calculate a CV is inappropriate.

Applying energy balance and conservation of momentum techniques to previously proposed injury criteria for the 95th percentile large male, certification test input energy levels were increased and used to evaluate dummy durability. The head, neck, thorax, and knee from both dummies were repeatedly subjected to testing at these higher energy levels with no adverse effects observed by physical inspection or by examination of the dummy responses.

Only two dummies have been examined: one each from two manufacturers. It appears that the dummies could meet certification specifications if the current specifications were adjusted. Durability of both dummies was satisfactory even when tested at very high input energy levels. Repeatability of each of the dummies was acceptable to excellent but reproducibility of several components was less than desirable when tested using the Student t-test with a time-based tolerance of 10%.

ACKNOWLEDGEMENTS

REFERENCES

Bendat, J., Piersol, A., Random Data: Analysis and Measurement Procedures, 3rd Edition, John Wiley & Sons, New York, NY. 2000.

Code of Federal Regulations, Title 49. United States Government. Washington, DC. 2004.

Mertz, H., Irwin, A., Melvin, J., Stalnaker, R., Beebe, M., "Size, Weight and Biomechanical Impact Response Requirements for Adult Size Small Female and Large Male Dummies." SAE International Congress and Exposition, Detroit, MI, 1989.

Rhule, D., Rhule, H., Donnelly, B., "The Process of Evaluation and Documentation of Crash Test Dummies for Part 572 of the Code of Federal Regulations." 19th International Technical Conference on the Enhanced Safety of Vehicles, Washington, D.C., USA, 2005.

SAE Dummy Testing Equipment Subcommittee. "User's Manual for the Hybrid III Large Male Test Dummy." Engineering Aid 26 Draft. Warrendale, PA. 2003.