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# An Improved Normalization Methodology for Developing Mean Human Response Curves

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*This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.*

## ABSTRACT

*Mean human response curves and associated biomechanical response corridors are commonly developed from human subject test data to guide the design of anthropomorphic test devices (ATDs) by providing "target" biomechanical responses to impact. Since differences in anthropometry and physical characteristics within a group of human test subjects can result in widely varying response data, the first step in developing target biomechanical responses is typically to normalize the responses to a certain "standard" anthropometry representing the dummy to be designed or evaluated. The normalization procedure should remove variation associated with anthropometric differences, thus collapsing the group of curves so that a single mean response can be more accurately established that characterizes the human response of the "standard" anthropometry. Several methods for normalizing human subject test data can be found in the literature, but there is no consensus as to which is the most effective. In this study, the two most common existing normalization techniques, as well as some newly developed methodologies, were evaluated by applying them to both a side impact PMHS sled test data set, and a component-level PMHS thoracic pendulum impact data set. The efficacy of the normalization techniques was assessed for each group of common signals by calculating the cumulative percent coefficient of variation (%CV) for time-history curves, and the cumulative ellipse error for two-dimensional force-deflection curves. Both of these measures provide a quantifiable assessment of the similitude of the group of curves (i.e., the normalization technique resulting in the lowest cumulative %CV value or cumulative ellipse error most effectively collapses the curves). The normalization technique found to consistently perform the best is a newly developed extension of impulse momentum-based normalization in which the stiffness ratio was determined from effective stiffness values calculated from the test data, rather than using characteristic lengths. Utilization of this normalization methodology in the development of mean human response curves should prove useful in more accurately characterizing the target human response to aid in the design of more biofidelic dummies.*

## INTRODUCTION

Biomechanical response corridors developed from human subject test data are commonly used to guide the design of anthropomorphic test devices (ATDs) by providing "target" biomechanical responses to impact. The ability of an ATD to match these target responses defines its biofidelity, and a biofidelic ATD is paramount to the design of safe vehicles and effective restraint systems.

The target responses are most often developed by subjecting a group of Post-Mortem Human Subjects (PMHS) to an impact or crash scenario, measuring the resulting responses, and then representing each group of responses such that it characterizes the response of the selected population and can be used to evaluate the biofidelity of the corresponding ATD response. One way to accomplish this is to encompass the entire group of response curves for a given measurement using straight-line segment corridors, and then a biofidelic dummy response is expected to lie within that corridor (ISO/TR9790, 1999; Lobdell et al., 1973). Another methodology is to reduce the group of responses into a single mean response curve, which itself represents the ATD design target (Cavanaugh et al., 1986; Maltese et al., 2002; Morgan et al., 1986). In addition to the mean response curve, standard deviation curves can be created around the mean to provide both a visual measure of the variation in the group of PMHS, as well as a quantitative measure of that variation for assessing the biofidelity of an ATD. These standard deviation curves, however, do not necessarily represent a corridor that a biofidelic ATD must lie within. Representing the target response using the mean response curve is more appealing than straight-line segment corridors because it maintains the shape and characteristics of the actual human response to impact.

Since there are a variety of ATDs, each representing a certain "standard" anthropometry or set of physical characteristics (i.e., 50$^{th}$ percentile male, 5$^{th}$ percentile female, etc.), it is important for the PMHS responses comprising the design targets to represent the same respective population. However, in reality there is often large variation in the physical characteristics within a group of human subjects (e.g., size, shape, inertial properties, etc.) which results in widely varying response data. Normalization is a procedure for mathematically adjusting the response data to account for the variation in physical characteristics, and is often the first step in developing target biomechanical responses. Successful normalization should collapse the group of curves closer to a single response so that a mean response can be more accurately established that represents that of the selected population.

Anthropometric variation between subjects such as differences in height and weight can obviously affect the magnitude of the response data, but differences in factors such as body mass distribution (i.e., fat-to-muscle ratio) can also affect the phase or timing of the response data, which is especially critical to the creation of a mean response curve. Figure 1 shows an example of two curves (blue and red) which are out of phase but similar in shape and magnitude. The resulting mean curve (black) is bimodal, much lower in magnitude, and has a shape nothing like either of the individual curves. Ideally, normalization would be able to account for the variation between the subjects which caused this out-of-phase response, thus resulting in a more representative mean response curve.

Although several methods for normalizing human subject test data can be found in the literature, the two most commonly implemented procedures are mass-based normalization as described by Eppinger et al. (1984), and impulse momentum-based normalization as described for single mass systems (e.g., sled & drop tests) by Mertz (1984) and for two-mass systems (e.g., pendulum tests) by Viano (1989).

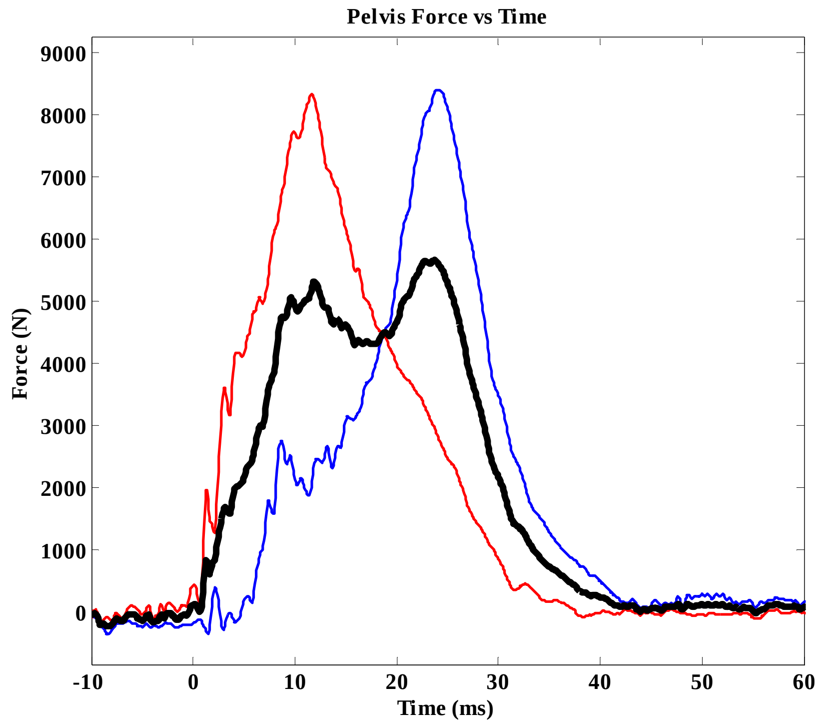


Figure 1: Mean curve resulting from two out-of-phase responses.

## Mass-based normalization (Eppinger et al., 1984)

The mass-based procedure normalizes human subject response data based solely on a mass ratio involving the subject's total body mass and the total body mass of the "standard" subject to which the responses are to be normalized. The underlying theory was developed based on a dimensional analysis approach to geometric scaling in which three scaling ratios containing the fundamental dimensions of mass, length, and time must be defined in order to derive scaling ratios for other engineering variables of interest. Two of these ratios were defined to assume constant density and modulus of elasticity among subjects; the third ratio is the total body mass ratio:

$$1 = \frac{\rho_{50th}}{\rho_{sub}} \qquad 1 = \frac{E_{50th}}{E_{sub}} \qquad \lambda = \frac{M_{50th}}{M_{sub}} \tag{1}$$

where $\rho$ is density, $E$ is the modulus of elasticity, $M$ is total body mass, $\lambda$ is the total body mass scaling ratio, and the subscripts "50th" and "sub" represent the "standard" subject and test subject, respectively. Note that since the most common "standard" subject is the 50$^{th}$ percentile male it will hereafter be referred to with the subscript "50th", and $M_{50th}$ can be easily obtained from anthropometric tables (typically, 167 lb or 76 kg).

Normalizing factors for engineering variables of interest ($L$ = length or deflection, $F$ = force, $A$ = acceleration, $T$ = time, and $V$ = velocity) can then be derived from the three ratios in Equation (1) in conjunction with fundamental laws of physics, as shown in Equations (2) – (6):

$$\rho = \frac{M}{L^3} \quad \Rightarrow \quad L_{50th} = \lambda^{1/3} L_{sub} \tag{2}$$

$$E = \frac{F}{L^2} \quad \Rightarrow \quad F_{50th} = \lambda^{2/3} F_{sub} \tag{3}$$

$$F = MA \quad \Rightarrow \quad A_{50th} = \lambda^{-1/3} A_{sub} \tag{4}$$

$$A = \frac{L}{T^2} \quad \Rightarrow \quad T_{50th} = \lambda^{1/3} T_{sub} \tag{5}$$

$$V = \frac{L}{T} \quad \Rightarrow \quad V_{50th} = V_{sub} \tag{6}$$

The strengths of mass-based normalization are that it is easy to implement, the procedure is independent of test condition (i.e., the same procedure is used for sled tests, drop tests, and pendulum tests), and the adjustment made to the response data is directly linked to the easy-to-obtain anthropometry measure of total body mass. The fact that the response data is adjusted based solely on total body mass may make it easy to implement, but it could also be considered a weakness because measures of anthropometry alone are often poor predictors of response data. The physical variation in the subjects includes not just anthropometry but also variables such as age, gender, nutrition, pathology, etc. which can not be accounted for and predicted by anthropometry. In addition, adjusting the signals based solely on total body mass often does not work well for component-level tests such as pendulum impacts.

A limitation of this type of normalization is that the underlying theory for geometric scaling forces an assumption of full-body geometric similitude (i.e., the ratio of lengths at one body region applies to all other body regions as well) even though in reality body regions are often proportioned differently from subject-to-subject. Also, while the two fundamental material constituency assumptions of constant density and constant modulus among subjects are likely reasonable approximations there will of course be some variation. The biggest limitation to this method is that the response data of a tall and thin osteoporotic subject with the same total body mass as an overweight and short healthy-boned subject would scale identically, implying that they would be expected to exhibit a similar response to an identical impact.

## Impulse momentum-based normalization (Mertz, 1984; Viano, 1989)

This procedure normalizes human subject response data based on both a mass ratio and a stiffness ratio, and then models the impacts as a simple spring-mass system:

$$\lambda_m = \frac{m_{50th}}{m_{sub}} \qquad \lambda_k = \frac{k_{50th}}{k_{sub}} \tag{7}$$

For the mass ratio, instead of a simple ratio of total body mass, an effective mass of the impacted body region is estimated from the response data using an impulse momentum analysis as shown in Equation (8):

$$\int_0^T F dt = m_{eff} v_0 \quad \Rightarrow \quad m_{eff} = \frac{\int_0^T F dt}{v_0} \tag{8}$$

where $m_{eff}$ is the effective mass, $F$ is the force during impact, $v_o$ is the change in velocity during the impact, and $T$ is the duration of impact. By incorporating the response data in the normalization procedure, some of the other causes for variation besides anthropometry (discussed earlier) can be somewhat accounted for. Unlike the total body mass ratio where the mass of the 50$^{th}$ percentile male is easily obtained from anthropometric tables, the standard effective mass of the 50$^{th}$ percentile male, $m_{50th}$, is dependent on the test condition and is thus typically unknown. Therefore, the value is estimated by averaging the percentage of effective mass to total body mass for each subject, and then multiplying that average by the known total body mass of the 50th percentile male (i.e., 76 kg).

For the stiffness ratio, Mertz (1984) showed that by assuming a constant modulus among subjects and geometric similitude within the impacted body region, the stiffness ratio could be approximated using a ratio of characteristic lengths. For example, if the impact involves the thorax, then chest depth or chest breadth might be chosen as the characteristic length to comprise the stiffness ratio. Once a characteristic length is chosen, the corresponding length for a 50th percentile male can be obtained from anthropometric tables.

Normalizing factors for engineering variables of interest ($T$ = time, $a$ = acceleration, $v$ = velocity, $x$ = length or deflection, and $F$ = force) can then be derived from the mass ratio and stiffness ratio in Equation (7) in conjunction with the solution to the differential equations of motion for a simple spring-mass system, as shown in Equations (9) – (13):

$$T = \pi\sqrt{\frac{m}{k}} \quad \Rightarrow \quad T_{50th} = \sqrt{\frac{\lambda_m}{\lambda_k}}\, T_{sub} \tag{9}$$

$$a = -v_o \sqrt{\frac{k}{m}} \sin\left(\sqrt{\frac{k}{m}}\, t\right) \quad \Rightarrow \quad a_{50th} = \sqrt{\frac{\lambda_k}{\lambda_m}}\, a_{sub} \tag{10}$$

$$v = -v_o \cos\left(\sqrt{\frac{k}{m}}\, t\right) \quad \Rightarrow \quad v_{50th} = v_{sub} \tag{11}$$

$$x = v_o \sqrt{\frac{m}{k}} \sin\left(\sqrt{\frac{k}{m}}\, t\right) \quad \Rightarrow \quad x_{50th} = \sqrt{\frac{\lambda_m}{\lambda_k}}\, x_{sub} \tag{12}$$

$$F = -v_o \sqrt{km} \sin\left(\sqrt{\frac{k}{m}}\, t\right) \quad \Rightarrow \quad F_{50th} = \sqrt{\lambda_m \lambda_k}\, F_{sub} \tag{13}$$

Note that the normalizing factors shown in Equations (9) - (13) were derived from the equation for a single mass, single spring system so they are only valid for sled tests and drop tests where the impacting mass can be assumed infinite. For pendulum impacts, the equations of motion for a two-mass system are used to derive the normalizing factors shown in Equations (14) – (18), where $m_p$ is the mass of the impactor.

$$T_{50th} = \sqrt{\frac{\lambda_m}{\lambda_k}} \sqrt{\frac{(m_p + m_{sub})}{(m_p + m_{50th})}}\, T_{sub} \tag{14}$$

$$a_{50th} = \sqrt{\frac{\lambda_k}{\lambda_m}} \sqrt{\frac{(m_p + m_{sub})}{(m_p + m_{50th})}}\, a_{sub} \tag{15}$$

$$v_{50th} = v_{sub} \tag{16}$$

$$x_{50th} = \sqrt{\frac{\lambda_m}{\lambda_k}} \sqrt{\frac{(m_p + m_{sub})}{(m_p + m_{50th})}}\, x_{sub} \tag{17}$$

$$F_{50th} = \sqrt{\lambda_m \lambda_k} \sqrt{\frac{(m_p + m_{sub})}{(m_p + m_{50th})}}\, F_{sub} \tag{18}$$

The primary strength of this normalization method is that it incorporates the response data so that it can potentially account for variation in response arising from subject differences other than just anthropometry. A weakness with this procedure involves using a characteristic length for the stiffness ratio, because the choice of which characteristic length to use is somewhat subjective, and it forces the assumptions of constant modulus and geometric similitude within the impacted body region. However, if the effective stiffness of the subject could be estimated from the response data, similar to the effective mass, then those assumptions would not be necessary.

To date, there is no quantitative consensus as to which of the normalization techniques discussed above is most effective. Furthermore, some areas of potential improvement for both methods have been identified. Therefore, the goal of this study was to quantify the effectiveness of the two existing normalization procedures as well as some new methodologies developed in this study based on potential improvements identified.

## METHODS

### Potential improvements to existing normalization methods

After reviewing the two most common existing normalization methods, some weaknesses and potential areas of improvement were identified, and some new methodologies were developed to address these areas. For the mass-based normalization, the most prominent limitation is that body mass distribution is unaccounted for. Therefore, replacing the ratio of total body mass with a ratio involving a measure of "body type" such as the Body Mass Index (BMI) in Equation (19), or the Ponderal Index (PI) in Equation (20), was investigated as a potential improvement.

$$BMI = \frac{Mass}{Height^2} \tag{19}$$

$$PI = 10\left(\frac{\sqrt[3]{Mass}}{Height}\right) \tag{20}$$

For the impulse momentum-based normalization, it would be valuable to know the importance of the choice of characteristic length in the stiffness ratio, so various characteristic lengths and combinations of characteristic lengths (i.e., aspect ratios) were evaluated. Specifically, a characteristic length was measured along each of the three axes of the body coordinate system (e.g., chest depth, chest breadth, and chest height), directly along the line of impact, and around the circumference of the impacted area. Each of these measurements was then used as the characteristic length for the stiffness ratio as well as multiple combinations of each of these measurements.

Also, replacing the characteristic length estimate of stiffness with an actual estimate of the effective stiffness calculated from the response data was investigated as a potential improvement. As long as deflection data for the relevant body region is measured, a methodology somewhat analogous to Equation (8) for calculating an effective mass can be implemented to estimate an effective stiffness, as illustrated in Equation (21):

$$\int F dx = \frac{1}{2} k_{eff} \; x_{\max}^2 \quad \Rightarrow \quad k_{eff} = \frac{2\int F dx}{x_{\max}^2} \tag{21}$$

## Data sets for normalization evaluation

Two data sets were chosen for the normalization evaluation – a full-body side impact sled test data set (Maltese et al., 2002) and a component-level thorax pendulum impact data set (Shaw et al., 2006).

*Full-body side impact sled test data set (Maltese et al., 2002)***.** For the sled test data set, normalization procedures were evaluated for all test conditions that contained three or more subjects after a subject exclusion evaluation. Subjects were excluded if they failed a conservation of momentum check (Nusholtz et al., 2007) or if there was significant "leaning" which was defined as the pelvis contacting the flat wall more than 10 ms after the thorax (Irwin et al., 2005). Four test conditions with three or more subjects remained for the evaluation after subject exclusion: Rigid High-Speed Flat Wall (RHF), Padded High-Speed Flat Wall (PHF), Rigid Low-Speed Flat Wall (RLF), and Padded Low-Speed Flat Wall (PLF).

The thoracic deflection for each subject was obtained by averaging the half-deflections measured by the upper and middle thoracic chestband signals (if they both existed), or using the half-deflection from either the upper or the middle thoracic chestband signals (if only one existed). The abdominal deflection for each subject was obtained from the half-deflection as measured by the bottom (abdominal) chest band signal. If the bottom chest band signal was not available, then the thoracic deflection was used for abdominal deflection. Although Maltese et al. (2002) calculated both full- and half-deflections, half-deflections were utilized in this study as they were deemed more relevant for comparison with an ATD.

The normalization techniques were applied to several signal groups from the four sled test conditions including multiple time-histories (Thorax load wall, Abdomen load wall, Pelvis load wall, Upper Spine Y-acceleration, Lower Spine Y-acceleration, Pelvis Y-acceleration, and Thoracic Deflection) as well as the two-dimensional force-deflection responses for both the thorax and abdomen.

*Component-level thorax pendulum impact data set (Shaw et al., 2006)***.** For the pendulum impact data set, normalization procedures were evaluated for both the lateral impact test condition and the oblique impact test condition, and no subjects were excluded based on the criteria discussed above.

Shaw et al. (2006) only reported results for full-deflection of the thorax, but half-deflections were also calculated in the study and the corresponding electronic data was obtained via personal communication and used for this evaluation to be consistent with the full-body sled test data set.

The signal groups analyzed for both the lateral and oblique test conditions included the force-time histories, deflection-time histories, and force-deflection responses.

## Assessment of efficacy of normalization techniques

Each normalization technique was evaluated based on its ability to collapse each group of curves to map onto a single response. Therefore, a quantifiable assessment of the similitude of a group of curves was required.

*Time-histories.* Since the percent coefficient of variation (%CV) is often used to assess the repeatability of a set of similar ATD responses, this quantity was deemed appropriate to assess the efficacy of the normalization techniques for the time-histories:

$$\%CV = \frac{\sigma}{\mu} \times 100 \tag{22}$$

where

$\sigma$ is the standard deviation of the responses
$\mu$ is the mean of the responses

Although this measure is typically calculated for single value peak responses, in this study it was important to evaluate the similitude of the curves across time as well. Therefore, the cumulative %CV was calculated across time for the relevant portion of each time-history signal group (upper 80% of the mean response) to provide a relative measure of how similar the curves are, where a lower %CV indicates better grouping of the curves.

*Force-deflection histories.* Since there is no immediately analogous percent coefficient of variation (%CV) for two-dimensional force-deflection space, the similitude of the curves was instead assessed by summing the cumulative error contained within the one standard deviation ellipses (i.e., summing the area of each ellipse) for the relevant portion of the force-deflection histories (intersection of the upper 80% of the mean force and mean deflection curves). As with %CV, lower values of ellipse error indicate better grouping of the curves, and hence more effective normalization.

## RESULTS

Although over thirty different variations of normalization techniques were evaluated, the majority of these variations involved different choices of characteristic length to comprise the stiffness ratio in the impulse momentum-based procedure (see Methods section). However, no discernable difference in the effectiveness of the impulse-momentum normalization procedure could be identified based on the choice of characteristic length, so the results for each individual choice of characteristic length will not be shown. Also, for the mass-based normalization, utilizing a ratio of BMI and/or PI instead of the total body mass ratio did not yield a noticeable difference in normalization effectiveness, so these methodologies will also not be presented.

The results from three normalization procedures will be presented in detail in this manuscript along with the non-normalized data for reference (referred to as “Non-normalized”). The first methodology, referred to as “Mass-based”, is the existing mass-based normalization procedure using a ratio of total body mass. The second methodology, referred to as “Eff Mass & Char Length”, is the standard impulse momentum-based procedure using a ratio of effective mass for the mass ratio and a ratio of characteristic lengths for the stiffness ratio. The characteristic lengths were chosen in this evaluation to be consistent with previous studies where the respective data sets were normalized using the impulse momentum-based method. Therefore, chest depth was used for the sled test data (Irwin, 2005) and chest breadth for the pendulum impact data (Shaw, 2006). The third methodology, referred to as “Eff Mass & Eff Stiff”, utilizes a ratio of effective mass for the mass ratio and a ratio of effective stiffness calculated from the response data as in Equation (21) for the stiffness ratio.

The results from the normalization evaluation are given in Table 1 for the full-body side impact sled test data set and in Table 2 for the component-level thorax pendulum impact data set. Since the cumulative %CV and the cumulative ellipse error were both utilized as relative measures of the effectiveness of a given normalization procedure, the percent improvement over the “Non-normalized” data are reported in Tables 1 and 2 for each of the three normalization techniques, rather than the actual numeric values of the measures. The normalization method resulting in the largest percent improvement for each signal group is highlighted in green.

For the full-body sled tests, Table 1 shows that for the eight signal groups that were analyzed in each of the four test conditions (RHF, PHF, RLF, and PLF), the “Eff Mass & Eff Stiff” normalization approach performed the best (i.e., resulted in the largest amount of improvement in curve grouping) for six of the eight RHF, PHF, and RLF signal groups and five of the eight PLF signal groups. For the component-level pendulum impacts, Table 2 shows that for the three signal groups that were analyzed in each of the two test conditions (Lateral and Oblique), the “Eff Mass & Eff Stiff” normalization approach performed the best in five of the six signal groups. In full, the “Eff Mass & Eff Stiff” normalization approach performed the best in 28 of 38 (~74%) of the signal groups analyzed, as compared to 7 of 38 (~18%) for the “Mass-based” approach and 3 of 38 (~8%) for the “Eff Mass & Char Length” approach.

Table 1. Normalization results for the full-body side impact sled test data set.

| | Signal | Mass-Based (% improvement) | Eff Mass & Char Length (% improvement) | Eff Mass & Eff Stiff (% improvement) |
|---|---|---|---|---|
| **RHF** | Thorax Loadwall | 28.4 % | 50.0 % | 68.3 % |
| | Abdomen Loadwall | 11.8 % | 22.7 % | 24.1 % |
| | Pelvis Loadwall | 11.7 % | 4.5 % | 37.8 % |
| | Upper Spine Y accel | 13.2 % | 9.0 % | 17.6 % |
| | Lower Spine Y accel | 14.1 % | -18.6 % | 12.4 % |
| | Pelvis Y accel | -1.9 % | -9.1 % | 13.1 % |
| | Deflection (Thorax) | 22.5 % | -39.6 % | -1.3 % |
| | F-D Thorax | 30.2 % | 8.4 % | 72.1 % |
| **PHF** | Thorax Loadwall | 47.4 % | 47.8 % | 63.2 % |
| | Abdomen Loadwall | 9.6 % | 36.8 % | 58.4 % |
| | Pelvis Loadwall | 60.4 % | 49.4 % | 65.1 % |
| | Upper Spine Y accel | -0.2 % | 4.1 % | 4.2 % |
| | Lower Spine Y accel | 12.2 % | 19.0 % | 17.0 % |
| | Pelvis Y accel | 12.0 % | 13.7 % | 9.2 % |
| | Deflection (Thorax) | 36.0 % | 28.7 % | 53.5 % |
| | F-D Thorax | 53.3 % | 50.1 % | 65.1 % |
| **RLF** | Thorax Loadwall | 10.7 % | 23.2 % | 27.9 % |
| | Abdomen Loadwall | 2.2 % | 26.5 % | 32.4 % |
| | Pelvis Loadwall | 1.3 % | 7.8 % | 25.6 % |
| | Upper Spine Y accel | -10.3 % | -72.7 % | -38.7 % |
| | Lower Spine Y accel | -1.0 % | 6.5 % | 9.3 % |
| | Pelvis Y accel | 2.3 % | 2.0 % | -0.3 % |
| | Deflection (Thorax) | -16.9 % | -32.9 % | -0.4 % |
| | F-D Thorax | -6.0% | 0.4 % | 19.2 % |
| **PLF** | Thorax Loadwall | 43.4 % | 5.7 % | 20.4 % |
| | Abdomen Loadwall | 33.4 % | 48.9 % | 54.2 % |
| | Pelvis Loadwall | -9.5 % | -38.0 % | 32.9 % |
| | Upper Spine Y accel | -7.0 % | -13.5 % | -7.5 % |
| | Lower Spine Y accel | 7.2 % | 6.4 % | 8.8 % |
| | Pelvis Y accel | 18.1 % | -30.9 % | 18.8 % |
| | Deflection (Thorax) | 25.0 % | 16.1 % | 34.2 % |
| | F-D Thorax | 25.8 % | -64.2 % | -30.6 % |

Table 2. Normalization results for the component-level thorax pendulum impact data set.

| | Signal | Mass-Based (% improvement) | Eff Mass & Char Length (% improvement) | Eff Mass & Eff Stiff (% improvement) |
|---|---|---|---|---|
| **Lateral** | Force | -14.3 % | 6.9 % | -17.7 % |
| | Deflection | -2.2 % | 13.0 % | 47.0 % |
| | F-D | -26.4 % | 16.6 % | 28.9 % |
| **Oblique** | Force | -3.3 % | 6.7 % | 33.5 % |
| | Deflection | -13.7 % | 3.3 % | 57.2 % |
| | F-D | -19.7 % | 8.6 % | 61.9 % |

## Discussion of results

*Normalization of time-histories.* To illustrate an example of normalization on time-histories, the thorax loadwall time-histories for the RHF condition are shown for the "Non-normalized" condition in Figure 2, and the "Mass-based", "Eff Mass & Char Length", and "Eff Mass & Eff Stiff" normalization conditions in Figures 3-5, respectively.

Visual inspection of Figures 2 and 3 reveals that "Mass-based" normalization results in a small level of improvement in curve group similitude, and in fact the cumulative %CV improves from 60.2 to 43.1 for a percent improvement of 28.4%. Inspection of Figures 2 and 4 shows that the "Eff Mass & Char Length" normalization results in an even more significant improvement in the curve grouping, with a corresponding 50.0% improvement in the %CV value. Finally, inspection of Figures 2 and 5 illustrates that the "Eff Mass & Eff Stiffness" normalization is very effective at bringing the curves together, resulting in a 68.3% improvement in the %CV value. The trend revealed above indicates that incorporating the response data into the normalization process results in better grouping of curves and thus more effective normalization.

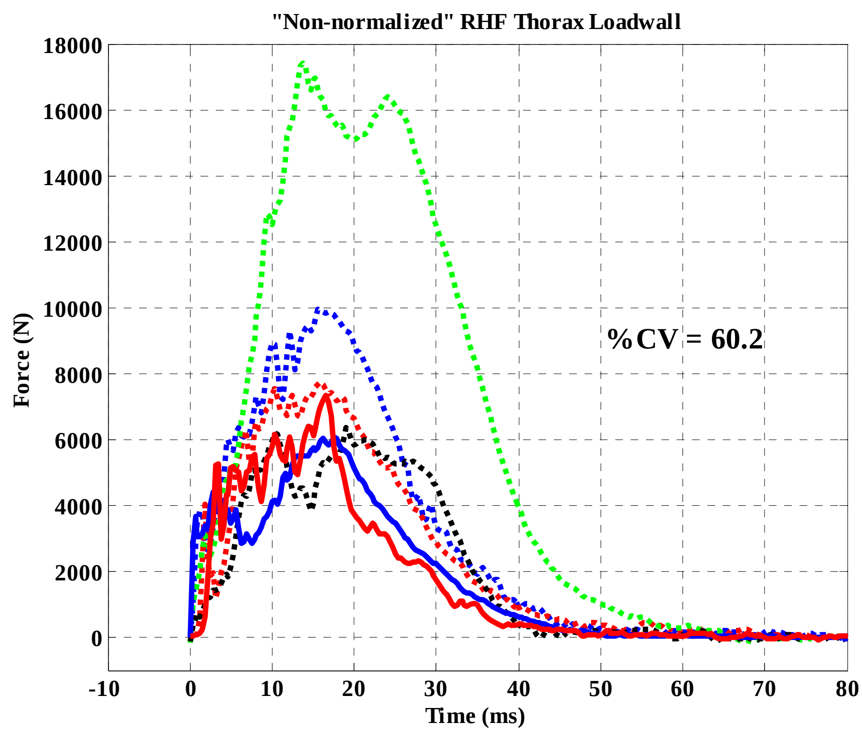


Figure 2: "Non-normalized" RHF thorax loadwall time-histories (%CV = 60.2).

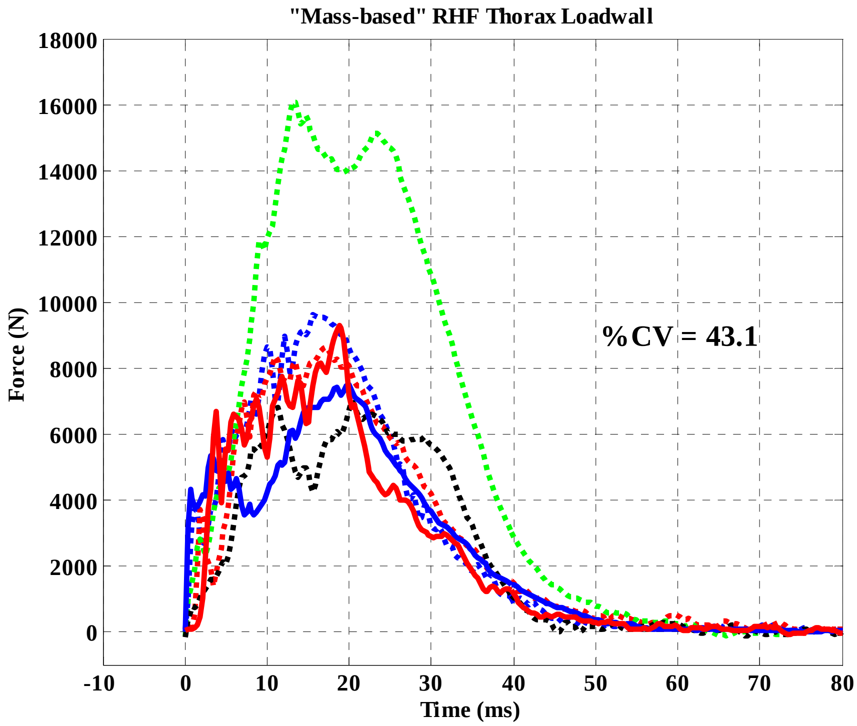


Figure 3: “Mass-based” RHF thorax loadwall time-histories (%CV = 43.1).

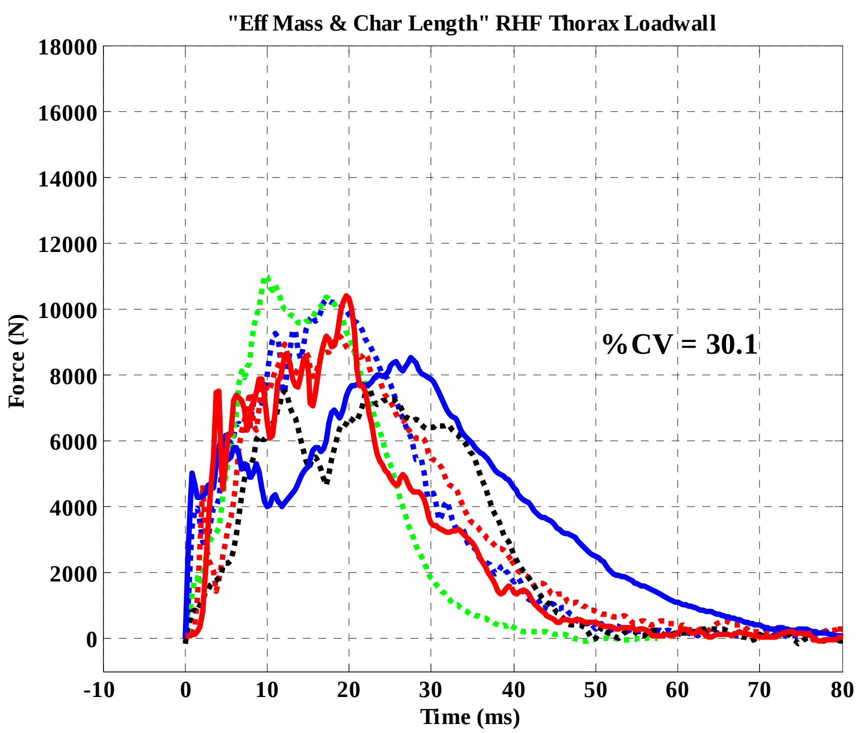


Figure 4: “Eff Mass & Char Length” RHF thorax loadwall time-histories (%CV = 30.1).

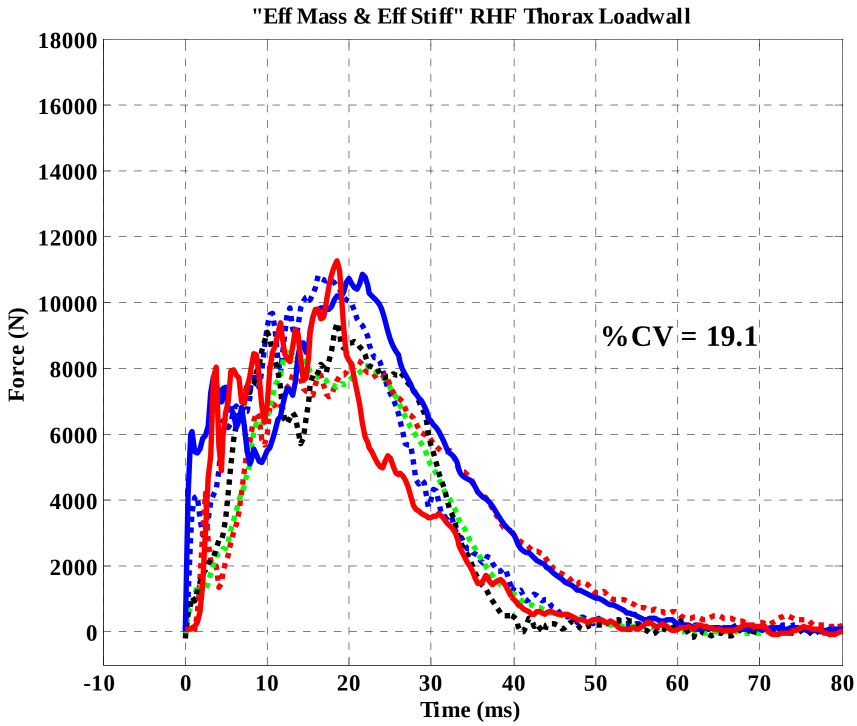


Figure 5: “Eff Mass & Eff Stiff” RHF thorax loadwall time-histories (%CV = 19.1).

*Normalization of force-deflection histories.* To illustrate an example of normalization on force-deflection histories, the force-deflection curves for the oblique thorax pendulum impacts are shown for the “Non-normalized” condition in Figure 6, and the “Mass-based”, “Eff Mass & Char Length”, and “Eff Mass & Eff Stiff” normalization conditions in Figures 7-9, respectively. The grey shaded regions represent the one standard deviation ellipses defined as in Shaw (2006) where at each point along the mean force-deflection curve there is an ellipse which contains a one standard deviation amount of error. Note that low values of cumulative ellipse error represent better grouping of the curves and typically correspond to noticeably smaller regions of grey shading.

Close visual inspection of Figures 6 and 7 reveals that the grey shaded error region actually gets a little bigger with “Mass-based” normalization, and in fact the cumulative ellipse error increases from 5.02 to 6.00 resulting in a negative percent improvement of -19.7%. As mentioned earlier, normalization based solely on total body mass often does not perform well in component-level tests like pendulum impacts. Inspection of Figures 6 and 8 shows that the “Eff Mass & Char Length” normalization results in a modest reduction in the grey shaded error region, with a corresponding 12.3% improvement in the ellipse error. Finally, inspection of Figures 6 and 9 reveals that the “Eff Mass & Eff Stiffness” normalization causes a rather dramatic alignment of the curves and large reduction in ellipse error of 61.9%.

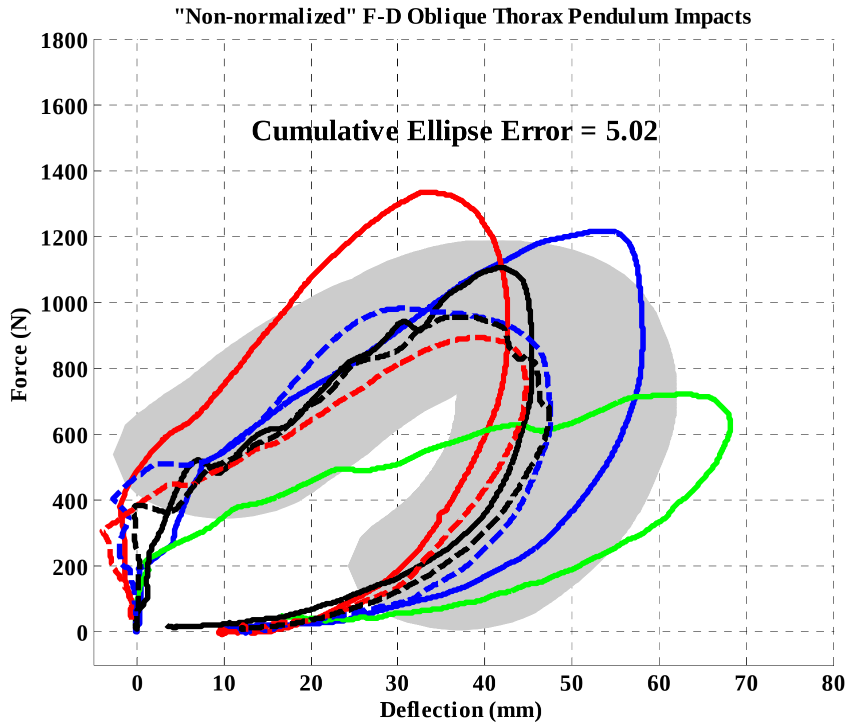


Figure 6: "Non-normalized" Oblique thorax force-deflection histories (Error = 5.02).

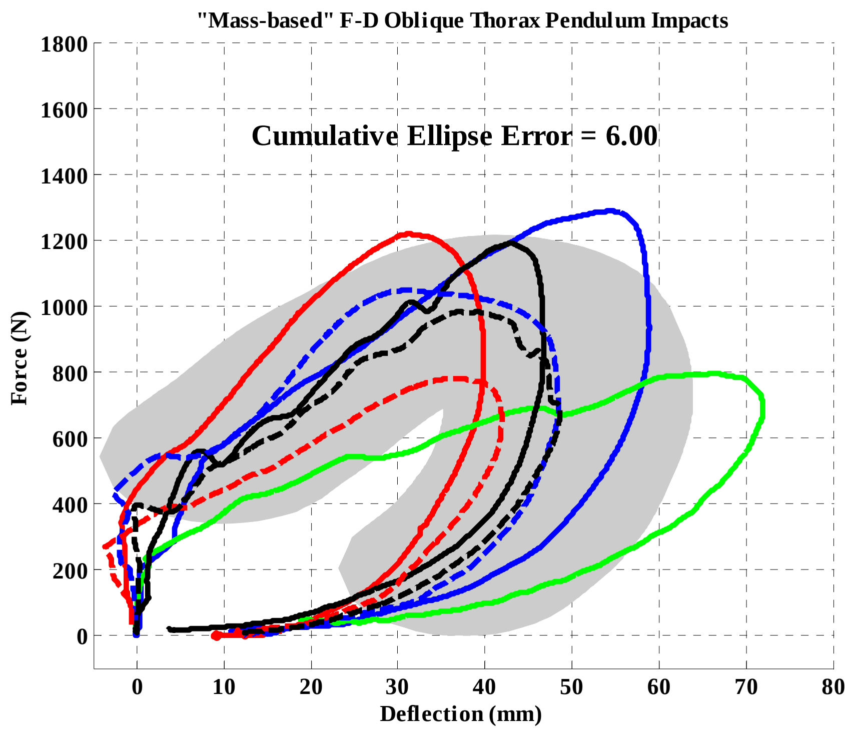


Figure 7: "Mass-based" Oblique thorax force-deflection histories (Error = 6.00).

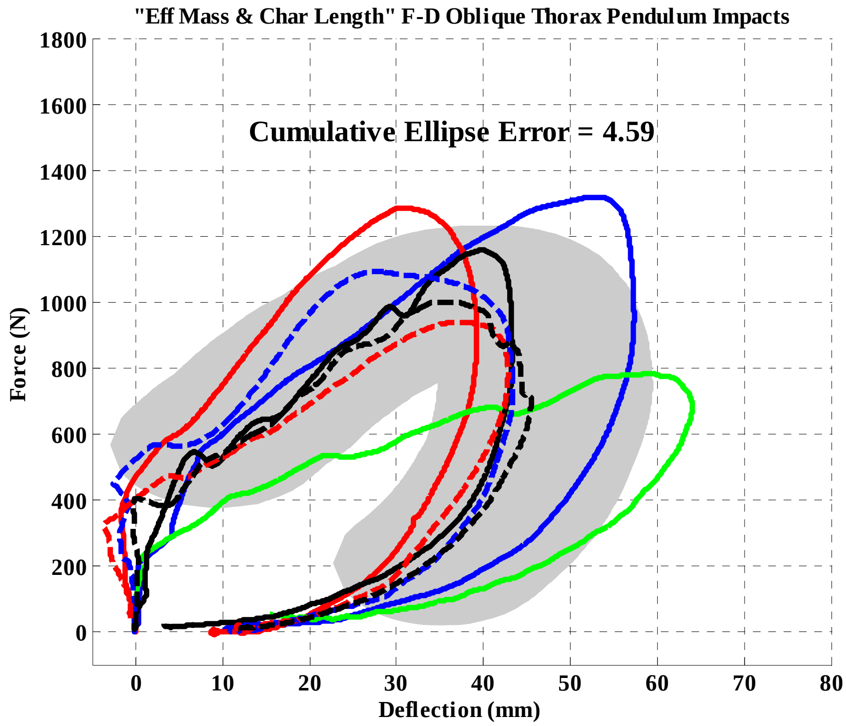


Figure 8: “Eff Mass & Char Length” Oblique thorax force-deflection histories (Error = 4.59).

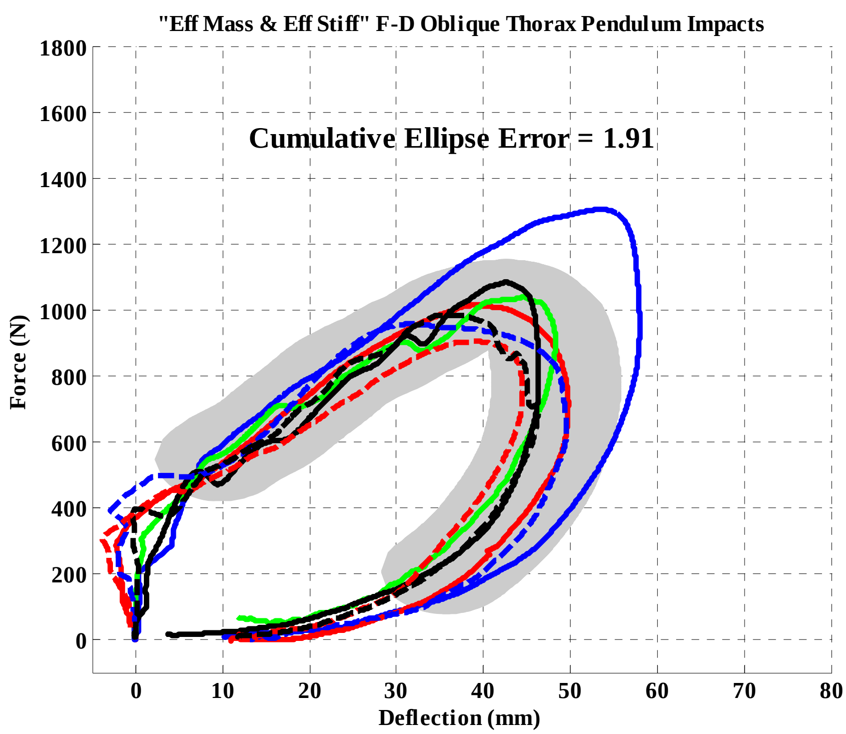


Figure 9: “Eff Mass & Eff Stiff” Oblique thorax force-deflection histories (Error = 1.91).

*Additional discussion.* Several additional observations can be made from examination of Tables 1 and 2. For the component-level pendulum impacts, the "Mass-based" normalization approach actually caused the grouping of the curves to get worse than the "Non-normalized" data in all six signal groups, as evidenced by the negative percent improvements. This again supports the indication that total body mass normalization does not perform well in component-level tests.

For the upper spine, lower spine, and pelvis acceleration signals in the sled test data set there were many instances where one or all of the normalization techniques did not improve the curve grouping relative to the non-normalized data. Furthermore, if the analysis of the normalization results is limited to only these 12 acceleration signal groups, it is much less clear which normalization methodology performed the best. It is likely that the complexity of these signals and the additional potential sources for variation associated with the installation of the instrumentation, greatly reduce the effectiveness of normalization for these "internal" signals. However, if the analysis of the results is limited to the other 26 signal groups (i.e., force, deflection, and two-dimensional force-deflection), normalization is much more effective in improving the grouping of the curves, and the "Eff Mass & Eff Stiffness" approach clearly performs the best. Specifically, it yields the greatest improvement in 22 of 26 (~85%) of these signal groups, as compared to 3 of 26 (~12%) for the "Mass-based" approach and 1 of 26 (~4%) for the "Eff Mass & Char Length" approach.

## Limitations

Although the results from this study demonstrate that the normalization of impact response data using the "Eff Mass & Eff Stiff" approach is clearly the most effective way to improve the similitude of a group of responses for the creation of a mean human response curve, a couple limitations in the methodology should be pointed out. First, the values for effective stiffness can only be obtained if deflection data is measured directly (e.g., chestband) or can be indirectly estimated (e.g., double integration of accelerometers). Also, the numerator of the stiffness ratio in Equation (7) for "Eff Mass & Eff Stiff" normalization is dependent on the test condition and can not be obtained from anthropometric tables. Recall that this is also true for the numerator of the effective mass ratio, but the effective mass can still be estimated and related directly back to the 50$^{th}$ percentile male (or selected population), as discussed previously. In contrast, the effective stiffness can not be related directly to any selected population, as stiffness data for various population groups are not available in anthropometric tables. As long as such data is unavailable, the numerator of the stiffness ratio can only be estimated by averaging the effective stiffness of each subject for a given test condition. Therefore, the "Eff Mass & Eff Stiff" normalization methodology should only be applied to test data where the subject set is representative of (or normally distributed about) the target population.

## CONCLUSIONS

Several normalization methodologies were quantitatively evaluated by applying them to time-history data and two dimensional force-deflection data from both a full-body sled test data set and a component-level pendulum impact data set. The normalization technique found to consistently perform the best is a newly developed extension of impulse-momentum-based normalization in which the stiffness ratio was determined from effective stiffness values calculated from the test data, rather than using characteristic lengths. Utilization of this normalization methodology in the development of mean human response curves should prove useful in more accurately characterizing the target human response to aid in the design of more biofidelic dummies.

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# DISCUSSION

PAPER: **An Improved Normalization Methodology for Developing Mean Human Response Curves**

PRESENTER: ***Kevin Moorhouse, Vehicle Research and Test Center, National Highway Traffic Safety Administration***

**Q**UESTION: *Richard Kent, University of Virginia*
I was going to ask you if you have tried this on a frontal impact. We try to scale things like chest acceleration and that sort of thing from a frontal impact. It seems like it's got a lot more geometric nonlinearities and things like that with the torso pitching and interacting with a complex restraint system. I'm wondering if you've looked at a frontal impact. And if so, can you get similar sorts of dramatic improvements? It seems like whenever we scale, you just rearrange the curves; they don't really come together any better. So I'm wondering if you've looked at a frontal impact.

**A**NSWER: Those are the only two data sets that we really looked at although we did look at the spinal accelerations in the side-impact data, which is probably similar to what you're talking about. The effect isn't quite as dramatic and the force-time histories or the force deflection, but it still does align the curves and they're included in the table. The effect of mass and the effect of stiffness did perform the best for most of those.

**Q:** It might be interesting to look at a frontal just because, sort of, a 1-D assumption for a lateral impact is probably okay, but a frontal impact is more of a 2-D—sometimes 3-D kind of thing.

**A:** Right. We're actually going to apply it soon to some rear-impact data that we're creating that would be similar because the body will be pitching.

**Q:** Good. Thank you.

**Q:** *Guy Nusholtz, Daimler Chrysler*
First a procedural question: How are you calculating CV? Is that a variation over the normalized value at that point in time and then you sum them?

**A:** Yes, basically calculate the CV at every point in time.

**Q:** There's sort of a small problem with it that you probably want to look into that when you have very small numbers, then that can drive your CV to be much larger and not really give you the insights that you're after.

**A:** Right. That's why we took the upper 80% of the curves to stay where the mean value was low.

**Q:** Oh, okay. So you had a limit.

**A:** Correct.

**Q:** Okay. Good. In your normalization process, it looks like I could just take my data and scale so that the integrals of all those curves were the same and my CV would be the minimized. I think, a little bit, that's what you're doing with your effective mass and effective stiffness. You're just changing the amount of area under the curve and keeping the shape somewhat the same.

**A:** Yes. So it's an extension where instead of using a characteristic length, we now add this other chance where we get to incorporate the response data to try to pick up on those other things. So yes, in a sense we are converging all those responses to the average response of that subject set.

**Q:** So you could actually do better just by taking the areas and normalizing them, and then you'd get a better CV.

**A:** Yes, but then you're not actually using a real physical parameter like mass or stiffness. At least here we're making an attempt to estimate a stiffness and estimate a mass and use that to normalize the data.

**Q:** But these are effective mass.

**A:** Right.

**Q:** And those are derived from a situation where you have a continuous body.

**A:** Yes.

**Q:** And you don't have a continuous stiffness. It's—

**A:** But it's better than just taking the curves.

**Q:** It's better than just taking the curves. Okay. Thank you.

**Q:** *Joel Stitzel, Wake Forest University*
Really neat stuff and I'm particularly interested in using the method and going back and looking at retrospective data to see if we can get it to create some tighter corridors for model validation. Do you have any thoughts on that? How often are we going to have the effective mass and the characteristics and these sort of things available from retrospective papers in order to--? Or, have you thought about how to take the data that will be available retrospectively and use it using your method?

**A:** Well, what we really need is a measure of deflection. If the data set had a measure of deflection—either chest band or estimate from accelerometers—and some external impacting force from either a pendulum or a load wall, then, yes, we could go back, if the data was electronic, and renormalize it and see how it changes.

**Q:** Thanks.

**Q:** *Erik Takhounts, NHTSA*
I have a question for you, Kevin. In the first slide, you had shown an example. There were two curves where the phase shifted and then you took an average and got a different curve. And then in your methodology, they seemed to be all aligned in phase. I was wondering if this methodology will work for curves that have a phase shift as well.

**A:** A lot of those curves that I normalize did have a phase shift and it works really well. There are examples where it doesn't, and that's where the next step of the whole process, which is optimization of the phase alignment, would come in. I didn't talk about that today, but we've also developed a methodology for further improving the phase difference in the curves.

**Q:** Thank you.

**Q:** *Frank Pintar, Medical College of Wisconsin*
I just want to know what different sized occupants have you tried, like to derive 5$^{th}$ female curves. Is it robust enough to handle those kinds of--?

**A:** I hadn't tried it yet. I mean if you were going to get 5$^{th}$ female curves, you'd either have to have 5$^{th}$ female subjects or you would just use the standard, probably, scaling procedures after you create your 50$^{th}$ corridors using this normalization procedure because your subjects were 50$^{th}$.

**Q:** Right.

**A:** Then you would probably just do the typical scaling of response from there down to a fifth without having the actual subjects.

**Q:** But you haven't tried that.

**A:** Haven't tried that.

**Q:** Okay.

**Q:** *Jeff Crandall, University of Virginia*
Interesting study. I had a question, though, sort of following up on Guy's comment, in that you're using these interval relations, which are from the data itself, the normalized—the amount or spread in the data. My concern is you may actually be doing too much normalization. For example, you've got effective mass or effective stiffness when in fact, those are coming from very different physical

components: inertia, viscous effects, stiffness effect. And so, I could see if you're going to compare this to a dummy, for example, one might say that we should normalize the dummy when we compare to those. I mean that would be a fair comparison because you're contriving how you develop these corridors. It's not—It's a scaling process and it's an effect.

**A:** I mean obviously in an ideal world, we would have a hundred subjects and they would all be a normal distribution around a $50^{th}$ percentile male, but we don't have that. Normalization existed before we did this impulse minimum-based thing. All we did was improve it another step by adding the deflection level.

**Q:** My concern is when you take this another step, when you develop corridors and the physical interpretation to those corridors relative to something like a standard deviation, what would be a reasonable response? Because right now when we're developing dummies or models, we're actually using some of that inherent variability. And here, we're sort of—I would contend—overly contriving it to be too narrow based on not necessarily—Everything's effective; I agree, but I think it could be overly constraining.

**A:** Okay.

**Q:** I don't know if that makes sense.

**A:** It makes sense. It's something you could discuss, I guess.