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Normalization Technique for Developing Corridors from Individual Subject Responses

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ABSTRACT

This paper presents a technique for developing corridors from individual subject responses contained in experimental biomechanical data sets. Force-deflection response is used as an illustrative example. The technique begins with a method for averaging human subject force-deflection responses in which curve shape characteristics are maintained and discontinuities are avoided. Individual responses sharing a common characteristic shape are averaged based upon normalized deflection values. The normalized average response is then scaled to represent the given data set using the mean peak deflection value associated with the set of experimental data. Finally, a procedure for developing a corridor around the scaled normalized average response is presented using standard deviation calculations for both force and deflection.

INTRODUCTION

Background

Injury biomechanics research often involves applying a loading input to a number of subjects and producing a set of individual subject responses. Variability due to mass, density, and elastic modulus is handled using dimensionless scaling techniques (c.f., Eppinger et al. 1984), although density and elasticity differences are infrequently quantified. Even with these scaling adjustments, inherent variability among specimens necessitates that corridors be developed to represent the range of responses.

Currently, there is no universally accepted method for corridor development and previous techniques have varied. While numerous techniques to normalize cadaveric data are found in the literature, only representative samples are presented here. Cavanaugh et al. (1986), Morgan et al. (1986), and Maltese et al. (2002) have developed corridor development techniques utilizing a time-based procedure. Conversely, Lobdell et al. (1973) utilized a time-independent approach in which an “eyeball average” was drawn through force-deformation data.

Each of these approaches has its associated set of advantages and disadvantages. A time approach is quantified and repeatable but may not be always able to retain the characteristic shape of the individual responses, particularly once the time base is removed by cross-plotting, for example, force deflection. Conversely, an “eyeball average”, while providing a method to retain response shape characteristics, is inherently subjective and cannot be repeated by another individual. The normalization technique proposed here provides, independently of time, a quantified and repeatable approach to developing corridors that retain the characteristic shape of the individual subject responses. The technique is demonstrated here using force-deflection responses but, with modification, could logically be extended to other data sets.

The thoracic force-deflection corridor, frequently referred to as the Kroell corridor, is used as an example to outline the general process of corridor development which begins with a set of subjects being introduced to a specific loading input (Figure 1). Measuring and recording the response of each subject results in a set of individual force-deflection responses (Figure 2). Finally, this individual response data can be used to develop a corridor, which serves as the target for anthropomorphic test device (ATD) and computational model design (Figure 3).

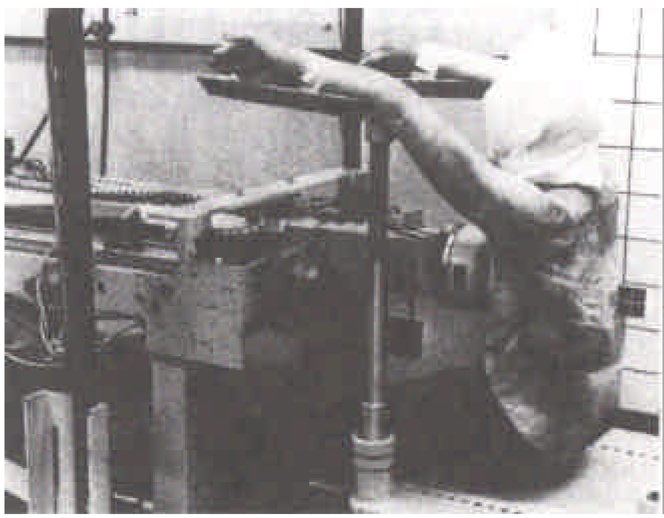

Figure 1: Thoracic impact tests (Kroell et al. 1971). A number of cadaver subjects were subjected to hub impacts to the sternum resulting in the response data illustrated in Figure 2.

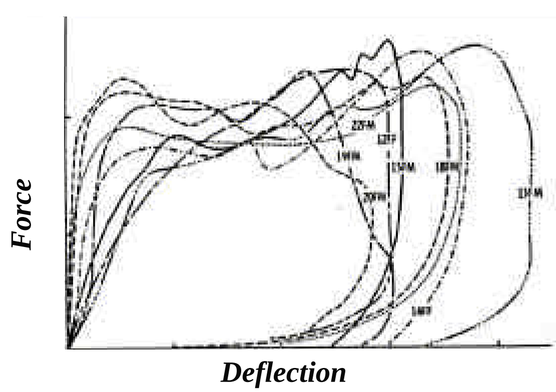

Figure 2: Individual responses (one for each subject) resulting from the selected thoracic tests illustrated in Figure 1 (Kroell et al. 1971).

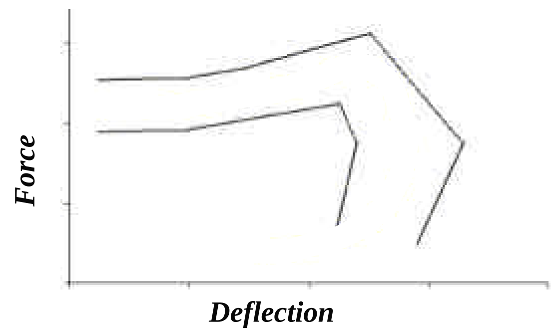

Figure 3: The "Kroell corridor" (Lobdell et al. 1973) developed from the data set a shown in Figure 2.

Quantifying the response

The process of corridor development begins with a set of individual responses (refer to Figure 2). These responses may exhibit a range of force and deflection maxima while sharing some common characteristic shape that should ultimately be retained in the corridor. The first step in developing the corridor is quantifying the response by determining an average response using an objective method capable of retaining the characteristic shape of the individual responses. Retaining this shape, however, typically requires more than simple averaging (averaging the available force data at each deflection level) which can result in discontinuities and a lack of correct shape characteristics. The normalization technique developed here utilizes a "characteristic average" which is a calculated average that retains the characteristic shape of the individual responses. The benefit of the characteristic average is shown most easily with an example.

Figure 4 illustrates an arbitrary set of response curves for which a representative average is to be calculated. Figure 5 contrasts the results of simple averaging with the characteristic average. The characteristic average is more representative of the individual responses and also shares the same characteristic shape. Conversely, the curve generated from simple averaging fails to represent the curves in the original data set. The procedure for calculating the characteristic average and developing a corridor around it is explained in detail in the following section.

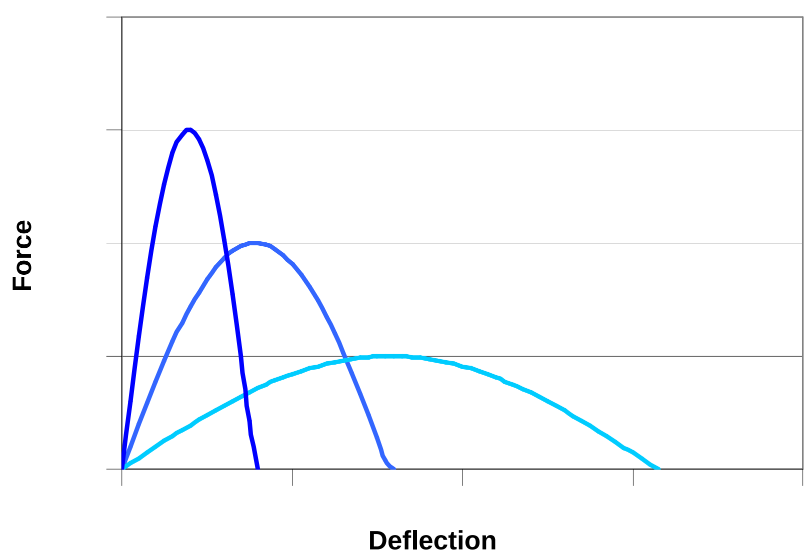

Figure 4: An arbitrary set of force-deflection responses for which an average response is to be calculated. (Units are also arbitrary).

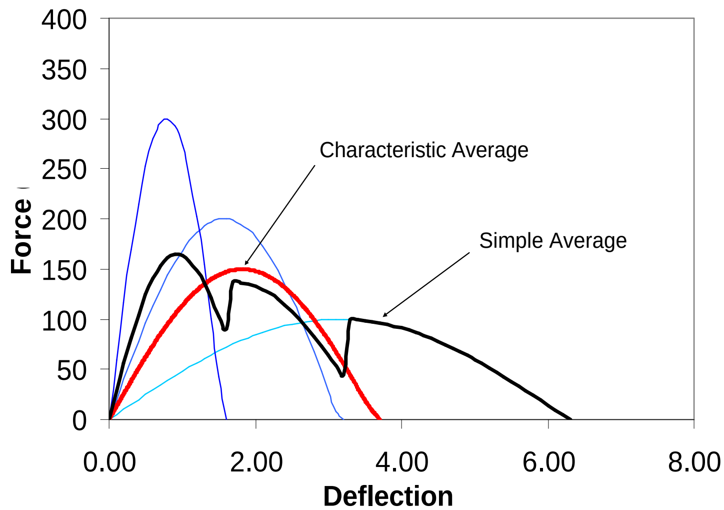

Figure 5: A comparison of two techniques for averaging the curves shown in Figure 4. The characteristic average possesses the same shape as the curves from which it was calculated. The simple average exhibits discontinuities and lacks the characteristic shape of the other curves.

METHODS

Obtaining the characteristic average

To demonstrate the fundamentals of the normalization technique and corridor development an arbitrary set of data curves (Figure 6) was chosen. It is important to note that prior to using the normalization technique, variation among the individual responses should be reduced by methods such as mass scaling (Eppinger et al. 1984). Table 1 provides an outline of the procedures involved in the normalization technique.

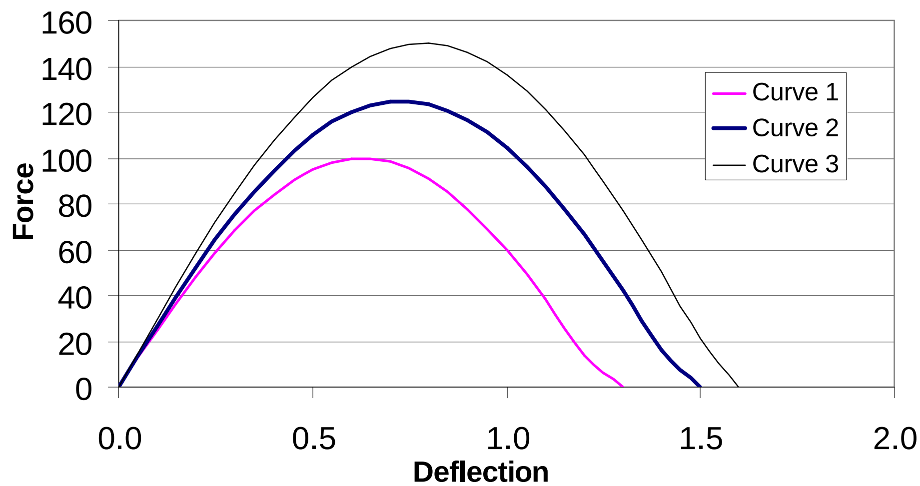

Figure 6: Arbitrary set of individual force-deflection responses (raw curves) used to demonstrate the normalization technique. Units are arbitrary.

Table 1. Outline Of Normalization Technique

Order of Action	***Action Performed***
Performed prior to normalization technique	Select individual responses to comprise data set from which the corridor will be constructed.
	Reduce variability using appropriate scaling methods.
Normalization Technique: Part I	**Calculate characteristic average**
Step 1	Normalize deflection by dividing the deflection data for each individual response (raw curve) by its associated maximum deflection (Dmax).
Step 2	Use an interpolation routine to obtain force values for all raw curves at common normalized deflection values, such as at each 1% of Dmax.
Step 3	Average force values from the interpolated curves (obtained in the previous step) at common normalized deflection values.
Step 4	Multiply the normalized deflection values by the average maximum deflection (Dmax_mean) of the raw curves in the data set. This results in the final characteristic average.
Normalization Technique: Part II	**Develop the corridor around the characteristic average**
Step 1	Calculate the S.D. in force for each point on the characteristic average curve.
Step 2	Normalize force by dividing the maximum force for each raw curve by its associated maximum deflection (Fmax).
Step 3	Use a linear interpolation routine to obtain deflection values for all raw curves at common normalized force values, such as at each 1% of Fmax.
Step 4	Calculate S.D. in deflection for each point on the characteristic average curve.
Step 5	Determine the “extreme” variation values associated with each point on the characteristic average curve.
Step 6	Plot the four variation “extreme” curves.
Step 7	Enclose the region bounded by the four extreme curves. This creates the corridor.

The first step in calculating the characteristic average is to normalize the deflection for each of the individual responses (referred to the “raw curves” from here on). This is accomplished by dividing the deflection data for each of the raw curves (those appearing in Figure 6) by its associated maximum deflection value (Dmax). Thus, each normalized raw curve will have a peak normalized deflection of 1 (or 100% of Dmax). At this point, however, there is no standard normalized deflection interval that is consistent for all of the normalized raw curves. This is due to experimental data point interval variance as well as the deflection data for each raw curve being normalized by a different value of Dmax.

The second step, therefore, is to obtain force values at common normalized deflection intervals. This is accomplished using a linear interpolation routine to interpolate each normalized raw curve at common normalized deflection values (such as at each 1% of Dmax). Figure 7 illustrates the interpolated force values for each raw curve plotted against normalized deflection (D/Dmax). The curves obtained using the interpolation routine will be referred to as interpolated curves from here on.

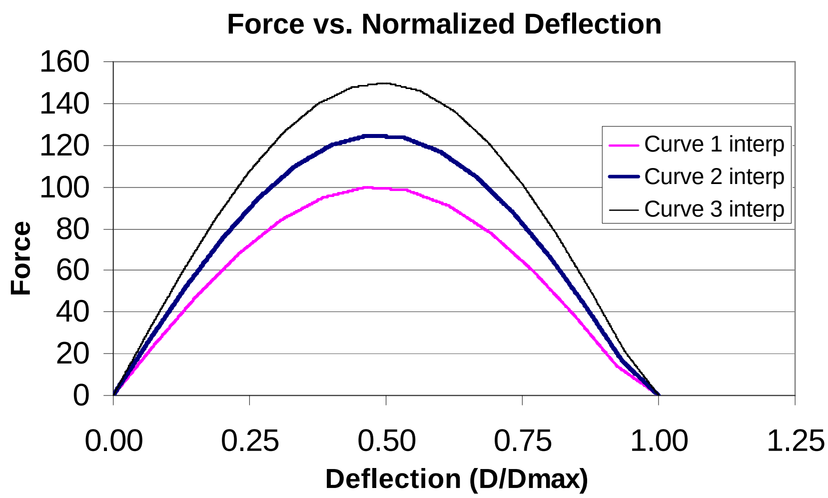

Figure 7: Interpolated curves (interpolated force vs. normalized deflection). Each of these curves is created using an interpolation routine to obtain force values at common normalized deflection intervals. These common deflection intervals are used to average the force data.

The third step is to average the interpolated curves (those in Figure 7) at each common normalized deflection value. Table 2 illustrates this process. Figure 8 shows the average force vs. normalized deflection (D/Dmax) curve relative to the interpolated curves from Figure 7.

Table 2. Averaging Forces At Each 1% Of Normalized Deflection
For each normalized deflection value in Figure 7 there are three force values (n=3) corresponding to the interpolated curves, resulting in an average value at each normalized deflection value.

Normalized Deflection (%)	Force From Curve i	Average Force
j = 0	$F_i\,(0)$	$F_{ave}\,(0) = \dfrac{\sum_{i=1}^{n} F_i(0)}{n}$
j = 1	$F_i\,(1)$	$F_{ave}\,(1) = \dfrac{\sum_{i=1}^{n} F_i(1)}{n}$
.	.	.
.	.	.
j = k= 100	$F_i\,(100)$	$F_{ave}\,(100) = \dfrac{\sum_{i=1}^{n} F_i(100)}{n}$

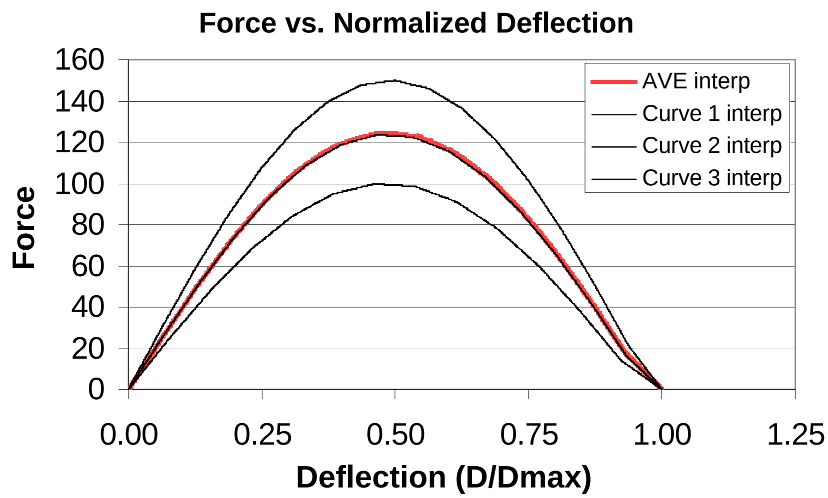

Figure 8: Average force vs. normalized deflection relative to the interpolated curves from Figure 7.

Referring to Figure 8, the average force is plotted versus normalized deflection, but the eventual goal is average force vs. deflection (rather than normalized deflection). Thus, the final step involves scaling (un-normalizing) the average curve in Figure 8. This is accomplished by multiplying (scaling) the normalized deflection values by an appropriate constant value to obtain the final characteristic average curve for the data set in terms of both force and deflection. Each individual curve has an associated maximum deflection value (Dmax). Averaging Dmax for all curves results in an average maximum deflection value (Dmax_mean) (Equation 1). The un-normalized deflection data for the average curve in Figure 8 is obtained by multiplying (scaling) each normalized deflection value by Dmax_mean (Equation 2-6). Figure 9 illustrates the final characteristic average curve relative to the raw curves comprising the original data set shown in Figure 6.

$$D_{\max\_mean} = \frac{\sum_{i=1}^{n} D_{i\max}}{n} \quad (1)$$

$$D_{scaled}(j) = D_{norm}(j) * D_{\max\_mean} \quad (2)$$

where j = 0..k,

$$D_{norm}(0) = 0 \quad (3)$$

$$D_{norm}(k) = 1 \quad (4)$$

$$D_{scaled}(0) = 0 \quad (5)$$

$$D_{scaled}(k) = D_{\max\_mean} \quad (6)$$

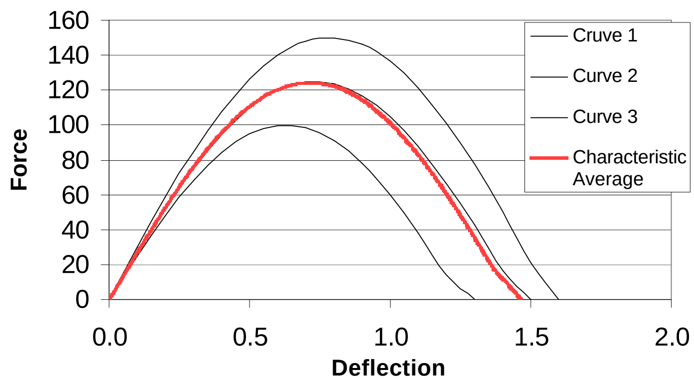

Figure 9: Final average force-deflection curve. This is the characteristic average around which a corridor will be constructed. Shown also are the raw curves comprising the original data set.

Developing a corridor

Part 2 of the normalization technique involves developing a representative corridor around the characteristic average curve. This is accomplished using standard deviations for both axes (force and deflection). The first step in the corridor development process is to calculate the standard deviation (S.D.) in force at each point (deflection value) on the characteristic average curve. This is done when the average force value is calculated for each normalized deflection value. Table 3 is the same as Table 2 with the addition of the S.D. calculation for force. Steps two through four of the corridor development process involve the S.D. calculation for deflection.

Table 3. Calculating The S.D. In Force At Each Normalized Deflection Value
For each normalized deflection value there are three force values corresponding to the interpolated curves resulting in an average value and an associated S.D. in force at each normalized deflection value.

Normalized Deflection%	Force From Curve i	Average Force (n of curves)	S.D. (n of curves)
0	F_i (0)	F_{ave} (0)	SD (0)
1	F_i (1)	F_{ave} (1)	SD (1)
2	F_i (2)	F_{ave} (2)	SD (2)
3	F_i (3)	F_{ave} (3)	SD (3)
.	.	.	.
.	.	.	.
100	F_i (100)	F_{ave} (100)	SD (100)

Step two is to normalize the force data for each of the raw curves. This is accomplished by dividing the force data for each raw curve by its associated maximum force value (Fmax). Thus, each force-normalized raw curve has a maximum normalized force of 1 (or 100% of Fmax). Similar to the approach with normalized deflection, the third step is to interpolate the force-normalized raw curves to obtain deflection values at common normalized force values (such as at each 1% of Fmax). Figure 10 illustrates the interpolated curves obtained using normalized force (interpolated curves in this section refer to those illustrated in Figure 10, not to be confused with those from the previous section).

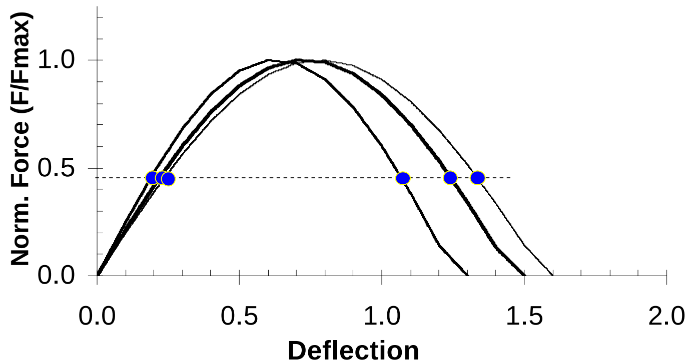

Figure 10: Interpolated curves based on normalized force. Note that there are multiple deflection values associated with each normalized force value for each interpolated curve.

Following the interpolation, step four is to calculate the S.D. in deflection for each point on the characteristic average curve. This is more involved than the force S.D. calculation since there are multiple (two) deflection values associated with each normalized force value for each interpolated curve. To overcome this problem, two deflection intervals were used to sort deflection values occurring at each normalized force value, one interval from 0-50% deflection (increasing force) and another from 51-100% deflection (decreasing force). For each normalized force value the corresponding deflection values were divided by Dmax from their respective raw curves resulting in a percentage value of Dmax. This percentage value determined the deflection interval in which the deflection value would be placed. Then, for each deflection interval, a deflection S.D. value was calculated for each normalized force value from the corresponding deflection values in that interval. Notably, there are two deflection S.D. values corresponding to each normalized force value (Table 4).

Using multiple intervals to calculate the deflection S.D. is necessary, since the occurrence of two deflection values (one occurring before the peak force and one occurring after) for each force value is a characteristic of the response. Thus, it is undesirable to group values from both sections into a single S.D. to be associated with one particular normalized force value. Doing this would cause the S.D. value to become unrealistically large since data would be included from two distinctly different regions of the curve. In general, it will be necessary to divide the deflection range into multiple intervals when calculating the deflection S.D.

Table 4. Calculating The S.D. In Deflection At Each Normalized Force Value
In general, this may need to be done for multiple deflection intervals, but is shown here with two for this example.

	Deflection Interval 1 (0-50%)				**Deflection Interval 2 (51-100%)**			
Normalized Force %	**Defl. (1)**	**Defl. (2)**	**Defl. (3)**	**S.D.**	**Defl. (1)**	**Defl. (2)**	**Defl. (3)**	**S.D.**
0	D_1 (0)	D_2 (0)	D_3 (0)	SD (0)	D_1 (0)	D_2 (0)	D_3 (0)	SD (0)
1	D_1 (1)	D_2 (1)	D_3 (1)	SD (1)	D_1 (1)	D_2 (1)	D_3 (1)	SD (1)
2	D_1 (2)	D_2 (2)	D_3 (2)	SD (2)	D_1 (2)	D_2 (2)	D_3 (2)	SD (2)
3	D_1 (3)	D_2 (3)	D_3 (3)	SD (3)	D_1 (3)	D_2 (3)	D_3 (3)	SD (3)
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
100	D_1 (100)	D_2 (100)	D_3 (100)	SD (100)	D_1 (100)	D_2 (100)	D_3 (100)	SD (100)

Following the S.D. calculations, the normalized force is scaled (un-normalized) by multiplying each normalized force value by the maximum force value (Fmax) of the characteristic average curve. Doing this yields force values ranging from 0 to Fmax (of the characteristic average curve) with associated S.D. values in deflection for both sections of the curve (deflections before Fmax and those after). Thus to obtain the S.D. in deflection for a given point on the characteristic average curve, the data in Table 4 can be interpolated to determine the S.D. for a given force and deflection location. This is done for every point comprising the characteristic average curve according to the force and deflection values associated with each particular point. Once this has been done for each point on the characteristic average curve, the S.D. in both force and deflection are known, defining a range of variation for each point. This is illustrated in Figure 11.

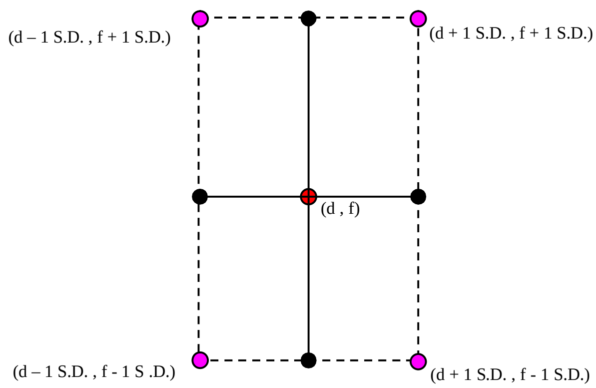

Figure 11: Range of variation (within one S.D.) for each data point on the average curve. Associated with this range of variation are four extreme points at the corners of the box bounding the region of variation.

The corridor is created by plotting the four extremes associated with each data point and enclosing the region bounded by the extreme curves. Figure 12 illustrates the extreme curves along with the characteristic average curve. The bounded region creating the corridor is shown in Figure 13. This corridor plotting method is similar to that used by Viano and Davidsson (2002). Figure 14 illustrates the corridor, the characteristic average curve, and the raw curves for the example data set.

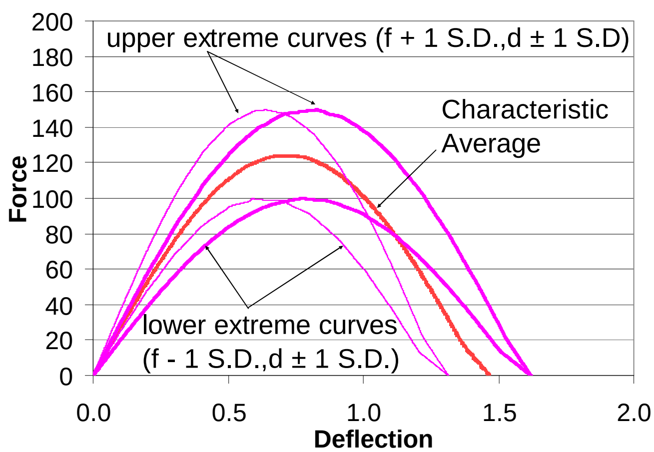

Figure 12: Four extreme curves are created by plotting the four extreme variation values for each point on the characteristic average curve.

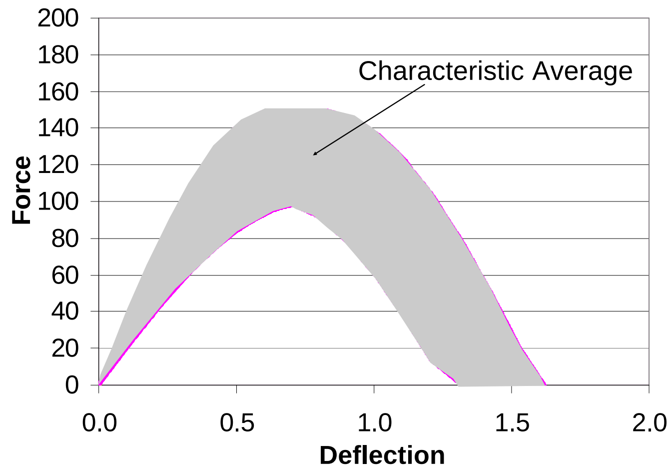

Figure 13: Enclosing the region bounded by the extreme curves creates a corridor based on one S.D. on both axes around the characteristic curve.

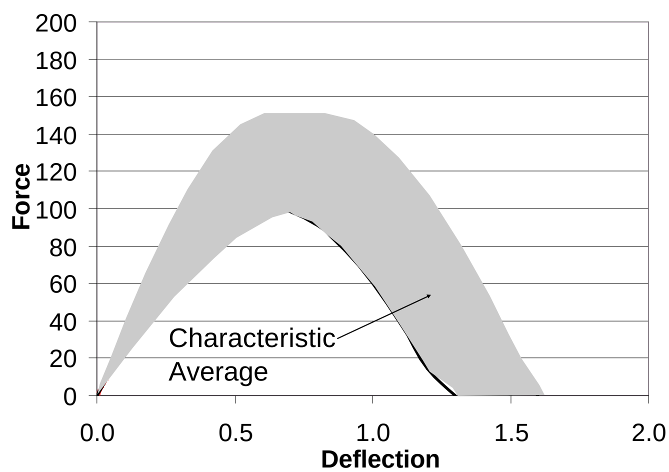

Figure 14: The characteristic average curve, raw curves, and the one-standard-deviation corridor (shaded region).

RESULTS

Application to experimental data

The following example illustrates the proposed corridor development technique applied to actual experimental data. The procedure outlined in Table 1 was followed to develop the characteristic average and associated corridor, but because experimental curves are often more complex in terms of shape than the arbitrary curves used in the prior examples, certain steps of the technique become more involved to accommodate the more complex characteristics of the experimental data set. Figure 15 presents the set of experimental data for a corridor and characteristic average to be determined.

As with the arbitrary example, each of these curves was interpolated at normalized deflection intervals (at each 0.1% of Dmax), and an average was taken at common normalized deflection values. It is important to note that there is an unloading section associated with each curve so the interpolation was done in two sections. One section for the loading part of the curve (deflection is increasing) and another section for the unloading part of the curve (deflection is decreasing).

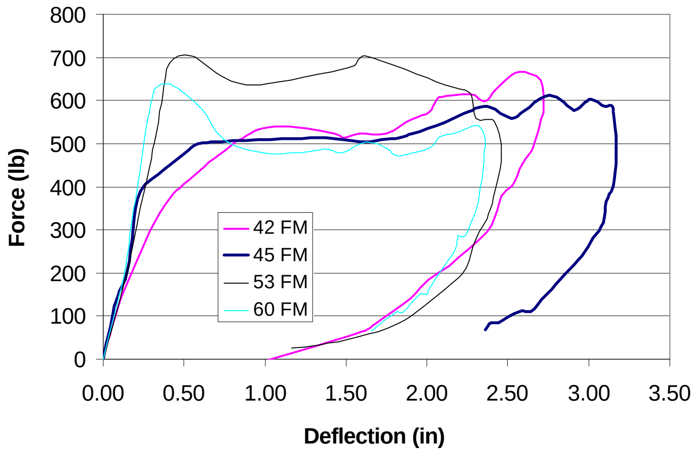

Figure 15: Experimental data set. Thoracic impact data (Kroell et al. 1974).

The characteristic average was determined for the experimental data following the same procedure outlined in the Method section. The data were averaged at common normalized deflection values for both loading and unloading sections of the curves. Then this curve was scaled using the Dmax_mean value. The result is illustrated in Figure 16 which shows the characteristic average curve in addition to the raw curves.

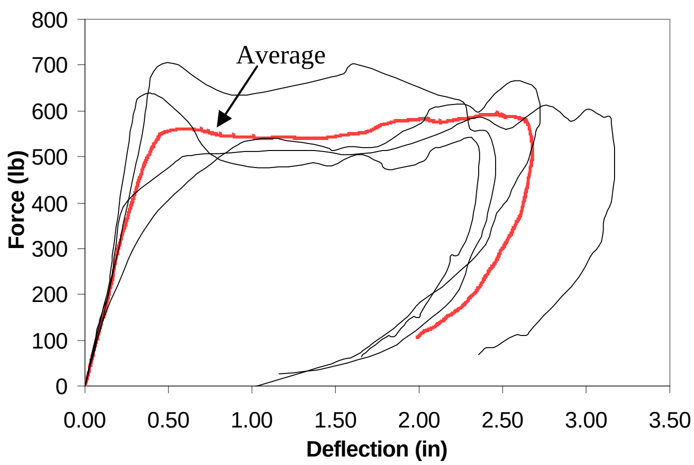

Figure 16: Characteristic average corresponding to the experimental data set. Raw curves shown also.

To obtain a corridor from the characteristic average response it was necessary to calculate the standard deviations for force and deflection at each point on the characteristic average curve. The S.D. in force was determined when each force value on the characteristic average curve was calculated (refer back to Table 3 for an example).

Determining the S.D. in deflection was more involved because of multiple deflection values associated with normalized force values. First, each curve was normalized based on force (F/Fmax). Second, the loading section of each curve was divided into five equal deflection segments of 20% each. Third, in each deflection segment, all deflection values corresponding to each normalized force value were determined. Fourth, the deflection S.D. for each segment was calculated using the deflection values from the other curves in that same segment and at the same normalized force value. Fifth, the unloading section was treated the same way except there was only one deflection segment which included the entire unloading section of the curve. These steps resulted in deflection S.D. values for each normalized force value (at 0.1 % intervals) for the unloading section of the curve and also for each of five deflection segments on the loading section of the curve. See Table 5 for more details.

Table 5. S.D. In Deflection At Each Normalized Force Value For Each Specified Segment Of The Characteristic Average Curve

	S.D. based on appropriate deflection segment					
Normalized Force %	**0-20%**	**21-40%**	**41-60%**	**61-80%**	**81-100%**	**UNLOADING**
0	SD_1 (0)†	SD_2 (0)	SD_3 (0)	SD_4 (0)	SD_5 (0)	SD_U (0)
1	SS_1 (1)	SD_2 (1)	SD_3 (1)	SD_4 (1)	SD_5 (1)	SD_U (1)
2	SD_1 (2)	SD_2 (2)	SD_3 (2)	SD_4 (2)	SD_5 (2)	SD_U (2)
3	SD_1 (3)	SD_2 (3)	SD_3 (3)	SD_4 (3)	SD_5 (3)	SD_U (3)
.	.	.	.	.	.	.
.	.	.	.	.	.	.
100	SD_1 (100)	SD_2 (100)	SD_3 (100)	SD_4 (100)	SD_5 (100)	SD_U (100)

† - A sorting algorithm was written to find all deflection values from the individual curves occurring in the appropriate deflection interval corresponding to the appropriate normalized force value, from these deflection values a S.D. was calculated.

Table 6. S.D. In Deflection At Each Scaled Force Value For Each Specified Segment Of The Characteristic Average Curve

	S.D. based on appropriate deflection segment					
Scaled Force %	**0-20%**	**21-40%**	**41-60%**	**61-80%**	**81-100%**	**UNLOADING**
F_0	SD_1 (0)	SD_2 (0)	SD_3 (0)	SD_4 (0)	SD_5 (0)	SD_U (0)
F_1	SS_1 (1)	SD_2 (1)	SD_3 (1)	SD_4 (1)	SD_5 (1)	SD_U (1)
F_2	SD_1 (2)	SD_2 (2)	SD_3 (2)	SD_4 (2)	SD_5 (2)	SD_U (2)
F_3	SD_1 (3)	SD_2 (3)	SD_3 (3)	SD_4 (3)	SD_5 (3)	SD_U (3)
.	.	.	.	.	.	.
.	.	.	.	.	.	.
F_n	SD_1 (n)	SD_2 (n)	SD_3 (n)	SD_4 (n)	SD_5 (n)	SD_U (n)

Following the deflection S.D. calculations, the normalized force data was scaled by multiplying each normalized force value by the maximum force observed in the characteristic average curve (Table 6). As mentioned previously, this provided deflection S.D. values relative to force on the characteristic average curve. The scaled force values did not directly coincide, however, with the force values comprising the characteristic average curve. Therefore, the S.D. in deflection was determined for each point on the average curve by interpolating the data in Table 6 according to the appropriate force and deflection values associated with each particular point. The calculated S.D. in force and deflection create a range of variation for each point on the average curve (refer back to Figure 11). Finally, the corridor was generated using the extreme variation values following the same procedure described in the Methods section for the arbitrary example. Figure 17 illustrates the corridor resulting from the experimental data set given in Figure 15.

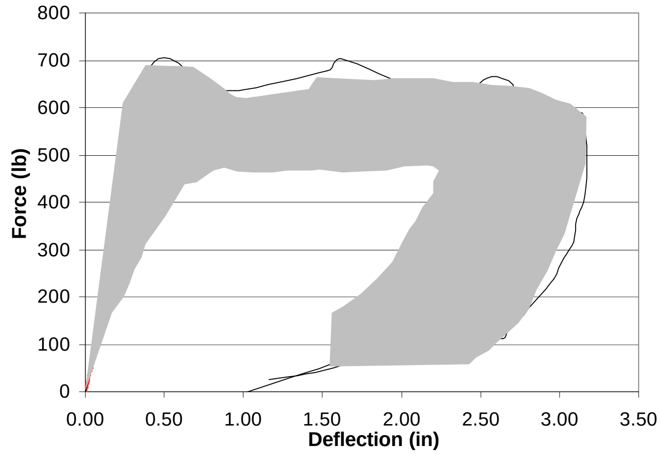

Figure 17: Experimental data corridor (shaded region), characteristic average, and raw curves.

DISCUSSION

The normalization technique for corridor development for force-deflection responses is an empirical approach that is both quantified and repeatable, and importantly can be performed by others. The results of the technique appear promising in that the developed corridors maintain correct shape characteristics while also bounding a one standard deviation range of variation associated with the set of individual responses.

This technique is best utilized when the response can be considered a structural response (such as force-deflection response) rather than a time response. This is an advantageous approach when dealing with tests that may result in velocity variations through the subject or where a corridor is to be constructed for some nominal velocity resulting from individual response data over a finite range of velocities. For these situations which present a challenge to a time-based solution, this technique provides a promising alternative to the "eyeball" approach. This approach also has advantages over creating a corridor by bounding the region between the minimum and maximum responses.

The shaded corridor region in Figure 14 is similar to that bounded by the raw curves. Therefore, for this arbitrary data set, simply bounding the region between the minimum and maximum responses would form a useful corridor. However, biomechanical data sets often contain "outliers". These are tests that exhibit a significant variation from the other responses in the data set. Often such outliers are excluded from the data set generating the corridor. However, in some situations it may be necessary to include such outliers or the associated influence of them in the corridor. Ideally, a representative corridor would include the influence of such outliers without being dominated by them, as would occur if the region between the minimum and maximum responses was defined to be the corridor.

Figure 18 illustrates an example data set. This set consists of the original three curves from the previous arbitrary example with the addition of one curve exhibiting substantially higher force and deflection magnitudes. This may be an exaggeration of what would be expected but is shown here to illustrate how the corridor includes the influence of such a test without simply enclosing the entire region bounded by the minimum and maximum response curves (Figure 19).

Referring to Figure 19, it is obvious that the corridor includes the influence of the outlier but it could also be argued that the corridor is being dominated by it. This is largely due to there being such a small number of curves (three) in the original data set. Thus, adding one substantially different curve has a large effect. However, the effect of any single curve on the corridor decreases as the number of curves within in the original set increases.

Figure 20 illustrates the effect of an outlier (the same outlier used in Figures 18 and 19) on the corridor if there are a substantial number of curves within a reasonably consistent range. Although minimum and maximum responses are the same as in Figure 19, the corridor is much tighter (since the effect of the outlier is less significant). Importantly, this ability to include the influence of an additional subject response is a desirable feature of this corridor development technique.

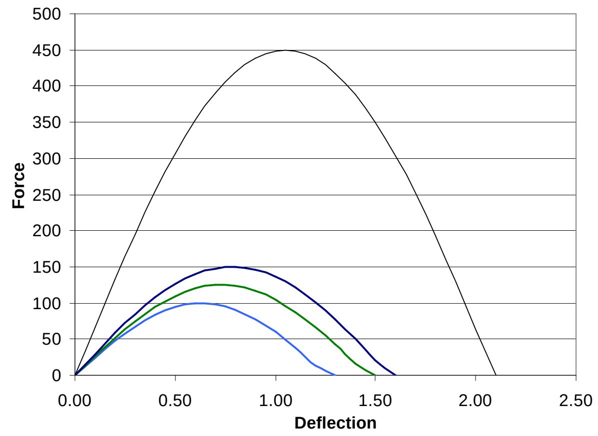

Figure 18: Arbitrary set of data curves including one that is substantially different from the others.

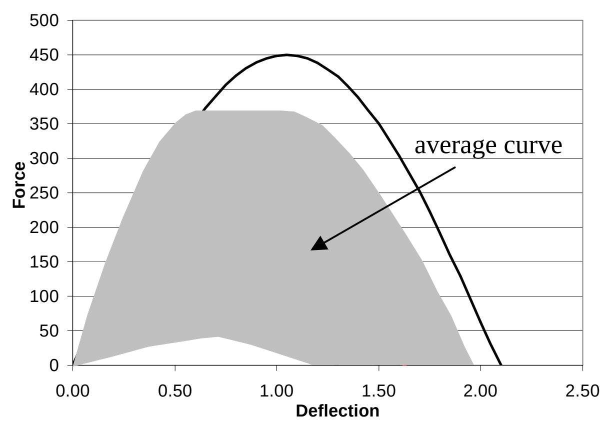

Figure 19: Data set from Figure 18 and associated corridor.

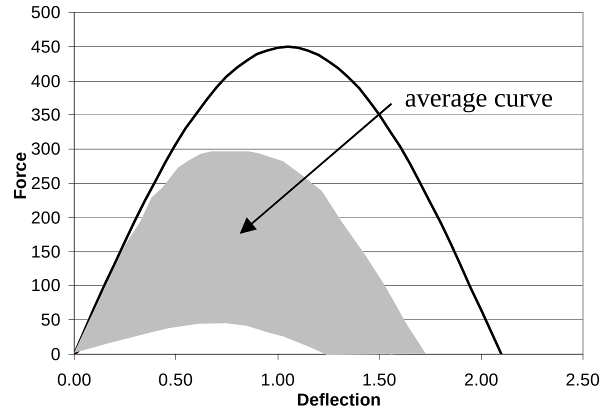

Figure 20: Data set and associated corridor. Note that the corridor is much tighter than that of Figure 19 even though the minimum and maximum responses are the same.

The details of the presented procedure for developing corridors using the normalization technique are specific to the examples illustrated in this paper. However, experimental data vary in complexity in terms of shape characteristics, and how these shapes are handled will in turn influence the complexity of this technique. Calculating the S.D. in deflection is typically the part of the process that can pose some difficultly due to the presence of multiple deflection values associated with each normalized force value. For example, the process was much more complex for the experimental example than for the arbitrary example. The plateau region associated with the experimental curves resulted in unrealistically large S.D. values for deflection over the middle part of the average curve (the plateau region) when the loading section was treated as one deflection segment. To eliminate the problem posed by the plateau, the deflection was broken into multiple deflection segments and a deflection S.D. was calculated for each segment resulting in multiple deflection S.D. values associated with each normalized force value. It should also be noted that there is a limit to the number of intervals that the curves can be broken into. Including too many will make the S.D. calculation artificially small since the S.D. upper limit will be prescribed by the size of the deflection interval. Therefore, there must be a balance between making the intervals large enough to retain the deflection variation associated with the data while remaining small enough to prevent a given segment's S.D. calculation from including deflection values from distinctively different regions of the curves (i.e. loading vs. unloading, initial rise vs. plateau, etc.).

Each set of experimental data will most likely present a unique set of challenges, but importantly, the specific details of how the technique is carried out will vary only slightly according to the shape and complexity of the data. Notably, the method still remains consistent with steps outlined in the method section of this paper.

Limitations and improvements

As with any type of corridor development technique there are limitations and improvements that could be made. While the results of this technique are promising for the types of examples shown, the technique has only been applied to a limited range of experimental data sets. Also, the probability of a given set of data falling within a developed corridor has not yet been determined. In addition, while this technique provides an objective approach, it does involve subjective judgment in its application.

Although the results appear reasonable for the arbitrary and experimental examples presented here, there may be situations where other techniques, such as those mentioned in the introduction, would be preferable. Currently, the normalization technique can only handle one significant shape characteristic. However, the technique could be refined to retain local maxima and minima or to retain multiple shape characteristics exhibiting phase differences relative to the peak deflection. Such modifications could broaden the range of application for this technique.

CONCLUSIONS

This technique provides a repeatable method for calculating a characteristic average response that retains proper shape characteristics. In addition, the technique provides the development of a representative corridor around this characteristic average response by utilizing standard deviations for both force and deflection, thereby retaining subject variance information. The normalization technique presented here is an empirical method to corridor development, and appears to be a promising alternative to an "eyeball average" for situations in which a time-based corridor development technique may not be an appropriate choice. However, the current technique may require further refinement in order to make it more useful over a broader range of applications.

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DISCUSSION

PAPER: **Normalization Technique for Developing Corridors from Individual Subject Responses**

PRESENTER: ***David Lessley, Automobile Safety Laboratory UVA***

QUESTION: *Barry Meyers, Duke University*

Thank you for the interesting paper. It's especially interesting because it doesn't have a right answer so we can argue about it for a long time. Preserving shape is very important in certain settings; for example, if I want to characterize the shape with a bunch of tibial plateaus. If I average them crudely, then I get a big blur...So in that setting, it's real important. On the hand, suppose I have very well behaved, non-failure force deflection data. So it goes up, and I average all my data of all my specimens before they break. So in other words, I go up to 0 when the first specimen breaks and I stop. In that respect, I haven't captured shape; but in fact, I have captured the mean response. It seems, then, in different settings, depending if I have complicated force deflection data like in the chest, I might want to preserve shape and in other settings, I really wouldn't even want to. What are your thoughts?

ANSWER: We--So far, we've only looked at a limited amount of test data with this technique; so obviously, this was an approach to try to generate an average response and create a corridor around it for a situation when you couldn't calculate one readily or when calculating one did indeed wash out some of the characteristics, in which case you would end up with a response that doesn’t resemble the individual responses. Something we're working on is looking at the range of application of this, and there are obviously situations--possibly the one you just suggested--where it's not the ideal approach.

Q: I think the interesting bit is that it's not so much that your technique will not look good; but that in fact, you don't necessarily need to impose it. And by imposing it, you ended up with capturing shape at the expense of capturing the average in which we're back to eye-balling which technique we want to use for corridors.

Q: Can I interject data? If you look at, sort of, force failure data, many times you have a sequence of failure points depending on what you're X axis is, displacement strain. So, you can get discontinuities in the corridor as you start to move the data. So you--Let's say you start with 5; one breaks; you're down to 4. You can get discontinuity. So, this technique will allow you--by the normalization technique--will allow you to handle those discontinuities. At least part of this would be advantageous to handle what you're describing.

A: Oh, I agree and that's why it's a caveat that says using just straight averages, you have to stop at the first specimen failure.

Q: Sure because you want to make corridors that'll get you toward a structural response and not necessarily all up to the average failure, that can often get you a long way there.

A: Sure, but I think you can take components of this and go even to failure response to get the normalization. You could merge the two even if you didn't want to use the extreme value of the corridor.

Q: Agreed. The hard part is going to be choosing limits.

A: Yes.

Q: Thank you. It was a great paper.

A: Thank you.

QUESTION: *Guy Nusholtz, Daimler/Chrysler*
In this case, you're trying to avoid the problem of having discontinuities in the corridors as a result of features of the signal occurring in time at different points in time, but you can also have a situation where you have features of a signal that occur at different points in space. And then by your technique, you would capture also these discontinuities, which you may not have if you trace it in terms of a time condition. So, you could actually create the problem you're trying to avoid by mapping into the displacement zone instead of the time zone. When you switch to much more complicated problems, you'll probably discover all of the issues associated with that. And once again, you're back to having to have a Lobdell eyeball to make the final decision.

A: Thank you. In response to that: Currently we're working--One of our statisticians is actually working on the timed response on that so it'll be interesting to see, to compare maybe, two variations with the same data and see if we can create situations that you described. That we would end up with one situation that's better and other situations that actually create some problems.

Q: Methods of capturing all of the necessary features in the signal are very difficult. I don't know if there's any actual solution. One may just be a little bit better, in general, than the other. In fact, displacement may be a better--Normalized displacement may be better than time, in general, but it probably won't capture all of it.

A: Sure. Sure. Thank you.

QUESTION: *Erik Takhounts, National Highway Traffic Safety Administration*
About a year ago or two maybe, Maltese, Smith and company introduced a paper, Stapp paper that defines, very nicely, from one viewpoint, the way of defining corridors and we come up with corridors for a particular function. And, I don't understand -- why do you feel compelled to go back and develop another method, especially for only well-behaved functions. Why--How does your method compare or better, if you will, to that of Maltese, Smith?

A: The first approach was just to eliminate time from the process, and this is essentially just a 2-D curve-fitting exercise where we're only looking at force and deflection. So, this goes back to just trying to fit an average response that otherwise would wash out. And, one thing I did look at with time-based is if you have any variation in speed through the subject, you can actually end up with your deflection values occurring over a range--You have an average deflection point on your average curve. Well, that could be averaged from several different places. One might be 20% deflection; another 40% and so on depending on variations of speed through the subject, just based on the subject variability. So, that's one thing that you avoid using this technique as opposed to a time-based technique.

Q: I'm not sure I understand, but thank you.

A: Thank you.

Q: *Matt Phillipine, TRW Automotive*
Thanks for the nice presentation. It's something we're struggling already for years to prepare if you want to compare dummy responses to develop corridors. The question came to my mind: Did you consider or evaluate the use of something like nisidase and split your signal in three phases and shape component and maybe corridor for that?

A: No, that's something we haven't looked at. This is definitely a work-in-progress, so there's a lot of things that we're keeping in mind and looking for as we move forward on this.

Q: It's just a question.

A: Okay. Thank you very much.