13

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Analysis of Current Biofidelity Corridor Construction as It Relates to Lateral Impacts

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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

Developing an effective side impact ATD for assessing vehicle impact responses requires a method for evaluating that ATD's bio-fidelity. ISO/TR9790 has been in existence for some years to serve that purpose. Recently, NHTSA sponsored a research project on the post-mortem human subjects (PMHS) responses subjected to side impact conditions. Based on those newly available PMHS data, Maltese generated a new approach for creating bio-fidelity corridors for human surrogates. The approach incorporates the time factor into the evaluation equation and automates the process (Maltese et al., 2002). This paper serves as the first attempt to look closely at the new bio-fidelity corridor generation process (hereafter referred as the Maltese approach) with respect to its validity, effectiveness, as well as its practicality. The effect of mass scaling was first examined in order to ensure the integrity of the data. The time alignment scheme and the formation of the corridors were then tested. The Maltese approach seems to represent the PMHS test responses. It appears to have some drawbacks due to the complexity of the PMHS responses. The approach works better for uni-modal responses but does not produce unique solutions for all sets of time histories. This study also shows that the Maltese approach has merit by taking the time shift into account. The new approach statistically evaluates side impact ATDs for a large portion of the time period and has a well defined numerical procedure that reduces some of the subjectivity seen in ISO/TR9790. Some possible modifications aimed at further simplifying the procedure, improving the efficiency of the approach, and eliminating the numerical problems are also studied and outlined in this paper.

INTRODUCTION

Side impact has been known to be a major cause of severe traffic injury and fatality. In search of better injury/fatality mitigation and prevention in a side impact event, a variety of side impact Anthropomorphic Testing Devices (ATDs), also known as side impact dummies (SIDs), have been developed for use in side impact crash simulation tests. To ensure that these ATDs can reproduce human-like responses in impacts, biomechanical corridors have been developed. If an ATD responds similarly to the data used to develop the corridors, it is considered bio-fidelic.

For years ISO/TR9790 corridors have been used to evaluate side impact dummies. Based on cadaver tests from researchers around the world, ISO/TR9790 includes a series of response corridors. The corridors are formed based on biomechanics experts' opinions of the PMHS test results and are drawn in forms from simple maximum-minimum limits to piecewise linear curves encompassing boundaries of the overlaid PMHS test data. ATDs are tested and their responses overlaid with ISO/TR9790 corridors. Scores of 0s, 5s and 10s are then assigned depending on the closeness/deviation of the ATD responses from such corridors. Clearly, the bio-fidelity quality of the corridors used to guide the dummy development and judge the dummy characteristics is critical when it comes to designing the dummy and enhancing the dummy's dynamic response characteristics. Over the last couple of years, more and more PMHS tests have been conducted by researchers from OEM's, research institutes, and government agencies. Powerful computational equipment has become more available. Many attempts have also been made to perfect the corridors. One of the basic tasks facing automotive biomechanics engineers in the process has been to subjectively and accurately evaluate dummy's bio-fidelity.

NHTSA sponsored various research in this area. More recently, Maltese et al. proposed a set of new dummy corridors based on these new PMHS test results. The proposed scheme to create the bio-corridors from PMHS test data combines typical scaling techniques and statistical tools with a computerized automated process. This paper evaluates the Maltese approach and compares it to the ISO/TR9790 procedures. In addition, analysis on different aspects of the corridor generation is presented.

MALTESE'S WORK AND THE MALTESE APPROACH

Toward that effort, 36 PMHS sled tests were run at the Medical College of Wisconsin and the NHTSA Vehicle Research Test Center (Pintar et al., 1997). Tests were conducted primarily at two velocities, 6.8m/s and 8.9m/s, and with a variety of configurations. Both flat and offset load plate conditions were used. Load plates with and without padding were also used in that study. The NHTSA sled force plate configuration was used. This configuration has a slightly different geometry from the Heidelberg sled or the WSU sled configuration (ISO/TR9790, 1997; Maltese et al., 2002).

The test data were first filtered according to SAE J211. They were then normalized to account for the PMHS mass differences using the technique developed by Eppinger (Eppinger et al., 1984). A time alignment scheme was developed and used in an attempt to address the "out-of-phase" issue typically seen in this type of test. The data were shifted according to a minimum variation method (Maltese et al., 2002). After the alignment, the corresponding means plus/minus one standard deviation formed the bio-fidelity corridors. In the following paragraph, the key characteristics of the numeric procedures in the Maltese approach are summarized. However, describing the Maltese approach in details is beyond the scope of this paper.

In the Maltese approach, various numeric procedures were applied in the signal alignment scheme. The time at which the signal last crosses a magnitude of 20% of the peak before the peak was defined as the characteristic time. Appendix A shows the flow chart of how the characteristic time was used in shifting individual signals as well as signals w.r.t. their means. The "minimum cumulative variance" defined as follows was used to align the signals.

$$V_{ab} = \sum_{t}^{t'} (a_i - b_i)^2$$

where

a_i is the magnitude of signal a at the i^{th} time step;

b_i is the magnitude of signal b at the i^{th} time step;

t is the greater of the start time of signal a and the start time of signal b;

t' is the lesser of the end time of signal a and the end time of signal b.

The start time and end time concept was explained in Maltese's paper (Maltese et al., 2002)

Maltese published the results in 2002 and updated the information in March of 2003 on the NHTSA website. The updated data from the website were used for this study.

CORRELATIONS

To ensure the signal integrity, an analysis was done on the trends in correlations of the signal response time history (accelerations, forces, and displacements) before and after mass scaling, with and without padding, for different test speeds and for different body regions. The mathematical tool used for this correlation study is similar to the one used to evaluate dummy repeatability and reproducibility (Lan Xu et al., 2000). In general, three descriptors are used. The magnitude represents the total power in the signal, the shape represents the geometric characteristics and the phase represents the differences in time between the centroids of the signals (Appendix B). They were used to measure the coherence of signals obtained from ATDs' transducers.

In Maltese's study, eight different test configurations were used:

RHF – **R**igid **H**igh-speed **F**lat wall (8 tests)

PHF – **P**added **H**igh-speed **F**lat wall (8 tests)

RLF – **R**igid **L**ow-speed **F**lat wall (6 tests)

PLF – **P**added **L**ow-speed **F**lat wall (5 tests)

RLT – **R**igid **L**ow-speed **T**horax offset (2 tests)

RLA – **R**igid **L**ow-speed **A**bdominal offset (3 tests)

RLP – **R**igid **L**ow-speed **P**elvis offset (3 tests)

PLP – **P**added **L**ow-speed **P**elvis offset (2 tests)

Some categories had limited number of tests. For instance, only 4 out of 8 test conditions had 5 or more tests (RHF, PHF, RLF and PLF). The analysis required a minimum of 5 signals in the test conditions studied.

Effect of mass scaling on correlations

The mass scaling technique by Eppinger was used in Maltese's process. Since the pre-processed data were not readily available, the "original" data were created from the scaled data based on the same scaling principle. In other words, the data were un-scaled using a reversed scaling formula as follows:

$$\textbf{Velocity:}\quad V_i = V_s$$

$$\textbf{Acceleration:}\quad A_i = \lambda_m^{1/3} A_s$$

$$\textbf{Deflection:}\quad D_i = \lambda_m^{-1/3} D_s$$

$$\textbf{Time:}\quad T_i = \lambda_m^{-1/3} T_s$$

$$\textbf{Force:}\quad F_i = \lambda_m^{-2/3} F_s$$

Where **s** is the subscript for scaled data, **i** is the subscript for i-th test subject and:

$$\lambda_{m_i} = \frac{75}{m}$$

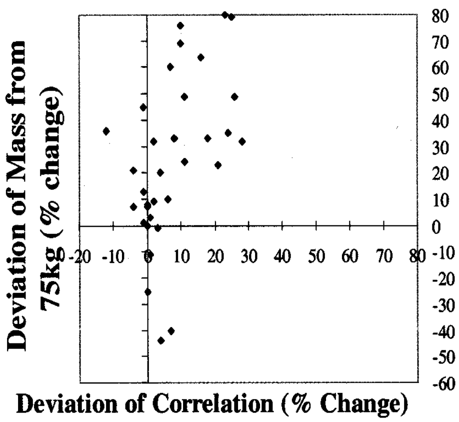
After the un-scaling, the study of correlation was performed on both scaled and "original" un-scaled data. The comparison was made from the results.

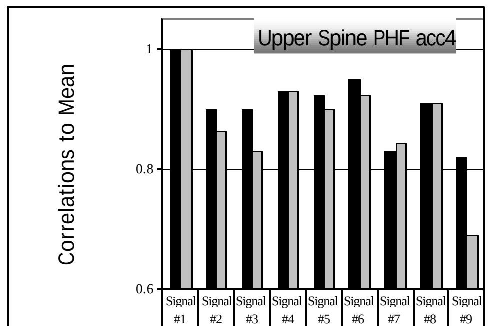
Figure 1 shows the correlation study results for the upper spine accelerations for the test condition of Rigid High speed Flat surface (RHF) after the signals were mass-scaled back to the original signals. The horizontal axis represents the percentage change in the magnitude correlations before and after the mass scaling,

(Corr $_{before}$-Corr $_{after}$) / Corr $_{after}$ X 100% .

The vertical axis represents the percent difference of the mass away from 75kg for each data point (test),

Mass / 75 kg X 100% .





	Signal #1	Signal #2	Signal #3	Signal #4	Signal #5	Signal #6	Signal #7	Signal #8	Signal #9
Mass-Scaled Data (Maltese)	1	0.9	0.9	0.93	0.92	0.95	0.83	0.91	0.82
Scaled Back(unscaling)	1	0.86	0.83	0.93	0.9	0.92	0.84	0.91	0.69

Figure 1: Relation between deviation of correction and deviation of mass from 75kg.

Figure 2: Correlation to means of mass-scaled Vs. non-scaled signals.

Hence, the closer the points lie toward the vertical axis, the less effect the mass difference has on the correlations. Since most points are seen to be within the top right quadrant near the vertical axis, it is believed that the correlations are not affected significantly by the mass differences. This is typical of the cases studied in this paper. Nevertheless, the graph does show more or less that the further the mass is away from the standard mass (75 kg), the more the correlations deteriorate. Assuming that the mass scaling is relevant, the results with similar masses should correlate to each other better. The mass scaling is seen to improve the correlations of the signals by a small amount compared to the non-scaled data. However, although the mass scaling appears to have some effect, it is not very significant.

In Figure 2, the correlations from the scaled acceleration data were compared to the non-scaled (scaled back) data in a group, in this case, the upper spine PHF acc4 signals. Signal #1 represents the mathematical mean of the signals in the group. The correlations of each signal (Signals #2 – #9) to their mean are shown for both scaled and non-scaled data. In general, the mass scaling is shown to improve the correlations (6 out of 8 cases). In those cases, mass scaling reduces the differences of the peaks. It puts signals from different masses more in phase with each other. Similar trends were observed in the effect of time scaling on correlations. Once again, the improvement is not very significant. This is partially due to limited capability of the mass scaling process in preserving the momentum. It could also be because it is based on a single degree of freedom model. Some other studies nevertheless have shown that the mass scaling is important where it has shown to improve the quality of the normalization of tests.

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Correlations for a given body region

For each corridor generated by the Maltese method a set of signals were used. Each signal represented a time history for a given body region for a similar test. To study the variability of these signals both correlations between the signals themselves and their means were examined. Correlations to means within the sets (scatter) are used to examine how well the mean represents the group. Only the magnitude correlations between signals from different body regions under three different test conditions are shown in Appendix C. Also shown are the averages of magnitude correlations for each group. The empty fields in the table were either due to the absence of data or the results of datasets that were not statistically meaningful. As mentioned previously, correlations were done only on those datasets with at least 5 signals (PHF/PLF/RHF/RLF groups).

In general, force signals yield the best correlations and acceleration signals yield the worst. One contributing factor to the improved correlations in the force signals could be its lower noise level. The displacement correlations appear better than those of the accelerations. This could also be, in part, the result of lower noise. PHF forces have the best average correlations to the means. The force and deflection groups have a minimum of .95 average correlation ratio to the means while the acceleration groups have a lower ratio of 0.84.

This study shows that the scaling has some impact on the magnitude correlations and significant impact on the shape correlations as well as on the phase correlations (results not shown here). However, no clear indication is observed that the correlation results are different for the padded plate groups vs. for the non-padded groups. No clear indication is observed that correlation results are affected by impact speeds either.

TIME SHIFTING SCHEME

Synthetic approach

ISO/TR9790 and the Maltese approach use different time alignment schemes. To gain a better insight as to how shifting scheme affects the signal correlations, a time alignment/shifting scheme evaluation process with generic/synthetic input was exercised. A selection of signals having similar and dissimilar momentum were created and processed using various alignment schemes including peak alignment, time zero alignment, phase (duration) alignment, maximum correlation alignment and the method used by Maltese. Several sets of half sine waves with 8-12 signals in each group having a frequency range of 20-99 Hz were chosen. Results from three of those alignment schemes are shown, aligning at time 0, at peaks and at 20% of peaks (Figures 3 a, b and c). All signals in these cases have the same momentum (integral).

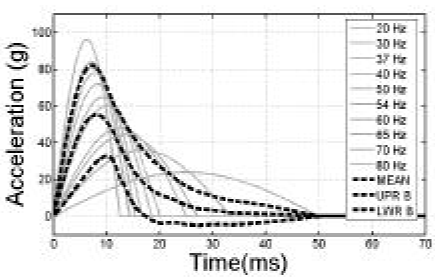


Figure 3a: Generic signals aligned at time zero.

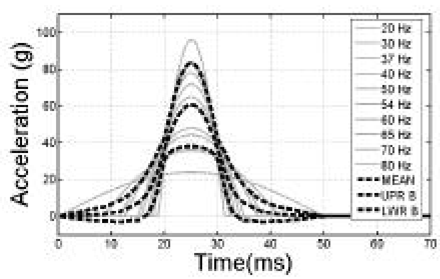


Figure 3b: Generic signals aligned at peaks.

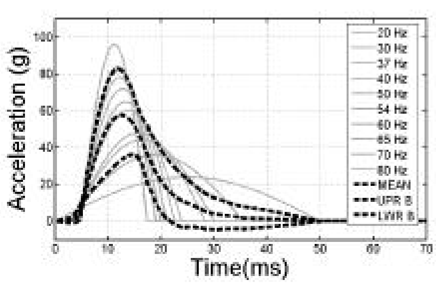


Figure 3c: Generic signals aligned at 20% of peaks.

In the case shown here, the signals consisted of frequencies ranging from 20 to 80Hz with variable intervals of between 5 to 10Hz. The signals were aligned using the three techniques described. The resultant correlations (variations) between each signal to the group mean are shown in Figure 4.

The results represent the typical trends seen in the study. Similar analyses were done on different frequency contents. The analysis produced similar results. Thus, the conclusions are seen not to be dependent on the signals chosen.

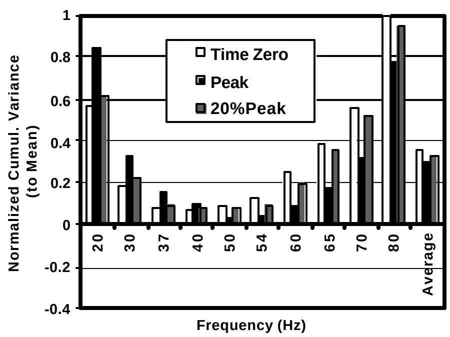


Figure 4: Comparison of variance of each signal to the group mean when aligned at time zero, peaks, and 20% of peaks.

In all cases, Method #1 (alignment at time zero) produces the best individual signal-to-mean correlations for low frequency signals with the correlations deteriorating for higher frequency signals, whereas Method #2 (alignment at signal peaks) produces the best individual signal to mean correlations for high frequency signals with the correlations deteriorating for lower frequency signals. General observations are that the peak alignment scheme seems to preserve the symmetrical shapes of the original signals while both 20% peak and time zero alignments yield to asymmetrical means and corridors. There seems to be no one consistently "better" alignment scheme.

To further study the robustness of various alignment scheme processes, some arbitrary signals were constructed. These signals are based on the stylized version of crash dummy signals from past experiences. An example is shown in Figures 5 a-d.

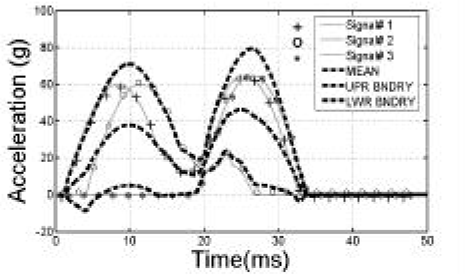


Figure 5a: Signals before time shifting

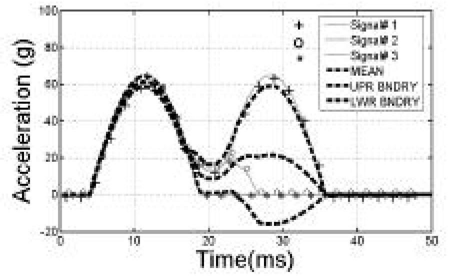


Figure 5b: Artificial signals aligned at 20% of Peaks.

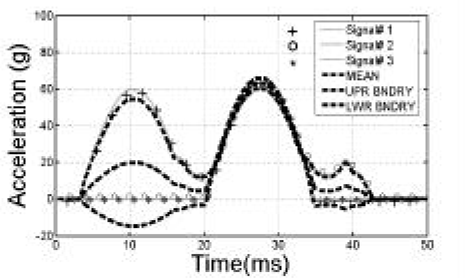


Figure 5c: Artificial signals aligned at signal peaks.

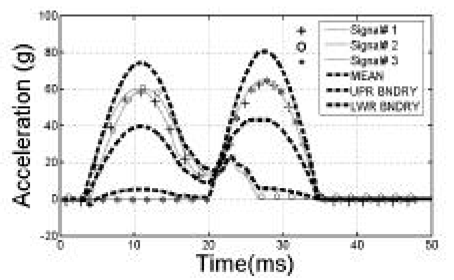


Figure 5d: Artificial signals aligned using Maltese approach.

As can be seen, the final corresponding corridors generated differ significantly from one another. This raises the issue that corridors are dependent on the alignment scheme. The complexity of real crashes may result in different corridors with different alignment schemes.

Real world signal time alignment

To complement the study of synthetic signals, signals from the NHTSA website were exercised to further gain understanding of the alignment schemes with actual crash data.

Figure 6 shows one set of the corridors arrived at by Maltese. The mathematical mean and its plus/minus one standard deviation corridors are shown as the thick dark lines. In the Maltese approach, the concepts of "standard signal" and "characteristic time" are defined. The average of "characteristic time" is aligned with the characteristic time of the mean of the signals based on the criterion of "minimum variance".

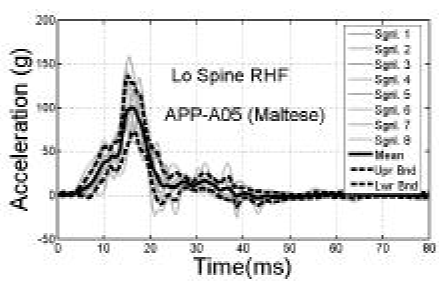


Figure 6: Bio-corridors using the Maltese Approach

Based on our understanding of the algorithm used for the corridor formation, we applied the Maltese approach and tested the robustness of the alignment scheme. As an example, the results from one set of signals are presented here.

The RHF data sets from Appendix A2 of Maltese's paper were used. A random shift of 0-20ms in the starting time was applied to the signals to simulate before-shifting signals (Figure 7). The standard curve as defined by Maltese (assumed to be the first curve) was maintained in all cases except in case 5.

Table 1 lists the results from this exercise. The corresponding corridor set from Figure A2 of Maltese's paper used in the study is also attached for reference (Appendix D). In cases 1-4, the standard curve as defined in Maltese's paper was maintained. In cases 1and 2, all the curves were moved forward or backward by a range from -10 to 10 milliseconds randomly to simulate the pre-alignment data. In cases 3-5, shifted data from the NHTSA site were used. However, in case 4, signals were swapped randomly or, reordered. In case 5, a different standard curve was chosen (the second curve in this case). The criterion used to measure the coherence of the alignment (correlations) is the cumulated variances of the signals to their means. Each row in Table 1 represents variances between the signals to the group means.

Table 1. Variance calculation results using dataset from Appendix A2 RHF with channels swapped (Maltese et al., 2002).

Signal #	Case 1		Case 2		Case 3		Case 4		Case 5	
	Before Alignment	Maltese Approach	Before Alignment	Maltese Approach	Before Alignment	Maltese Approach	Before Alignment	Maltese Approach	Before Alignment	Maltese Approach
1	69.60	31.90	43.20	25.89	23.05	22.71	23.05	22.71	14.96	14.75
2	34.70	17.60	22.40	17.09	14.96	15.03	17.74	18.24	17.74	17.80
3	23.20	15.10	9.00	18.70	17.74	18.24	10.41	10.68	13.65	12.65
4	11.10	10.40	3.90	12.49	13.65	14.12	20.82	21.23	13.06	12.13
5	54.10	14.10	24.15	13.30	13.06	13.59	25.25	24.15	25.25	23.83
6	53.90	27.10	38.42	24.98	25.25	24.15	13.06	13.59	20.82	17.54
7	41.80	23.20	23.82	19.47	20.82	21.23	13.65	14.12	10.41	10.13
8	49.40	11.80	14.90	12.06	10.40	10.68	14.96	15.03	23.05	22.57
Sum of Variances	337.70	151.20	179.83	143.96	138.93	139.75	138.93	139.75	138.93	131.41

(X 10^6)

Case 1 Random time shift (-10ms~+10ms) but maintain the standard signal curve
Case 2 Random time shift (-10ms~+10ms) but maintain the standard signal curve
Case 3 Maintain the standard signal curve (data directly from NHTSA website)
Case 4 Maintain the standard signal curve, but swap the order of the rest of signals
Case 5 Swap the order of the signals

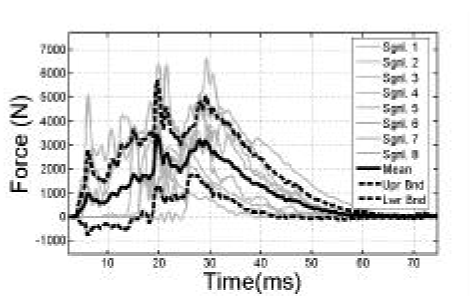


Figure 7: Signals and the corridor before time shifting.

The minimum variance scheme in the Maltese approach worked without any problem when the standard curve as defined was maintained. This was independent of how the secondary curves were swapped or shifted. The optimized variance was achieved. Figures 8 and 9 show the obtained corridors and the corresponding overlay of their means before and after the alignment.

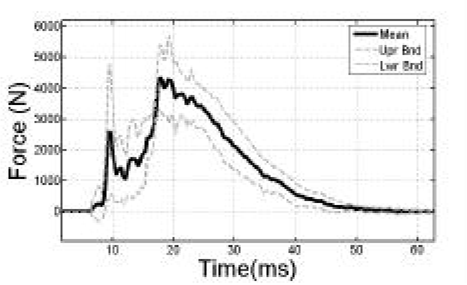


Figure 8: Corridors with signals aligned using the Maltese approach (20% peak criterion for integration duration).

The results indicate that the Maltese approach worked well - the minimum variance was achieved. Specifically, if the approach works, no further shifting should occur in case 3 and the sum of the variances from the shifted signals should remain unchanged. The swapping of non-standard signals did not lead to different means or corridors in case 4. However, in case 5, the change of the standard curve resulted in a better sum of variances and a new corridor with smaller variances (better correlations). This indicates that the choice of the standard curve is critical - the corridors are not unique for a given set of signals. The approach could then result in arbitrary corridors depending on the choice of the st andard curve. More of these types of exercises seem necessary in order to gain better understanding of the issue.

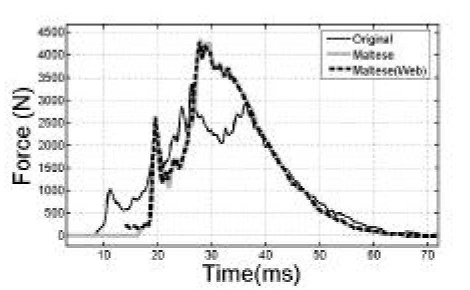


Figure 9: Overlay of the corridor means before and after shifting. And that from NHTSA website.

It should be pointed out that in Figure 8 there is a negative portion of the corridor despite the fact that there are no actual negative signal traces in that same time period - the method produces characteristic corridors that are non-representative of the input signals. This appears to be the result of assuming normal distribution of the data, when it may not be appropriate.

A variation of the Maltese approach, i.e., using 0%, 10% and 30% of the peaks in stead of 20%, as the start and end time criterion was tried. Some of the res ults along with overlays are shown in Figures 10, 11, 12 and 13. Another variation by using the complete signal durations instead of 20% start/end times for the variance calculation was also tried with the intention of studying the impact of integration duration on the corridor generation (Figures 8, 14 and 15). The manual alignment of signals to time zero by “eyeballing” technique similar to the one used for ISO/TR9790 was also tried and the corridors created (Figures 16 and 17).

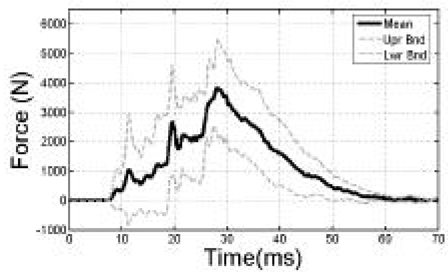


Figure 10: Corridor with signals aligned using Maltese approach (0% peaks).

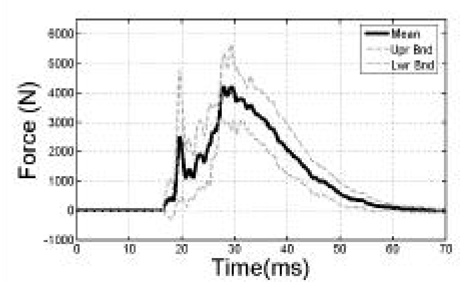


Figure 11: Corridor with signals aligned using Maltese approach (10% peaks).

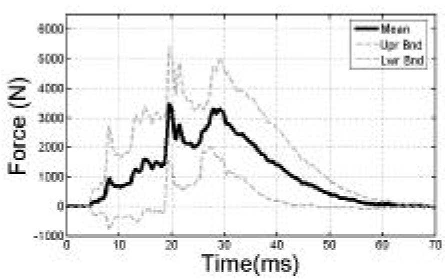


Figure 12: Corridor with signals aligned using Maltese approach (20% peaks).

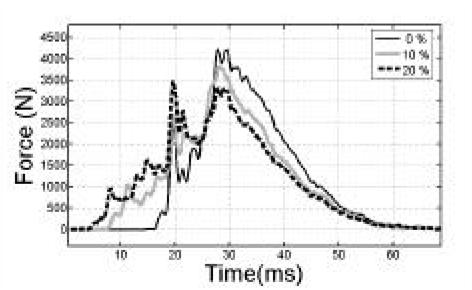


Figure 13. Overlay of corridor means with signals aligned with 0%, 10%, and 20% of peaks.

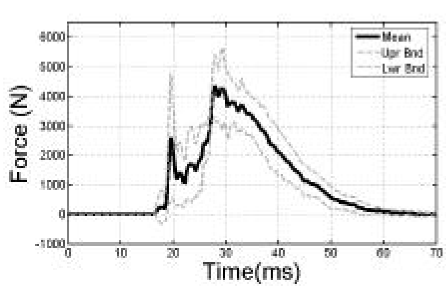


Figure 14: Corridor with signals aligned using the Maltese approach (20% of peak start/end time) and integration over the entire time duration.

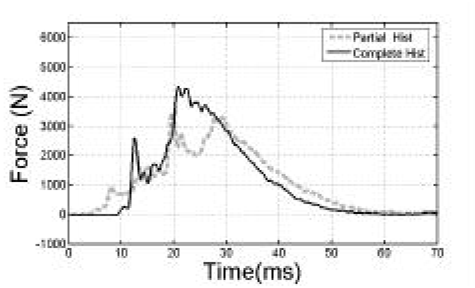


Figure 15a: Overlay of corridor means using Integrations with partial and complete time histories.

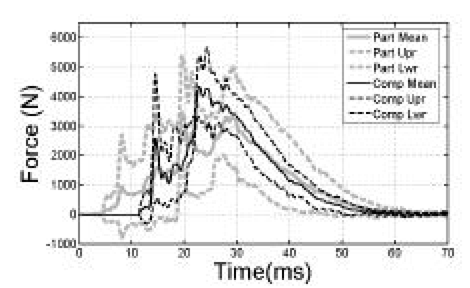


Figure 15b: Overlay of corridors using integrations with partial and complete time histories.

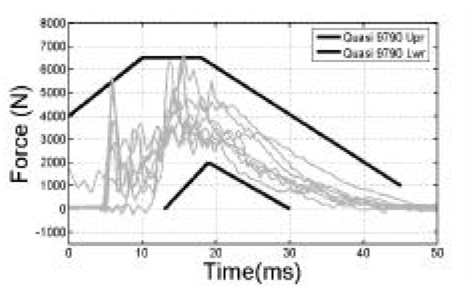


Figure 16: Corridor using ISO/TR9790 technique.

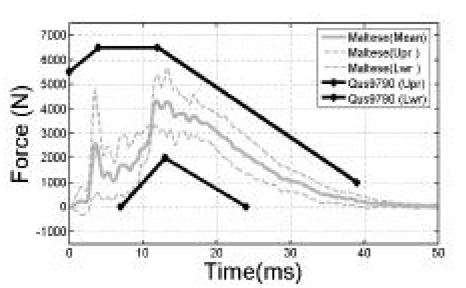


Figure 17: Overlay of corridors from Maltese Approach and Quasi ISO/TR9790.

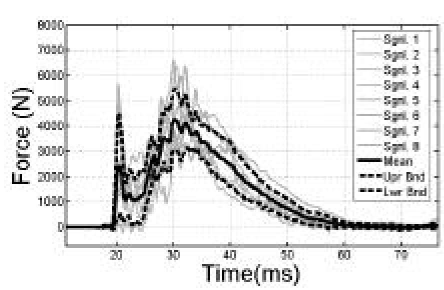


Figure 18: Corridor created with Signal #3 as the standard curve using Maltese approach.

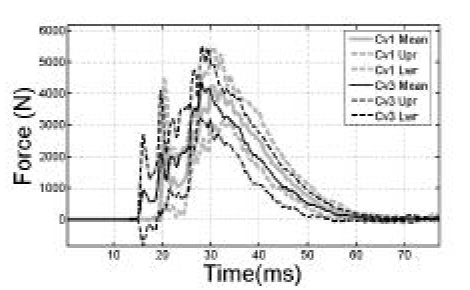


Figure 19: Overlay of corridors using different standard curves.

DISCUSSION

Standard signal

It does not appear that there is a well defined time alignment scheme out there for the PMHS transducer time histories that can be used without producing some form of artifact. Although in our study the alignment scheme from the Maltese approach often came out to be among the best in terms of signal to signal correlations, inconsistencies have been noticed in the exercises. The main reasons are believed to be the issues with the selection of the standard curve, the start/end time definition and the unique characteristics of cadaver data.

The choice of the standard curve is subjective and was seen to affect the corridors. Choosing a standard curve which has "the most typical shape of all signals" can be a challenge and its procedure is not well defined. Since the selection of a standard curve could differ from person to person, objective selection of the standard curve is not guaranteed and its impact is sometimes hard to predict. The standard curve is used as the controlling curve to be evaluated against. Changing the standard curve leads to a change of the baseline and thus of the resulting corridors. So long as the signals to be worked on are similar in shapes and magnitudes, this is not going to be a big issue. Nevertheless, PMHS data are rarely seen to be in this category. There could be cases where different corridors would be generated with the very same group of signals with the Maltese approach, depending on which standard curve is selected (Figures 18 and 19). Appendix F shows different bio-corridors created with different signal in the group as the standard curve.

Start/end time

The definition of "start/end time" could be another issue when dealing with groups of dissimilar signals. The start/end times in the Maltese approach are used to determine the range of evaluation time spans. It was noticed that, when the span as defined in Maltese's paper is used, the compounding factor of changing both the start/end times and integration (summation) duration affects the calculation results. Two variables involved here are the timing and the total data points. The maximum/minimum start/end times of the two curves can flip if they are initially near each other. The concept of the start and end times introduces additional variables into the formula: with every integration step advance, the integration spans which are used to calculate the sum of variances are also changed. To prove this, a case was tried in which the time history of the signals was not truncated (0% of peak) as opposed to in the 10% and 20% peak force cases. The effect of the constantly changing duration in Maltese's approach was studied. Shown in Figures 10-12 are different corridors created with the very same set of data.[1] The corridors created with different start/end time definitions are visibly different (Figure 13). It was also noticed that the choice of the start and end times of 20/80% peaks would not always lead to the optimal results, such as in cases where spikes or noise result in a short pulse crossing the 20/80% thresholds.

The use of one third of the total "duration" for the purpose of alignment check could also be an issue for certain signals, when coupled with the use of 20/80% lesser or greater start/end time scheme. It has been seen to lead to problems such as too short of a duration was used in the variance calculation.

Signal characteristics

It has been noticed that the above-mentioned inconsistencies may or may not happen and the differences were sometimes insignificant but at other times drastic. For instance, signals that are bimodal produced drastically different corridors in the study. One reason is that they have multiple "20% peak" points. In addition, signals with the majority of the energy in the form of low magnitude/long duration along with a sharp rise to peak also produced drastically different corridors, depending on how the parameters are chosen. The complexity of crash data can thus cause inconsistent corridors for some signal traces.

Acceleration signals

In the Maltese approach, the acceleration data would be first integrated before the alignment. The start/end times are determined in the subsequent step. Maltese suggests using 20% and 80% of peaks of the

[1] For practical purpose, 0.1% is used for the 0% case.

integrated signals to define the start and end times for acceleration signals. This could be an issue for some types of signals with special characteristics. For example, in a triangular pulse, this results in a situation where only 40% (18 out of 50 ms) of the time history is used for the variance calculation as vs. 80% (40ms out of 50ms) for the force and velocity signals (Figure 20).

Other Issues

It was also noticed in this study that the approach could create unrealistically narrow corridor sections in cases where the standard deviation is near zero. This is the results of incidental near-intersections of many signals at given times (38 ms, Figure 21). These corridors become unrealistic.

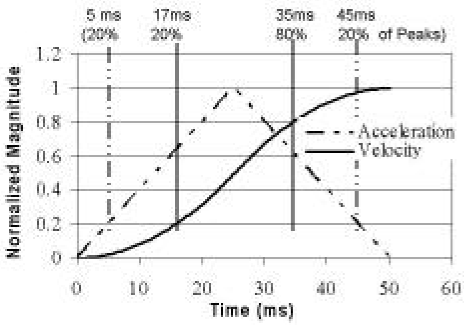
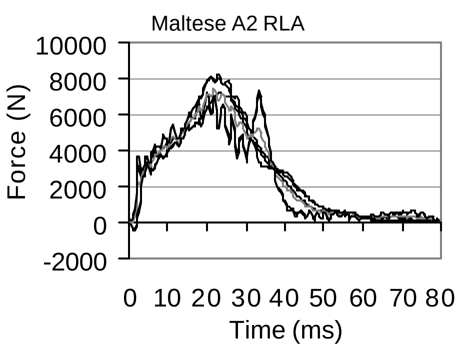


Figure 20: Only 40% of the time history is used for the variance calculation in a triangular pulse.



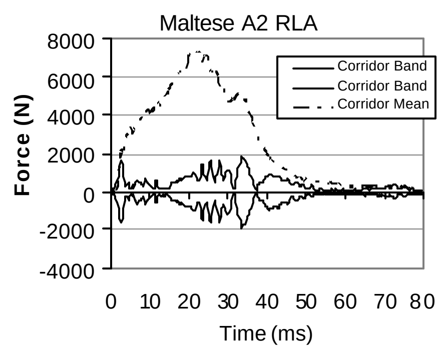


Figure 21a: Narrow corridor issue resulting from incidental intersection of signals in time history.

Figure 21b: Narrow corridor resulting from incidental intersection of signals in time history.

Maltese approach and ISO9790

In comparison to other approaches in the tested cases, the results from the manual alignment (quasi ISO 9790 alignment) were inferior in terms of correlations of the signals to their means. The corridors generated using that approach typically are broader and over simplified. Some qualitative comparisons of Maltese scheme to ISO/TR9790 are:

	Maltese	9790
Alignment Algorithm	peak	time zero
Negative corridor yes	no	
Narrow Corridor Issue	yes	no
Subjectivity	less	yes

ISO/TR9790 typically aligns data using the natural event onsets from the tests. This seems to preserve the original timing. The most significant improvement seen in the Maltese approach is its objectivity and reduced requirement on human judgment in the evaluation process. In addition, it also incorporates more recent data and broader spectrum of testing environments. For the Maltese approach to be used as the ISO/TR9790 replacement, more corridors, in addition to those currently available, are needed to form a complete library similar to those of ISO/TR9790. As mentioned previously, the Maltese alignment scheme could have problems when the signals are drastically different from each other and where the momentum (areas under the curve) is not constant. The Maltese approach is generally more systematic and objective in comparison to ISO/TR9790's piece-wise linear and localized approach.

SUGGESTIONS FOR IMPROVEMENTS

Some modifications to the Maltese approach were tested. They were aimed at further simplifying the procedure, improving the efficiency of the approach and eliminating the numerical problems without reduction in its quality.

Cross-Correlation Approach

The underlying algorithm for the Maltese approach is the statistical correlations between signals. If the corridors can be generated through common correlation tools, the method can be simplified. The corridors obtained by aligning the signals using cross-correlation tools were compared to those from the Maltese approach. The corridors were relatively easy to generate. Only small differences in time shifting were observed. Figure 22 shows the time shifting differences between those from the cross-correlation approach vs. those from the Maltese approach in a case studied. The differences are shown as positive when the cross-correlation method required more time shifting than the Maltese approach. Only a 0.6 millisecond additional time shift for two signals was required in this case.

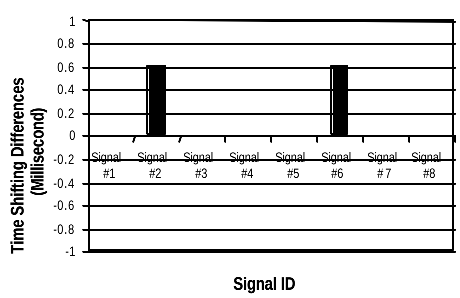


Figure 22: The time shifting differences using Cross correlation approach vs. the Maltese approach.

Averaging Approach

Maltese et al. suggest using a signal that appears to have the most typical shape of all signals as the standard curve. This injects into the approach undesirable subjectivity, weakening the strong point of this numeric procedure. The subjectivity caused by the standard signal selection as discussed in the previous section could in reality be eliminated by rerunning the corridor generation scheme with each one of the signals as the standard signal.

Eight sets of corridors were generated using each one of the signals in that eight-signal group as the standard signal. With these eight corridor means, the cross-correlation was checked and the means as well as upper and lower boundaries were shifted accordingly. The averages of the means, upper boundaries and the lower boundaries were then calculated to form the final corridor. The corridors generated with each one of the curves in the group as the standard curve are shown in Appendix F. Figure 23 shows the resulted corridor means created using each of eight signals in the group as the standard curve. Figure 24 shows the overlay of the final corridor and the one derived by Maltese. The corridor generated from the averaging approach is similar to Maltese's in this case. It has a smoother shape as compared to Maltese's and it eliminates the narrow corridor issue at 23-24 ms time frame (Figure 25).

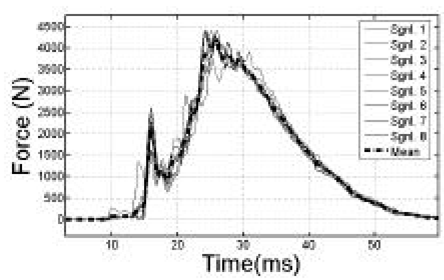


Figure 23: Corridor means with each curve in the group as standard curve.

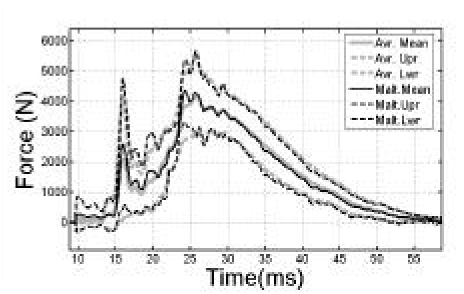


Figure 24. Overlay of corridors using averaging approach vs. Maltese's approach

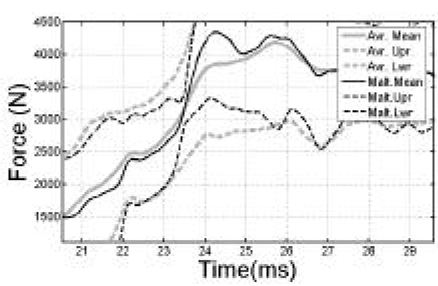


Figure 25: Overlay of corridors using averaging approach vs. Maltese's approach.

OBSERVATIONS

It may be more desirable to incorporate the complete time history in the variance calculation. This way, the corridors might be more representative and further improved. When limited tests are available, corridors formed using a weighted combination of standard deviations and 20% of means might be more realistic. Questions such as whether one should base corridors on mass scaling, or just use only those of the cadavers having a mass close to 50%-ile, or more weight be given to near 50%-ile PMHS data than to the others, remain to be answered.

Shifting has been seen to have a significant impact on shaping the bio-fidelity corridors. One should exercise caution not to disguise the variability of signals in the process of aligning signals. In the PMHS tests, the variances between signals are quite high, indicating that PMHS test data are technically always "bad" data in a statistical point of view. It could also be the nature of cadaver data. There are situations where the variations in signals are truly the characteristics of the data, not artifacts. The natural misalignments could be part of signal characteristics. It is not clear if the minimum variation alignment scheme best represents the characteristics of the PMHS signals.

CONCLUSIONS

The corridor generation scheme by Maltese seems to be logical through the inclusion of time histories, alignment scheme and statistical averaging. It statistically evaluates signals for a reasonably large portion of the time period and has a well-defined numerical procedure. It reduces some of the subjectivities seen in the ISO/TR9790 procedures and is less arbitrary. The approach has nevertheless a few limitations. It works better with signals of relatively smaller variance or uni-modal responses than it does for multimodal responses. The corridor generation procedure works well for some sets of signals but does not produce unique solutions for all sets of time histories.

More work seems necessary to ensure that the corridors attainable from the Maltese approach represent the underlying PMHS biomechanics. Whether the procedure can successfully replace ISO/TR9790, remains to be seen. In its current state it requires some changes to the numerical procedures before it should be used. However, it has the potential to address important biomechanics issues which cannot be addressed by ISO/TR9790 and may become a good tool in the future in forming statistically meaningful biofidelity corridors.

ACKNOWLEGMENTS

The authors wish to express their appreciation to Matthew Maltese for providing many valuable insights and assistance.

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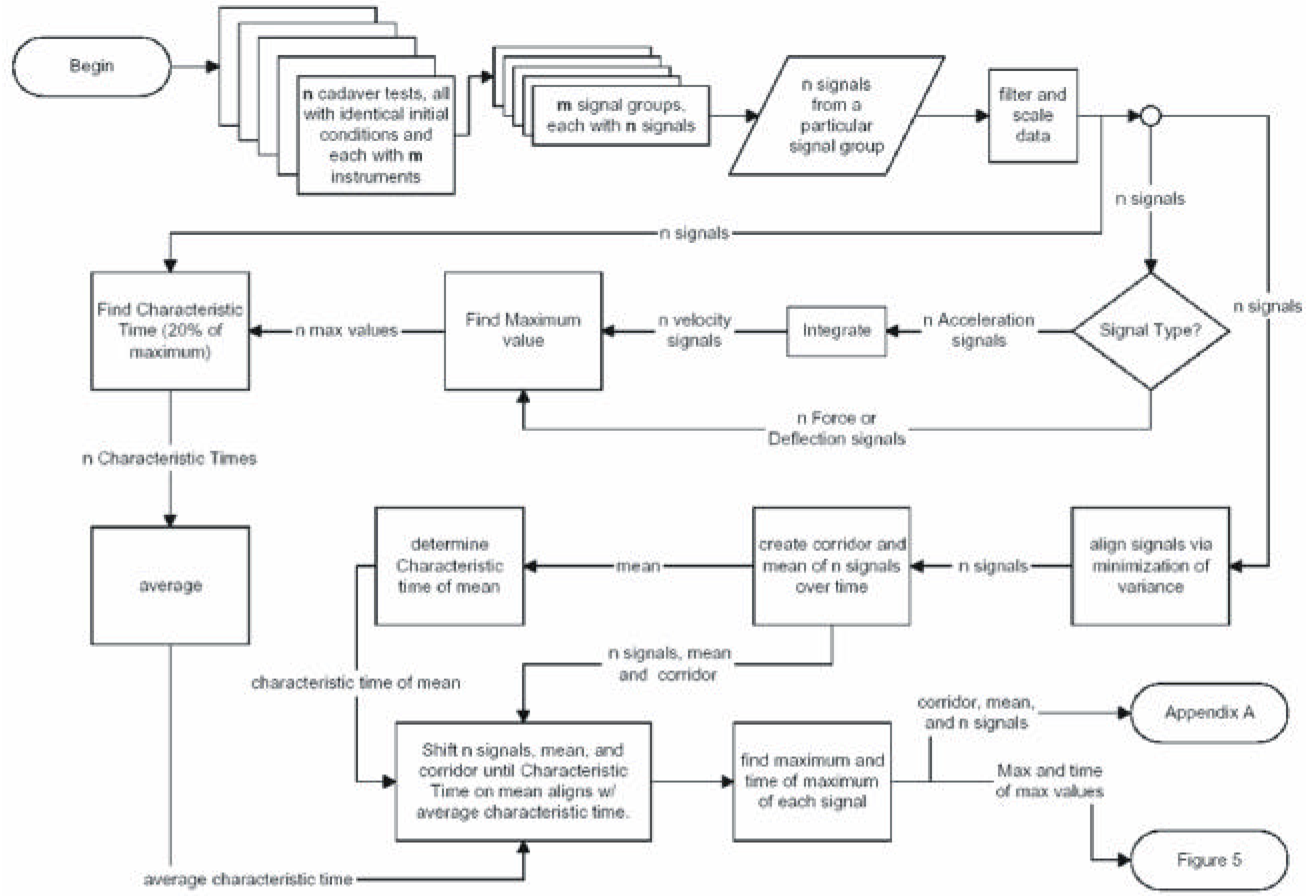
APPENDIX A. FLOW CHART OF PROCESS FOR CALCULATING CORRIDORS FROM TEST DATA (FIGURE 4) (MALTESE ET AL., 2002)



APPENDIX B. MATHEMATICAL TOOL FOR THE CORRELATION STUDY (XU ET AL., 2000)

Appendix A: Basis for the Similarity Analysis

The definition of the similarity between the two signals is presented in this section. The similarity is represented in terms of magnitude, shape, and phase respectively.

Definition 1:,The Magnitude of a signal $x(t)$ is its norm:

$$\|x\| = \int_{-\infty}^{\infty} x^2(t)dt$$

Definition 2: The coefficient for the magnitude similarity between the two signals, x(t) and y(t) is

$$\frac{\|x\|}{\|y\|}$$

They have an identical magnitude if,

$$\frac{\|x\|}{\|y\|} = 1.$$

Definition 3: The coefficient for the shape similarity between the two signals, $x(t)$ and $y(t)$, is, $p(x,y,0)$. where the function $p(x,y,h)$ is defined as,

$$p(x,y,h) = \frac{\int_{-\infty}^{\infty} x(t)y(t+h)dt}{\sqrt{\int_{-\infty}^{\infty} x^2(t)dt \int_{-\infty}^{\infty} y^2(t)dt}}$$

Furthermore, two signals have an identical shape, if

$$p(x,y,0)=1.$$

Lemma: Two signals, $x(t)$ and y(t), have an identical shape if and only if $y(t)=ax(t)$, where a is a positive constant.

Proof: part 1, if $y(t)=ax(t)$, and a>0, then,

$p(x,y,0)=1$.

$$p(x,y,0) = \frac{\int_{-\infty}^{\infty} x(t)y(t+0)dt}{\sqrt{\int_{-\infty}^{\infty} x^2(t)dt \int_{-\infty}^{\infty} y^2(t)dt}}$$

$$= \frac{\int_{-\infty}^{\infty} ax(t)x(t)dt}{\sqrt{\int_{-\infty}^{\infty} x^2(t)dt \int_{-\infty}^{\infty} a^2x^2(t)dt}} = sign(a) = 1$$

Part 2, if $p(x,y,0)=1$, then $y(t)=ax(t)$.

First, it is true for the normalized signals. Define

$$f(x,y,h) = \int_{-\infty}^{\infty} x(t)y(t+h)dt.$$

Then, $f(x,x,0)=f(y,y,0)=1$

For normalized signals, $f(x,y,0)=p(x,y,0)=1$

$f(x-y,x-y,h)=f(x,x,h)-f(x,y,h)-f(y,x,h)+f(y,y,h)$

$=f(x,x,h)-f(x,y,h)-f(x,y,-h)+f(y,y,h)$

$f(x-y,x-y,0)=f(x,x,0)-f(x,y,0)-f(x,y,-0)+f(y,y,0)$

$=2-2f(x,y,0)=0$

on the other hand,

$$f(x-y,x-y,0) = \int_{-\infty}^{\infty} (x(t)-y(t))^2 dt$$

which can only be true if, $x(t)-y(t)=0$, that is $x(t)=y(t)$;

For unnormalized signals, let

$$\frac{x(t)}{f(x,x,0)} = \frac{y(t)}{f(y,y,0)} \text{ and } a = \frac{f(y,y,0)}{f(x,x,0)}$$

Then, $y(t)=ax(t)$.

APPENDIX B. MATHEMATICAL TOOL FOR THE CORRELATION STUDY (XU ET AL., 2000) (continued)

It should be mentioned that the shape correlation numbers in Table 3 are presented by $p^2(x,y,h)$.

For two signals that are "similar" in shape, the cross-correlation

$$\int_{-\infty}^{\infty} x(t)\,y(t+h)\,dt$$

will be a maximum when two signals are lined up similar to a zero lag on the autocorrelation. Therefore, we have the following definition for the phase difference between the signals.

Definition 4: The phase difference between the two signals, $x(t)$ and $y(t)$, is the time h when $p(x,y,h)$ reaches its maximum value.

APPENDIX C. MAGNITUDE CORRELATIONS OF SIGNALS BETWEEN THEMSELVES AND TO THEIR MEANS AT DIFFERENT BODY REGIONS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Thorax Force	Abdomen Force	Pelvis Force	Spine ACC	Spine ACC	Rib upr ACC	Rib lwr ACC	Pelvis ACC	Thorax up Defl	Thorax up Defl	Thorax lwr Defl	Thorax lwr Defl	Abdomen Defl	Abdomen Defl
PHF(Signal 1)	0.99	1	1	0.9	0.73	0.92	0.66		0.95	0.95	0.94	0.93		
PHF(Signal 2)	0.99	1	1	0.9	0.93	0.98	0.65		0.97	0.99	0.90	0.97		
PHF(Signal 3)	1	0.99	1	0.93	0.95	0.95	0.92		0.96	0.96	0.97	0.97		
PHF(Signal 4)	1	0.99	1	0.92	0.94	0.96	0.76		0.99	0.99	0.99	0.99		
PHF(Signal 5)	1	1	1	0.95	0.96	0.99	0.83		0.90	0.97	1	1		
PHF(Signal 6)	1	1	0.99	0.83	0.88	0.9	0.83		0.92	0.98	0.99	0.99		
PHF(Signal 7)	1	1	1	0.91	0.89	0.98	0.76		0.96	0.95	0.96	0.95		
PHF(Signal 8)				0.82	0.89	0.97								
Average	**1.00**	**1.00**	**1.00**	**0.90**	**0.90**	**0.96**	**0.84**		**0.96**	**0.95**	**0.97**	**0.97**		
RLF (Signal 1)	0.99	0.84	0.99	0.9	0.94				0.98	0.97	0.99	0.99	1	1
RLF (Signal 2)	0.99	0.72	0.95	0.94	0.97				0.99	0.99	0.99	0.99	0.99	0.98
RLF (Signal 3)	0.99	0.95	0.95	0.9	0.95				1	1	1	0.99	0.99	0.99
RLF (Signal 4)	1	0.93	0.96	0.95	0.93				0.98	0.99	1	0.99	0.97	0.90
RLF (Signal 5)	0.99	0.95	0.99	0.94	0.91				0.99	0.99	0.98	0.97	0.98	0.90
Average	**0.99**	**0.88**	**0.97**	**0.93**	**0.94**				**0.99**	**0.99**	**0.99**	**0.98**	**0.99**	**0.99**
RHF (Signal 1)				0.91	0.9	0.94								
RHF (Signal 2)				0.92	0.94	0.89								
RHF (Signal 3)				0.80	0.94	0.83								
RHF (Signal 4)				0.66	0.87	0.85								
RHF (Signal 5)				0.94	0.95	0.93								
RHF (Signal 6)				0.92	0.96	0.95								
RHF (Signal 7)				0.92	0.92	0.81								
RHF (Signal 8)				0.63	0.97	0.92								
Average				**0.87**	**0.93**	**0.88**								
PLF (Signal 1)								0.87						
PLF (Signal 2)								0.96						
PLF (Signal 3)								0.91						
PLF (Signal 4)								0.77						
PLF (Signal 5)								0.85						
Average								0.83						

APPENDIX D. DATA SETS FROM STAPP PAPER 2002-22-0017 USED FOR THIS STUDY

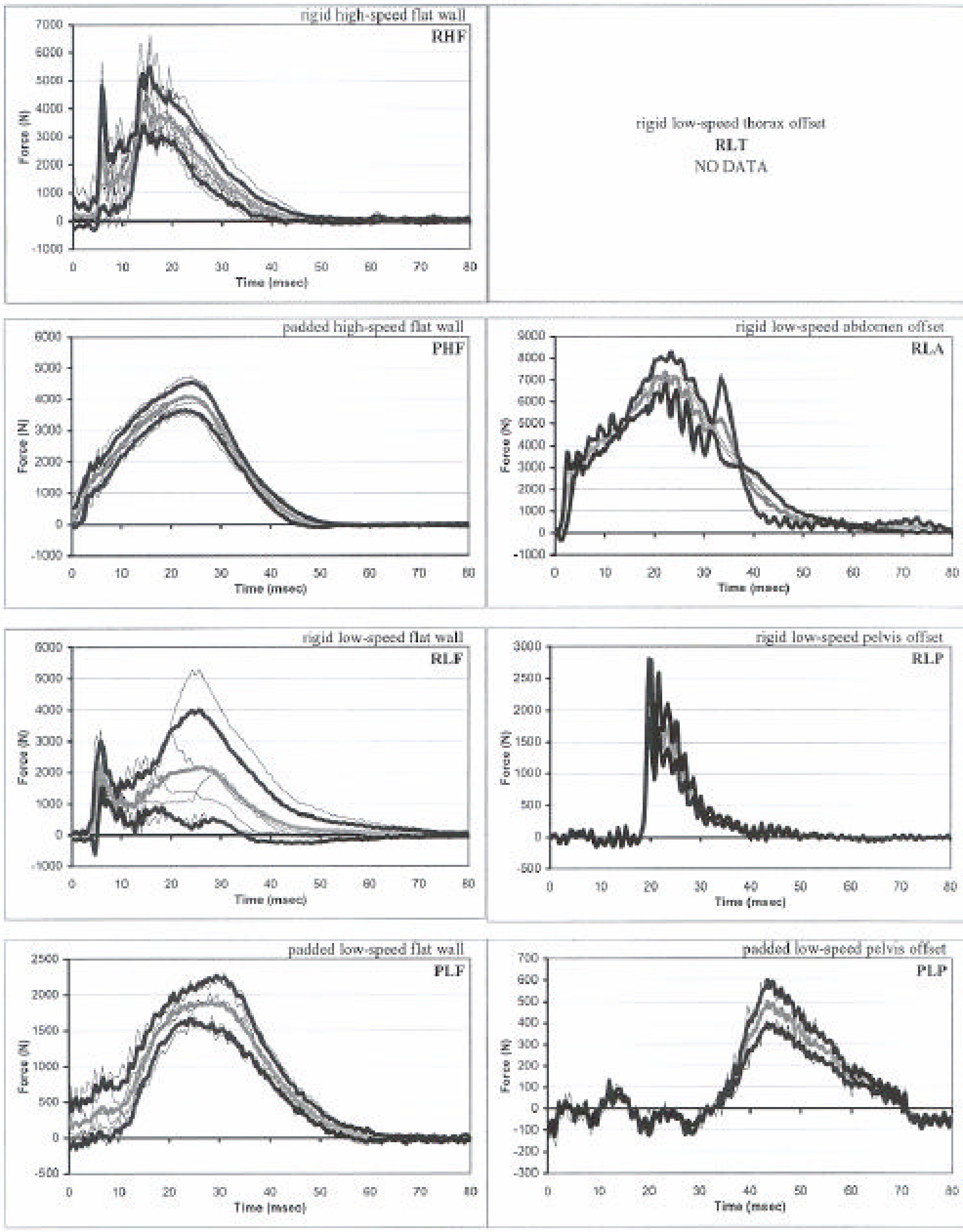


Figure A2. Abdomen load wall force-time histories (CFC 1000). Individual PMHS runs are shown in thin lines; mean response is dark grey; corridor is dark black.

APPENDIX E. CORRIDORS USING DIFFERENT STANDARD CURVES

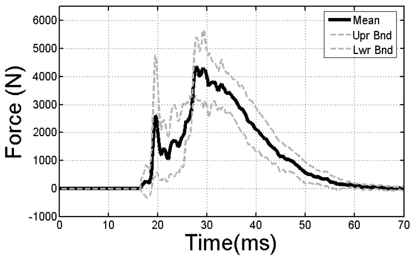


Figure E1: Corridors with curve 1 as the standard curve.

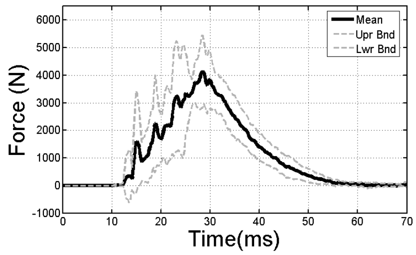


Figure E2: Corridors with curve 2 as the standard curve.

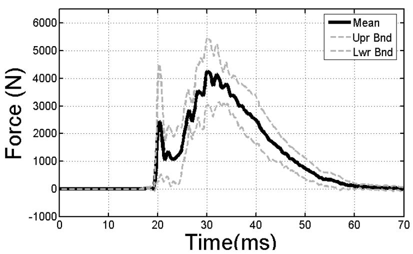


Figure E3: Corridors with curve 3 as the standard curve.

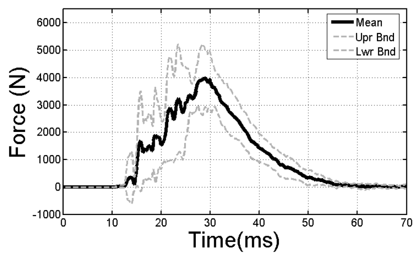


Figure E4: Corridors with curve 4 as the standard curve.

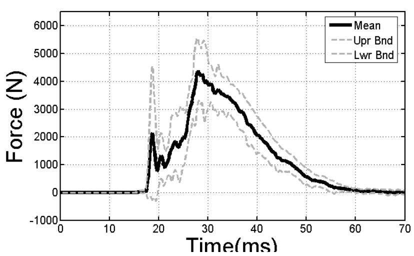


Figure E5: Corridors with curve 5 as the standard curve.

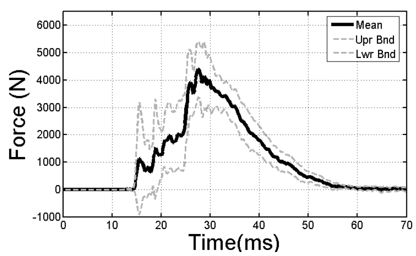


Figure E6: Corridors with curve 6 as the standard curve.

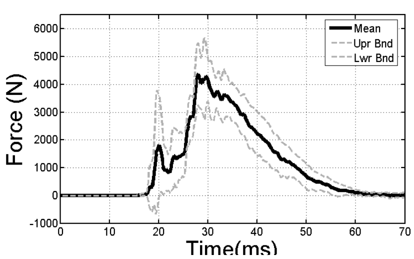


Figure E7: Corridors with curve 7 as the standard curve.

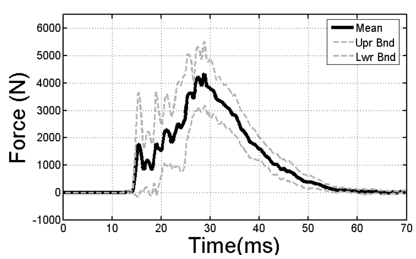


Figure E8: Corridors with curve 8 as the standard curve.

DISCUSSION

PAPER: **Analysis of Current Biofidelity Corridor Construction as It Relates to Lateral Impacts**

PRESENTER: ***Guy Nusholtz, DaimlerChrysler***

QUESTION: *Erik Takhounts, NHTSA*

I think your data that you generated it goes to half-periods, changes about three times, I think? If you go back to your slide…

ANSWER: Yeah. Okay.

Q: I don't think it's quite fair to the cadavers. There's not that much spread by 300%.

A: I've never been fair to a cadaver.

Q: Yeah. The reason you generated that new mean is because your period is 50 versus 12, so it's more like four times difference. So to be a little bit more fair to Maltese, you have to assume, which he does I think in his theory, that the curves are sort of not completely arbitrary. They're sort of the same with some variation.

A: We've done it. We've done it. I didn't present all the data, but we've done it both ways where we took half-sizes. This is sort of an exaggeration for an extreme to present the issue, but we've also done it on signals, which are about the same time width and yet they're different in shape and you get the same type of changes of the mean. Not just to this magnitude, but you do get changes.

Q: Where is the non-uniqueness coming from?

A: What?

Q: Non-uniqueness, where is it coming from?

A: The non-uniqueness of the signal is, depends on which signal you choose first. If you make an arbitrary choice of the signal, you get a different result. If you choose the first signal—If I have five signals and I label them 1-2-3-4-5, and each time—and if I say, okay, I'm going to choose one as the original curve [Right] and then I'll compare everything to that. Then I take two and I say that's the first signal and I compare everything to them, I get a different curve.

Q: I still don't understand where non-uniqueness is coming from.

A: Well, each one will produce a different mean. So, the means are not unique.

Q: You may have to explain it a new way there.

A: Matt can explain it.

QUESTION: *Matt Maltese, Children's Hospital of Philadelphia*

Actually, I wasn't listening.

A: I guess I'll have to explain it

Q: Thank you for a rigorous analysis or it appears to be the beginning of a rigorous analysis of the technique, but I want to just comment on one thing. When we were doing the analysis and comparing the method of alignment and then developing the corridors that we developed, and then comparing that with 97/91, one thing we found was it really gets messed up when the curves from the same test don't have the same shape. That is, the 97/90 technique tends to encompass all the data and you get really, really wide corridors and—

A: You can drive a truck through.

Q: That you can drive a truck through, and the so-called Maltese technique: You get these really narrow and almost arbitrary corridors that develop kind of a new signal that's an average of the two; kind of like what you showed there. [Yeah] But then when the shapes are very similar—of all the signals and the stat —the 97/90 and Maltese Method kind of converge.

A: I would think that the 97/90 is still going to be—If the signals are the same, then the Maltese Method should rely on the Central Mean Theorem and it should be an improvement of the estimate of the mean, if it's just random noise. So, it should be an improvement over 97/90 if that's the case, and it'll be able to discriminate better than what 97/90 could.

QUESTION: *Jeff Crandall, University of Virginia*

Guy, if I could just make a comment, maybe, to Matt's question and comment. For structural analysis not temporal analysis, what we've done is actually created a characteristic shape to the signal, gone and normalized that by a maximum deflection or maximum whatever—Here you could do it temporally. Then, you provide a characteristic signal and then you do the analysis. So, I think Leslie presented that last year here and then did a follow-up at SAE. So I think combining that technique with your methodology could solve a lot of these problems in terms of how to average and how to find a characteristic signal.

A: Yeah. That's basically what I mean by there are a lot of solutions it solves. Everything—Everything that's been observed, I think, is solvable without too much difficulty.

Q: Okay. Thank you, Guy.