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Biofidelity Corridors for the Thorax in Frontal Impact - Update by an International Task Force

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ABSTRACT

The purpose of this paper is to propose a set of frontal biofidelity corridors for the thorax in frontal impact. The corridors have been developed by biomechanical experts from several organizations including CEESAR, EEVC, Ford Motor Company, Humanetics, G.M Company, IFSTTAR, JAMA, JARI, LTU, LAB, PDB, UVa, and VRTC. The experts agreed on a complete process including the identification of the PMHS tests appropriate for biofidelity target definition and the data processing resulting in corridors. ***Impactor test:*** *the Kroell tests series dataset have been reanalyzed and expanded with recent impactor tests. Two new force-deflection impactor corridors are then proposed. The total deflection is used rather than the skeletal deflection. In addition, based on the Kent et al. 2004 muscle tensing study, it was decided not to perform any force shift to the corridors.* ***Sled tests with 3 point belt restraint corridors:*** *the 8 PMHS tests described in Shaw et al. 2009 have been used to develop shoulder belt load versus time corridors and skeletal 3D deflection versus time corridors at 5 different locations on the thorax.* ***Table Top test:*** *no corridor but the relative reaction Force value at 20% of thoracic compression was proposed as biofidelity targets using the Kent et al. 2004 series, which gathers four different types of loading.*

INTRODUCTION

Many efforts have been performed in the past to develop frontal dummies and FE-models to assess the injury risk sustained by a car occupant in frontal crash. The thorax has been a major concern for a long time for it is one of the most exposed body segment to injury and for it encloses vital organs. The ability of a FE-model or a dummy to behave like a human when loaded under car crash conditions is commonly defined as biofidelity. It is believed that the biofidelity of the thorax is a key condition in the development of an acute injury assessment tool.

In the 70's in the USA, General Motors laboratories performed the Kroell impactor test series to enhance the Hybrid II dummy thorax biofidelity. The aim was to provide sternum Force/Deflection specifications in loading condition corresponding to the most common thoracic impact that occurred in US car crash at that time: the hub strike. The two resulting corridors (4.3 m/s and 6.7 m/s impacts) developed by Neathery et al. in 1974 guided the design of the Hybrid III dummy thorax.

In the 80's, as the use of shoulder belts, airbags or combination of both aroused, the loadings on the thorax varied and became more complex. Differences in the injury tolerance with regard to the restrain systems were also observed. Consequently, NHTSA[1] launched the AATD (Advanced Anthropomorphic Test Device) program in an effort to enhance the Hybrid III dummy capabilities. One of the goals of improvement for the dummy thorax was the ability to provide realistic response and injury assessment for both concentrated and distributed types of loading. For that purpose, an extensive literature review was performed to provide biofidelity specifications and design guidelines for the new dummy (Melvin et al. 1985, Schneider et al. 1989). In addition to the Kroell 0° impactor test, it included a few sled tests and Table Top tests (L'abbée et al. 1982, Cavanaugh et al. 1988) primarily used to get regional and interregional stiffness and coupling estimates. This program yielded the TAD-50 prototype dummy, which only strong biofidelity requirements was the 4.3 m/s impactor Force/Deflection response (Schneider et al. 1992). The relevance of the prototype dummy thorax was further assessed with various sled tests but it was not done against PMHS response targets. The sled tests only checked the ability of its 4 points-3D deflection measurement device to discriminate between various restraint types.

Later in the 90's, the THOR dummy was born. Biofidelity requirements for this dummy were released in 2001 and updated in 2005 (GESAC 2001, 2005). It included 0° impactor tests (Neathery et al. 1974) and oblique impactor tests (Yoganandan et al. 1997). It also proposed in section III to develop additional biofidelity requirements using Table Top test series (Cavanaugh et al. 1988, Schneider et al. 1992, Cesari et al. 1990).

In 2011, the SAE THOR Evaluation Task Group is still working on enlarging the biofidelity requirements. The update regarding the thorax segment concerns the 0° impactor tests. Indeed, the 6.7 m/s test was abandoned and the 4.3 m/s test was kept but without the force-shift initially added to account for muscle tensing. The biofidelity targets for the configuration proposed in the section III have not been developed.

In the 90's, European laboratories followed up the NHTSA's AATD program outcome. EEVC[2] Working Group 12 underlined the extensive use of 3pt belt restraint in Europe and the importance of an accurate torso/belt biofidelic interaction. They also emphasized the need of a worldwide acceptable frontal dummy (Beusenberg et al. 1996). ADRIA[3] European project consortium stated that no clear biofidelity targets but Kroell impactor corridors were available in the literature to assess the frontal dummies (ADRIA final report, 2000). They underlined that Kroell tests was not a representative loading of the thorax during a frontal impact and recommended to develop biofidelity targets with recent test series using belt restraint: Table Top tests (Cesari et al. 1994) and Sled tests (Kallieris et al. 1995 and Morgan et al. 1994). They also concluded that more effort was necessary to come to a world-wide accepted list of frontal dummy performance requirements.

Following this findings, FID[4] European project consortium proposed a set of biofidelity requirements for all body segments, based on new biomechanical investigations and literature review (Van Don et al. 2003). It comprised for the thorax: 0° impactor tests (Neathery et al. 1974), oblique impactor tests (Yoganandan et al. 1997) and sled tests (Vezin et al. 2002). However, the Vezin et al. 2002 sled tests used upper and lower sternum resultant acceleration time history as biofidelity targets and did not provided Force/Deflection responses. In addition, the Sled tests from the 90's and the Table Top test series were not retained for no biofidelity corridors already developed were available.

[1] NHTSA: National Highway Traffic Safety Administration
[2] EEVC: European Experimental Vehicle Committee
[3] ADRIA : Advanced crash Dummy Research for Injury Assessment in frontal test conditions
[4] FID: improved frontal impact protection through a world Frontal Impact Dummy

In 2009, the THORAX[5] European project started. It aimed at providing a frontal impact dummy thorax prototype, with enhanced biofidelity and injury risk assessment capability that could be retrofitted on the THOR dummy. To assess the biofidelity of the thorax prototype, the consortium have been selected a set of test series from an up-to-date literature review. This selection is not published as of today.

From this background, it appeared that some discrepancies remain between EEVC and NHTSA thoracic biofidelity recommendations and that some published test series are still unexploited to define biofidelity corridors. It also appeared that no strong collaboration between Europe, Japan and the USA occurred so far.

For those reasons, ACEA-TFD[6] proposed in 2008 a Preliminary Work Item (PWI n°2882) at ISO/TC22/SC12/WG5, which aims at promoting a world-wide accepted set of biofidelity targets for all body segment of the mid-male frontal dummy in an ISO Technical Report. In particular, it was established that this Preliminary Work Item must comprise: 1) a collaboration between corporations, institutions, universities and laboratories from Japan, Europe and the USA in order to reach a world-wide consensus; 2) an effort to develop biofidelity targets from test configurations selected among published and unpublished data, including the most recent ones. It was also stated that this work does not aim at developing a biofidelity ranking tool.

This paper presents the achievements of an international collaboration regarding the Thorax segment.

METHODS

International Task Force

In order to facilitate the development of consensual biofidelity targets, an International Task Force was created. This Task Force is composed of experts from CEESAR, Chalmers, EEVC, Ford Motor Company, Humanetics, General Motors Company, IFSTTAR, JAMA, JARI, LTU (Lawrence Technological University), LAB PSA Peugeot-Citroën Renault, NHTSA, PDB, TRL, UVa, and VRTC. These organizations volunteered to either actively participate in the development of biofidelity targets, or to give feedback on a regular basis. The Task Force meets monthly via a web conference and works in connection with other groups working on thorax biofidelity such as the THORAX consortium or the SAE THOR Evaluation Task Groups. Consequently, the achievements presented below are the result of a collegiate process.

Literature review

The major biomechanical journals (Stapp Car Crash journal, IRCOBI proceedings, SAE collection, ESV proceedings) were searched from the 70's to 2010 to identify relevant test series. In addition, NHTSA online database and unpublished reports (from Calspan, Heidelberg University, UMTRI, etc.) were screened to increase the chance to get relevant test series. In the end, a quasi-exhaustive database gathering published and unpublished thoracic tests was set up. It is composed of almost 700 tests. The identified test configurations can be sorted into 3 principal categories: Impactor tests, Sled tests, and Table Top tests.

Impactor. In the impactor configurations, the subject was seated erect on a low-friction surface; the back was unrestrained most of the time. The impactors were of various sizes and impact directions, the most common being the 15.4 cm in diameter rigid striker face, weighting approximately 23 kg, and impacting at 0° at mid-sternum level.

Table Top: the subject laid supine on a table. Most of the table top tests used a shoulder belt as a loading device (L'abbée et al. 1982, Cesari et al. 1990, Cesari et al. 1994, Kent et al. 2004). The torso deformation at different location of the ribcage was examined. Other test series also investigated distributed loading (L'abbée et al. 1982, Kent et al. 2004) or localized loading (Cavanaugh et al. 1988, Kent et al. 2004).

[5] THORAX: Thoracic injury assessment for improved vehicle safety
[6] ACEA-TFD: European Automobile Manufacturer's Association – Task Force Dummy

Both quasi-static and dynamic tests were found. Some table top configurations constraint the spine only and let the posterior part of the ribs free to move rearward (Cavanaugh et al. 1988, Lessley et al. 2008).

Sled. Numerous sled tests were conducted and therefore represent the majority of the test database. A real car crash was simulated with an occupant surrogate seated in a car buck or a rigid sled representing the car interior environment, and decelerated at levels representative of real accidents. All the restraint combinations were available in the literature: lap belts, 2 pt shoulder belts, 3pt belts, 4pt belts, with various anchorages, with or without force-limiters and pretensioners, with or without airbag of various sizes, with pre-deployed airbags, etc. Many different types of interior geometry and component such as the seat were found, as well as various initial speeds and deceleration pulses.

Selection criteria

The International Task Force set up a list of criteria in order to select the most appropriate tests to be used for the development of biofidelity targets. They are as following:

Criterion 1: Relevance of the test configuration. From discussions within the Task Force and with experts from other groups such as the THORAX consortium or the ISO/TC22/SC12/Working Group 5, two general features of the test configuration appeared to be critical: 1) it should be close to the loading conditions of a real world car crash and 2) it should be relatively easy to implement in small laboratory facilities. In addition, given the huge database of tests and the timeline constraint, the task force prioritized a) the dynamic loadings over the static ones, b) the 0° loading over oblique ones, c) the research of configurations offering simple basics loadings: shoulder belt only and airbag only before trying to select configurations using a combined loading.

Criterion 2: Reproducibility of the test configuration. The reproducibility of the test configuration was mandatory. A detailed description of the test environment and the initial positioning of the subject was required, and the availability of the test set up components, such as the seat for the sled tests was checked.

Criterion 3: Relevance of the measurements. In the literature – from the 80's until recently (Melvin et al. 1985, Bose et al. 2010) – multipoint deformation of the torso was felt to be a promising path to allow the dummy to discriminate between various restraint types. Consequently, thoracic force and deflection were required and were preferred over accelerations measured on the ribcage or the spine. In general, the tests for which the force or the deflection measurements were not available were not considered by the Task Force for biofidelity target development.

Criterion 4: Reliability of the measurements. The reliability of the measurement was also investigated. Special attention was given to the chestband device. Bass et al. 2000 and Shaw et al. 1999 established that the chestband could not accurately measure the deflection associated to a local loading such as a belt loading when equipped with less than 40 gages. Consequently, such cases were excluded. However, less than 40-gages chestband could be accepted for distributed loadings such as airbag contact.

Criterion 5: PMHS features. The general meaning of this criterion was that PMHS tests were primarily considered before animal tests. Detailed PMHS features were required for it could be necessary to explain unusual cadaver response, which can lead to the exclusion of the test. Embalmed PMHS tests were systematically excluded.

Criterion 6: size of the test sample. This criterion was not mandatory but was highly considered for the confidence and the relevance of an average curve or a corridor increase when computed from a large sample test.

According to these selection criteria, relevant test series were retained among the 700 tests of the database. They are presented in the Results section.

Biofidelity target definition

The Task Force worked on a consensual way to define biofidelity targets. First, the literature was reviewed to find out what should be used as biofidelity target. It was observed that it varied from one paper to another. For instance: Nusholtz et al. 2007 recommended to use a set of response curves: the dummy response curve is compared with each PMHS response curve. Rhule et al. 2002 used the CCV[7] for which the calculation of a mean response curve is necessary. Lobdell et al. 1973 proposed to use a corridor, which was built by straddling the mean cadaver response curve by approximately ±15% of the load out to peak load and, during unloading ± 15% of the deflection out to maximum deflection. Irwin et al. 2005 (or ISO TR9790) also proposed also to use a corridor, the latter being built to encompass all the individual cadaver response curve. Given these observations, the Task Force agreed to provide a corridor and a mean response curve as biofidelity targets such that each scientist is free to use whatever target he needs.

In addition, it was observed that several methods existed to develop a biofidelity corridor from a test sample. For instance, ISO/TC22/SC12/WG5 released a method in the TR9790 in 1990 (revised in 1999) and NHTSA released another one in 2002 (Maltese et al. 2002). The two approaches were very different. They were compared by Irwin et al. in 2005 and it was observed that a same test sample could yield very different corridors depending on the method used. In general, each paper that proposes biofidelity corridors has its own approach. No standard method exists but 5 necessary steps from the initial test sample to the final biofidelity corridor were identified. This steps are 1) test inclusion/exclusion, 2) response curve normalization, 3) response signal alignment, 4) Biofidelity Corridor/Target computation, 5) Adjustment for muscle tension. For each step, the task force reached a consensus with the following principle in mind: reduce the amount of subjectivity at each step of the process and stick to the reality of the response shapes. Details on the 5 steps are given below.

*Step 1 - Test inclusion/exclusion***.** Basically, no limit neither on the injury level nor on the body size or mass were put to determine the tests to be excluded from a sample. The similarity of the response shapes and amplitude were the primary criteria that allow to sort the tests. A signal analysis could be performed on the test to objectivize this similarity (Nusholtz et al. 2007). Unsimilar response shapes were allowed to be excluded from the sample on the basis of signal analysis only if an explanation could be found in the test or PMHS characteristics.

*Step 2 - Response curve normalization***.** When several normalization techniques existed in the literature, their effectiveness were compared following the method proposed in Moorhouse 2008. It consisted in calculating the cumulative percent coefficient of variation (%CV) for time-history curves, and the cumulative ellipse[8] error for two-dimensional force-deflection curves This method relies on the assumption that a relevant normalization technique must collapse a set of response curves.

*Step 3 - Response signal alignment***.** Although some techniques to align the signals were identified in the literature (Maltese et al. 2002, Xu et al. 2000), none have been chosen by the task force so far. Consequently, no response curve alignment was performed in this paper.

*Step 4 - Biofidelity target computation***.** Lobdell et al. 1973 and Irwin et al. 2005 designed corridor using straight lines. Shaw et al. 2006 proposed corridor computed using ± 1 Standard Deviation around the average curve. The Shaw et al. 2006 method was retained by the Task Force to develop biofidelity targets. Thus, the corridor bounds were computed directly from the response curves and therefore no subjective judgment was used in their design. The ± 1 Standard Deviation was an easy to define and well accepted standard for the corridors. In addition, compared to the “straight line techniques”, the corridors bounds generated using this method have a shape closer to the one of the individual response curves.

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[7] CCV: the Cumulative Variance of the mean Cadaver response relative to the mean plus one standard deviation. DCV : the Cumulative Variance of the Dummy response relative to the mean cadaver response. The ratio of DCV/CCV expresses how well the dummy response duplicates the mean cadaver response: a smaller ratio indicating better biofidelity.

[8] see step 4 for details on the ellipse technique

To develop cross-plotted Force-Deflection corridors – hereafter named "2D corridors" – the "ellipse technique" (Shaw et al. 2006, Appendix B) was employed. It relies also on the computation of a mean response curve. The ± 1 standard deviation error is spread around each point of the mean curve using ellipses.

*Step 5 - Adjustment accounting for muscle tension***.** Kent et al. (2004) studied the effect of muscle tension on the thorax response using swine as surrogate. They were tested with a table top configuration and were submitted to dynamic impacts with different loading types (such as a belt) with and without muscle tension. The thorax responses were compared. From their observations, the authors estimated that muscle tensing:

- had no significant effect on the force-deflection response, above 20% of compression (these intensity of compression is commonly reached for 20 kg mass – 6.7 m/s impactor tests)
- had some effect under 20% of compression but taking it into account would require too many assumptions and would be complicated and uncertain to apply.

They recommended not to take the muscle tensing into account whatever the level of deflection in dynamic loading. Consequently, no correction to account for muscle tensing was applied to the corridors released in the present paper.

RESULTS

Selection of a relevant set of test configurations

Given the variety of possible combinations of loadings in the test database, the task force screen work focused on identifying the configurations with simple basic loadings – shoulder belt only and airbag only – before trying to select configurations using a combined loading. The reason supporting this was to get a limited but relevant number of test configurations, relatively easy to implement.

When no eligible configurations using belt loading only or airbag loading only was available, they were replaced respectively by devices generating localized loading and distributed loading.

The test database was screened for biofidelity reference tests using the guidelines previously defined. The results are presented below per configuration categories.

Sled test. Among the 500 sled tests, only 1 test series was found to fully meet the selection criteria: the test series performed at UVa and published by Shaw et al. in 2009. It is composed of eight PMHS, tested in the same impact and restraint conditions. It used a 3pt belt restraint without neither force-limiter nor pretensioner. Belt tension and 3D multi-point thoracic deflection were measured. The use of a rigid-seat allowed to easily reproduce the tests in the future. The lower body was constrained by means of the lap belt, knee-bolsters and foot straps. It facilitated the test repeatability and reproducibility and its use for thoracic biofidelity assessment.

The major reasons for having excluded all the other sled tests were the following:

- Embalmed subjects
- No deflection measurement available or too small number of strain gages on the chestbands
- No force measurement available
- Insufficient description of the environment geometry and subject initial position
- Seat model no more available
- Airbag model not available (prototype or not manufactured anymore)
- Unstable configuration such as unrestrained subjects or 2 pt belt restraint facilitating submarining leading to a lack of repeatability
- Non prioritized restraint condition (6 point belt, combination of 3pt belt + airbag restraints)
- Similar configuration as the Shaw et al. 2009 test series but using less tests (smaller sample size)

The reason why only 1 configuration (8 tests) was found out of approximately 500 tests was that the tests were primarily designed for the study of the body/thorax injury tolerance. This resulted in two notable consequences: 1) the reproducibility of the tests in the future was barely taken into consideration. 2) the same test condition was not so much repeated, yielding to small test samples.

Table Top test. As previously mentioned, most of the table top studies used a belt loading, but studies using distributed loading and localized loadings were also found. Both quasi-static and dynamic tests exist but the quasi-static tests were excluded by the task force.

The Table Top configurations were designed to load the torso in more controlled and repeatable conditions than in sled tests. It also required a smaller test set-up, which was easier to implement. As such, it was felt to be an interesting configuration that could yield to biofidelity corridors for the thorax. In addition, no sled tests using pure airbag loading and fulfilling the selection criteria were found in the database. It was replaced by a table top tests using distributed loading. However, the Table Top configuration was questioned within the Task Force as potentially resulting in local thoracic relative stiffness substantially different from the one observed in the vehicle impact condition. Consequently, a minimal consensus was reached. It consisted into picking up only one Table Top study, in which both the distributed and 3pt belt loadings were used. Light biofidelity targets should be developed in which the responses to a distributed loading and a 3pt belt loading should be compared relatively to each other.

Among the study available in the literature, Kent et al. 2004 test series was chosen as meeting the requirements.

Impactor test. The impactor configurations were also considered for it is the easiest configuration to be implemented. As such, it can be set-up in any laboratory.

Although it was pointed out that it is not the most relevant configuration as far as belt loading is concerned (ADRIA report 2000), it was identified as being relevant enough for it simulates a blunt impact. In addition, Trosseille et al. 2008 observed that the thorax submitted to a 15.4 cm in diameter, 23.4 kg, 4 m/s impactor strike yielded rib strain profiles in a way similar to an airbag. Therefore, the impactor test was found usable as a spare configuration to assess airbag loading.

Finally, the impactor configuration is still a worldwide accepted standard that provides interesting guidance to assess biofidelity of a frontal dummy or a FE model.

Among the available impactor tests (approximately 100), only 0° impact, non restrained back tests were considered. Many tests were excluded for they did not fulfill the selection criteria. Some tests were set aside for it was relatively small samples (less than 10) as for instance the Calspan tests using large square plates as impactor shape. In the end, one impactor configuration was retained to develop biofidelity targets: the Kroell-like impactor shape striking the thorax at mid-sternum level. The prime reason was that it was the larger sample. Three tests series were found to correspond to this configuration: CEESAR test (Trosseille et al. 2008), INRETS tests (Bouquet et al. 1994) and GM tests (Nahum et al. 1970, Kroell et al. 1971, 1974). They were used together to develop impactor biofidelity targets.

Biofidelity targets for Sled with 3 point belt restraint test configuration

The tests series presented in the Shaw et al. 2009 Stapp paper was used. It is composed on 8 PMHS all loaded in the same condition: the initial speed of the sled is 40 km/h and the deceleration is 14 g. Full description of the test configuration can also be found in Shaw et al. 2009 and Shaw et al. 2010 IRCOBI papers and in reports available on the NHTSA online biomechanics database : http://www-nrd.nhtsa.dot.gov/database/aspx/biodb/querytesttable.aspx (search for test numbers 9546 and 9547).

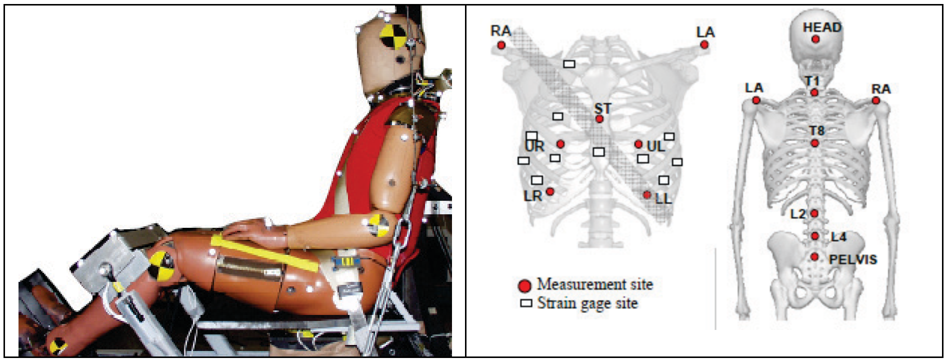

Figure 1 - Sled test set-up (left) and Measurement sites (right)

The XYZ deflection of the five points located on the anterior wall of the ribcage were used to define biofidelity targets. The task force agreed to express the deflections of the 5 points in the same thoracic frame: the T8 "spline Coordinate System" as defined in Shaw et al. 2009 Stapp paper. It means that the measured deflections represent the global deformation of the upper torso, that is to say: rib deformation + rib movement relatively to its attached vertebral body + for the upper target attached to the 4th ribs, T4 vertebra displacements relative to T8 vertebra. Details on the rationale that led to this choice are given in appendix B.

Regarding the force measurements, it was suggested as a prime intention to use the normal force applied to the thorax in order to get Force/Deflection responses. However, the normal force was not available at the time when this test series was investigated. Such data was somehow tedious to calculate and may need assumptions. Consequently, the belt Tension time-history was taken as biofidelity target and was not cross-plotted with any Deflection.

Raw data. An agreement between ISO/TC22/SC12/WG5 and JARI is in progress to allow the computing of biofidelity targets using the data of tests 1358, 1359 and 1360 in numerical format. The agreement is not completed yet and consequently, the data of these 3 tests used in the present report were digitized from Shaw et al. 2009 Stapp paper. For the tests 1294, 1295, 1378, 1379 and 1380 the data time-history were provided up to 250 ms in numerical format by UVa.

Data interpolation. In some cases, movements of the upper extremities and head occluded targets from view of the optical system. In such cases, anatomical trajectories were not obtained over the affected time interval. These time intervals will be referred to as "gaps" from here on.

The average duration of the gaps is 42 ms, so many datapoints remained available to compute the biofidelity target. In addition, gaps were observed on the most extreme response curves, which would have a significant weight in the width of the final corridor. However, when computed with the datapoints available at each time step, the sudden disappearance or reappearance of one or several datapoints over time generated strong uneven profile of the average curves and corridor bounds. Consequently, the task force decided to interpolate the missing datapoints in order to smoothen the bounds of biofidelity corridor and average curve.

A Matlab routine was developed following the interpolation scheme described in Appendix D of Shaw et al. 2009 Stapp paper: missing displacement data were computed using the datapoints of the other PMHS response curves for which the tracked targets were not occluded. Since more than one curve presented gaps and not during the same time interval (see table D1, Appendix D in Shaw et al. 2009 Stapp paper), the number of curves used to interpolate the signal changed over time.

The quantity of non-interpolated curves (or true responses) used to build the average curve and the bounds of the corridor should be provided for each time step, such that the consistency of the biofidelity targets is clear. This data are not presented in this paper.

Data extrapolation. The digitized time-history responses of the "JAMA/JARI tests" – provided up to 150 ms in the Stapp paper – were extrapolated up to 250 ms using a similar process to the one described in Appendix D of the Shaw et al. 2009 Stapp paper. The Task Force allowed this extrapolation operation for the JAMA/JARI data in numerical format are expected in a close future, which will allow computing the biofidelity target up to 250 ms.

Determination of outliers (step 1). Because of the interpolated curves, no signal analysis was performed to identify outliers. Shaw et al. 2009 observed singular locations of some targets on the PMHS ribcages. The response curves related to these targets were excluded. Namely:

- XYZ upper right deflections of the test 1378 and,
- X lower right deflection of the test 1379.

Normalization (step 2). Two scaling techniques were assessed to normalize the belt Tension versus time and the thoracic Deflections versus time responses: Equal stress/Equal velocity (Eppinger 1976, Eppinger et al. 1984) and Mass/spring model (Mertz 1984) adapted to a constant deceleration. The equations for the latter are given in Appendix C. The chest depth as reported in the anthropometry table was used to work-out the stiffness ratio because the skeletal ribcage depth was not available for all the PMHS.

The collapsing of the set of curves was assessed by looking at the cumulative variance over time. It was calculated using either the coefficient of variation as defined by Moorhouse 2008, or the standard deviation. The values are given in Table 9 in Appendix D. Table 1 shows the efficiency of each technique by calculating the percentage of collapsing of each set of response curves.

Table 1 shows that the mass-spring model failed to collapse the set of curves. This may be due to the numerous assumptions necessary to apply a mass-spring model to a frontal sled test (see Appendix C).

The Eppinger technique significantly collapsed the belt load responses. However, the collapsing effect was not systematic on the deflection response curves. For the set of curves presenting a collapsing, the improvement was small compared to the one observed on the belt load responses. A greater number of set of curves showed a collapsing than the number of sets where a scattering was observed. For the set of curves presenting a scattering, the percentage value were low except for sternum X, upper right Z and lower right X.

Finally, since the Eppinger normalization gave satisfactory results on the force responses, it was chosen to use it for the deflection responses as well, in order to have consistent time basis (i.e. normalized time basis for both the force and the deflection responses). It should be noticed that the effect of the normalization on the deflections responses is minor in general, in the collapsing cases as in the scattering cases.

Signal alignment (step 3). No attempt to alignment the response curves was made.

Biofidelity targets computation (step4). The biofidelity targets processed from the belt tension and XYZ deflection measurements are presented in Figure 2 and in Figure 3, Figure 4, Figure 5, Figure 6 and Figure 7 respectively. A mean curve and a -/+1 SD corridor were computed from the set of curves.

Adjustment accounting for muscle tension (step 5). No correction to account for muscle tensing was applied to the biofidelity targets.

Table 1 - % of improvement of the cumulative variance between unscaled and scaled set of curves. The efficacy of Eppinger and Mass-spring techniques are compared. The cells are dashed in green when the scaling technique diminished the cumulative variance.

	scaled using Eppinger		scaled using Mass-spring	
	%CV improvement	av Std (% improvement)	%CV improvement	av Std (% improvement)
lower shoulder belt	14%	14%	-27%	-16%
upper shoulder belt	16%	19%	-15%	1%
Sternum X	-18%	-16%	-33%	-39%
Sternum Y	7%	-1%	0%	-7%
Sternum Z	3%	-2%	-5%	-17%
Upper Left X	0%	0%	-13%	-8%
Upper Left Y	6%	2%	0%	-7%
Upper Left Z	1%	1%	1%	-9%
Upper Right X	3%	1%	-53%	-39%
Upper Right Y	5%	2%	5%	-2%
Upper Right Z	-20%	0%	-80%	-27%
Lower Left X	-3%	-5%	-13%	100%
Lower Left Y	5%	2%	14%	5%
Lower Left Z	1%	3%	-1%	-3%
Lower right X	-48%	0%	-1%	-38%
Lower right Y	-6%	-5%	-4%	-4%
Lower right Z	-7%	-5%	-87%	-12%

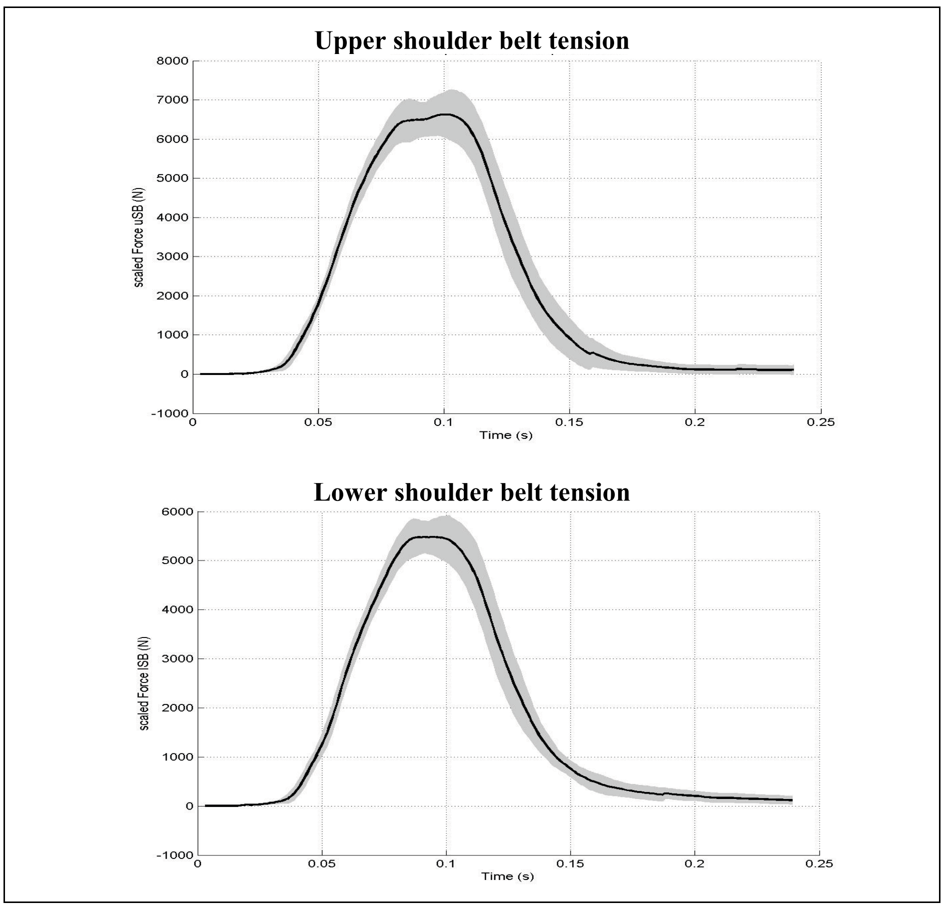

Figure 2 – Upper and Lower shoulder belt tension time history: mean response curves and corridors for a 50th male human surrogate loaded in the Shaw et al. 2009 conditions.

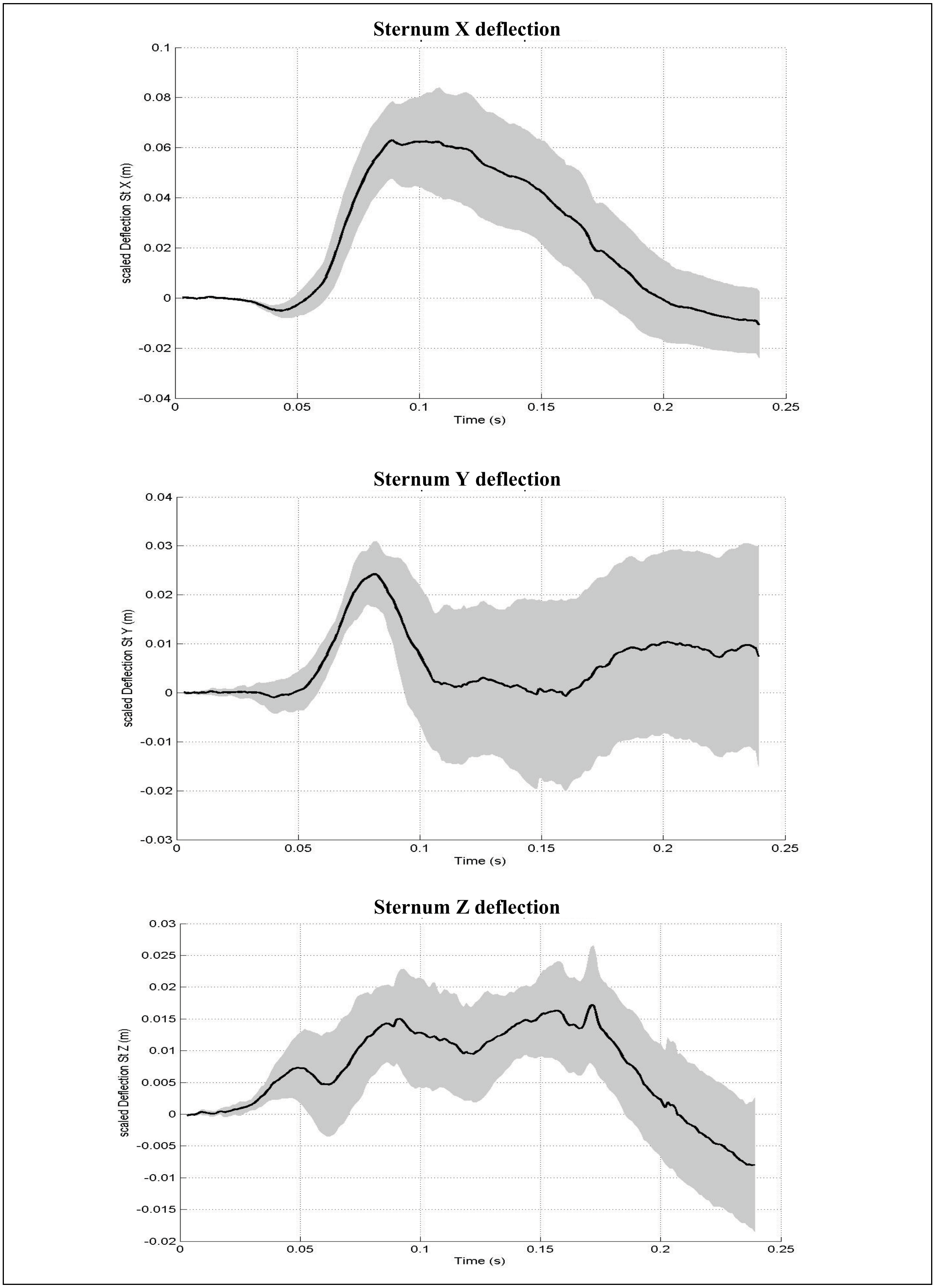

Figure 3 – Sternum 3D deflection time history: mean response curves and corridors for a 50th male human surrogate loaded in the Shaw et al. 2009 conditions.

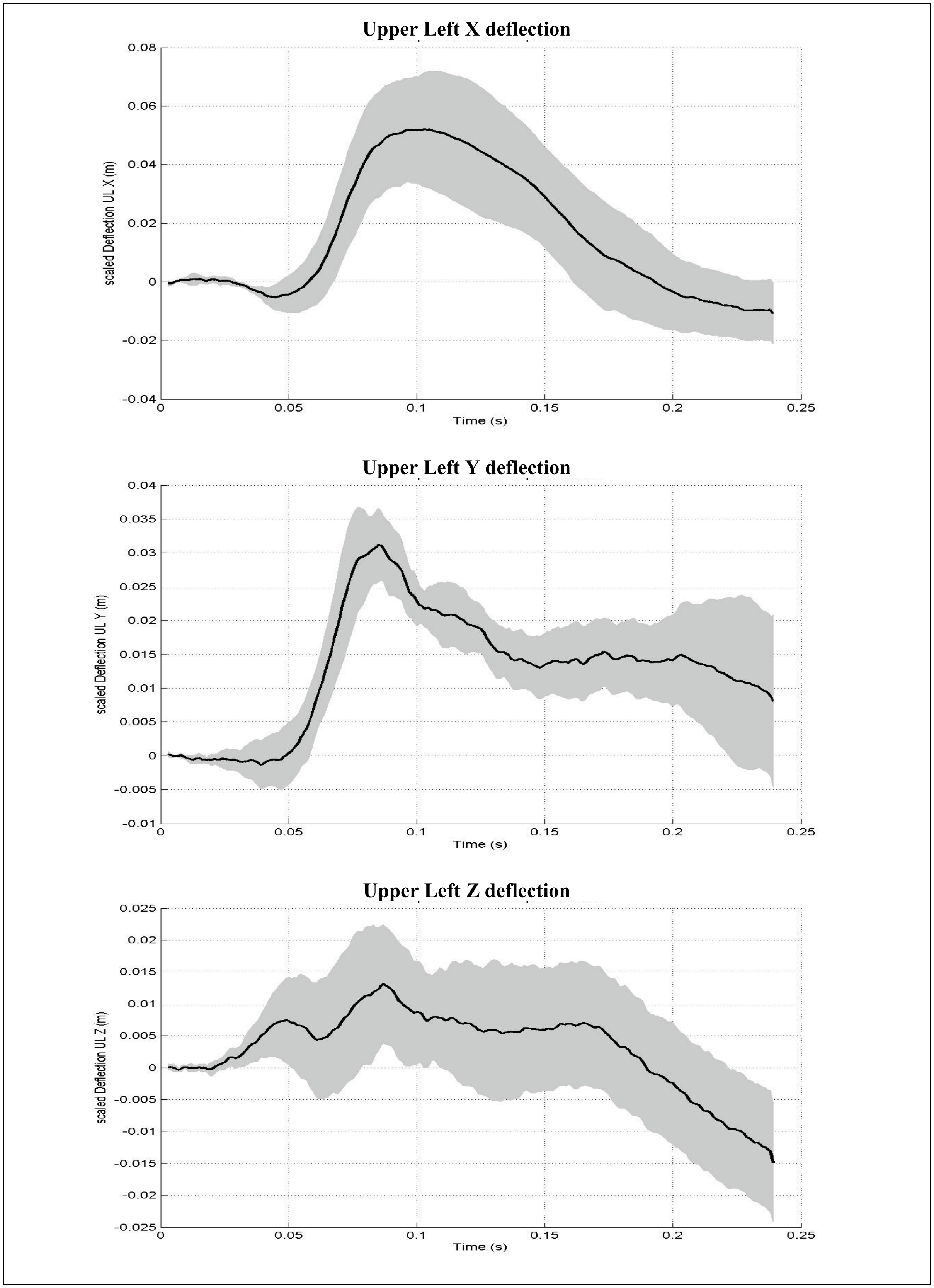

Figure 4 – Upper Left 3D deflection time history: mean response curves and corridors for a 50th male human surrogate loaded in the Shaw et al. 2009 conditions.

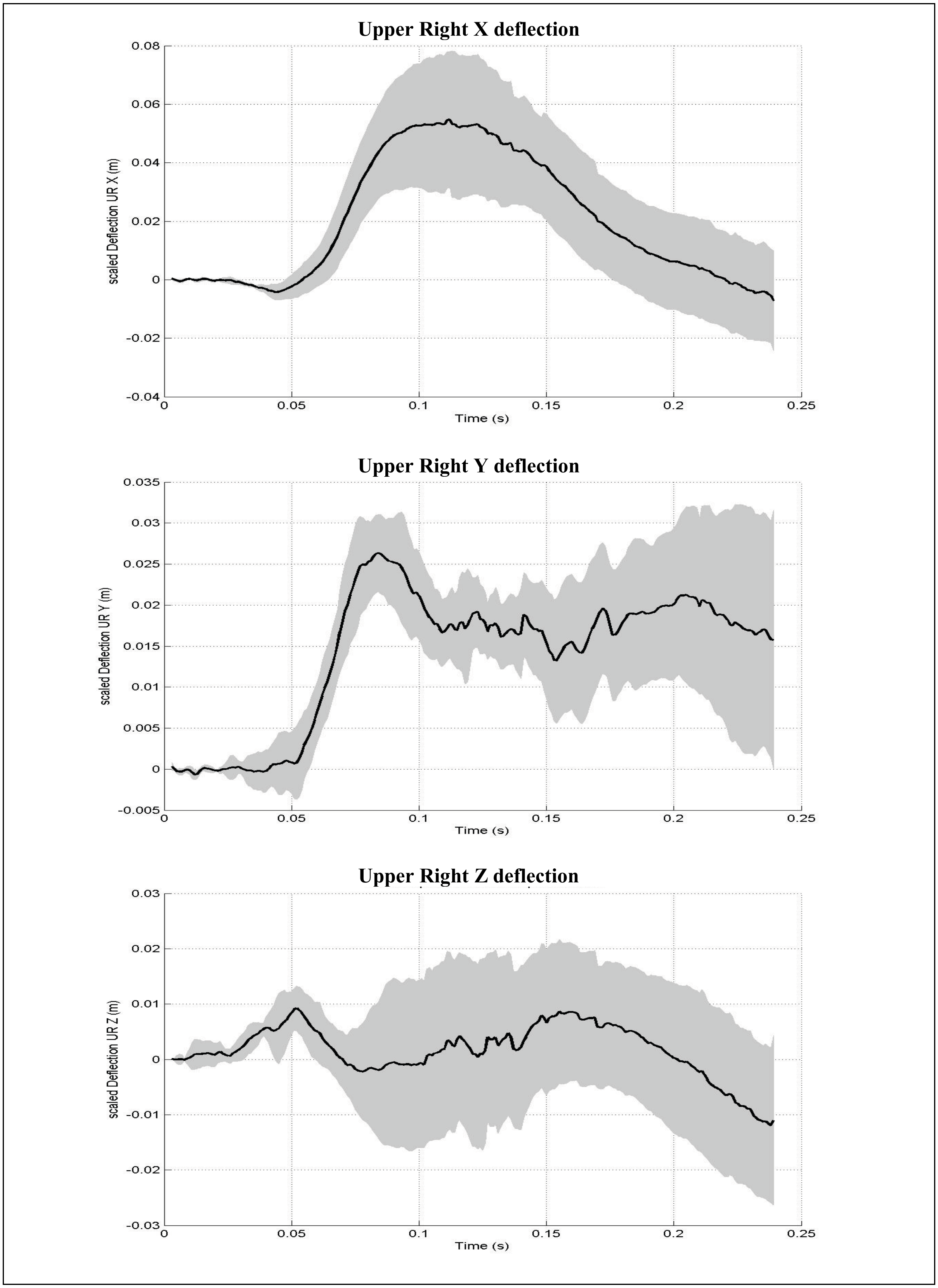

Figure 5 – Upper Right 3D deflection time history: mean response curves and corridors for a 50th male human surrogate loaded in the Shaw et al. 2009 conditions.

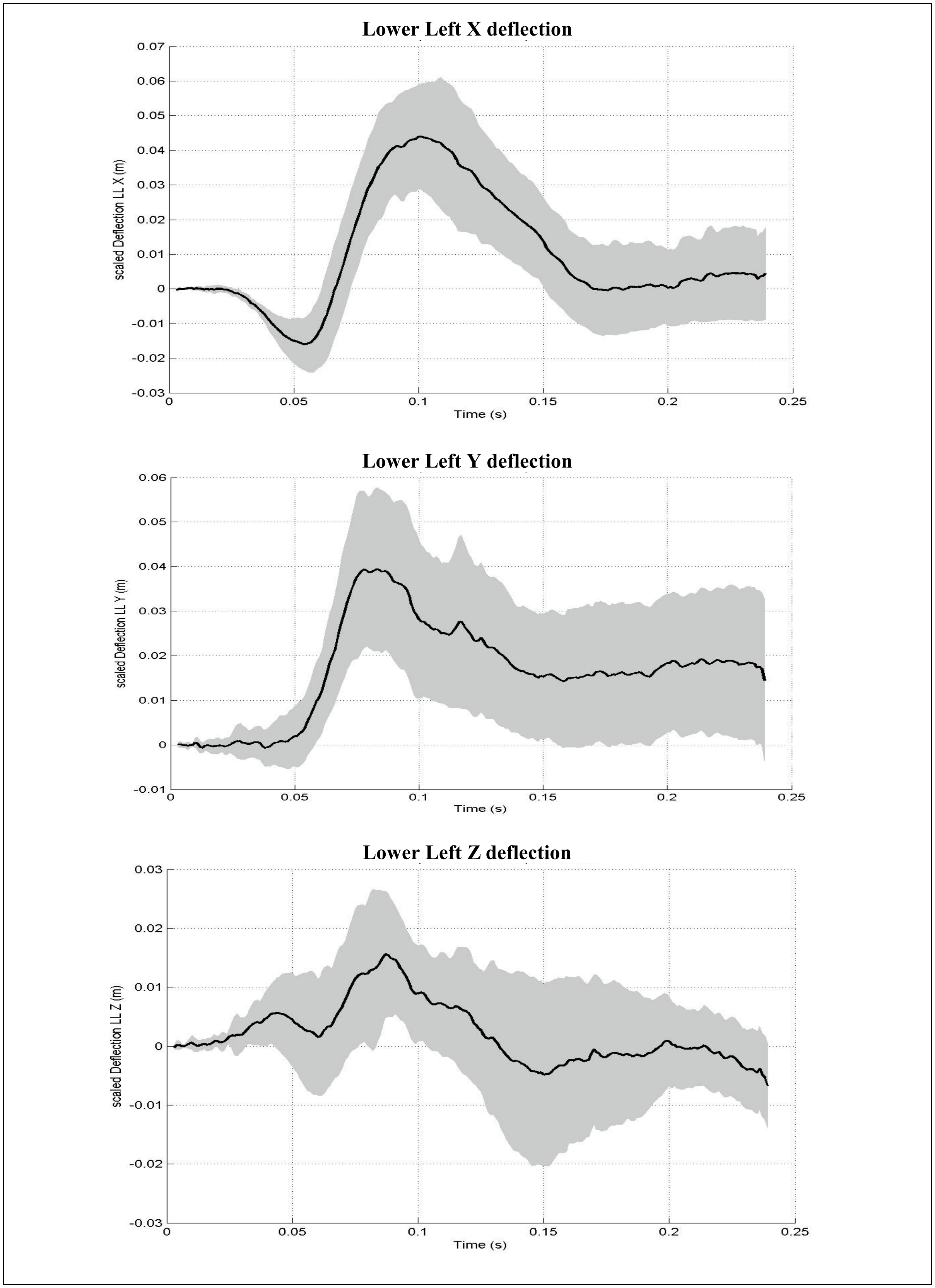

Figure 6 – Lower Left 3D deflection time history: mean response curves and corridors for a 50th male human surrogate loaded in the Shaw et al. 2009 conditions.

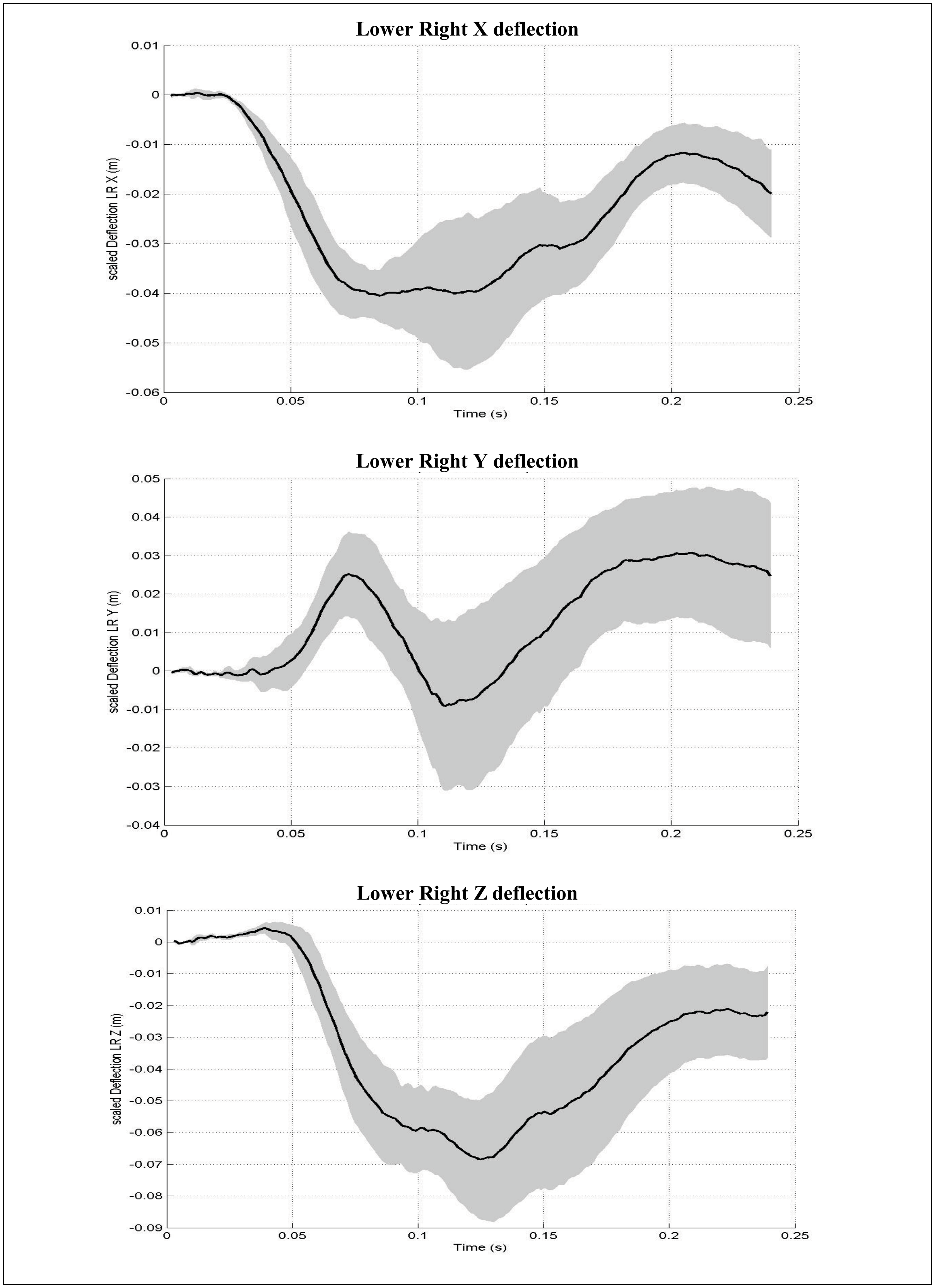

Figure 7 – Lower Right 3D deflection time history: mean response curves and corridors for a 50th male human surrogate loaded in the Shaw et al. 2009 conditions.

Biofidelity targets for Table top test configuration

The chosen test series was presented in a Stapp paper from Kent et al. (UVa) in 2004. Sixty-seven dynamic tests on fifteen PMHS were tested for each of four loading conditions on the anterior thorax: single diagonal belt loading, double diagonal belt loading, distributed loading, and hub loading (see Figure 8).

- The 5-cm-wide diagonal belt passed over the shoulder and crossed the anterior thorax approximately 30° from the sagittal plane. The belt engaged the PMHS clavicle at approximately the proximal third, crossed the midline approximately mid-sternally, and exited the body laterally at approximately the superior-inferior location of the 9th rib.
- The double diagonal belt condition involved a second diagonal belt oriented symmetrically to the diagonal belt described above.
- For distributed loading, a 20.3-cm-wide belt loaded the area approximately between the second and seventh ribs.
- The hub load was applied with a 15.2-cm diameter steel circular plate intended to mimic the loading surface described by Kroell (Kroell et al. 1994). The center of the hub was located at the intersection of the mid-sagittal plane and approximately the 4th intercostal space. The hub edges were beveled to reduce edge stresses. A frame with a bearing track was used with the hub condition to ensure anterior-posterior loading and to prevent the hub from rotating during loading.

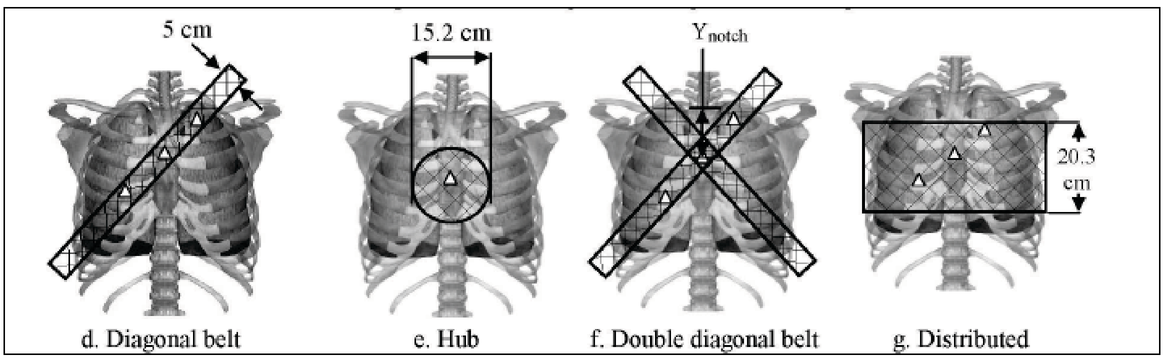

Figure 8 – Schematic depictions of loading conditions (small triangles represent string potentiometer attachment sites).

The posterior boundary condition was a rigid flat plate on which the subject was laid. The subject was not fixed to the flat plate and the spinal curvature was not controlled other than by the flat plate interface. The thoracic spine was virtually free of lordotic or kyphotic curvature at the start and throughout each test.

Minimal biofidelity targets were worked out directly from the corridors developed by Kent et al. 2004. The data processing used in the Kent's paper is summarized below. Since it was intended to develop minimal biofidelity targets, it was estimated that it was not worth to reprocess the Kent's data in the Task Force's fashion (see Method section).

Kent's data processing. Kent et al. 2004 released thoracic force-deflection corridors for the four loading configurations. The posterior reaction force and the mid-sternal chest deflection were used.

The force and deflection responses were normalized to a 45 year-old, 50_{th} percentile Male subject. The effect of age was considered by scaling for age-related changes in the modulus of bone and soft tissues, while the effect of size was considered by scaling based on whole-body mass (Eppinger 1976, Eppinger et al. 1984).

Some features of the corridor development technique of Kent et al. 2004 are recalled hereafter: for each test a second-order curve was fit to the normalized Force-Deflection cross-plot using a least-squares approach. These curves were used to compute the corridors using the technique described by Lessley et al. (2004). A one-standard deviation range was used in both deflection and force.

Biofidelity target definition. The Table Top configuration does not exactly reproduce a real case loading conditions. In particular, important artifact may come from the interaction between the table and the back of the dummy. This part of the dummy which biofidelity is neglectable for a use in real car crash condition can have an important effect on the Force results (superficial tissue/skin properties and spine curvature may play a role).

Consequently, the task force agreed on two major recommendations to take into account the limitations of the configuration: 1) Use the responses comparatively which each other in order to reduce the artifact portion contained in each loading configuration, and 2) target the force values at a determined compression rather than full force-deflection corridors.

The maximum force values at 20% of compression were extracted from the corridors proposed by Kent et al. 2004, which were built using second order best fit curves. Thus, the values were easy to compute using the best fit curve coefficients (see Table 2). Then, these force values were normalized relative to the force value of the average curve of the Single Diagonal Belt loading conditions. The resulting targets are shown in Figure 9 and in Table 2.

Table 2 – Second order curve coefficients, force values and normalized force values at 20% of compression

		Second order curve coefficients		Force value at 20% comp.	**Normalized force value at 20% comp.**
		alpha	beta		
Hub	up. bound	24617	3083.3	1601	**73%**
	ave. curve	22988	781.8	1076	**49%**
	low. bound	17898	-675.7	581	**26%**
Single Diag. Belt	up. bound	11299	12178	2888	**131%**
	ave. curve	28601	5274.9	2199	**100%**
	low. bound	37658	178.6	1542	**70%**
Double Diag. Belt	up. bound	33939	13027	3963	**180%**
	ave. curve	45482	7076.7	3235	**147%**
	low. bound	50994	2501.6	2540	**116%**
Distributed	up. bound	23216	17723	4473	**203%**
	ave. curve	35764	9742.5	3379	**154%**
	low. bound	37692	4260.4	2360	**107%**

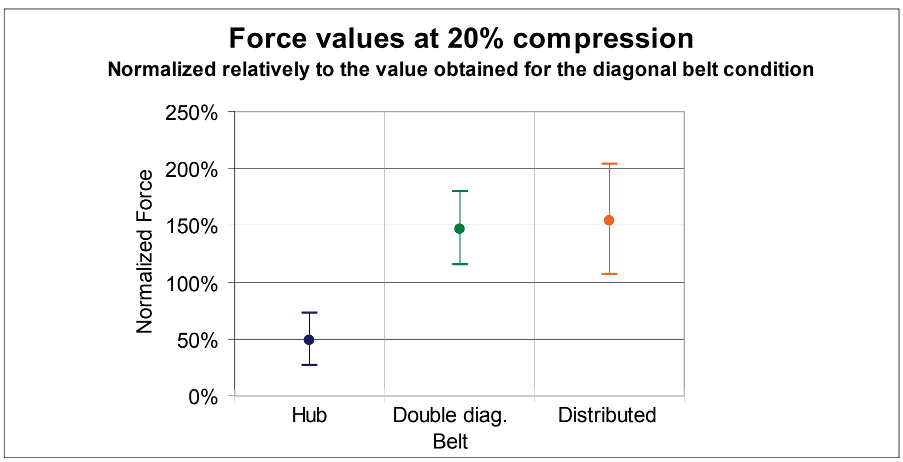

Figure 9 – Proposed biofidelity targets for the Table Top tests.

Biofidelity targets for Impactor test configuration

The initial impactor test sample comprised 38 tests. 30 from GM series (Kroell et al. 1971 and 1974), 7 tests from INRETS series (Bouquet et al. 1994) and 1 test from CEESAR series (Trosseille et al. 2008). The tests consist in a 152 mm diameter, rigid, flat impacting surface with a 12.7 mm edge radius, which strikes the sternum at the 4th rib interspace. The impactor mass and speed varied.

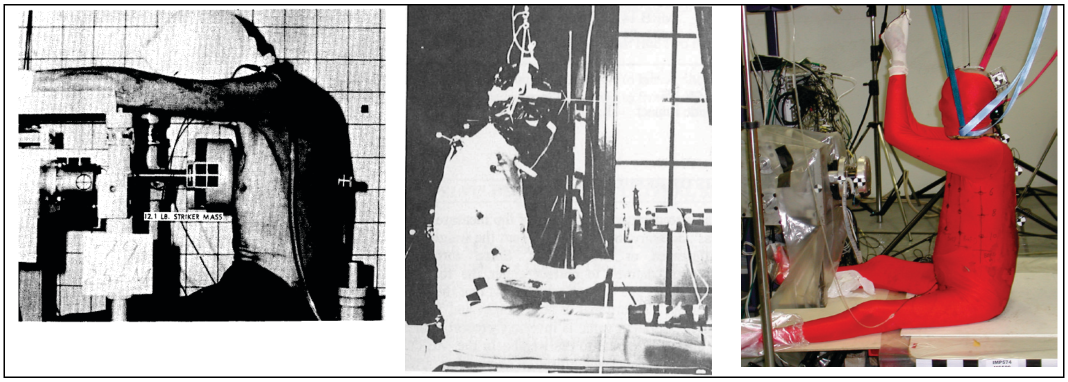

Figure 10 – GM (left), INRETS (center) and CEESAR (right) configurations

Raw data. Except for the test MS589, the data in numerical format were not available any longer. Therefore, the curves were acquired by digitalization from pdf format of the paper in which they were published. The WinDig freeware (http://www.unige.ch/sciences/chifi/cpb/windig.html) was used to digitize Force/time and Deflection/time response curves.

Early force spikes were observed on the response curve at the beginning of the impact. Kroell et al. (1971, 1974) established that these spikes are clearly part of the PMHS response but a doubt remained on a possible part of resonance artifact from the striker. Consequently, the Task Force decided to keep the early spike in the Force/Deflection corridor computation but to define the corresponding portion of the curve as not mandatory for the biofidelity requirement.

Total deflection. The skeletal deflection was estimated for the GM series in but not for the INRETS and CEESAR series, for which the total deflection was kept. The procedure described in Kroell et al. 1971 and 1974 was not clearly defined and could not be applied in similar way on the INRETS and CEESAR tests. Consequently, in order to get consistent measurements between the 3 series, it was preferred to keep the total deflection measurement for all the tests. This choice also avoided to use assumptions to estimate the skeletal deflection.

Test inclusion/exclusion (step 1). The normalized Force/Deflection response signals of the initial test sample were submitted to a shape analysis until maximum deflection using the Nusholtz et al. 2007 technique. The shape resemblance threshold were set to 0,7. Details on the shape analysis are provided in appendix A and a summary is provided in Table 3. Finally, the signal analysis allow to identify four outliers, which have been removed from the initial dataset. It also allowed to separate the tests in 3 different samples, which must not be used together to compute biofidelity targets. These 3 samples are: the very-high-speed/low-mass (v13), the high-speed/high-mass (v6_v9) and the low-speed/high-mass (v3_v5). Their characteristics are given in Table 3. The v13 sample was not used to define biofidelity targets and the work of the Task Force focused on the v6_v9 and v3_v5 samples, also named high speed and low speed samples respectively.

Normalization (step 2). The efficacy of Several scaling techniques were assessed using the method described in Moorhouse 2008. The mass-spring model (Mertz 1984) was the one that offered the best collapsing of the set of curves. The effective mass of the model was dig out from the equation of the dissipated energy (Horsch and Patrick 1976, equation 12) combined with the conservation of momentum equation (Horsch and Patrick 1976, equation 10). The energy dissipated by the thorax at maximum deflection was computed from the Force/Deflection response curves. The chest depth was used to calculate the stiffness ratio. Both samples were normalized to the 50th percentile dimensions and to a 23.4 kg impactor mass. The low speed and high speed samples were normalized to 4.3 m/s and 6.7 m/s impactor speeds respectively.

Signal alignment (step 3). No attempt to align the response curves was made.

Biofidelity targets computation (step 4). Force/Deflection biofidelity targets were developed using the "ellipse technique" described in Shaw et al. 2006. They are shown in Figure 12 and Figure 11 for the low speed and the high speed samples respectively. The k factor was set to 1.52 so that the corridor width corresponds to one standard deviation. The deviation was wide at the end of the impact and ellipses of the unloading phase superimposed over ellipses of the loading phase. Consequently, corridors for the loading and the releasing phases are shown distinctively in Figure 12 and Figure 11. Force/time and Deflection/time responses are provided for the convenience of the user and shown in Figure 13.

Adjustment accounting for muscle tension (step 5). No correction to account for muscle tensing was applied to the biofidelity targets.

Table 3 – Average of the test features and of the shape auto-correlation scores for each sub-sample after the removal of outliers.

- v3 to v13 are sub-samples ranged per impactor speed
- v3_v5 gather the tests of v3, v4 and v5 sub-samples
- v6_v9 gather the tests of v6, v7 and v9 sub-samples
- v3_v9 gather the tests from v3 to v9 sub-samples
- row 2 means that outliers were removed from the sample

sample B (row2)	N		Age	NRF	Height (m)	Weight (kg)	Chest Depth (mm)	Impactor mass (kg)	Impactor speed (m/s)	Shape_corr B (row2)
v3 (row2)	5	**Mean**	**70.6**	**14.5**	**1.74**	**73.3**	**218**	**23.4**	**3.8**	**0.77**
		Std dev.	*11.8*	*7.8*	*0.0*	*8.9*	*25.9*	*0.2*	*0.5*	*0.08*
v4	3	**Mean**	**66.7**	**4.3**	**1.79**	**65.2**	**237**	**23.0**	**5.1**	**0.85**
		Std dev.	*7.37*	*5.13*	*0.05*	*11.39*	*19.31*	*0.06*	*0.2*	*0.02*
v5 (row2)	3	**Mean**	**61.0**	**7.7**	**1.69**	**68.0**	**217**	**22.1**	**6.0**	**0.85**
		Std dev.	*4.6*	*5.8*	*0.1*	*8.6*	*11.55*	*2.25*	*0.3*	*0.03*
v6 (row2)	7	**Mean**	**57.0**	**8.1**	**1.75**	**60.3**	**210**	**22.9**	**6.8**	**0.85**
		Std dev.	*24.9*	*6.8*	*0.1*	*12.7*	*9.8*	*1.5*	*0.1*	*0.03*
v7	7	**Mean**	**63.4**	**13.3**	**1.70**	**69.5**	**233**	**20.8**	**7.5**	**0.74**
		Std dev.	*12.54*	*8.99*	*0.10*	*13.42*	*30.32*	*1.99*	*0.4*	*0.06*
v9	5	**Mean**	**57.0**	**15.0**	**1.79**	**73.2**	**245**	**22.3**	**9.9**	**0.84**
		Std dev.	*12.5*	*6.9*	*0.0*	*11.1*	*5.3*	*1.5*	*0.2*	*0.07*
v13	4	**Mean**	**61.5**	**5**	**1.699**	**56.7**	**218**	**2.7**	**13.3**	**0.82**
		Std dev.	*10.66*	*8.62*	*0.11*	*12.01*	*30.87*	*1.91*	*1.4*	*0.06*
v3_v5	11	**Mean**	**66.9**	**8.1**	**1.7**	**69.6**	**203.9**	**22.9**	**4.7**	**0.75**
		Std dev.	*9.4*	*6.6*	*0.1*	*9.3*	*70.8*	*1.2*	*1.0*	*0.04*
v6_v9	19	**Mean**	**59.4**	**11.8**	**1.7**	**67.0**	**227.7**	**22.0**	**7.9**	**0.75**
		Std dev.	*17.4*	*7.9*	*0.1*	*13.1*	*23.6*	*1.9*	*1.3*	*0.07*
v3_v9	30	**Mean**	**62.1**	**10.7**	**1.7**	**68.0**	**219.0**	**22.3**	**6.7**	**0.70**
		Std dev.	*15.2*	*7.6*	*0.1*	*11.7*	*47.0*	*1.7*	*2.0*	*0.07*

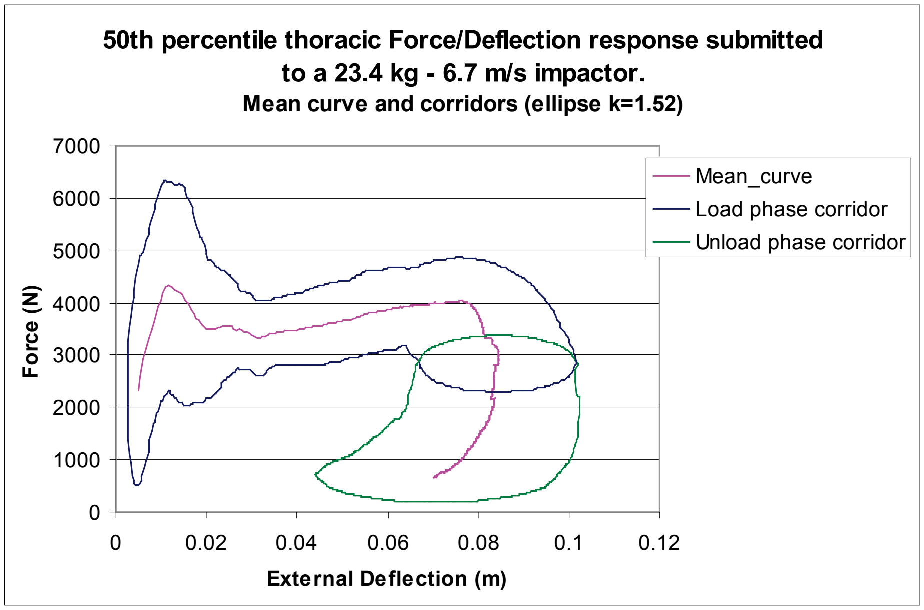

Figure 11 – Proposed biofidelity targets for the high speed impactor test

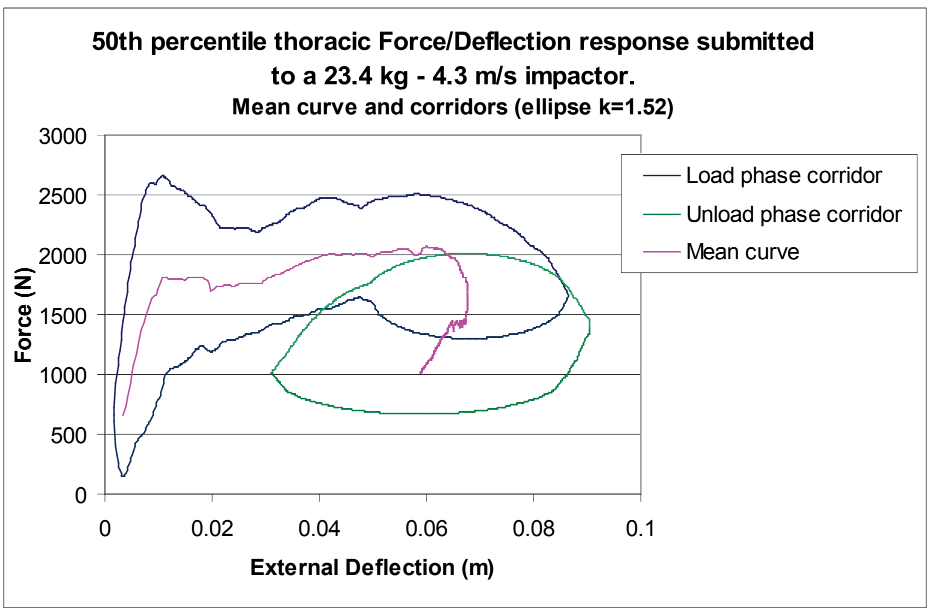

Figure 12 – Proposed biofidelity targets for the low speed impactor test

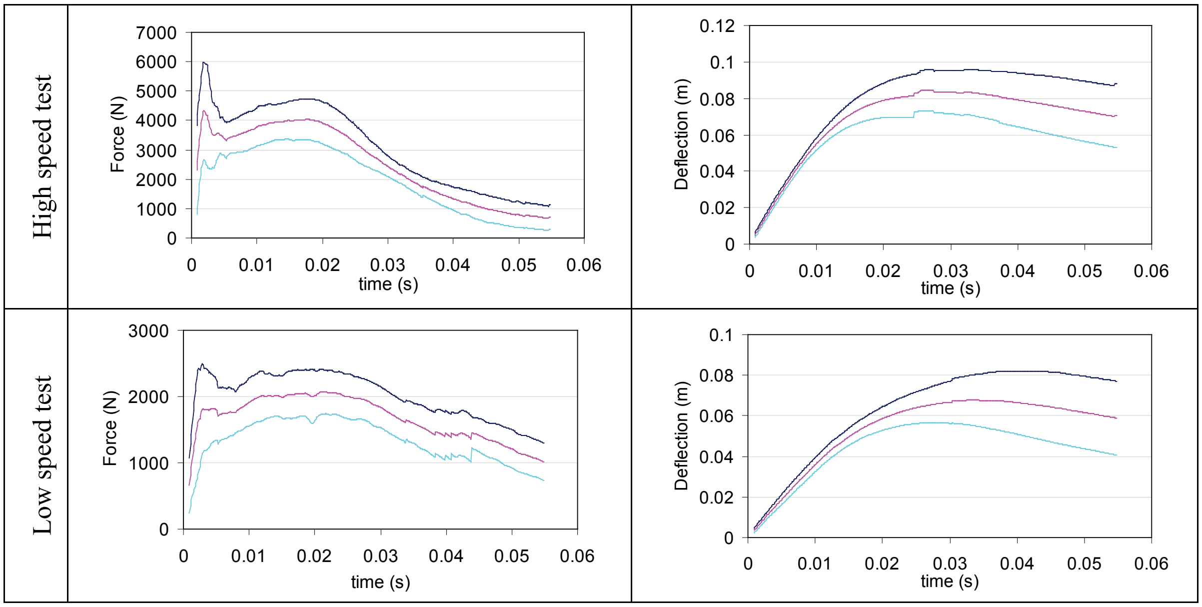

Figure 13 – Force/time and Deflection/time biofidelity targets for the high speed test (6.7 m/s) and the low speed sample (4.3 m/s)

DISCUSSION

Advantages and limitations of the chosen test configurations

The Sled test is the most realistic configuration compared to real world accidents. However, the whole body is put in motion and it may be difficult to assess the biofidelity of the thorax alone. Even in this case where the lower body is well constrained, the lumbar spine stiffness and the head and upper limbs intertia play a role in the response. At least, biofidelity targets for the T8 vertebra displacement time history needs to be developed. In addition, it requires large facilities. For those reasons, additional "sub-system" tests were also very desirable.

The Table Top configuration was found to be controversial for some experts estimate that these kind of tests differs substantially from the vehicle impact condition. Minimal biofidelity targets have been developed to account for the possible artifact generated by these test conditions. The selected test series (Kent et al. 2004) allowed to compare the thoracic responses of different kind of loading relatively to the 3pt belt loading. In particular a response target for the distributed condition is provided. However, it was not known how close from an airbag loading condition it is.

Though it was pointed out that the Impactor test is not the most appropriate configuration as far as belt loading is concerned (ADRIA report 2000), it is still relevant for it simulates a blunt impact. In addition, Trosseille et al. 2008 observed that the thorax submitted to a 15.4 cm diameter, 23.4 kg, 4 m/s impactor strike yielded similar rib strain profiles as the ones observed for an airbag loading. Thus, the Impactor test may be used as a spare configuration to assess airbag loading.

The Task Force did not give any recommendation on the biofidelity targets that should be met in priority. This question belongs to biofidelity ranking, which was out of the scope of the Task Force. For that reason, biofidelity targets for the high speed impactor test were presented although it has been abandoned in the THOR 2011 specifications.

Possible additional test configurations

This set of 3 configurations represents the minimal world wide consensus to assess the thorax biofidelity given the data available today. Nevertheless, it is clear that additional configurations are highly desirable to complete this set of tests.

In particular, relevant configuration for the pure airbag loading is still lacking. Most of the tests found in the literature that used an airbag were excluded for it was poorly described or because the airbag model was not available anymore. For one test configuration the exclusion reason was that it did not contain force measurements: it is a sled test series performed at MCW (Yoganandan et al. 1993, Laituri et al. 2003), which used a lap belt + airbag restraint. If the airbag model is found to be still available, the test series could be further investigated to see if it can provide additional biofidelity guidelines for the airbag loading condition.

However, the availability of an airbag model over a long period of time is never guaranteed and it is believed that the development of generic laboratory airbag would help to solve this reproducibility issue.

Regarding the pure belt loading, the proposed test configurations have limitations: the Shaw et al. 2009 Sled configuration requires large facilities and the Kent et al. 2004 Table Top configuration provided limited biofidelity targets. More convenient and indisputable dynamic belt loading configuration could also be developed in the future. Such configuration could resemble to the one presented in Trosseille et al. 2010 and shown in Figure 14 (this test series was excluded because the thoracic deflection was not measured).

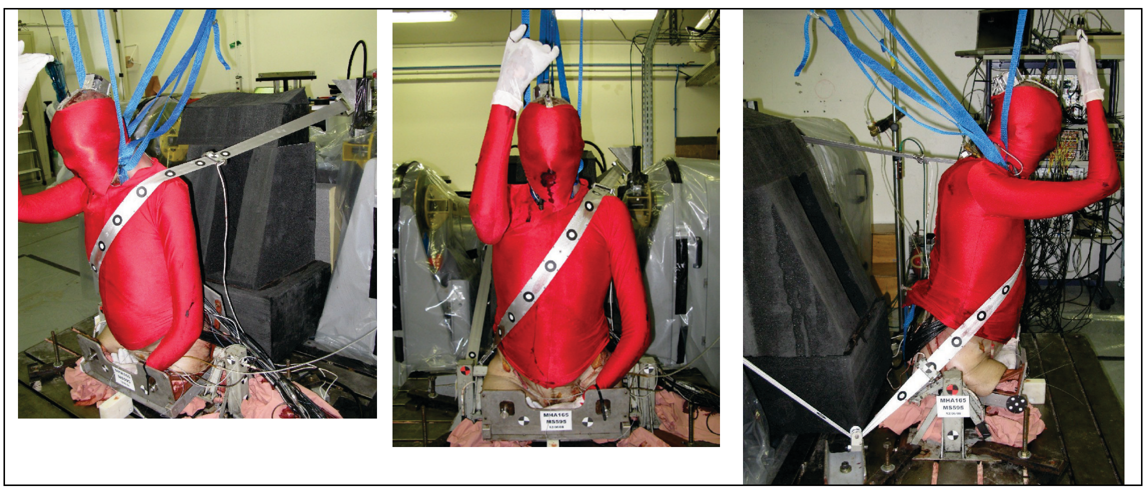

Figure 14 – Sub-system dynamic shoulder belt loading without back constraint (Trosseille et al. 2010)

Although not prioritized by the Task Force, some sled tests using combined loading are still under investigation by Task Force volunteers and the THORAX European consortium. In particular, two Sled test configurations performed at UVa (Kent et al. 2001, Forman et al. 2006) are being investigated. They comprised tests using an airbag + a 3pt force-limited belt with pretensioner restraint (4 PMHS) and tests using an airbag + a standard 3pt belt restraint (4 PMHS). The deflections were measured using a chestband.

Also, MCW performed oblique impacts on the thorax using a padded striker (Yoganadan et al. 1997). They could be used to develop performance requirements if the padding reproducibility is established. This configuration may be useful with regard to small overlap or oblique crashes, which can cause oblique hard contact with the thorax.

Alternative measurements as biofidelity targets

Lastly, it should be underlined that some alternative measurements than the thoracic deflection and sustained force may also be used as biofidelity targets. For instance:

- Accelerations recorded at key points of the ribcage, as proposed in Van Don et al. 2003.
- The strain recorded on the rib as suggested in recent papers from Trosseille et al. (2008, 2009), Baudrit et al. 2010 and Lecuyer et al. 2010. This option is being considered by the THORAX European consortium.

The above items were not discussed within the Task Force.

CONCLUSION

An extensive and up-to-date frontal thoracic test database has been set-up and screened by an International Task Force. Three test configurations has been proposed to assess the thorax biofidelity in frontal impact. They were chosen using selection and priority criteria defined by the Task Force. These three configurations are:

- Table Top tests using diagonal belt, hub and distributed loading,
- Impactor tests using two impact speeds (4.3 m/s and 6.7 m/s),
- Sled test using a 3 point belt restraint, 40 km/h impact, 14 g deceleration.

The biofidelity targets developed from them are :

- Table Top tests: Relative Force at 20% thorax compression,
- Impactor tests: mean curves + corridors for the Force/Deflection responses,
- Sled test: mean curves + corridors for the upper and lower shoulder belt Tension vs. time responses and for the XYZ Deflections vs. time responses measured at 5 points of the anterior wall of the ribcage.

However, this set is not sufficient to fully respond to the biofidelity needs in the present day. The desirable additional test configurations are:

- A pure airbag loading condition.
- A belt plus airbag combined loading condition
- A small laboratory pure belt loading condition
- An oblique hard contact condition

The pure airbag loading test condition may be the most desirable.

Some Sled test series now available in the literature could be used to develop biofidelity targets for these lacking configurations. Some Task Force volunteers and the THORAX European consortium are still working on the item.

Nevertheless, it should be kept in mind that the great majority of the frontal thoracic tests performed in the past were designed to study the injury tolerance and for that reason, very few test series suitable for thorax biofidelity assessment were found. This is particularly true for the sled test configurations: reproducibility issues were not taken into account and too small test series were available. As far as the other configurations are concerned – i.e. the Kroell-like Impactor and the Table Top, which are well defined and for which many PMHS tests are available – it was estimated that their relevance was limited.

Consequently, it is felt that new test series exclusively dedicated to thorax biofidelity should be performed in a close future in order to get relevant and easy to implement test configurations. In particular, two ways of progress were identified by the Task Force:

- The development of a generic laboratory airbag, which would ensure the test reproducibility over time.
- The development of an undisputable sub-system laboratory test mimicking the dynamic belt loading condition that occurred in a real world frontal car crash.

ACKNOWLEDGEMENTS

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APPENDIX

Appendix A – Shape correlation of the impactor Force/Deflection response curves

The initial 38 tests sample was divided into 8 sub-samples, per impactor initial velocity categories. For each test, the shape correlation with the sub-sample it belongs to was calculated. The results are presented in Table 4.

Table 4 – Shape correlation and test features of the 8 subsamples

Tests shaded in grey are outliers.

	Age	NRF	Height (m)	Weight (kg)	Chest Depth (mm)	Impactor mass (kg)	Impactor speed (m/s)	**Shape_corr B**	**sample B**
30FF	52	3	1,56	40,8	180	1,6	13,3	0,88	v13
26FM	75	0	1,73	63,5	248	1,9	11,3	0,86	v13
25FM	65	18	1,68	54,4	207	5,5	13,9	0,8	v13
28FM	54	0	1,83	68,0	238	1,6	14,6	0,74	v13
Mean (all)	**61,5**	**5**	**1,699**	**56,7**	**218**	**2,7**	**13,3**	**0,82**	**v13**
Std dev.	***10,66***	***8,62***	***0,11***	***12,01***	***30,87***	***1,91***	***1,4***	***0,06***	***v13***
MRS03	57	?	1,74	76,0	230	23,4	3,43	0,77	v3
MRS01	76	?	1,73	82,0	250	23,4	3,36	0,76	v3
MS589	88	20	1,69	60,0	180	23,67	4,4	0,75	v3
MRS05	66	?	1,72	69,0	210	23,4	3,39	0,72	v3
60FM	66	9	1,80	79,4	222	23	4,3	0,56	v3
MRS07	69	?	1,64	52,0	220	23,4	3,4	0,53	v3
Mean (all)	**70,3**	**14,5**	**1,72**	**69,7**	**219**	**23,4**	**3,7**	**0,68**	**v3**
Std dev.	***10,6***	***7,8***	***0,1***	***11,8***	***23,2***	***0,2***	***0,5***	***0,11***	***v3***
42FM	61	0	1,83	54,4	216	22,9	4,87	0,87	v4
53FM	75	3	1,74	77,1	241	23	5,2	0,84	v4
45FM	64	10	1,81	64,0	254	23	5,1	0,82	v4
Mean (all)	**66,7**	**4,3**	**1,79**	**65,2**	**237**	**23,0**	**5,1**	**0,85**	**v4**
Std dev.	***7,37***	***5,13***	***0,05***	***11,39***	***19,31***	***0,06***	***0,2***	***0,02***	***v4***
MRS06	66	11	1,72	69,0	210	23,4	5,88	0,77	v5
MRS04	57	1	1,74	76,0	230	23,4	5,81	0,76	v5
11FF	60	11	1,60	59,0	210	19,5	6,3	0,72	v5
MRS08	69	11	1,64	52,0	220	23,4	5,77	0,58	v5
Mean (all)	**63,0**	**8,5**	**1,68**	**64,0**	**218**	**22,4**	**5,9**	**0,71**	**v5**
Std dev.	***5,5***	***5,0***	***0,1***	***10,6***	***9,57***	***1,95***	***0,2***	***0,09***	***v5***
64FM	72	6	1,63	63,0	216	23	6,93	0,80	v6
18FM	78	14	1,77	65,8	219	23,6	6,7	0,80	v6
22FM	72	17	1,83	74,8	226	23,6	6,7	0,78	v6
54FF	49	7	1,63	37,2	205	19,6	6,71	0,75	v6
15FM	80	13	1,65	53,1	200	23,6	6,9	0,75	v6
19FM	19	0	1,96	71,2	203	23,6	6,7	0,75	v6
20FM	29	0	1,80	56,7	203	23,6	6,7	0,72	v6
62FM	76	(AIS 4)	1,74	50,3	245	9,98	6,93	0,66	v6
21FF	45	18	1,74	68,5	213	23,6	6,8	0,47	v6
Mean (all)	**57,8**	**9,4**	**1,75**	**60,1**	**214**	**21,6**	**6,8**	**0,72**	**v6**
Std dev.	***22,9***	***7,2***	***0,1***	***11,9***	***14,2***	***4,5***	***0,1***	***0,10***	***v6***
34FM	64	13	1,78	59,0	241	19	8,3	0,81	v7
14FF	76	7	1,56	57,6	216	22,9	7,3	0,79	v7
23FF	58	23	1,63	61,2	226	19,5	7,8	0,78	v7
46FM	46	0	1,78	94,8	286	19,3	7,4	0,74	v7
13FM	81	21	1,68	76,2	246	22,9	7,4	0,70	v7
12FF	67	22	1,63	62,6	187	22,9	7,2	0,67	v7
36FM	52	7	1,83	74,8	226	19	7,2	0,67	v7
Mean (all)	**63,4**	**13,3**	**1,70**	**69,5**	**233**	**20,8**	**7,5**	**0,74**	**v7**
Std dev.	***12,54***	***8,99***	***0,10***	***13,42***	***30,32***	***1,99***	***0,4***	***0,06***	***v7***
24FM	65	24	1,83	81,6	251	22,9	9,7	0,88	v9
31FM	51	14	1,83	74,8	238	23	10,2	0,88	v9
55FF	46	8	1,77	81,2	241	19,6	9,92	0,87	v9
32FM	75	20	1,71	54,4	248	22,9	9,9	0,84	v9
37FM	48	9	1,79	73,9	248	22,9	9,8	0,72	v9
Mean (all)	**57,0**	**15,0**	**1,79**	**73,2**	**245**	**22,3**	**9,9**	**0,84**	**v9**
Std dev.	***12,5***	***6,9***	***0,0***	***11,1***	***5,3***	***1,5***	***0,2***	***0,07***	***v9***

For each sub-sample, the mean shape resemblance scores is higher than for the whole 38 tests sample, which suggests more homogenous type of shape within each sub-sample. The smaller size of the samples may also explain these results. The low resemblance score is set to equal or less than 0,7. According to Table 4, the tests 60FM, MRS07, MRS08, 62FM, 21FF, 12FF, 13FM, 36FM are potential outliers. Reasons for these deviations have been sought in the test features. For MRS07 and MRS08, the difference can be attributed to the low weight of the PMHS (52 kg) though other light PMHS (such as 42FM, 15FM, 32FM, …) have a similar response with the sub-sample they belong to. 62FM was impacted by a 10 kg impactor while it was 19kg or 23kg for all the other tests of the subsample. Large breast on 21FF has been noted by Kroell et al. 1971. This observation is not quantitative but since it has been noted on this PMHS only, it can be assumed that the 21FF had a quite unusual anthropometry compared to the other PMHS of the Kroell series. Lastly, no explanation has been found for the 60FM, 12FF, 13FM, 36FM tests.

60FM, 12FF, 13FM, 36FM has been kept in the data set. 21FF, 62FM, MRS07 and MRS08 has been considered as outliers and excluded from the data set. After the removal of the outliers, the shape analysis in the sub-sample has been performed again. When it occurred, this second analysis is noted as "row2". The results are presented in Table 5. As expected the average shape correlation scores improved.

Then force-deflection mean curves were developed from each of the 8 sub-samples without outliers. They are presented in Figure 15. Although the curves were supposed to be all normalized to the same impactor mass and speed and PMHS weight and stiffness, variation in the amplitude and duration can be observed. The trend is that the duration shortens and the amplitude increases as the impactor velocity increases. Regarding the shape, the early peak force seems more pronounced for high impactor velocity sub-samples. This suggests that all the tests should not be used in a single sample but at least separated into three speed ranges.

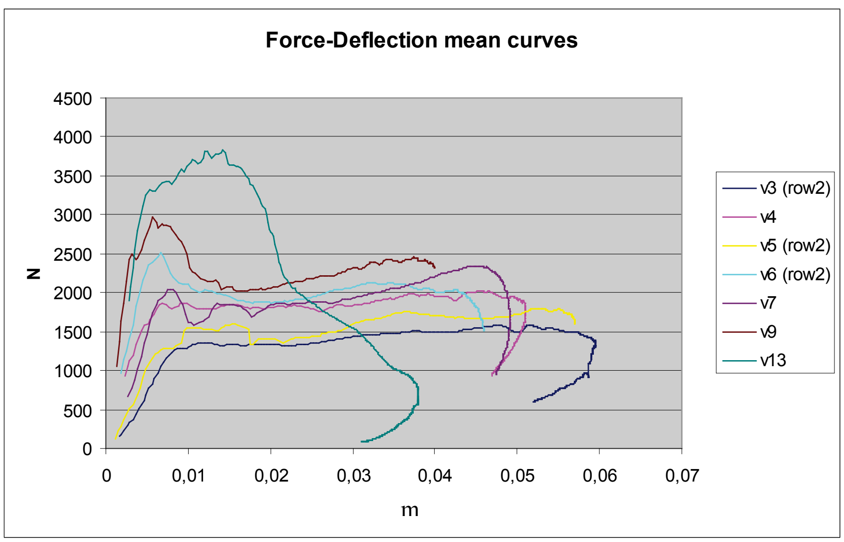

Figure 15 – Average force-deflection responses for the 8 sub-samples without outlier

From this observation, the high speed-low mass sub-sample (v13) has been set aside, and the 7 other sub-samples have been gathered in 2 new sub-samples: A "low speed" and a "high speed" impact sub-samples, named v3_v5 and v6_v9 respectively. Shape correlations have been calculated again for each sub-sample (see Table 5). The mean shape resemblance scores are 0.75 for both sub-samples. Therefore, the homogeneity of the response shapes of the two sub-samples have been considered satisfactory. Average Force-Deflection response curves for the high and low speed sub-samples are shown in Figure 16.

Table 5 – Shape correlation and test features of the 8 subsamples without outliers

	Age	NRF	Height (m)	Weight (kg)	Chest Depth (mm)	Impactor mass (kg)	Impactor speed (m/s)	**Shape_corr B (row2)**	**sample B (row2)**
30FF	52	3	1,56	40,8	180	1,6	13,3	0,88	v13
26FM	75	0	1,73	63,5	248	1,9	11,3	0,86	v13
25FM	65	18	1,68	54,4	207	5,5	13,9	0,8	v13
28FM	54	0	1,83	68,0	238	1,6	14,6	0,74	v13
Mean (all)	**61,5**	**5**	**1,699**	**56,7**	**218**	**2,7**	**13,3**	**0,82**	**v13**
Std dev.	***10,66***	***8,62***	***0,11***	***12,01***	***30,87***	***1,91***	***1,4***	***0,06***	***v13***
MRS03	57	?	1,74	76,0	230	23,4	3,43	0,81	v3 (row2)
MRS01	76	?	1,73	82,0	250	23,4	3,36	0,81	v3 (row2)
MS589	88	20	1,69	60,0	180	23,67	4,4	0,78	v3 (row2)
MRS05	66	?	1,72	69,0	210	23,4	3,39	0,79	v3 (row2)
60FM	66	9	1,80	79,4	222	23	4,3	0,63	v3 (row2)
Mean (all)	**70,6**	**14,5**	**1,74**	**73,3**	**218**	**23,4**	**3,8**	**0,77**	**v3 (row2)**
Std dev.	***11,8***	***7,8***	***0,0***	***8,9***	***25,9***	***0,2***	***0,5***	***0,08***	***v3 (row2)***
42FM	61	0	1,83	54,4	216	22,9	4,87	0,87	v4
53FM	75	3	1,74	77,1	241	23	5,2	0,84	v4
45FM	64	10	1,81	64,0	254	23	5,1	0,82	v4
Mean (all)	**66,7**	**4,3**	**1,79**	**65,2**	**237**	**23,0**	**5,1**	**0,85**	**v4**
Std dev.	***7,37***	***5,13***	***0,05***	***11,39***	***19,31***	***0,06***	***0,2***	***0,02***	***v4***
MRS06	66	11	1,72	69,0	210	23,4	5,88	0,82	v5 (row2)
MRS04	57	1	1,74	76,0	230	23,4	5,81	0,88	v5 (row2)
11FF	60	11	1,60	59,0	210	19,5	6,3	0,85	v5 (row2)
Mean (all)	**61,0**	**7,7**	**1,69**	**68,0**	**217**	**22,1**	**6,0**	**0,85**	**v5 (row2)**
Std dev.	***4,6***	***5,8***	***0,1***	***8,6***	***11,55***	***2,25***	***0,3***	***0,03***	***v5 (row2)***
64FM	72	6	1,63	63,0	216	23	6,93	0,88	v6 (row2)
18FM	78	14	1,77	65,8	219	23,6	6,7	0,89	v6 (row2)
22FM	72	17	1,83	74,8	226	23,6	6,7	0,86	v6 (row2)
54FF	49	7	1,63	37,2	205	19,6	6,71	0,80	v6 (row2)
15FM	80	13	1,65	53,1	200	23,6	6,9	0,83	v6 (row2)
19FM	19	0	1,96	71,2	203	23,6	6,7	0,85	v6 (row2)
20FM	29	0	1,80	56,7	203	23,6	6,7	0,82	v6 (row2)
Mean (all)	**57,0**	**8,1**	**1,75**	**60,3**	**210**	**22,9**	**6,8**	**0,85**	**v6 (row2)**
Std dev.	***24,9***	***6,8***	***0,1***	***12,7***	***9,8***	***1,5***	***0,1***	***0,03***	***v6 (row2)***
34FM	64	13	1,78	59,0	241	19	8,3	0,81	v7
14FF	76	7	1,56	57,6	216	22,9	7,3	0,79	v7
23FF	58	23	1,63	61,2	226	19,5	7,8	0,78	v7
46FM	46	0	1,78	94,8	286	19,3	7,4	0,74	v7
13FM	81	21	1,68	76,2	246	22,9	7,4	0,70	v7
12FF	67	22	1,63	62,6	187	22,9	7,2	0,67	v7
36FM	52	7	1,83	74,8	226	19	7,2	0,67	v7
Mean (all)	**63,4**	**13,3**	**1,70**	**69,5**	**233**	**20,8**	**7,5**	**0,74**	**v7**
Std dev.	***12,54***	***8,99***	***0,10***	***13,42***	***30,32***	***1,99***	***0,4***	***0,06***	***v7***
24FM	65	24	1,83	81,6	251	22,9	9,7	0,88	v9
31FM	51	14	1,83	74,8	238	23	10,2	0,88	v9
55FF	46	8	1,77	81,2	241	19,6	9,92	0,87	v9
32FM	75	20	1,71	54,4	248	22,9	9,9	0,84	v9
37FM	48	9	1,79	73,9	248	22,9	9,8	0,72	v9
Mean (all)	**57,0**	**15,0**	**1,79**	**73,2**	**245**	**22,3**	**9,9**	**0,84**	**v9**
Std dev.	***12,5***	***6,9***	***0,0***	***11,1***	***5,3***	***1,5***	***0,2***	***0,07***	***v9***

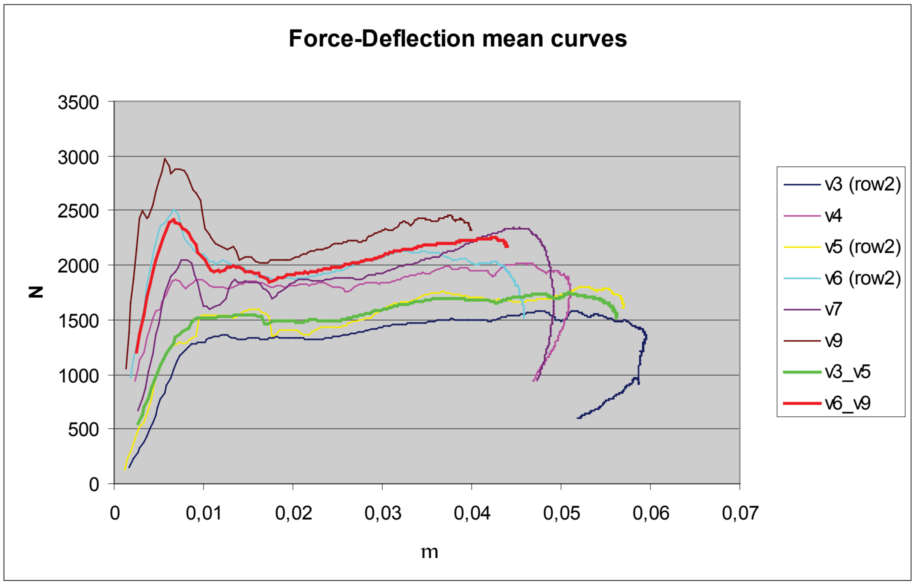

Figure 16 – Average force-deflection responses of the 2 sub-samples "high speed" (v6_v9) and "low speed" (v3_v5) compared to the ones of 7 sub-samples with ranging speeds and without outliers.

The cumulative coefficient of variation (%CV), which reflects the collapsing of the corridor, has been calculated for each sub-sample and presented in Table 6. The %CV values for v6_v9 (high speed sample) and v3_v5 (low speed sample) were considered satisfactory compared to the values of the other sub-samples.

Table 6 – cumulative CV% calculated on force-time, force-deflection and force-deflection sets of curves using VRTC's routine

	Force-time	Deflection-time	Force-Deflection	sample size
v3 (row2)	35,43	19,16	24,32	5
v4	14,71	12,13	5,45	3
v5 (row2)	25,79	6,58	5,58	3
v6 (row2)	20,73	8,51	6,48	7
v7	19,8	11,53	7,05	7
v9	17,31	8,66	5,9	5
v13	33,55	11,07	14,47	4
v3_v5	24,51	11,65	9,64	11
v6_v9	20,87	8,9	6,72	19
v3_v9	26,26	10,12	9,27	30
fover9	23,92	8,61	7,17	14
funder9	26,56	11,78	10,59	16

Study of the effect of rib fractures on the force-deflection response. An analysis was performed to assess the influence of the injury on the shape of the response. The sample v3_v9 (without outliers) was divided into 2 sub-samples, which gather slightly-injured PMHS (named "Fu9": under or equal to 9 rib fractures) and highly-injured PMHS (named "Fo9": over 9 rib fractures) respectively. Table 7 below shows that PMHS anthropometry and impactor initial conditions are similar for both sub-samples.

Table 7 – Average test features for the over 9 (Fo9) and under 9 (Fu9) rib fractures sub-samples

sample B	N		Age	NRF	Height (m)	Weight (kg)	Chest Depth (mm)	Impactor mass (kg)	Impactor speed (m/s)
Fu9	19	***Mean***	***51.6***	***3.8***	***1.75***	***68.2***	***226.8***	***19.0***	***7.3***
		Strd dev.	*12.3*	*3.7*	*0.10*	*14.3*	*23.5*	*7.9*	*3.2*
Fo9	15	**Mean**	**64.8**	**16.7**	**1.72**	**64.7**	**222.7**	**21.3**	**7.8**
		Strd dev.	*10.6*	*4.7*	*0.08*	*8.8*	*23.6*	*4.7*	*2.4*

N column indicates the number of test included in each subsample

The resulting average Force-Deflection curves calculated with Fu9 and Fo9 samples are shown in Figure 17. The differences in shape, magnitude and duration are small. It suggests that the injury is a minor contributing factor in the resulting shape of the response, compared to the impactor mass and speed factors.

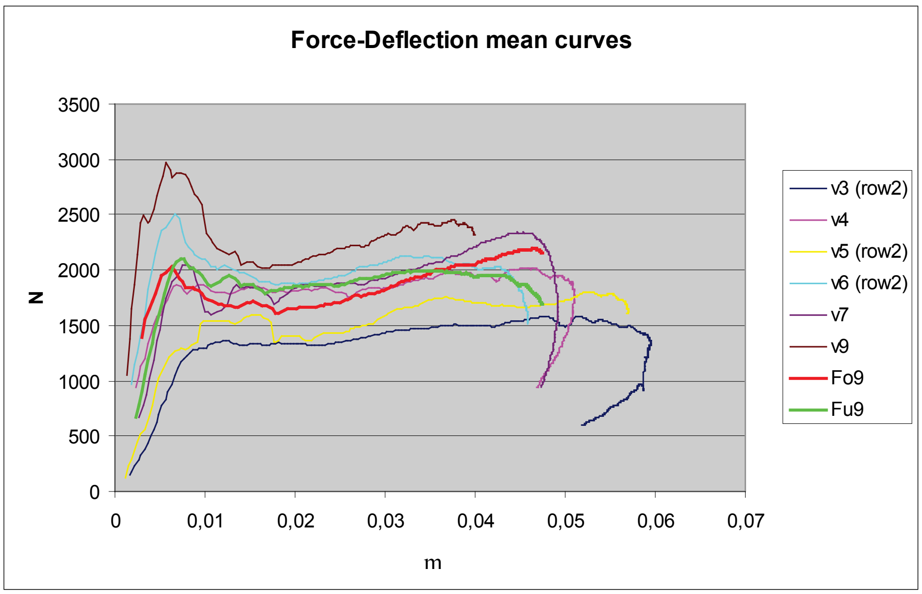

Figure 17 – Average force-deflection responses for the 2 sub-samples: over 9 (Fo9) and under 9 (Fu9) rib fractures compared to the ones of 7 sub-samples without outlier

Appendix B – Discussion on the thoracic coordinate system for the Shaw et al. 2009 sled test series

Shaw et al. 2010 observed that the rotation mobility of the PMHS spine resulted in spine coordinate systems that also rotated relative to the anterior ribcage. This rotation created apparent translations of anterior ribcage sites. In some cases, this resulted in x-axis movement, the established chest deflection metric, which did not reflect the proximity of the anterior site relative to the spine. Figure 18 shows how rotation of the spine-based coordinate system can result in a reduction of the x-axis motion of the anterior ribcage site when the distance between the origin of the coordinate system and the anterior site does not change.

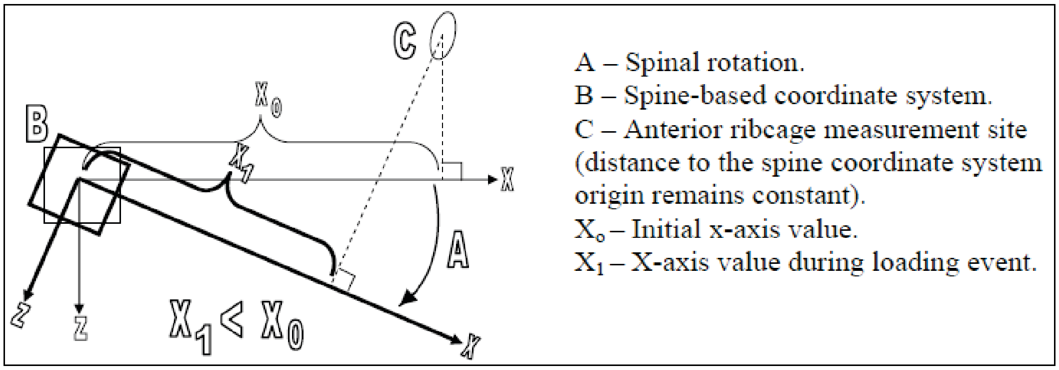

Figure 18 – Effect of spinal rotation on X-axis motion (from Shaw et al. 2010)

However, it was observed that this possible artifact is minimal when the initial position of the anterior ribcage measurement site is close to the X axis of the initial frame (as the red circle on Figure 19): if the Spine-based coordinate system rotates, the resulting X_1 value is closest from the X_0 one. Table 8 shows the XYZ coordinates of the targets in the T8 frame at time 0 for 5 tests. It appears that the upper targets (attached to the right and left ribs and sternum) are close to the X axis of the coordinate system. As expected, the lower targets are the furthest from the X axis. The use of a different coordinate system (T10 or T11 for instance) for the lower targets was considered by the task force but such data were not available at that time and could not be investigated.

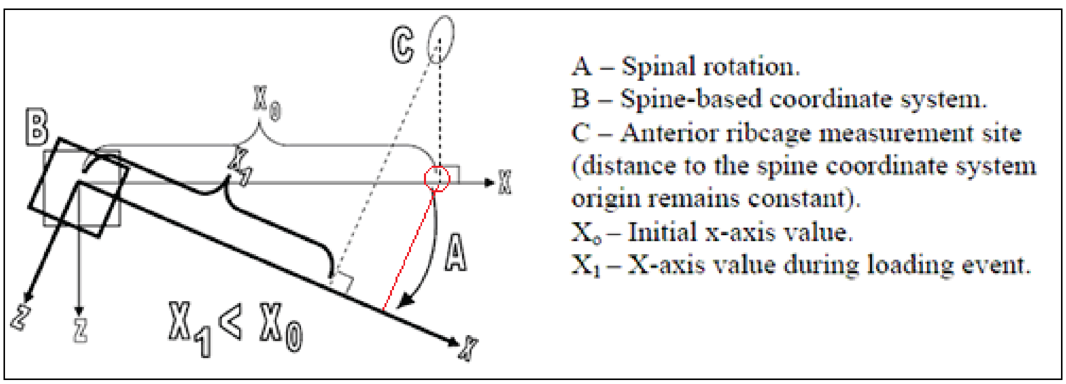

Figure 19 – Effect of spinal rotation on X-axis motion for a measurement site initially aligned with the X-axis of the spine-based coordinate system (red circle) – featuring Shaw et al. 2010.

Consequently, the T8 “spline Coordinate System” was kept to express the deflection of all the targets. As far as the proximity of the anterior wall of the thorax relative to the spine was concerned – the X deflection –, the relevance or accuracy of the X deflection in the T8 frame is deemed satisfactory for the upper targets. The lower targets X response may include a greater contribution of the spine movement. Although spine curvature variation is part of the thorax response, it may be more difficult to meet the lower targets for a dummy with a stiff thoracic spine.

Table 8 – Initial XYZ coordinates of the 5 ribcage measurement sites in the T8 spine-based coordinate system for five of the height tests of the series.

		Initial position in the T8 frame (mm)						
		1294	**1295**	**1378**	**1379**	**1380**	Mean	Std dev.
Sternum	**X**	149	150	134	152	144	146	7
	Y	6	7	-9	-13	-17	-5	11
	Z	31	10	9	-5	16	12	13
Upper left chest	**X**	146	143	129	143	133	139	7
	Y	-47	-34	-58	-45	-61	-49	11
	Z	25	20	48	-14	31	22	23
Upper right chest	**X**	149	144	113	145	135	137	15
	Y	42	37	68	18	24	38	19
	Z	23	4	40	-5	15	15	18
Lower left chest	**X**	111	166	127	135	122	132	21
	Y	-120	-70	-119	-124	-135	-114	25
	Z	130	137	101	92	141	120	22
Lower right chest	**X**	127	173	130	150	145	145	18
	Y	96	101	89	61	83	86	15
	Z	129	116	110	65	125	109	26

Appendix C – Equations of a Mass-spring model adapted to a frontal sled test configuration

A simple mass-spring model is used to work out scaling ratios applicable to a sled test. A constant deceleration is applied to the mass-spring system.

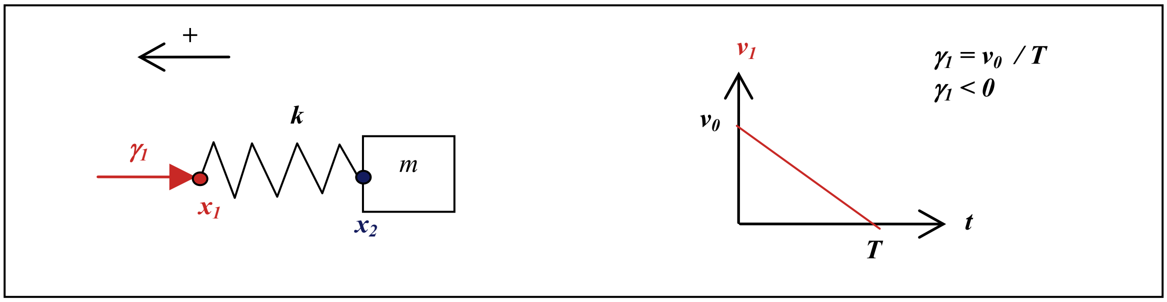

Figure 20 – mass spring model, with a constant deceleration which duration is T

The first assumptions are:

- the torso is assimilated to the rigid mass m
- abdomen shear forces and head and upper limbs inertia are included in this rigid mass value m. Consequently, m is the effective mass of the torso.
- the stiffness of the torso is modelized with the linear spring k. The stiffness of the belt is assumed to be very high
- the deceleration is applied at the belt anchorages reduce to one point on the model

$$m.\frac{d^2x_2}{dt^2} = -k.(x_2 - x_1)$$

$$m.\frac{d^2(x_2 - x_1)}{dt^2} + k.(x_2 - x_1) = -m.\frac{d^2x_1}{dt^2}$$

Let put $x = x_2 - x_1$

$$m.\frac{d^2x}{dt^2} + k.x = -m.\gamma_1 \quad (1)$$

Equation (1) is right until t = T

At $t = 0$: $\begin{cases} x = 0 \\ \dfrac{dx}{dt} = 0 \end{cases}$

General solution: $x = x_0 . \sin(\omega.t+\varphi)$ *with* $\omega^2 = k / m$
Particular solution: $x = - m.\gamma_1 / k$

And so : $x = x_0 . \sin(\omega.t+\varphi) - m.\gamma_1 / k$

At $t = 0$: $\begin{cases} x = 0 \\ \dfrac{dx}{dt} = 0 \end{cases} \Rightarrow \quad \omega.x_0 \cos\varphi = 0 \quad \Rightarrow \quad \varphi = \dfrac{\pi}{2}$

So for $t < T$, $x = \dfrac{m.\gamma_1}{k}(\cos\omega.t - 1)$

<u>Case 1:</u> $T > \pi / \omega$
The maximum x occurs <u>before</u> γ_1 stops

x is maximum for $\omega.\, t = \pi$ → $t = \pi / \omega$
$\Rightarrow x_{\max} = \dfrac{m.\varphi_1}{k}(-1-1) = -2\dfrac{m.\gamma_1}{k}$
So $F_{max} = -2.m.\gamma_1$

<u>Case 2:</u> $T < \pi / \omega$
The maximum x occurs <u>after</u> γ_1 stops

This case is not developed here, because it is believed that Shaw et al. 2009 sled test correspond to case 1. This is the second assumption.

Second assumption: Figure 21 show that the sled deceleration has a trapezoïde profile rather than a square profile as required to exactly fit the model proposed in Figure 20. At 120 ms, the deceleration is almost over. The middle of the descending slope is around 100 ms, which could be the end of the equivalent square profile. A quasi-plateau is observed on the force and deflection responses. The deflection maxima are reported to occur between 90 and 110 ms in the Stapp paper. Considering the deceleration, belt force and thoracic deflection profiles, we are at the limit between case 1 and case 2 resolutions. For convenience matter, case 1 will be chosen.

This yields the following equations at the time when the deflection X is maximum:

$$\begin{cases} t = \pi.\sqrt{\dfrac{m}{k}} \\ X_{\max} = -2.\dfrac{m.\gamma_1}{k} \\ F_{\max} = -2.m.\gamma_1 \end{cases}$$

Our normalization targets are:
- The same impact features : belt position, initial speed and deceleration profile → the deceleration ratio is equal to 1.
- The 50^{th} percentile mass and stiffness characteristics

Which give the following scaling ratios:

$$\begin{cases} \lambda_t = \sqrt{\dfrac{\lambda_m}{\lambda_k}} \\ \lambda_X = \dfrac{\lambda_m}{\lambda_k} \\ \lambda_F = \lambda_m \end{cases}$$

Third assumptions:

- A geometric similarity is assumed between the subjects. Thus the chest depth (as given by the Shaw et al. 2009 anthropometry table for the PMHS and as given by the Robin's drawing of UMTRI reports for the 50^{th} percentile) will be used to compute the stiffness ratio.
- The ratio (torso effective mass / total body mass) is constant from a subject to another. Thus, the total body mass will used to calculate the mass scaling ratio.
- The belt tension is proportional to the normal force applied to the thorax → the force ratio can be applied to the belt tension.

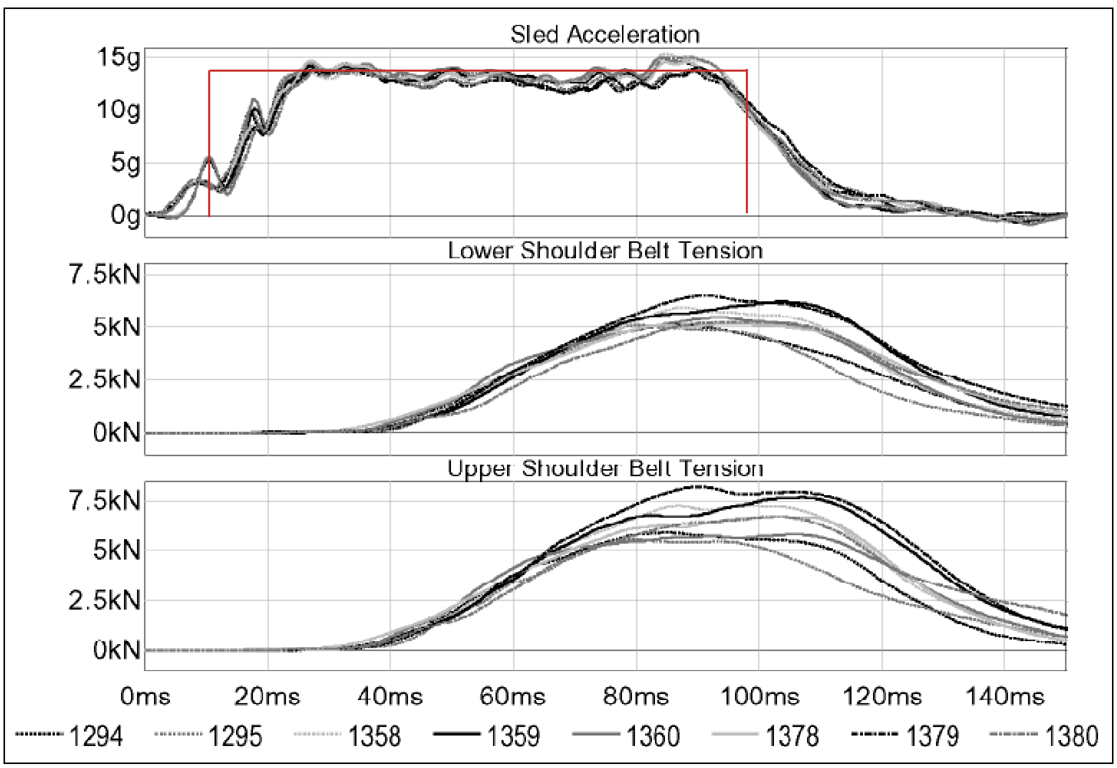

Figure 21 - Sensor time-history plots. Time in milliseconds on the X-axis (from Shaw et al. 2009 Stapp paper)

Appendix D – Sled test: %CV and standard deviation values of unscaled and scaled set of curves

Table 9 – average %CV and standard deviation from 0 to 250 ms for unscaled and scaled set of curves

	Unscaled		scaled using Eppinger		scaled using Mass-spring	
	%CV	av Std (N and mm)	%CV	av Std (N and mm)	%CV	av Std (N and mm)
lower shoulder belt	15.9	283.5	13.7	244.1	20.2	328
upper shoulder belt	17.7	391.1	14.8	316.7	20.4	386.1
Sternum X	42.47	11.9	50	13.8	56.4	16.6
Sternum Y	175.9	12.3	164.3	12.4	176.7	13.1
Sternum Z	77.5	6.6	74.9	6.7	81.3	7.7
Upper Left X	60.1	13.2	59.8	13.2	68.1	14.3
Upper Left Y	46.6	5.5	43.9	5.4	46.8	5.9
Upper Left Z	139.6	8.1	138.1	8	138	8.8
Upper Right X	58.5	14	56.8	13.9	89.3	19.5
Upper Right Y	45.5	6.4	43	6.3	43.1	6.5
Upper Right Z	202.8	10.5	243.3	10.5	365	13.3
Lower Left X	57.5	10.8	59	11.3	64.8	0.013
Lower Left Y	84	13.3	80	13.1	71.9	12.6
Lower Left Z	129.3	9.2	127.9	8.9	130.3	9.5
Lower right X	277.2	7.4	411.5	7.4	281.1	10.2
Lower right Y	78.6	13.1	83	13.7	82	13.6
Lower right Z	64.7	13.2	69	13.8	121	14.8