# New Biofidelity Targets for the Thorax of a 50th Percentile Adult Male in Frontal Impact

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***Abstract*** Since the 1970s, many biofidelity targets for the thorax in frontal impact have been proposed for both dummy and finite element (FE) model application. This paper proposes an update using three test configurations: impactor, sled with a 3-point belt restraint and table top. For the impactor configuration, an extensive Post Mortem Human Subject (PMHS) test database was constituted using both recent and old tests. The considered responses were the impactor force versus thoracic external deflection. The normalization process was updated using a mass-spring model. Recent published methods were used to exclude outliers and pool the PMHS tests into consistent samples. For the sled configuration, a recent test series of 8 PMHS subjected to the same impact conditions was chosen. The considered responses were the shoulder belt tension versus time and the deflection versus time of 5 points at the anterior wall of the ribcage in the X, Y and Z directions. The responses were normalized using a mass-based technique. Interpolation of missing portions of signals were performed for some tests. The T8 vertebra was chosen to define the thoracic coordinate system. The average PMHS response curve plus and minus one standard deviation was proposed as a biofidelity target for both the impactor and sled configurations. The table top configuration was considered in order to develop a biofidelity target for a distributed loading condition. A recent test series that used both distributed and diagonal belt loading conditions was chosen. To account for the limitations of this test configuration with respect to a real car crash, only the force values at 20% of thoracic compression were taken and were used relatively to the diagonal belt loading.

***Keywords*** 50th Percentile, Biofidelity, Frontal impact, PMHS, Thorax.

## I. INTRODUCTION

In frontal impact, the thoracic biofidelity of dummies and FE-models has been a subject of concern for years [1]-[10]. In the 1970s, General Motors Research Laboratories conducted impact tests [12], [14] using Post Mortem Human Subjects (PMHS) in order to guide the design of the Hybrid III dummy thorax. It consisted of impactor strikes, which aimed at mimicking the blunt impact of an unrestrained driver against the hub of a steering wheel. The associated biofidelity corridors [15] were developed using the thoracic force versus skeletal deflection responses of the PMHS. Then, the implementation in cars of enhanced restraint systems such as seat belts or airbags motivated researchers to develop new biofidelity targets corresponding to these new loading patterns on the thorax. Consequently, new PMHS test series were conducted. For the great majority, it consisted of either sled test configurations [20]-[23], where the whole body was submitted to a deceleration, or table top test configurations [24]-[30], where the subject lied supine on a horizontal rigid table. In both configuration cases, diagonal belt loadings, distributed loadings or a combination of both were applied on the PMHS torsos and applied force vs. thoracic deflection biofidelity response targets were worked out from these tests.

The last noticeable needs for thoracic biofidelity targets were for the design of the THOR-α dummy in the 1990s [3]-[5] and the development of FE-model [6]-[7] such as THUMS in 2002 [7]. Besides, through the FID project in

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2003, EEVC-Working Group 12 proposed a selection of test configurations with associated response targets to assess the biofidelity of 50$^{th}$ percentile surrogates (anthropomorphic test devices (ATDs) or FE-models) [9].

Since that date, new PMHS tests were performed and there is a continuing effort to enhance the biofidelity of Human Body FE-models or ATDs. As examples of these efforts, the Global Human Body Modeling Consortium[4] (GHBMC) launched in 2006 and the European Union's THORAX project[5] launched in 2009. Accurate response biofidelity targets are then still needed and this paper proposes an update on three test configurations commonly used to assess the thorax biofidelity in frontal impact: impactor, sled and table top.

## II. METHODS

Different proposals can be found in the literature to define and compute biofidelity targets [13], [38], [39], [40], the more commonly used being the corridor. It was chosen in the present paper to provide as biofidelity targets: a mean response curve plus a one standard deviation data band corridor. The mean response curve is the target that a human surrogate should approach. The standard deviation around the mean curve reflects the reality of the dispersion of the tested PMHS and can be used either as a corridor or as an indication of the consistency of the mean response.

### *Impactor test*

The test series that used a rigid 15.2 cm diameter cylindrical impactor striking the sternum at the 4th rib interspace were selected. Originally designed to mimic a hub impact [11], this test configuration is consequently limited to assess the biofidelity of a thorax submitted to a 3pt-belt and airbag loading conditions [8]. However, Trosseille et al. [19] observed that the ribcage strain pattern induced by an impactor was similar to the one induced by an airbag. But the major interest of the impactor test is its easy implementation for both FE-model and ATDs, and it still remained a well-accepted standard to assess the biofidelity of the thorax [6]-[10]. In addition, many PMHS were tested in this configuration, which provided a large initial data set.

Two biofidelity corridors for low speed and high speed impact respectively were proposed by Lobdell et al. in 1973 [13] using the test series published by Nahum et al. [11] in 1970 and Kroell et al. [12] in 1971. “Eyeball“ averages of the Impactor force versus Skeletal deflection non-normalized responses were worked out from 3 PMHS tests published by Nahum et al. [11] for the low speed corridor, and from 8 PMHS tests published by Kroell et al. [12] for the high speed impact corridor. Then, to approximate muscular stiffening for a maximally tensed condition, a constant force augment of 667.5 N was applied to the entire force-deflection corridor for both the low speed and high speed tests. Finally, corridor bounds were constructed with segments by straddling the averaged curves by approximately ± 15% of the load out to peak load and, during unloading, ± 15% of the deflection, from maximum deflection down to the 890 N level.

An update of these biofidelity corridors was performed by Neathery [15] in 1974. The average responses proposed by Lobdell et al. [13] were adjusted by using normalization equations established using the data of the expanded data set [11], [12], [14]. Corridor bounds were constructed using the same principle as Lobdell et al. [13] but the shape of the corridor defined by the segments differed slightly.

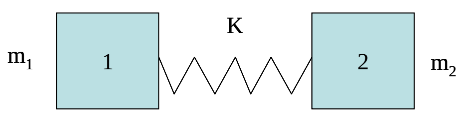
In addition to the fact that more impactor test series were performed [16]-[19] since that time, it was estimated desirable to update the corridors using more common and recent normalization techniques [32], and using the most recent biofidelity target construction methods [39].

[4] http://www.ghbmc.com
[5] http://www.thorax-project.eu

Thus, the initial impactor test sample comprised 38 tests and was composed of four test series: Kroell et al. [12], [14], Bouquet et al. [16] and Trosseille et al. [19]. The back of the PMHS was not constrained for all the tests. Test features and PMHS anthropometry are given in Table 1.

Raw data – Contrary to the previous studies [11]-[15], it was chosen to consider the total deflection of the thorax rather than the skeletal deflection and to keep the early spikes observed on some force/time responses. The older test series performed by Nahum et al. [11] provided only skeletal deflection data. This explains why it was not included in the initial impactor test sample. Except for the test MS589, the data in numerical format were not available any longer. Therefore, the curves were acquired by digitalization of the figures published in the original papers [12], [14] for the Kroell et al. series and in a CEESAR internal report [17] for the Bouquet et al. series.

Normalization – A normalization technique was published by Mertz in 1984 [32] and adapted to pendulum impact test configuration by Viano in 1989 [33]. It consisted in using a lumped parameter model composed of two masses representing the impactor and the PMHS respectively, and one linear spring representing the stiffness of the impacted body region, assumed to be constant during impact. The equations derived from this model allowed to normalize the PMHS biomechanical responses to a desired impactor mass and speed and PMHS 50$^{th}$ percentile anthropometry. This normalization technique was applied to the present data set but adapted to the test conditions. First, compared to the equations presented by Viano ([33], p. 118), an impactor mass ratio was added to account for variations of impactor mass in the dataset. Second, because the PMHS spine acceleration was not available for all the tests, the PMHS effective mass was computed as proposed by Horsch and Patrick [34] in 1976 [34], by combining the equations of the dissipated energy and of the conservation of momentum (see equation 4 in Figure 1). Lastly, the chest depth rather than the chest breadth was used to calculate the stiffness ratio to adapt to a frontal impact case. The resulting normalization factors $\lambda_t$ , $\lambda_X$ , and $\lambda_F$ for the time, deflection and impactor force respectively are given in Figure 1**.**




$$\begin{cases} \lambda_t = (\lambda_K)^{-1/2} * (\lambda_{m_2})^{1/2} * (\lambda_{m_1})^{1/2} * (\lambda_{m_1+m_2})^{-1/2} \quad (1) \\ \lambda_X = (\lambda_K)^{-1/2} * (\lambda_{m_2})^{1/2} * (\lambda_{m_1})^{1/2} * (\lambda_{m_1+m_2})^{-1/2} * \lambda_{v_0} \quad (2) \\ \lambda_F = (\lambda_K)^{1/2} * (\lambda_{m_2})^{1/2} * (\lambda_{m_1})^{1/2} * (\lambda_{m_1+m_2})^{-1/2} * \lambda_{v_0} \quad (3) \end{cases}$$

- For U being any parameter, the normalization ratio is defined as $\lambda_U = U_r / U_i$ , where subscript i refers to any original test, and subscript r refers to the standard test targeted by the normalization.
- $m_1$ is the impactor mass.
- $v_0$ is the impactor initial speed.
- $K$ is the PMHS stiffness. The stiffness ratio is computed using the chest depth: $\lambda_K = \lambda_D$ . The chest depth of a 50$^{th}$ percentile adult male is $D_r$ = 229,5 mm.

**- $m_2$** is the PMHS effective mass computed as follows : $m_2 = \dfrac{2.E_d.m_1}{m_1.v_0^{\,2} - 2.E_d}$ (4) , where $\boldsymbol{E_d}$ is the dissipated energy computed on the force/deflection curves until maximum deflection. The effective mass $\boldsymbol{m_2}$ for a 50th percentile is computed as follow: $m_{2-r} = m_{total-r} * \left( \sum_i^n \dfrac{m_{2-i}}{m_{total-i}} \right) / n$ , with $\boldsymbol{m_{total-r}}$ being the total body weight of a 50$^{th}$ percentile adult male : 76 kg

Figure 1 – Illustration of the Mertz (1984) normalization technique adapted to a frontal impactor strike

Table 1 – Test features

**In the "PMHS n°" column, the * symbol denotes an excluded test (outlier). From "Age" column to "Impactor speed" column, the * symbol indicates an odd parameter supporting the exclusion of the outlier. In the "Shape resemblance" column, the * symbol denotes a value under 0.7 indicating a possible outlier. In the "injury group" column, "L" stands for "Less than 9 rib fractures" (or equal) and "M" for "More than 9 rib fractures".**

| | | PMHS n° | Age | NRF | Height (m) | Weight (kg) | Chest depth (mm) | Impactor mass (kg) | Impactor speed (m/s) | Shape resem-blance | Injury group |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Low speed sample | Group 1 | MRS01 | 76 | na | 1.73 | 82.0 | 250 | 23.4 | 3.36 | 0.76 | L |
| | | MRS05 | 66 | na | 1.72 | 69.0 | 210 | 23.4 | 3.39 | 0.72 | L |
| | | *MRS07** | 69 | na | 1.64 | 52.0* | 220 | 23.4 | 3.4 | 0.53* | / |
| | | MRS03 | 57 | na | 1.74 | 76.0 | 230 | 23.4 | 3.43 | 0.77 | L |
| | | 60FM | 66 | 9 | 1.80 | 79.4 | 222 | 23 | 4.3 | 0.56* | L |
| | | MS589 | 88 | 20 | 1.69 | 60.0 | 180 | 23.67 | 4.4 | 0.75 | M |
| | | **Mean** | **70.3** | **14.5** | **1.72** | **69.7** | **218.7** | **23.4** | **3.7** | **0.68** | |
| | | ***Std dev.*** | ***10.6*** | ***7.8*** | ***0.05*** | ***11.8*** | ***23.2*** | ***0.2*** | ***0.5*** | ***0.11*** | |
| | Group 2 | 42FM | 61 | 0 | 1.83 | 54.4 | 216 | 22.9 | 4.87 | 0.87 | L |
| | | 45FM | 64 | 10 | 1.81 | 64.0 | 254 | 23 | 5.1 | 0.82 | M |
| | | 53FM | 75 | 3 | 1.74 | 77.1 | 241 | 23 | 5.2 | 0.84 | L |
| | | **Mean** | **66.7** | **4.3** | **1.79** | **65.2** | **237.0** | **23.0** | **5.1** | **0.85** | |
| | | ***Std dev.*** | ***7.4*** | ***5.1*** | ***0.05*** | ***11.4*** | ***19.3*** | ***0.1*** | ***0.2*** | ***0.02*** | |
| | Group 3 | *MRS08** | 69 | 11 | 1.64 | 52.0* | 220 | 23.4 | 5.77 | 0.58* | / |
| | | MRS04 | 57 | 1 | 1.74 | 76.0 | 230 | 23.4 | 5.81 | 0.76 | L |
| | | MRS06 | 66 | 11 | 1.72 | 69.0 | 210 | 23.4 | 5.88 | 0.77 | M |
| | | 11FF | 60 | 11 | 1.60 | 59.0 | 0 | 19.5 | 6.3 | 0.72 | M |
| | | **Mean** | **63.0** | **8.5** | **1.68** | **64.0** | **165.0** | **22.4** | **5.9** | **0.71** | |
| | | ***Std dev.*** | ***5.5*** | ***5.0*** | ***0.07*** | ***10.6*** | ***110.3*** | ***2.0*** | ***0.2*** | ***0.09*** | |
| High speed sample | Group 4 | 18FM | 78 | 14 | 1.77 | 65.8 | 219 | 23.6 | 6.7 | 0.80 | M |
| | | 22FM | 72 | 17 | 1.83 | 74.8 | 226 | 23.6 | 6.7 | 0.78 | M |
| | | 19FM | 19 | 0 | 1.96 | 71.2 | 203 | 23.6 | 6.7 | 0.75 | L |
| | | 20FM | 29 | 0 | 1.80 | 56.7 | 203 | 23.6 | 6.7 | 0.72 | L |
| | | 54FF | 49 | 7 | 1.63 | 37.2 | 205 | 19.6 | 6.71 | 0.75 | L |
| | | *21FF** | 45 | 18 | 1.74 | 68.5 | 213 | 23.6 | 6.8 | 0.47* | / |
| | | 15FM | 80 | 13 | 1.65 | 53.1 | 200 | 23.6 | 6.9 | 0.75 | M |
| | | 64FM | 72 | 6 | 1.63 | 63.0 | 216 | 23 | 6.93 | 0.80 | L |
| | | *62FM** | 76 | (AIS 4) | 1.74 | 50.3 | 245 | 9.98* | 6.93 | 0.66* | / |
| | | **Mean** | **57.8** | **9.4** | **1.75** | **60.1** | **214.4** | **21.6** | **6.8** | **0.72** | |
| | | ***Std dev.*** | ***22.9*** | ***7.2*** | ***0.11*** | ***11.9*** | ***14.2*** | ***4.5*** | ***0.1*** | ***0.10*** | |
| | Group 5 | 36FM | 52 | 7 | 1.83 | 74.8 | 226 | 19 | 7.2 | 0.67* | L |
| | | 12FF | 67 | 22 | 1.63 | 62.6 | 187 | 22.9 | 7.2 | 0.67* | M |
| | | 14FF | 76 | 7 | 1.56 | 57.6 | 216 | 22.9 | 7.3 | 0.79 | L |
| | | 46FM | 46 | 0 | 1.78 | 94.8 | 286 | 19.3 | 7.4 | 0.74 | L |
| | | 13FM | 81 | 21 | 1.68 | 76.2 | 246 | 22.9 | 7.4 | 0.70 | M |
| | | 23FF | 58 | 23 | 1.63 | 61.2 | 226 | 19.5 | 7.8 | 0.78 | M |
| | | 34FM | 64 | 13 | 1.78 | 59.0 | 241 | 19 | 8.3 | 0.81 | M |
| | | **Mean** | **63.4** | **13.3** | **1.70** | **69.5** | **232.6** | **20.8** | **7.5** | **0.74** | |
| | | ***Std dev.*** | ***12.5*** | ***9.0*** | ***0.10*** | ***13.4*** | ***30.3*** | ***2.0*** | ***0.4*** | ***0.06*** | |
| | Group 6 | 24FM | 65 | 24 | 1.83 | 81.6 | 251 | 22.9 | 9.7 | 0.88 | M |
| | | 37FM | 48 | 9 | 1.79 | 73.9 | 248 | 22.9 | 9.8 | 0.72 | L |
| | | 32FM | 75 | 20 | 1.71 | 54.4 | 248 | 22.9 | 9.9 | 0.84 | M |
| | | 55FF | 46 | 8 | 1.77 | 81.2 | 241 | 19.6 | 9.92 | 0.87 | L |
| | | 31FM | 51 | 14 | 1.83 | 74.8 | 238 | 23 | 10.2 | 0.88 | M |
| | | **Mean** | **57.0** | **15.0** | **1.79** | **73.2** | **245.2** | **22.3** | **9.9** | **0.84** | |
| | | ***Std dev.*** | ***12.5*** | ***6.9*** | ***0.05*** | ***11.1*** | ***5.3*** | ***1.5*** | ***0.2*** | ***0.07*** | |
| | Group 7 | 26FM | 75 | 0 | 1.73 | 63.5 | 248 | 1.9 | 11.3 | 0.86 | / |
| | | 30FF | 52 | 3 | 1.56 | 40.8 | 180 | 1.6 | 13.3 | 0.88 | / |
| | | 25FM | 65 | 18 | 1.68 | 54.4 | 207 | 5.5 | 13.9 | 0.8 | / |
| | | 28FM | 54 | 0 | 1.83 | 68.0 | 238 | 1.6 | 14.6 | 0.74 | / |
| | | **Mean** | **61.5** | **5.3** | **1.70** | **56.7** | **218.1** | **2.7** | **13.3** | **0.82** | |
| | | ***Std dev.*** | ***10.7*** | ***8.6*** | ***0.11*** | ***12.0*** | ***30.9*** | ***1.9*** | ***1.4*** | ***0.06*** | |

Sorting and grouping of the tests – Kroell et al. [12], [14] observed early spikes on some of the thorax force response signals. The impact speed was identified as one of the factors responsible for this early spike. In other words, the impact speed affects the shape of the response signals. In addition, the Mertz normalization technique only applied scaling factors to the time, force and deflection values, which is not sufficient to model the shape of the response in accordance with the speed. Therefore, the signal shapes were examined to identify which test speeds could be used together to develop a biofidelity target. A similar shape examination was performed to check on the effect of the injury result, which is clearly not taken into account in the normalization equations. Prior to these two examinations, the outliers were identified and excluded using a specific procedure. These three sorting steps are described hereafter.

Outlier exclusion – The following procedure was used to identify outliers: 1) All the force/deflection response curves were normalized to the same anthropometry and impactor mass and speed. 2) The tests were divided into seven groups of similar impactor speed (see Table 1). 3) The force/deflection signals of each group were submitted to a shape correlation analysis until maximum deflection using the procedure described in Nusholtz et al. [40]: the correlation score between two signals is ranked from 0 (totally different shapes) to 1 (identical shapes). To obtain the shape resemblance value of a signal S compared to a group of signals, one computes the average of the shape correlation scores of the signal S with each of the others signals including signal S. In the present paper, a signal that yields a shape resemblance value under 0.7 was deemed outlier-like. 4) An outlier-like was declared an outlier and excluded from the dataset if an odd value was found in the test features related to the test (Table 1**)**. By odd value is understood a value that significantly diverges from the mean value of the group.

Sorting of the signals according to the speed – 1) All the force/deflection response curves were normalized to the same anthropometry and impactor mass and speed. 2) The average force/deflection response was computed for each of the seven groups previously defined (without the outliers) and compared.

Sorting of the signals according to the injury – 1) All the force/deflection response curves were normalized to the same anthropometry and impactor mass and speed. 2) The whole data set without outliers was split into two groups gathering on the one hand the PMHS with 9 rib fractures or less, and on the other hand the PMHS with more than 9 rib fractures (see Table 1). 3) The average force/deflection response was computed for each of the two sub-samples (without the outliers) and compared.

Biofidelity target computation – After the determination of consistent samples of tests and a normalization of the individual response curves in accordance with the sample features, the procedure described by Shaw et al. [39] was used to develop the biofidelity target. This procedure allowed generating a one standard deviation corridor for “2 Dimensions” cross-plot responses such as the force versus deflection. A one standard deviation ellipse is computed at each time step. The cloud of ellipses defines the corridor.

Muscle tensing – To account for muscle tensing in the thorax response, Neathery [15] applied a 667 N-force shift to his response corridors. This was based on the findings of Lobdell et al. [13] and Stalnaker et al. [35]. Since then, additional studies on the effect of muscle tensing on the thorax response were performed such as Patrick et al. [36], that used one volunteer, or Kent et al. [37], that used animals. In the most recent study (Kent [37], the authors applied hub dynamic impacts on thoraces of tensed and untensed swine. The swine were prone or supine on a table top. Using their results and those of the precedent studies, the authors observed that the influence of muscle tension decreased with increasing chest deflection and with increasing impact speed. Thus, the effect of muscle tone would be negligible at chest deflections of greater than around 20%, and for impact speeds greater than 4 m/s. Below deflection of 20%, the muscle tensing was found to modify the force magnitude but also the shape of the force-deflection response. An adjustment only on the force magnitude is then inapropriate. Consequently, Kent et al. [37] recommended to neglect any muscle tensing effect and use the cadaver responses without any adjustment all along the impact duration. The authors of the present paper followed this recommendation. No force shift or other adjustment was added to the biofidelity targets to account for muscle tensing.

***Sled test***

The series described in Shaw et al. [23] was selected. Eight male PMHS were subjected to the same simulated 40 km/h frontal crash on a deceleration test sled. A trapezoidal pulse reaching a 14g plateau was applied to the sled. The subjects were seated on a rigid seat and restrained using individual lap and shoulder belts without load limiter, mimicking a 3-point belt restraint. The lower body, from the pelvis to the lower extremities, was constrained using straps and adjusted knee bolsters in order to isolate the thoracic response. Five tracking targets were attached to the anterior wall of the ribcage (on the 4th and 8th ribs bilaterally, distance from the centerline similar to the THOR dummy measurement locations). Marker locations were transformed to the center of the cross-section of the rib. The prime interest of this configuration was the efforts made for its reproducibility and, at the same time, its strong similarity with real car crash loading conditions. Other major advantages were its important number of tested PMHS for a sled configuration and its numerous measurements on the thorax. Released in 2009, no biofidelity targets were developed from those tests at that time.

The XYZ deflection of the five points located on the anterior wall of the ribcage and the shoulder belt tension time histories were used to define biofidelity targets. The deflections of the 5 points were taken in a common thoracic local coordinate system centered on the T8 vertebra, as defined in Shaw et al. [23].

Raw data – The response curves of tests 1358, 1359 and 1360 were digitized from Shaw et al. [23] up to 150 ms. For the tests 1294, 1295, 1378, 1379 and 1380 the data time-history were provided up to 250 ms in numerical by the University of Virginia. The filter classes are CFC600 for the force and CFC180 for the deflection.

Data interpolation – The deflections were measured using a three-dimensional motion tracking system. 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 time interval of occlusion (see figure 8, 9, and 10 in the original paper [23]). These time intervals were referred to as "gaps".

The average duration of the gaps was 42 ms so many data points remained available to compute the biofidelity targets. In addition, gaps were observed on the most extreme response curves, which would have a significant weight in the width of the final corridor. Otherwise, when computed with the data points available at each time step, the sudden disappearance or reappearance of one or several data points over time would generate strong uneven profile of the average curves and corridor bounds. Consequently, the missing data points were interpolated in order to smooth the bounds of biofidelity corridor and average curve. This was performed using a Matlab routine that followed the interpolation scheme described in Appendix D of [23].

Data extrapolation – Similarly, the digitized time-history responses of the tests 1358, 1359 and 1360 – acquired up to 150 ms by digitalization – were extrapolated up to 250 ms using a similar process to the one described in Appendix D of [23].

Determination of outliers – Because of the interpolated curves, no signal analysis was performed to identify outliers. Shaw et al. [23] stated that rib fractures were not observed to affect displacement trajectories to a detectable level. However, the distance from the belt of the measurement sites was found to substantially affect the deflection response. The latter observation was used to remove some suspicious response curves.

Normalization – No example of the Mertz [32] normalization technique applied to a subject restrained by a 3-point belt and submitted to a deceleration pulse was found in the literature. Consequently, the Equal stress/Equal velocity technique [31], which uses the total body mass of the PMHS, was used to normalize the responses.

Biofidelity targets computation – The average and standard deviation responses were processed for the time histories of shoulder belt tension and XYZ deflection.

Muscle tensing – As mentioned previously in the impactor section, the Kent et al. study [37] that used a hub loading recommended no adjustments on the response corridors. Since no muscle tensing study using a belt loading was found in the literature, this recommendation was also applied for the biofidelity targets of the sled test.

***Table top test***

Among the table top tests of the literature, the series performed at the University of Virginia in 2004 [28] was selected. It comprised sixty-seven dynamic tests performed on fifteen PMHS. Four different kinds of loading of the anterior thorax were conducted: single diagonal belt loading, double diagonal belt loading, distributed loading, and hub loading. The prime interest of this configuration was that it provided response data of a dynamic distributed loading on the thorax. The major advantages were its well defined boundary conditions and its easy implementation in a small lab. This test is reproducible contrary to laboratory tests that used airbag models, which are not manufactured anymore.

Kent et al. [28] already proposed biofidelity targets for each of the four loading conditions. It used the normal force measured at the back of the PMHS and the antero-posterior compression of the whole thorax measured at the level of the $4^{th}$ rib interspace. The data were processed as follows: 1) the responses were normalized to a $50^{th}$ percentile 45 year-old adult male features using the equal stress/equal velocity technique [31] plus a procedure taking the age effect into account. 2) A second-order curve was fit to the normalized force-Compression cross-plot using a least-squares approach. 3) A mean curve and a one standard deviation corridor were computed from these second-order curves and proposed as biofidelity targets.

However, the biofidelity targets proposed by Kent et al. [29] were not taken as such. Despite its above-mentioned advantages, the table top test configuration had some limitations. Indeed, a thorax compressed between two surfaces (table top case) necessarily presents a different strain pattern than a thorax with an unconstrained back but an inertial gradient in the field (real car crash case). More specifically, the table top may interact with the posterior part of the ribs and may induce a different deformation of the ribcage than the one obtained in a sled test.

To account for this limitation, the authors of the present paper proposed to use the biofidelity targets developed by Kent et al. relatively with each other. It allows to get rid of the table artifact, assuming that it is the same for each test configuration. As a precaution, only the force values at maximum compression were used rather than the full force versus compression corridors.

## III. RESULTS

For reading convenience of tables and figures, all external forces were signed positive and the X-polarity of the PMHS local coordinate system was reversed compared to SAE J-211 standard. Thus, a positive X-deflection means a rearward motion of the anterior wall of the thorax, and a negative X-deflection, a forward motion.

***Impactor test***

Outlier exclusion – Seven tests obtained a shape resemblance under 0.7 (see Table 1). PMHS MRS07 and MRS08 had a relative low body weight, PMHS 21FF was documented in Kroell et al. [12] for having a large breast compared to the other PMHS, and PMHS 62FM was impacted by an impactor of less than half the mass (9.98 kg against approximately 23 kg for the other tests). These “odd” parameters were estimated sufficient to support the outlier status of these tests, which were excluded from the dataset. No odd parameters were found for the tests 60FM, 36FM and 12FF and they were kept in the dataset.

Sorting of the test according to the impact speed – The averages of the normalized responses of the seven groups are presented in Figure 2A. Group 7 showed a response obviously different from the others, presumably because of impactor masses drastically different from the rest of the data set. However, the responses of the six other groups with similar impactor masses do not provide identical responses. As expected, the appearance and worsening of the early force spike as the impact speed rises can be clearly seen. A trend is also observed on the magnitude of force and deflection: the higher the impact speed, the higher the magnitude of force and the shorter the magnitude of the deflection. The difference is clear between group 1 and group 6 but less clear between groups of closer impact speed. As far as force magnitude and early spikes are concerned, the responses of groups 2 and 5 are quite similar but it is not the case for groups 3 and 4, of closer impact speed. Group 3 response lies within group 1 and group 2 responses, and group 4 response within group 5 and group 6. Consequently, it was estimated that groups 1, 2, and 3 on the one hand, and groups 4, 5 and 6 on the other hand could be pooled in a same sample. These two samples are named "low speed sample" and "high speed sample" respectively. The threshold between low and high speed is 6.5 m/s. The average force/deflection responses of these two new samples are compared in Figure 2B. One observes remarkably different profiles: the high speed sample shows a higher force magnitude and a lower maximum deflection than the low speed sample, and a clear early force spike whereas the low speed sample does not. As a consequence, these two samples must not be merged.

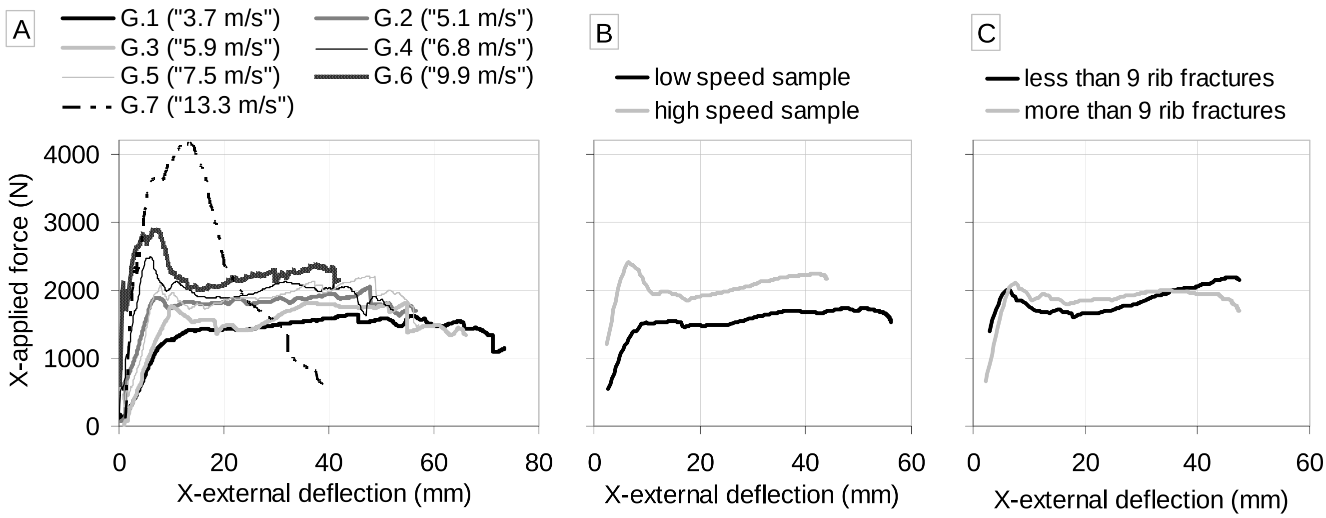



Figure 2 – Average responses of different groups of tests. All responses were normalized to a 19 kg, 4 m/s impactor mass and speed and to a 50th percentile anthropometry prior to being averaged. In figure A, 34 tests (whole dataset without the outliers) were split into seven groups of similar impact speed. The mean speed for each group is noted in the caption. Group 7, denoted "G.7", has a mean impactor mass of 2.7 kg whereas it is around 21 kg for the other groups. In figure B and C, 30 tests (whole dataset without the outliers and tests from group 7), were split into two groups: of similar speed in figure B (the threshold between the two groups is 6.5 m/s) and of similar injury in figure C. Averaged values of the latter subsamples are given in Table 2.

Sorting of the test according to the injury – Given the previous results, the tests of group 7 were excluded from the analysis that follows as well as the outliers. The 30 remaining tests were sorted according to the rib fractures in two sub-samples: "less than 9 rib fractures" and "more than 9 rib fractures" (see Table 1). The resulting averaged force/deflection responses were plotted in Figure 2C. The shapes of the early spike, and the magnitudes of force and deflection are comparable but not similar. However, the difference is far less than when the 30 tests are sorted according to the impact speed (Figure 2B). This observation suggests that the number of rib fractures is of less influence than the impact speed on the response profiles. Considering the latter, it was decided not to take the injury level into consideration in the sorting of the tests.

Table 2

| **Sample name** | **Sampl e size** | | **Age** | **NRF** | **Height (m)** | **Weight (kg)** | **Chest depth (mm)** | **Impactor mass (kg)** | **Impactor speed (m/s)** |
|---|---|---|---|---|---|---|---|---|---|
| 30 tests | 30 | Mean | 62.1 | 10.7 | 1.74 | 68.0 | 219 | 22.3 | 6.7 |
| | | *Std dev.* | *15.2* | *7.6* | *0.09* | *11.7* | *47* | *1.7* | *2.0* |
| Low speed | 11 | Mean | 66.9 | 8.1 | 1.74 | 69.6 | 204 | 22.9 | 4.7 |
| | | *Std dev.* | *9.4* | *6.6* | *0.06* | *9.3* | *71* | *1.2* | *1.0* |
| High speed | 19 | Mean | 59.4 | 11.8 | 1.74 | 67.0 | 228 | 22.0 | 7.9 |
| | | *Std dev.* | *17.4* | *7.9* | *0.10* | *13.1* | *24* | *1.9* | *1.3* |
| Less than 9 fractures | 16 | Mean | 55.9 | 4.4 | 1.8 | 70.3 | 227.7 | 22.3 | 6.2 |
| | | *Std dev.* | *16.5* | *3.8* | *0.1* | *13.7* | *21.8* | *1.7* | *2.0* |
| More than 9 fractures | 14 | Mean | 69.2 | 16.6 | 1.7 | 65.4 | 209.0 | 22.4 | 7.3 |
| | | *Std dev.* | *10.2* | *4.9* | *0.1* | *8.7* | *64.6* | *1.7* | *1.7* |

Biofidelity target computation – The low speed and high speed samples were used as basis to develop two biofidelity targets. The responses of the tests were normalized to a 50$^{th}$ percentile anthropometry (see Figure 1) and to the impactor mass and speed combinations commonly used in standard tests [15]: 23.4 kg – 4.3 m/s for the low speed sample and 23.4 kg – 6.7 m/s for the high speed sample. These values fit in the mass and speed ranges of each sample, which means that the normalization is appropriate with respect to the force/deflection response shapes of each sample. The resulting biofidelity targets computed using the "ellipse technique" [39] are shown in Figure 3. For the low speed sample, deviations in the responses during the unloading phase (after maximum deflection) were much larger than those that occurred during the loading phase. This had the consequence of generating wide ellipses during the unloading phase that overlapped the small ellipses of the loading phase. In order to better identify the deviation along the response, separated corridors were presented for the load phase and the unload phase.

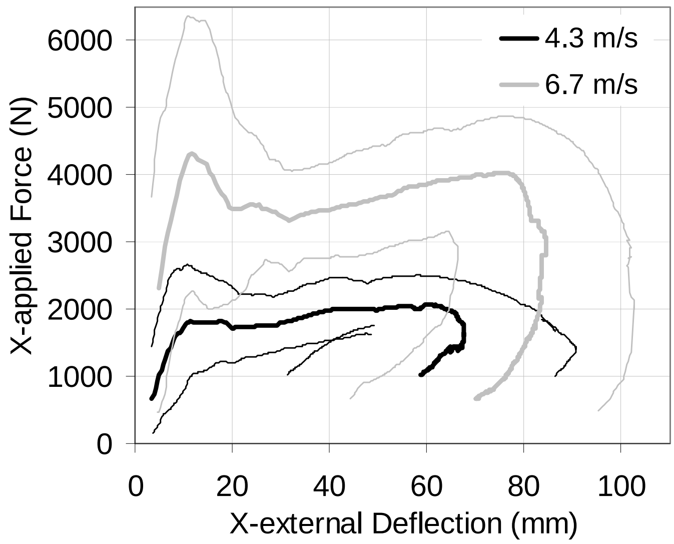



Figure 3 – Proposed biofidelity targets for a 50$^{th}$ percentile adult male surrogate submitted to a 23.4 kg impactor test. The tests were normalized accordingly prior to computing the mean curves and the corridors.

***Sled test***

Outlier exclusion – XYZ upper right deflections of the test 1378 and X lower right deflection of the test 1379 presented odd response signals compared to the signals of the other tests for the same location on the ribcage. As shown in Shaw et al. [23], the upper right and lower right targets for PMHS 1378 and 1979 respectively were located singularly compared to the location of the other PMHS targets. Consequently, the response curves related to these targets were excluded, including YZ for test 1379.

Biofidelity target – The biofidelity targets for the upper shoulder belt tension and for the X-deflection at the 5 locations of the anterior wall of the ribcage are given in Figure 4. Y and Z-deflections are not shown.

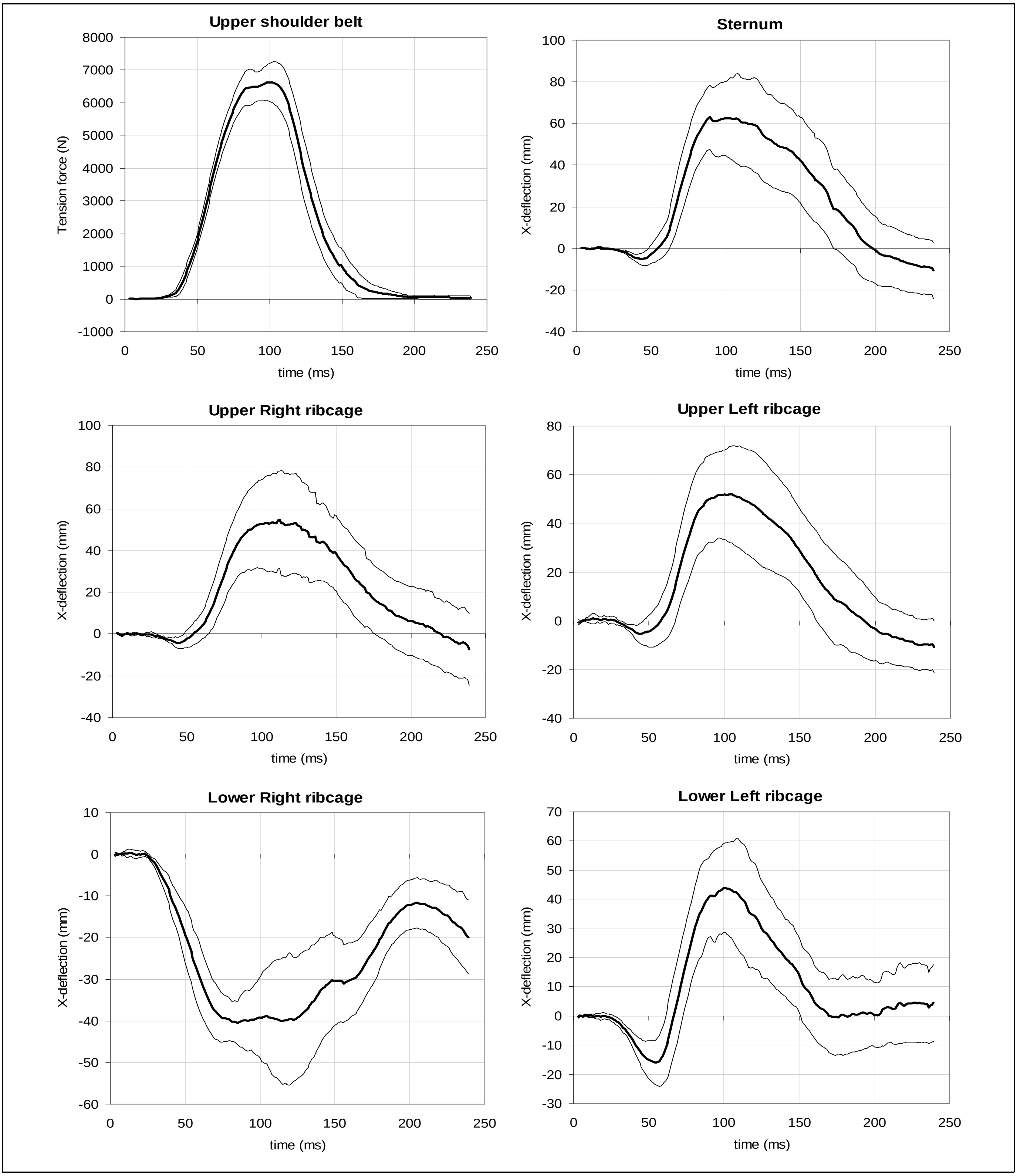



Figure 4 – Proposed biofidelity targets for the shoulder belt upper tension and ribcage X-deflections of a 50th percentile adult male surrogate submitted to 40 km/h sled test with a 14 g trapezoidal pulse.

***Table top test***

Biofidelity targets – The equations of the second order curves for the average response and the corridor bounds published in Kent et al. [29] were used to compute the force values at 20% compression. It is shown in Table 3. The single diagonal belt loading is taken as the reference. The force values of the distributing loading are divided by the mean value of the single diagonal belt loading. The resulting biofidelity target for the distributing loading of the table top test is illustrated in Figure 5.

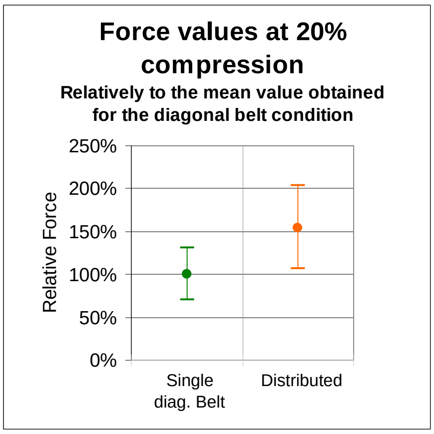



Figure 5 – Proposed biofidelity targets for the table top test

Table 3 – Coefficients of the second order curves (Kent et al. 2004) $y=\alpha x^2+\beta x$ (x being the chest compression) and resulting force values at 20% of compression

| | | Second order curve coef. | | Force value at 20% of compression | |
|---|---|---|---|---|---|
| | | α | β | Absolute | Relative |
| Single Diagonal Belt | up. bound | 11299 | 12178 | 2888 | 131% |
| | ave. curve | 28601 | 5274.9 | **2199** | **100%** |
| | low. bound | 37658 | 178.6 | 1542 | 70% |
| Distributed | up. bound | 23216 | 17723 | 4473 | 203% |
| | ave. curve | 35764 | 9742.5 | 3379 | 154% |
| | low. bound | 37692 | 4260.4 | 2360 | 107% |

## IV. DISCUSSION

***Impactor test***

External deflection – The skeletal deflection was estimated for the GM Laboratories series but not for the INRETS and CEESAR series, for which the total deflection was kept. The procedure described in Kroell et al. [12], [14] was not clearly defined and could not be applied in a similar way on the INRETS and CEESAR tests. Thus, in order to avoid doing the assumptions to estimate the skeletal deflection, it was preferred to keep the total deflection measurement for all the tests. It is believed that it increased the consistency between the measurements of each series.

Normalization method – Though a simple lumped parameter model can significantly increase the grouping of the curves [32] [33], a remaining sensitivity to the speed was observed. The normalization technique was unable to yield close force and deflection magnitudes and consistent signal shapes between all the response curves. Two reasons explain this fact. Firstly, the lumped parameter, with a single linear spring between two masses, is probably too simple to adequately integrate the effect of the speed. Secondly, the Mertz normalization process uses scaling factors that only affect the duration and the magnitude of the response curves and not the shape. The latter is also true for other common normalization processes used in the literature such as Eppinger [31] or Neathery [15]. If a future effort of biofidelity target development for impactor test is conducted, it may be valuable to develop an alternative normalization technique using, for instance, a finer lumped parameter model. The Lobdell et al. [13] model could be used as a basis, and enhanced. For the present study, as no alternative normalization processes were found in the literature, the data set was split into small sub-samples of consistent speed before analysis and biofidelity target computing.

Sorting of the tests – It was chosen to keep in the data set the outlier-like signals for which no odd values were found in the test features. This choice may be discussed since the test features given in Table 1 are only gross parameters that may not reflect the complexity of the human body and its interaction with an impacting mass.

Normalization target - The 4.3 m/s and 6.7 m/s were retained as impact speeds to conform to the historical values commonly used in the field. However, to guarantee even more the relevance of the average responses issued from these two samples, the signals should be normalized to the average impact speed, i.e. 4.7 and 7.9 m/s respectively (see Table 2).

Biofidelity target computation – The Shaw et al. [39] technique allowed computation of the standard deviation for “2D responses”. However, it is not fully satisfactory because the overlap of the ellipses prevents transformation of the cloud of ellipses into corridor bounds. Enhancement of this technique is required for future work.

***Sled test***

Using the measurements performed at five locations of the anterior wall of the ribcage, the Shaw et al. [23] test series provided the thoracic deformation of a PMHS sustaining a shoulder belt loading. As underlined by Schneider et al. [4], multipoint deflection would allow improved assessment of complex restraint systems such as belt, airbag, or a combination of both. However, similar response targets for an airbag or a distributed loading remains to be developed.

A common T8 local coordinate system was used for the 5 deflection points. It means that the measured deflections represent the global deformation of the upper torso, that is to say: the rib deformation, plus the rib movement relative to its attached vertebral body, plus the movement of the vertebral bodies relative to each other. Consequently, in order to be relevant, this biofidelity target should be used for human surrogates for whom the spine demonstrates good biofidelity.

***Table top test***

No repeatable test series that used airbag only (i.e. not combined with a 3 point belt restraint) were found in the literature. The main interest in the use of the Kent et al. [29] table top test series was that it could provide a response biofidelity target for a distributed loading. The loading device used, made of belt fabric, is different from an airbag but is repeatable over time. However, to account for the differences of the table top test loading with respect to a car crash loading, it was proposed to use the force/deflection responses of the loading conditions relatively with each other. The data available in the Kent et al. paper [29] were used but it is possible to further enhance the biofidelity targets proposed in the present paper. First, with respect to the data processing, one may consider to rather compute the distributed/diagonal belt force ratio at 20% of compression of each test and then calculate the mean ratio. These data were only available in the format of tiny graphs in the Appendix section of Kent et al. [29]. Second, it was mentioned that the deflection was measured at three points of the torso but the data were not provided in the paper. It may be valuable in future work to develop biofidelity targets out of these measurements for it would provide additional information on the torso deformation.

## V. CONCLUSIONS

New targets based on test series presented in the literature were proposed to assess the biofidelity of the thorax response of ATDs or a human body FE-models in frontal impact. The targets of the standard impactor tests (23.4 kg, 4.3 m/s and 6.7 m/s strikes) were updated using additional test series [14], [16], [18], [19], and recent normalization [32] and corridor development procedures [39]. New targets for a sled test using a 3 point belt-like restraint, 40 km/h impact, 14 g deceleration were developed from the data released in 2009 by the University of Virginia [23]. It provides the global deformation of the thorax using the XYZ deflection measured at 5 different locations on the anterior wall of the ribcage. Finally, for the table top test, a minimal target was derived from the findings of Kent et al. [29]. The distributed loading is primarily considered. Only, the reaction force value at 20% of thoracic compression is taken as biofidelity target and should be used relatively to the value obtained with the diagonal belt loading.

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