A Frontal Response Specification for Assessing the Biofidelity of an Anthropometric Test Dummy
Part 1 - Upper Body

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Abstract This paper describes the laboratory test procedures and provides objective impact response targets for assessing the frontal impact biofidelity of the head, neck, thorax, and abdomen of anthropometric crash test dummies, component test devices, and mathematical models that are used to represent the 50th percentile male adult. A companion paper covers the knee/thigh/hip complex and the leg. The test procedures and associated data used to establish the biofidelity targets were selected from a review of all relevant and available post-mortem human subject testing. Reliable data from well-defined tests were synthesized to create objective biofidelity targets.

Keywords biofidelity targets, frontal impact, ATD, 50th percentile, upper body

I. INTRODUCTION

Crash test dummies and human body computer models are key tools for the improvement of occupant safety in car crashes. Indeed, they are used worldwide by both design engineers for the development of cars and by consumer and regulatory car safety evaluation programs.

The effectiveness of the injury countermeasures implemented in cars is dependent on the ability of dummies to mimic the human body response in various crash conditions and to provide data for assessing the injury risk. This is referred to as biofidelity.

In 2008, the European Car Manufacturer's Association (ACEA) Dummy Task Force established a group of experts from institutions worldwide. This group gathered regularly and reviewed all of the Post-Mortem Human Subject (PMHS) tests available in the literature in an effort to define biofidelity targets for dummies in frontal impact. This paper and its companion paper [1] are based on the recommendations of that group. A selection of laboratory test configurations and objective response targets are recommended for assessing the frontal impact biofidelity of the upper body (head, neck, thorax, and abdomen) and lower body (knee versus thigh/hip complex and lower leg) of a 50th percentile adult male human surrogate, i.e. anthropometric crash test dummies, component test devices, and mathematical models. The present paper covers the upper body. The lower body is covered in the companion paper [1].

The content of the present paper and its companion paper [1] focuses on the data processing performed to develop the biofidelity targets. Thus, the complete literature review could not be enclosed but the guidelines for the selection of the test configurations are recalled. The selected test series are referenced and brief descriptions of the test conditions are given. An effort was made to provide the features of the selected PMHS test sample, the normalization parameters, and the origin of the response data (numerical format and reference if digitized from hard copies). The detailed definition of test procedures applicable to any frontal dummy is beyond the scope of the present paper and its companion paper [1]. However, if clear and well accepted test procedures already existed, they will be recalled.

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II. METHODS

Literature review and selection of the test configurations

The literature review was extensive and covered published and unpublished papers, reports and biomechanical databases. In particular, it included: a) papers dealing with frontal dummy development and specifications as [2]-[7] for instance; b) papers dealing with Finite Element Human Body model development and specifications as [8]-[9] for instance; c) existing "literature review papers" on frontal biofidelity as [10]-[11] for instance; and d) any other papers reporting PMHS test series in frontal impact. To select test configurations from the literature, the following inclusion criteria were defined. The test configurations should be relevant with respect to the current restraints of car occupants. Dynamic tests were preferred over static ones. The test set-up should be sufficiently described to allow any well-equipped laboratory to reproduce it. Animal tests were excluded. If possible, embalmed PMHS tests were not used. The sample size of the PMHS test series was wished as large as possible. Lastly, the original response measurements were examined to assess their reliability: suspicious tests were excluded.

Normalization

Two widely accepted techniques exist in the literature [10][13] to normalize the response of a given subject to the one of a 50th percentile male. Both are based on assumptions of geometric similarity, equal density, and equal material properties of the two subjects. The first approach is the "Eppinger technique" and is also referred to in the literature as the "Equal Stress-Equal Velocity" technique. All of the normalization factors are based on the body weight ratio of the two subjects. The second approach is the "Mertz technique" and uses a mass-spring model to represent the test. For a pendulum impact test, [14] proposed 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. This approach develops normalization factors based on mass ratios, length ratios (often used to compute the stiffness ratio) and speed ratios. Both approaches were used to develop biofidelity targets in this study depending on the type of test and which method better groups the PMHS response data. The anthropometric reference values used to estimate the normalization ratios are taken from the Advanced Anthropometric Motor Vehicle Occupant Study [15].

Biofidelity targets

Different proposals can be found in the literature to define and compute biofidelity targets [16][20]. The most common is a corridor approach. However, in this paper the time history based biofidelity targets are presented as a mean response curve plus a one standard deviation tolerance band. The mean response curve is the target that a human surrogate should approach and the standard deviation around the mean curve reflects the variance of the tested PMHS.

For the one dimensional targets, i.e. the time history responses, the standard deviation value applied to define the tolerance band is the average of the standard deviations at each point in time until the last data point. For the two dimensional targets, such as a force versus deflection response, the "ellipse technique" described in [19] was used. In this method the two available time history signals (force vs. time and deflection vs. time, for example) and the standard deviations are used to compute the standard deviation variance in the shape of an ellipse on the force versus deflection plot. Again, an averaged value of standard deviation was used and a constant-size of ellipse is plotted all along the mean response. In practice, the averaged standard deviations computed on the force and deflection time histories should be multiplied by 1.52 to obtain the "a" and "b" diameters of the ellipse tolerance band for the two dimensional targets (see the Appendix B of [19]). When the time history curves were not available then the force versus deflection target was created by computing the average and the standard deviation of the force for each deflection value.

Head Test 1 – Pendulum impact (whole body)

The re-analyzed data of two PMHS nonfracture head impact test series from the 70's were selected for a head impact biofidelity target [4]. The first test series consisted in 28 head impacts performed on seven embalmed PMHS [21]. Each PMHS head was submitted successively to frontal, lateral, top, and rear impacts. The test set-up consisted basically in strapping the subject to a pallet that was free to rotate at the feet. The cadaver's head and neck extended over the free end. The pallet was released at a fixed distance from the impact surface. The force was recorded at the impact location and the skull was instrumented with accelerometers for some tests. The second test series consisted in 7 tests with 7 unembalmed PMHS where a 4.54 kg impact mass was dropped onto the frontal region of the PMHS heads [21]. Impact force and head accelerations were measured in all tests. The proposed biofidelity target is the peak force applied onto the head with maximum boundaries for the force response shape (rise and fall) and duration.

Test procedure – An equivalent head biofidelity test procedure was developed by [4] that equated the impact energy in the above mentioned tests with the effective impact energy from a 23.4 kg – 2.0 m/s pendulum impact test on the forehead of a whole seated subject. This procedure has advantages over a head drop test in that the problem of orienting the head during a head drop test is avoided, determining what mass is head mass and what is neck mass is eliminated, and the dummy head does not have to be removed from the dummy. The head of the dummy should be placed such that the axis of the impactor is aimed at a point on the forehead on the mid-sagittal plane and 30 mm above a horizontal line through the nasion. The tilt of the dummy head/neck assembly is adjusted so that the impact area on the head is parallel to the face of the impactor.

Data processing – A summary of the data processing described in [4] is given hereafter. First of all, the authors of [4] corrected the original drop speeds reported in [21] for the first test series (embalmed subjects multi-impacted at different location of the head). Then, the peak forces (filtered at approximately SAE channel class 1000) were normalized to the 4.54 kg weight of a 50th percentile head using the Eppinger technique. Ref. [4] observed that the peak forces for different impact directions were very similar for a given subject, whereas the variations between PMHS were very large for a given impact direction. Thus, all of the 28 head impacts of the first test series were included to compute a mean peak force and pulse duration response for the head. It yields a mean force of 5.16 KN ± 1.15 kN S.D. with a 5.8 ms pulse duration for the equivalent 23.4 kg – 2.0 m/s impactor test. Similarly, the peak forces of the second test series (unembalmed subjects, single impact onto the frontal region) were normalized to a 50th percentile head impacted by a 23.4 kg – 2.0 m/s impactor and yields a mean peak force of 6.42 kN ± 1.0 kN S.D. with a 2.1 ms pulse duration. The difference (higher peak force, shorter duration) with the first test series was attributed to the unembalmed state of the subjects. Assuming that the living human values are somewhere between those of the embalmed cadaver with its toughened tissues and the unembalmed, unperfused cadaver with its flaccid tissues, the authors of [4] combined the results of the 28 embalmed and 7 unembalmed impact tests and proposed a mean peak force response of 5.8 ± 0.58 kN with a mean pulse duration of 4.2 ± 0.6 ms for the 23.4 kg – 2.0 m/s rigid impactor frontal test. A 1 ms time window defined the width of the peak force box.

Neck Test 1 – Flexion test

The re-analyzed data from a set of volunteer sled tests performed at the Naval Biodynamics Laboratory (NBDL) were selected for a frontal neck flexion biofidelity target [22]. In the original NBDL experiment, the volunteers were seated with a belt arrangement firmly constraining the torso and the pelvis, and submitted to a frontal deceleration. Target markers and accelerometers allowed measuring the kinematics of the T1 vertebra and of the Head. The proposed biofidelity targets are the head center of gravity (CG) motion – angular displacement, X and Y displacement and the XY trajectory in the sagittal plane – with respect to T1 vertebra, and the head CG resultant acceleration in the laboratory coordinate system.

Data processing – A large number of human volunteer sled tests were performed by [24] at the NBDL in the late 60s and early 70s. These data were analyzed by [23] and the head motion was described with respect to the T1 location in terms of angle, acceleration and X and Y motion. These motions were later compared to PMHS head motion data from similar sled tests [23], [25] and significant differences were found which were originally attributed to lack of muscle action in the PMHS. Reference [22] re-analyzed the volunteer and PMHS data and realized the T1 mount used for volunteer testing allowed rotational movement due to a less than rigid mounting strap system. This additional high speed film analysis allowed a correction to be made to the T1 motion which brought the volunteer and PMHS results much closer together and new biofidelity targets were constructed from the volunteer data for head motion with respect to the T1 location.

The biofidelity targets presented here utilized a representative set of nine experiments out of the most severe human volunteer experiments (9 experiments with 5 subjects, see [22], where each subject was tested twice except for one subject). These volunteer experiments were conducted at 150 m/s^2 with a velocity change in excess of 17 m/s. The mean and standard deviation of the time history responses (head CG resultant acceleration, X and Z displacement, head Y rotation) were calculated from the data processed by [22]. Then, the

X versus Z displacement biofidelity target was computed using the ellipse technique.

Test procedure – A simplified test procedure was also proposed by [22]. The head and neck of the human surrogate should be mounted rigidly to a pendulum or mini-sled at the T1 location. Thus, the acceleration pulse seen at T1 becomes the input condition. A specific T1 X-acceleration input corridor was computed by [22].

Thorax Tests 1 and 2 – Rigid Impactor Low Speed and High Speed Impact at the 4th costal interspace

This impact test data and the resulting biofidelity targets have been published in [16]. They are described here for convenience. The tests consist of a subject seated on a horizontal surface with the torso upright and vertical and with the arms and legs extended anteriorly. A cylindrical (15.2 cm diameter), flat-faced, 23.4 kg rigid impactor moving at 4.3 m/s or at 6.7 m/s strikes the thorax in the mid-sagittal plane at the level of the 4th costal interspace. PMHS data from test series performed at General Motors (GM) Laboratories [26]-[27], INRETS [28], and LAB PSA Peugeot Citroen Renault [29] were selected for the biofidelity target and are presented in Table 1 and Table 2 for the low speed impact and the high speed impact, respectively. The proposed biofidelity targets are the thoracic force versus time, deflection versus time, and force versus deflection responses.

Data processing – Force versus time and external deflection versus time signals were digitized from the graphs released in the original publications ([26][27] for the GM Laboratories tests and [30] for the INRETS tests. The LAB data was available in digital format (MS589) [29]. Force and deflection response data were filtered at CFC600 and were normalized using a mass-spring model to represent a 50th percentile male subjected to the biofidelity test impact conditions. The PMHS chest effective mass and depth were used to respectively compute the mass and stiffness ratios (λ_{m2} and λ_k). They are given in Table 1 and Table 2 along with the resulting normalization factors. The mean and standard deviation of force and deflection time histories were calculated from the processed data. The force versus deflection biofidelity target was computed using the ellipse technique.

Thorax Test 3 – Rigid Impactor Oblique Impact at the 8th rib

The oblique frontal pendulum impactor test biofidelity targets are based on data from tests performed at the Medical College of Wisconsin (MCW). The subject was seated with the torso upright and vertical and with arms and legs extended anteriorly. The subject was rotated about a vertical axis 15 degrees to the left (counterclockwise looking down at the head) to expose the right side of the thorax. Dynamic pendulum impactor loading was applied approximately at the level of the 8th rib in the anterior region on the right side at a velocity of 4.3 m/s. The mass of the impactor is 23.5 kg. The impactor face dimensions are the same as in thorax tests 1 and 2 (152 mm in diameter with a 12.7 mm edge radius). The face of the impactor was covered with an Ensolite padding (40 mm thick). The proposed biofidelity targets are the force and deflection time history responses and the force versus deflection response.

Data processing – The test features are presented in

. For each subject, force and chestband deflection data were digitized from unpublished reports provided by MCW. The force and deflection channels were re-mapped to encompass the same time domain. The force, deflection, and time channels were then normalized to the 50th percentile male using the Eppinger technique. The channels were again re-mapped to obtain a consistent time domain. The force time histories were phase aligned by eye to minimize time shifts and the deflection time histories were shifted to match. All channels were cropped to end at the earliest of the deflection channels. The mean and standard deviation of force and deflection time histories were calculated from the processed data. The force versus deflection biofidelity target was computed using the ellipse technique.

Test procedure – According to [6], a 19 mm thick padding of Rubatex can be used to cover the impactor face instead of the 40 mm thick padding of Ensolite. Material characteristics for the Rubatex are provided in [6].

Thorax Test 4 – Sled Test using belt restraint without load limiting

Data from a series of sled tests performed at the University of Virginia [32] were selected as biofidelity targets for a sled test with a belt restraint. The 40 km/h pulse applied to the sled is trapezoidal in shape with a 130m/s^2 plateau. The subject was seated on a rigid seat and restrained with lap and shoulder belts without any load limiting. The lower body and lower limbs were constrained to remain in place during the impact. Five video targets were placed on the anterior surface of the thorax: four bilaterally on the 4th and 8th ribs and one on the sternum at the 4th intercostal space. The target displacements are recorded with a three dimensional video tracking system and are transformed to the center of the cross-section of the underlying ribs and sternum. The proposed biofidelity targets are the upper shoulder belt tension time history and the rib and sternum X displacement time histories measured in a local thoracic coordinate system with an origin at the T8 vertebra.

TABLE 1
Thorax test 1. Details of the PMHS test sample [26][28][29].

TEST	PMHS							IMPACTOR		NORMALIZATION FACTORS†		
N°	N°	Sex	Age	Height (cm)	Weight (kg)	Chest depth (mm)	Effective mass (kg)	Mass (kg)	Speed (m/s)	λ_F	λ_D	λ_t
MRS01	MRS01	M	76	173	82	250	20.3	23.4	3.36	1.24	1.35	1.06
MRS05	MRS05	M	66	172	69	210	11.2	23.4	3.39	1.20	1.09	0.86
MRS03	MRS03	M	57	174	76	230	20	23.4	3.43	1.27	1.27	1.01
60FM	60FM	M	66	180	79.4	222	35.7	23	4.3	1.22	1.17	1.17
IMP574	MS589	M	88	169	60	180	9.7	23.67	4.4	0.97	0.76	0.77
42FM	42FM	M	61	183	54.4	216	29.4	22.9	4.87	1.03	0.97	1.10
45FM	45FM	M	64	181	64	254	33.8	23	5.1	0.94	1.04	1.23
53FM	53FM	M	75	174	77.1	241	26.8	23	5.2	0.89	0.93	1.13
MRS04	MRS04	M	57	174	76	230	13.6	23.4	5.81	0.69	0.69	0.93
MRS06	MRS06	M	66	172	69	210	16.3	23.4	5.88	0.74	0.67	0.92
11FF	11FF	M	60	160	59	208*	19.1	19.5	6.3	0.82	0.74	1.09
Mean			*66.9*	*173.8*	*69.6*	*223.0*	*21.4*	*22.9*	*4.7*			

† Normalization factors were computed for a 50th percentile adult male (Chest effective mass 28.5 kg, Chest depth 230 mm) and the impactor mass and velocity (23.4 kg, 4.3 m/s).
*the chest depth of the PMHS n°11FF was computed by averaging the chest depth value of four PMHS of similar height and weight characteristics (23FF, 14FF, 12FF and 64FM).

TABLE 2
Thorax test 2. Details of the PMHS test sample [26][27].

TEST	PMHS							IMPACTOR		NORMALIZATION FACTORS†		
N°	N°	Sex	Age	Height (cm)	Weight (kg)	Chest depth (mm)	Effective mass (kg)	Mass (kg)	Speed (m/s)	λ_F	λ_D	λ_t
18FM	18FM	M	78	1.77	65.8	219	41.1	23.6	6.7	0.95	0.90	0.90
22FM	22FM	M	72	1.83	74.8	226	40.8	23.6	6.7	0.94	0.92	0.92
19FM	19FM	M	19	1.96	71.2	203	22.6	23.6	6.7	1.12	0.99	0.99
20FM	20FM	M	29	1.8	56.7	203	22.2	23.6	6.7	1.13	1.00	1.00
54FF	54FF	F	49	1.63	37.2	205	17.7	19.6	6.71	1.24	1.11	1.11
15FM	15FM	M	80	1.65	53.1	200	19.9	23.6	6.9	1.14	0.99	1.02
64FM	64FM	M	72	1.63	63	216	15	23	6.93	1.19	1.11	1.15
36FM	36FM	M	52	1.83	74.8	226	39.3	19	7.2	0.94	0.92	0.99
12FF	12FF	F	67	1.63	62.6	187	18.9	22.9	7.2	1.15	0.93	1.00
14FF	14FF	F	76	1.56	57.6	216	23.5	22.9	7.3	1.00	0.94	1.02
46FM	46FM	M	46	1.78	94.8	286	28.9	19.3	7.4	0.86	1.06	1.18
13FM	13FM	M	81	1.68	76.2	246	29	22.9	7.4	0.88	0.94	1.04
23FF	23FF	F	58	1.63	61.2	226	24.8	19.5	7.8	0.94	0.92	1.08
34FM	34FM	M	64	1.78	59	241	33.6	19	8.3	0.81	0.85	1.05
24FM	24FM	M	65	1.83	81.6	251	35.5	22.9	9.7	0.64	0.69	1.00
37FM	37FM	M	48	1.79	73.9	248	26.5	22.9	9.8	0.67	0.73	1.06
32FM	32FM	M	75	1.71	54.4	248	24.9	22.9	9.9	0.68	0.73	1.08
55FF	55FF	F	46	1.77	81.2	241	19	19.6	9.92	0.76	0.80	1.18
31FM	31FM	M	51	1.83	74.8	238	27	23	10.2	0.66	0.68	1.03
Mean			*59.4*	*1.7*	*67.0*	*227.7*	*26.9*	*22.0*	*7.9*			

† Normalization factors were computed for a 50th percentile adult male (Chest effective mass 28.5 kg, Chest depth 230 mm) f and the impactor mass and velocity (23.4 kg, 6.7 m/s).

TABLE 3
Thorax test 3. Details of the PMHS test sample [31].

	PMHS				IMPACTOR		NORMALIZATION FACTORS		
I.D.	Age (years)	Height (cm)	Weight (kg)	Chest Depth (mm)	Mass (kg)	Speed (m/s)	λ_F	λ_D	λ_t
1	72	170	82	234.2	23.5	4.3	0.98	0.98	0.96
2	81	175	63	218.9	23.5	4.3	1.07	1.07	1.14
3	84	168	68	233.2	23.5	4.3	1.04	1.04	1.08
4	86	170	56	210.6	23.5	4.3	1.11	1.11	1.23
5	62	174	61	240.0	23.5	4.3	1.08	1.08	1.16
6	70	169	91	312.4	23.5	4.3	0.94	0.94	0.89
7	68	178	83	282.4	23.5	4.3	0.97	0.97	0.95
Mean	*74.7*	*172*	*72*	*247.4*	*23.5*	*4.3*			

Data processing – The data processing was described in [16]. The filter classes were CFC600, CFC180, and CFC60, for the force, the deflections, and the acceleration respectively. Features of the PMHS and normalization factors are recalled in

. The mean and standard deviation of the sled acceleration, the belt tension, and the torso deflection time histories were calculated from the processed data.

TABLE 4
Thorax test 4. Details of the PMHS test sample [32].

Test N°	PMHS N°	Sex	Age	Height (cm)	Weight (kg)	Overall chest depth (mm)	Skeletal chest depth (mm)	Normalization factors† λ_F	λ_D	λ_t
1294	411	M	76	178	70	239	222	1.03	1.03	1.06
1295	403	M	47	177	68	230	214	1.04	1.04	1.08
1358	425	M	54	177	79	239	209	0.99	0.99	0.98
1359	426	M	49	184	76	266	216	1.00	1.00	1.01
1360	428	M	57	175	64	237	212	1.06	1.06	1.13
1378	443	M	72	184	81	218	192	0.98	0.98	0.96
1379	433	M	40	179	88	270	217	0.96	0.96	0.91
1380	441	M	37	180	78	225	206	0.99	0.99	0.99
Mean			*54*	*179.3*	*75.5*	*241.0*	*211*			

†Normalization factors were computed for a 50th percentile adult male (76.7 kg total body weight).

Abdomen test 1 and 2 – Rigid Bar Low Speed and High Speed Impacts at the level of the L3 vertebra

The data from the PMHS impact tests of [33] were selected as frontal biofidelity tests for the abdomen. The subject was seated with the torso in an upright position at 90 degrees to a horizontal surface with the legs forward and no restraint behind the torso (free back). The impactor was a 25mm diameter, 381mm long rigid bar of circular cross section aligned parallel to the seating surface and perpendicular to the subject X-axis. The subject was impacted at the level of the L3 vertebra. Two impactor mass and initial speeds combinations were chosen for the biofidelity tests: 32 kg at 6.1 m/s and 44 kg at 10.8 m/s, respectively. The proposed biofidelity targets are the abdomen force and deflection time histories and the abdomen force versus deflection response.

TABLE 5
Abdomen test 1. Details of the PMHS test sample [33].

Test		PMHS						Impactor		Time shift	Normalization factors†		
NHTSA N°	Paper N°	N°	Sex	Age	Height (cm)	Weight (kg)	Abdo depth (mm)	Mass (kg)	Speed (m/s)	(ms)	λ_F	λ_D	λ_t
824	24	525	M	57	187	45	283	31.2	4.87	+1	1.25	1.54	1.23
769	19	473	F	43	159	53	231	31.2	5.00	+3	1.30	1.31	1.07
977	28	578	F	57	163	75	257	31.5	6.66	-1	0.87	0.98	1.07
765	14	458	M	56	182	68	275	31.2	6.84	-3	0.84	1.00	1.12
1038	33	590	F	51	163	68	261	31.5	7.24	0	0.81	0.92	1.09
	Mean			*52.8*	*170.8*	*61.8*	*261.4*	*31.4*	*6.1*				

†Normalization factors were computed for a 50th percentile adult male (Body weight 76.7 kg, Abdomen depth 230 mm) and the impactor mass and velocity (32 kg, 6.1 m/s).

TABLE 6
Abdomen test 2. Details of the PMHS test sample [33].

Test		PMHS						Impactor		Time shift	Normalization factors†		
NHTSA N°	Paper N°	N°	Sex	Age	Height (cm)	Weight (kg)	Abdo depth (mm)	Mass (kg)	Speed (m/s)	(ms)	λ_F	λ_D	λ_t
NA	43	721	M	66	170	70	332	63.6	9.07	0	0.91	1.31	1.10
NA	45	731	M	58	176	92	270	63.6	9.79	0	0.88	1.03	0.93
1334	37	684	M	50	169	88	290	31.3	10.59	+2	1.00	1.26	1.24
NA	61	786	M	60	180	79	321	31.5	11.62	-2*	0.88	1.22	1.32
NA	57	751	M	64	184	90	322	31.5	13.01	0	0.77	1.07	1.29
	Mean			*58.0*	*177.3*	*87.3*	*300.8*	*39.5*	*11.3*				

†Normalization factors were computed for a 50th percentile adult male (Body weight 76.7 kg, Abdomen depth 230 mm) and the impactor mass and velocity (44 kg, 10.8 m/s).

*in addition to the time shift mentioned in the table, this test also required a deflection shift of +2.5 mm on the deflection/time curve

Data processing – Descriptive data for the PMHS tests selected to develop the biofidelity targets for the low speed and high speed tests are given in Table 5 and in Table 6 respectively. The 100 Hz filtered, non-normalized force versus time and deflection versus time signals were digitized from the original paper [33] and processed so that – when combined – they yielded the force versus deflection responses presented in the paper. It was necessary, in some cases, to apply a time shift to the deflection versus time signal to obtain the proper force versus deflection shape. The time-shift values are given in Table 5 and in Table 6. Force versus time and time-shifted deflection versus time response curves were normalized using a mass-spring model to represent a 50th percentile male subjected to the corresponding impact condition (low speed or high speed). The total body mass of each PMHS was used to compute the PMHS mass ratio (λ_{m2}) because the available data was insufficient to compute a PMHS abdomen effective mass. The abdomen depth was used to compute a λ_k ratio. All the normalization factors are given in Table 5 and in Table 6. The mean and standard deviation of force and deflection time histories were calculated from the processed data. The force versus deflection biofidelity target was computed using the ellipse technique.

Abdomen Test 3 – Rigid Steering Wheel Rim Impact at the level of the level of the L2 vertebra

The abdomen data from the PMHS test series of [34]-[35] was selected as a biofidelity target. The subject was seated on a flat horizontal surface with the torso vertical at 90^o from horizontal and the legs hanging down over an edge. The torso was not restricted horizontally (free back). The impactor was a rigid lower steering wheel rim shape at 20^o from vertical. The impactor strikes the abdomen at the L2 vertebra level and the upper portion of the impactor shape can contact the lower ribs. The impactor mass was 18 kg and the impact velocity was 8 m/s. The proposed biofidelity targets are the abdomen reaction force and deflection time histories and the abdomen force versus deflection response.

Data processing – The PMHS tests selected to develop the biofidelity targets are given in Table 7. First, the force versus time and deflection versus time signals were digitized from the graphs released in [34]. The filter classes were not available in [34], neither in [35]. An observation of these signals shows that at the time when the deflection starts to rise from its zero baseline, the force level was around 50 N which indicates that the abdomen was engaged by the impactor. Consequently, no time shift was applied on the force and deflection time history signals. Force versus time and deflection versus time response curves were normalized using a mass-spring model to represent a 50th percentile male subjected to the biofidelity test impact conditions. The total body mass of each PMHS was used to compute the PMHS mass ratio (λ_{m2}) because the available data was insufficient to compute the PMHS abdomen effective mass. The abdomen depth was used to compute the stiffness ratio (λ_k). All the resulting normalization factors are given in Table 7. The mean and standard deviation of force and deflection time histories were calculated from the processed data. The force versus deflection biofidelity target was computed using the ellipse technique.

TABLE 7
Abdomen test 3. Details of the PMHS test sample [34][35].

Test	PMHS features						Impactor		Normalization factors†		
N°	N°	Sex	Age	Height (cm)	Weight (kg)	Abdo depth (mm)	Mass (kg)	Speed (m/s)	λ_F	λ_D	λ_t
86M006	86M001	M	63	180	70.1	321	18	10	0.72	0.91	1.13
86M016	86M010	F	52	168	40.2	237	18	6.5	1.38	1.28	1.04
86M026	86M020	F	44	165	57.5	278	18	7.5	1.05	1.15	1.08
86M042	86M040	M	46	176	50	292	18	10.8	0.73	0.83	1.12
86M052	86M050	F	55	162	70.3	312	18	9.3	0.78	0.96	1.12
Mean			*52*	*170.2*	*57.6*	*288*	*18*	*8.82*			

†Normalization factors were computed for a 50th percentile adult male (Body weight 76.7 kg, Abdomen depth 255 mm) and the impactor mass and velocity (18 kg, 8 m/s).

Abdomen Test 4 – Rigid Steering Wheel Rim Impact at the level of the T12 vertebra

The abdomen response data from the PMHS test series of [36] was selected as a biofidelity target. The subject spine was fixed to a rigid vertical support (fixed back). A 64 kg linear sliding impactor was propelled at a speed of 4 m/s against the subject abdomen and was arrested when the compression reached 30% or 50%, i.e. 76 to 145 mm, of impactor penetration. The impactor shape was a rigid half steering wheel (the inferior part) oriented at 45^o from vertical. The half-wheel was made of a tube, which diameter was 25.4 mm. The inner and outer diameters of the half-wheel were 152.4 mm and 177.8 mm respectively. The ends of the half-wheel were connected via a square section tube (25.4 mm side). The impactor was aligned such that the lower wheel rim contacted the subject at the level of the T12 thoracic vertebra. The proposed biofidelity targets are the abdomen force and deflection time histories and the force versus deflection curve.

Data processing – The PMHS tests selected to develop the biofidelity targets are given in Table 8. The raw signals of the impactor acceleration, force and displacement sensors were downloaded from the online NHTSA database and filtered at CFC 180, CFC 180, CFC 1000 respectively. The data processing described in [36] was applied: 1) the force was inertially compensated to get force at the abdomen interface, 2) the time of abdomen contact (time zero) was determined at the rise of the processed force versus time signal, 3) the displacement value at time zero was subtracted from the displacement versus time signal to get the abdomen deflection time history. Force versus time and deflection versus time response curves were normalized using a mass-spring model to represent a 50th percentile male subjected to the biofidelity test impact conditions. The total body mass of each PMHS was used to compute the PMHS mass ratio (λ_{m2}). The abdomen depth was used to compute the λ_k factor. All the normalization factors are given in Table 8. The mean and standard deviation of force and deflection time histories were calculated from the processed data until 17 ms (65 mm of deflection). The force versus deflection biofidelity target was computed using the ellipse technique.

TABLE 8
Abdomen test 4. Details of the PMHS test sample from [36].

Test		PMHS features						Impactor		Normalization factors†		
NHTSA N°	Ref. [36] N°	N°	Sex	Age	Height (cm)	Weight (kg)	Chest depth (mm)	Mass (kg)	Speed (m/s)	λ_F	λ_D	λ_t
b07365	Cad.1	2000-FRM-135	M	63	172.6	69.1	285	64	4	0.97	1.08	1.08
b07366	Cad.2	2002-FRM-159	M	66	166.5	65.9	251	64	4	1.04	1.03	1.03
b07367	Cad.3	2001-FRM-149	M	40	158.3	43.1	247	64	4	1.18	1.15	1.15
b07368	Cad.4	2002-FRM-161	M	61	181.7	65.8	284	64	4	0.98	1.09	1.09
Mean				*57.5*	*169.8*	*61.0*	*267*	*64*	*4*			

†Normalization factors were computed for a 50th percentile adult male (Body weight 76.7 kg, Abdomen depth 230 mm) and the impactor mass and velocity (64 kg, 4 m/s).

Abdomen Test 5 – Belt loading at the level of the L2 vertebra

The abdomen data from the test series of [37] was selected to be an abdomen biofidelity test. The test setup consisted of a static rigid seat and back support (fixed back). The PMHS was seated upright against the back plate. A 50 mm wide standard seatbelt (elongation of 9% at 10 kN) was initially positioned around the abdomen at the level of the umbilicus (equivalent to L2 vertebral level) and orientated horizontally to simulate an Out Of Positon (OOP) worst case. An initial preload of 20 N was applied to the lap belt (10 N in each strand).The belt was routed symmetrically rearward on both sides of the subject using a hydraulic cylinder to provide the pull force. The proposed biofidelity target is the belt tension versus abdomen deflection response. It is proposed to use as input the velocity time history of the belt strands located at each side of the back support.

Data processing – The PMHS tests selected to develop the biofidelity targets are given in Table 9. The force versus time and deflection versus time data were provided in numerical format by LAB PSA Peugeot Citroen Renault and were processed as in [37]. The filter classes were CFC1000 and CFC180 for the force and deflection response data respectively. No normalization was applied to the curves. The mean and standard deviation of the belt tension and abdomen deflection time histories were calculated from the processed data. The belt tension versus deflection biofidelity target was computed using the ellipse technique.

TABLE 9
Abdomen test 5. Details of the PMHS test sample [37].

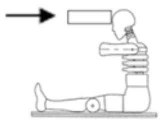
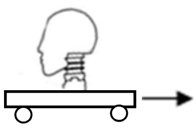
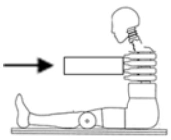
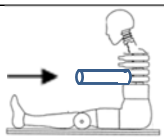
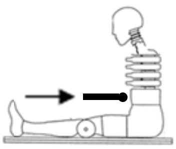
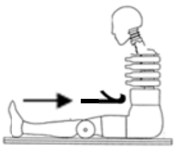
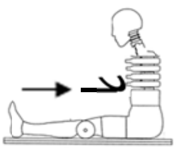
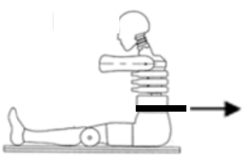
Test	PMHS features					
N°	N°	Sex	Age	Height (cm)	Weight (kg)	Chest depth (mm)
MHA111	MS586	M	74	175	77	287
MHA115	MS587	M	82	180	78	268
MHA151	MS588	M	88	166	69	249
MHA155	MS589	M	88	169	60	234
Mean			83	172.5	71	259.5

III. RESULTS

The Table 10 provides a summary of the proposed biofidelity tests for the upper body and their related biofidelity targets. The figures showing the plots of the biofidelity targets are shown in this section. Two dimensional targets are colored in yellow. The figure number for a given biofidelity target is given in Table 10. The digital data for all of the plots that follow can be found in the IRCOBI supplementary material associated with this paper and will also be made available in the NHTSA online database.

TABLE 10

SUMMARY OF THE PROPOSED BIOFIDELITY TESTS FOR THE UPPER BODY.

Test Name	Test schematic	Test Description	Ref.	Biofidelity targets
Head Test 1		Rigid impactor 23.4 kg – 2.0 m/s Mid-sagittal plane 30 mm above a horizontal line through the nasion	[4] [21]	Peak force at the Head, (Figure 1)
Neck Test 1		Sled test Acceleration input (Figure 2) The head/neck assembly is fixed to the sled at the level of T1 vertebra	[22] [23] [24] [25]	Head CG resultant acc. vs time , Head CG X and Z displ. vs time, Head Y rotation vs time, Head CG X displ. vs Z displ. (Figure 2)
Thorax Test 1		Rigid impactor 23.4 kg – 4.3 m/s Mid-saggital plane 4th intercostal space level	[16] [26] [28] [29]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 3)
Thorax Test 2		Rigid impactor 23.4 kg – 6.7 m/s Mid-saggital plane 4th intercostal space level	[16] [26] [27]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 4)
Thorax Test 3		Padded impactor 23.5 kg – 4.3 m/s 30° left rotation 8th rib level	[31]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 5)
Thorax Test 4		Sled test, belt restraint 40 kph – 14 G's plateau deceleration (Figure 6) 3 points belt, no load limiting, no pretensioner Rigid seat Lower body constrained	[32]	X deflection vs time at five location of the anterior wall of the thorax, Upper belt tension, (Figure 6)
Abdomen Test 1		Rigid bar impact 32 kg – 6.1 m/s L3 vertebra	[33]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 7)
Abdomen Test 2		Rigid bar impact 44 kg – 10.8 m/s L3 vertebral level	[33]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 8)
Abdomen Test 3		Rigid steering wheel impact Lower rim angulated at 20° from vertical 18 kg – 8 m/s L2 vertebral level	[34] [35]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 9)
Abdomen Test 4		Rigid steering wheel impact Half steering wheel angulated 45° from vertical 64 kg – 4 m/s, snubbed T12 vertebral level Fixed back	[36]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 10)
Abdomen Test 5		Belt pull Velocity input (Figure 11) Fixed back Umbilicus (~L2 vertebra) level	[37]	Force vs time, Deflection vs time, Force vs Deflection, (Figure 11)

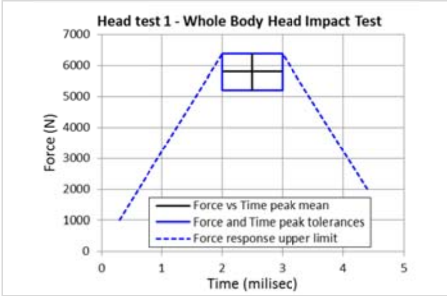


Figure 1. Head test 1 – Biofidelity target for the rigid impactor whole body test (23.4 kg, 2 m/s).

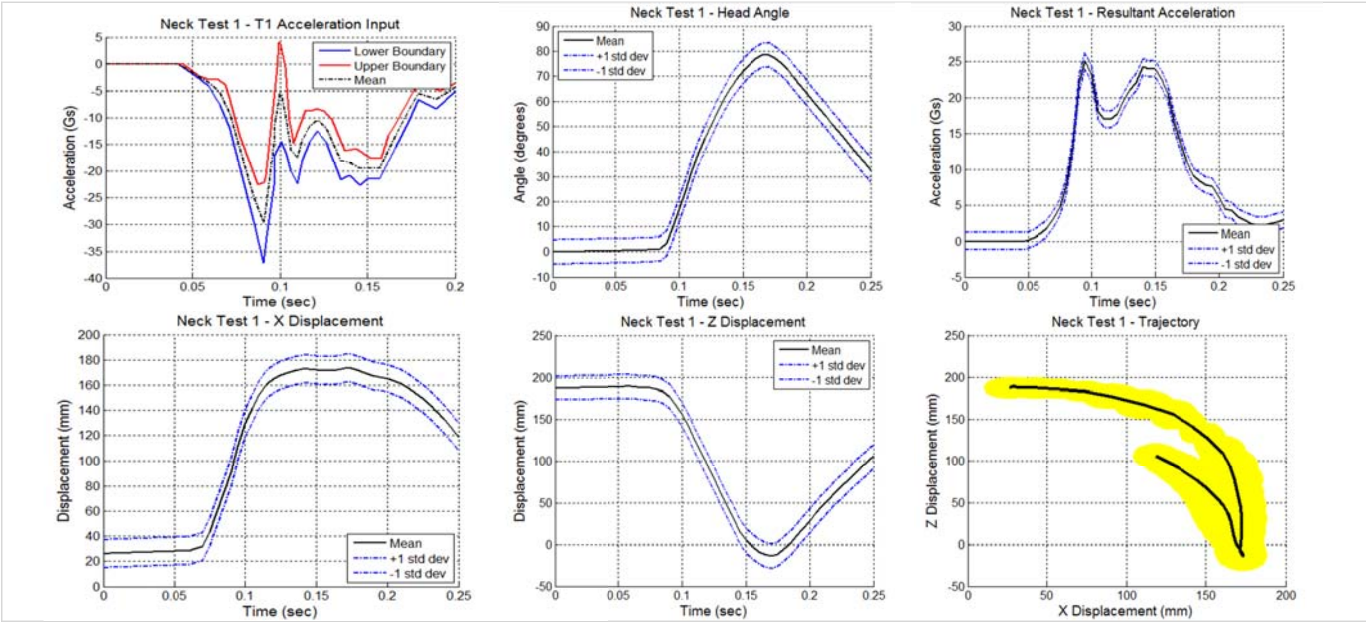


Figure 2. Neck test 1 – Biofidelity targets for the flexion test. Top left: acceleration input condition at T1. Others: response targets for the head CG.

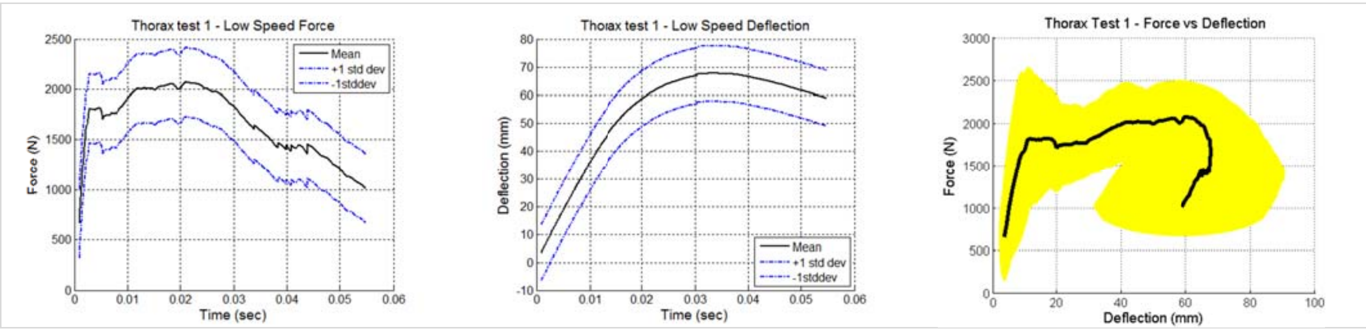


Figure 3. Thorax test 1 – Biofidelity targets for the rigid impactor low speed impact at the 4th costal interspace (23.4 kg, 4.3 m/s).

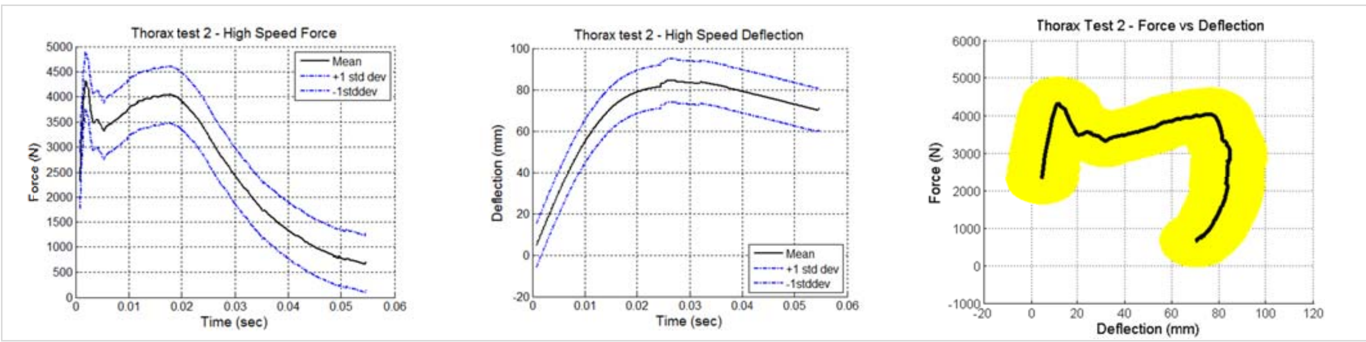


Figure 4. Thorax test 2 – Biofidelity targets for the rigid impactor high speed impact at the 4th costal interspace (23.4 kg, 6.7 m/s).

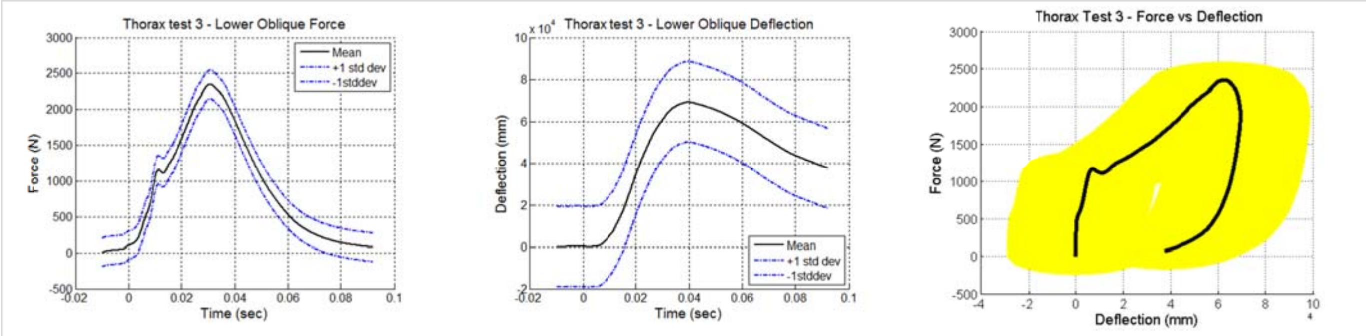


Figure 5. Thorax test 3 – Biofidelity targets for the rigid impactor oblique impact at the 8th rib (23.5 kg, 4.3 m/s).

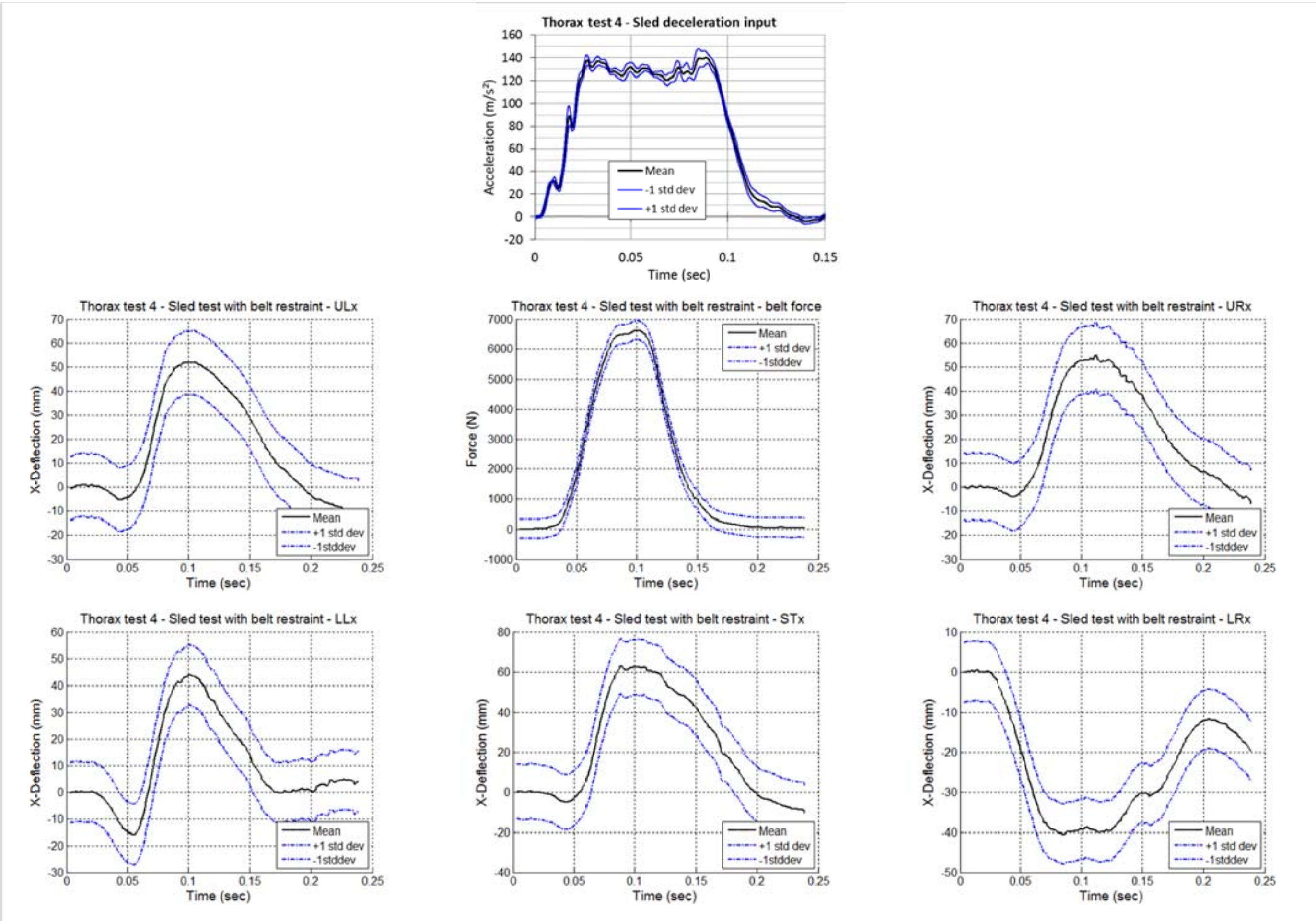


Figure 6. Thorax test 4 – Sled test (130 m/s ^{2}) using belt restraint without load limiting. Top row: input sled acceleration time history. Middle and bottom rows arranged as if looking at the torso from the rear, upper left deflection(ULx), upper torso belt tension, upper right deflection(URx), lower left deflection(LLx), sternum deflection(STx), lower right deflection(LRx).

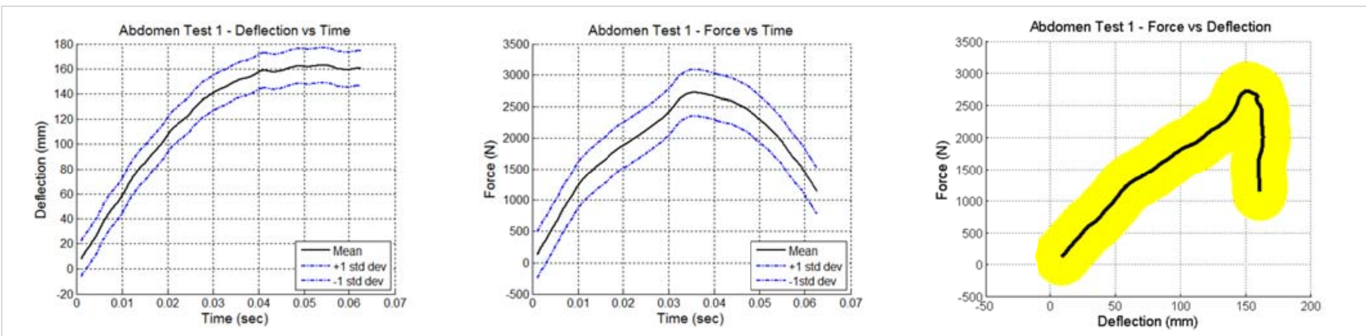


Figure 7. Abdomen test 1 – Biofidelity targets for the rigid bar low speed impact at L3 (32 kg, 6.1 m/s).

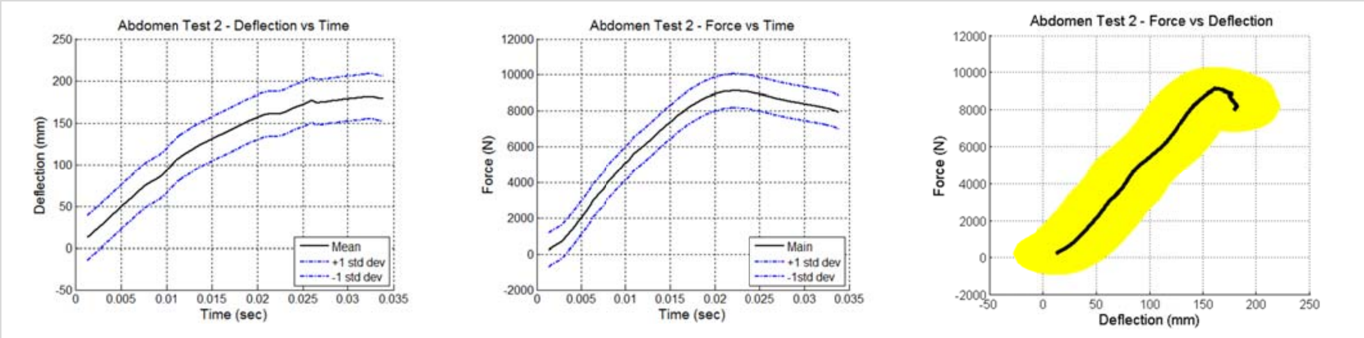


Figure 8. Abdomen test 2 – Biofidelity targets for the rigid bar high speed impact at L3 (44 kg, 10.8 m/s).

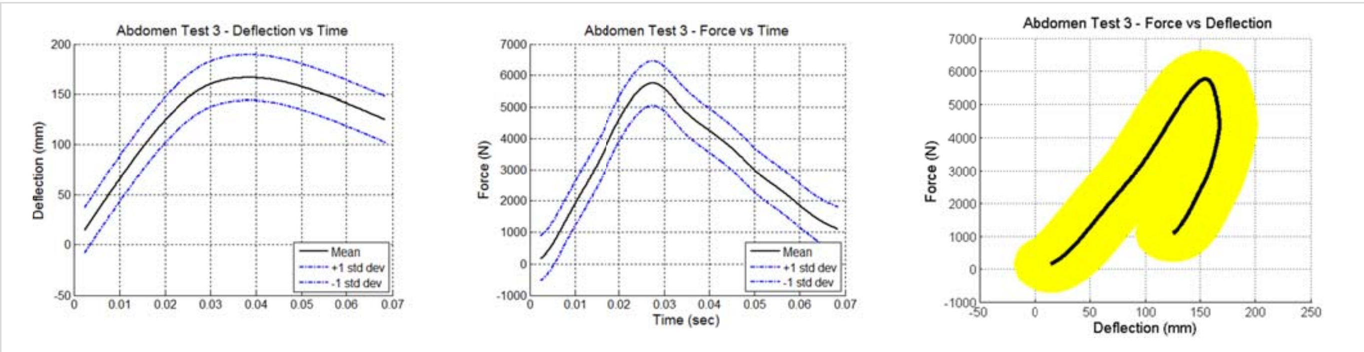


Figure 9. Abdomen test 3 – Biofidelity targets for the rigid steering wheel rim impact at L2 (18 kg, 8 m/s).

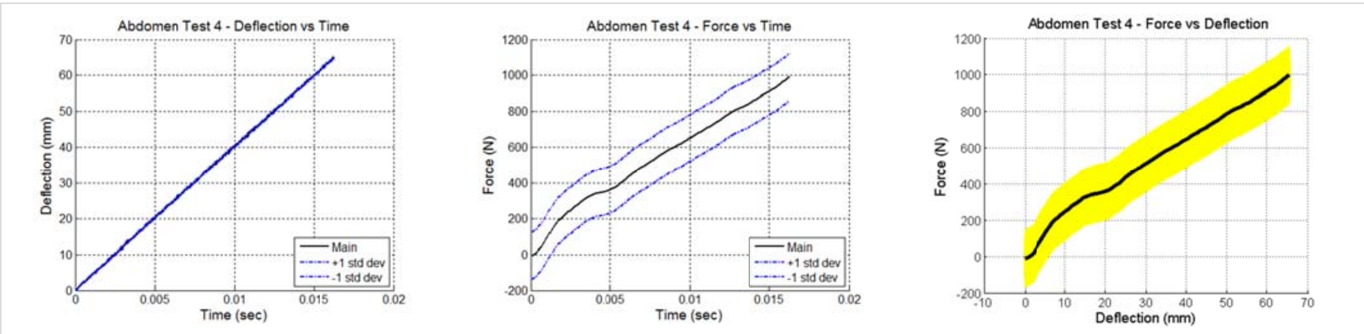


Figure 10. Abdomen test 4 – Biofidelity targets for rigid steering wheel rim impact at T12 (64 kg, 4 m/s).

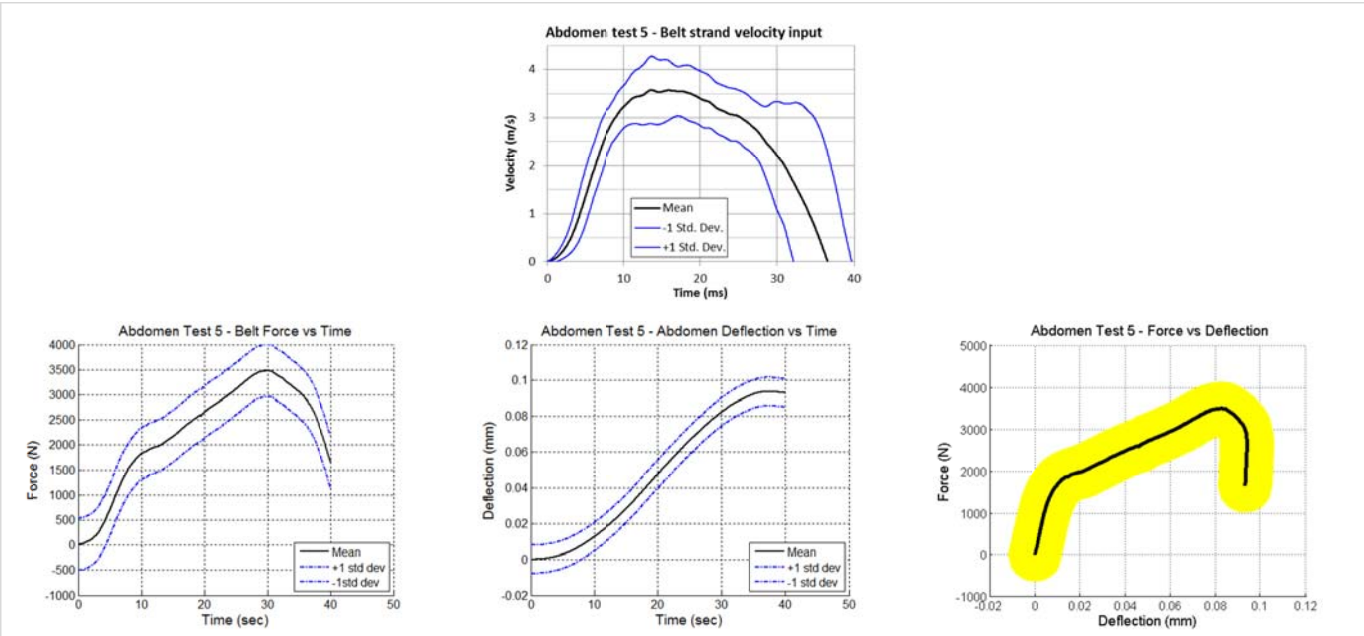


Figure 11. Abdomen test 5 – Biofidelity targets for the belt loading at L2 (~3.5 m/s). Top: input condition target. Bottom: belt force and abdomen deflection biofidelity targets.

IV. DISCUSSION

Relevance of the test configurations

Considering improvements in modern vehicle restraint systems the relevance of some test configurations might be questioned. This could be the case for all the upper body mid-sagittal plane impactor tests. The development of aircushion restraints with wide dissemination in the developed countries has dramatically diminished the number of blunt impacts. However, such cases likely still exist, especially in emerging countries where cars not equipped with airbags may be more common. Thus, some impactor tests such as the thorax test 2 at high speed might correspond to worst case scenarios. The thorax test 1 at low speed could be considered as a spare configuration for airbag loading conditions. Indeed, [29] observed that the ribcage strain pattern induced by an impactor was similar to the one induced by an airbag. The oblique impactor thorax test 3 is important for blunt impact can still occur in small overlap frontal crashes [39]-[40]. With respect to the abdomen, the various speeds of the impactor tests could assess this soft viscoelastic body region. Clearly, for the upper body, additional biofidelity tests that represent aircushion restraints are desirable. At the present time, reliable, reproducible airbag tests could not be found in the literature. However, it should be underlined that belt loading test configurations for the thorax and the abdomen (sub-marining scenario) were included in the set.

Data processing

The authors, and the task force, closely examined the published data used to build the biofidelity targets and made an effort to only select the most reliable data for the frontal biofidelity targets. However, some of the test descriptions and data had limitations that should be mentioned to provide a complete and thorough representation of the biofidelity targets.

Abdomen tests 1 and 2 [33] – Numerical data were available for some tests in the NHTSA database (see NHTSA test numbers in Table 5 and Table 6). However, there were not used for the following reasons: a) they were not available for all the tests; b) some numerical data were found to be corrupted (force and deflection time histories for the tests 14 and 19); c) the numerical data for the force is the raw signal from the force sensor and it was not possible to go back to the inertially compensated force signals released in the original paper (the half mass of the sensor was lacking and the acceleration data were corrupted for the tests n°24, 28, and 33); d) important time shifts were needed to be applied to the deflection versus time curves were necessary to reconstruct the correct force versus deflection response released in the original paper. In addition, ref. [33] does not say how was defined t0 – the time of impact from which it was started to track the impactor displacement against the L3 displacement on the movie. If we assumed that the force rise defined the time of impact and that the synchronization with the movie was made by eye, the definition of time 0 remained difficult because significant oscillations above and below zero force were observed, both in the published filtered data and in the numerical filtered data, before the force rise indicating that the abdomen was impacted. It may be for this latter reason that, for some of the tests, small time shifts (see Table 5 and Table 6) still needed to be applied to the digitized deflection versus time signal to obtain – when combined to the force versus time signal – the proper force versus deflection curve shapes released in [33]. As the time shift was apparently not necessary for all of the tests and the shift was always small (3 ms maximum, and 1.2 ms on average – see Table 5 and Table 6), this discrepancy in the data from [33] was deemed acceptable.

For all the above mentioned reasons, it was chosen to trust the data processing yielding the force versus deflection of the original paper [33] despite key pieces of information to double check their reliability were lacking.

Abdomen tests 3 – The above approach was not used for the [34]-[35] test series for which the authors of the present paper preferred to go back to the original time history signals released in [34]. It was observed that a time shift was systematically applied to the time history signals (4.6 ms on average) to obtain the force versus deflection responses released in [35]. This time shift was likely applied to get rid of the initial toe region for the purpose of comparison with dummy abdomens constructed of materials that are often quite stiff at small deflections. This updated biofidelity target abdomen test 3, did not incorporate this time shift and is thought to be more accurate and a better target, especially for mathematical models.

Regarding the PMHS test sample, it should also be mentioned that prior to the test series used to develop the biofidelity target, the PMHS were submitted to abdomen low speed (2.8 m/s approximately) impact tests using the same impactor. Thus, the abdomens sustained between four (PMHS n° 86M05) and eighteen (PMHS n°86M001) preliminary impacts. The necropsies performed after the ultimate test series revealed important abdomen injuries that may well be the result of the repeated impacts and not only of the final test. The influence of these injuries on the soft abdomen response is not known but should be of lesser influence than for hard body region such as the thorax.

Normalization

An effort was made to normalize the data when possible (see Table 11). This was achieved for all the test configurations for the head, the thorax, and the abdomen except one. The Mertz technique was widely employed because it has historically proved its efficacy in grouping the response curves of different PMHS, especially in the cases of impactor test configurations [14]. The Mertz technique was adapted for the thorax sled test but it failed to group the response curves. The Eppinger technique demonstrated more efficacy in grouping the sled response curves even if a spread was still observed for some deflection responses.

The response curves of [37] (abdomen test 5 – belt loading test) were not normalized because there was no lumped-parameter model readily available and the Eppinger technique demonstrated little success at grouping the curves in another abdomen belt loading study [47]. Limited success at grouping the curves using the Eppinger technique was also reported in the [43]-[44] studies relative to KTH tests [1]. For that reason, no normalization was applied to the response curves of the head and neck tests.

Two more recent normalization techniques have been proposed by [48] and [49] that utilize subject elastic stiffness and viscoelastic deformation energy, respectively, to estimate scale factors. These newer methods have not been applied by other researchers to additional data sets and cannot be considered accepted by the biomechanics community at this time. Because the objective of this paper is to provide a reliable set of biofidelity test data to be used by the biomechanics community as a standard assessment tool for the evaluation of dummies and numerical human body models it was decided to utilize the more accepted normalization approaches. The newer, and more sophisticated, normalization approaches will be examined by the authors in the future.

Muscle tensing

The only upper body biofidelity targets that include human muscle tone for sure are those of neck test 1 which are based on a set of volunteers tests. For all the other targets, no correction of the data accounting for the absence of muscle tone in the cadavers was applied. The effect of muscle tone on the response is believed to be marginal for the head test. For the thorax, Kent et al. [46] established that the effect was non-existent beyond 20% of chest compression and marginal below. For the abdomen, the effect of muscle tensing is not known so far as the authors of the present paper know.

Reproducibility

For some test configurations, key information on the test-set up that could affect the ability of another laboratory to accurately perform the tests is lacking.

For the thorax test 3 (oblique impactor test), a clarification regarding the padding material would be in principle desirable. Indeed, the characteristics of the Ensolite padding were not available in the original paper. The purpose of this padding was to spread the loading on the PMHS torso, which was equipped by chest bands, and prevent the latter instrumentation from being damaged. It should have less meaning for an impact against a anthropomorphic test device or a FE-model. In addition, it could be assumed that the energy dissipated by this padding was neglectable compared to the one dissipated by the torso. Thus, it is believed that any soft foam with sufficient thickness to spread the load at the torso interface could be used. That is the reason why it was proposed to use a 19 mm-thick Rubatex padding like for the THOR dummy biofidelity assessment [6] and for which the static F/D characteristics were provided [6].

For the thorax test 4 (sled test), the rigid seat structure and configuration are not defined and the locations of the five targets on the chest are not well defined in [32]. The NHTSA reports relative to the PMHS tests (NHTSA n°9546, 9547, 11014, 11015, and 11016) and made available online for the public may help to reproduce the test. In particular the NHTSA report describing how the test has been performed with the THOR dummy [50] provides many helpful details to reproduce the test configuration.

For the abdomen tests 3, the diameter values of the rim and of the wheel are lacking. Ref. [34] mentioned a “SGMRL Steering Wheel Assembly Model” and referred to a paper by Horsch et al. [41] but no further specifications were found in that latter reference.

For the abdomen test 5 (belt pull test), the input condition is presented as a velocity corridor for the belt extremities because the piston that pulled the belt rearward was not really servo-controlled. Indeed, the hydraulic machine was operated at "full-power", and we know that the resistance of the abdomen necessarily influenced the piston displacement and the force recorded in the belt. As a matter of fact, the belt force response of one subject (MS 588) significantly differed in phase and magnitude from the three others but still, the four tests of the sample resulted in a reasonable force variance. The ideal test set-up would be to give a displacement (or force) law to the machine. Despite these limitations, the [37] test series was included due to both the lack of alternate data sets (the abdomen belt test series of [47] was assessed by NHTSA, VRTC and found to be not reproducible) and the importance of including an abdomen belt loading scenario similar to a real-world submarining condition.

Test procedure for frontal dummies

As far as human computer model goes, it is believed that the details provided in this paper and in the original paper relative to each test series are sufficient to accurately reproduce the tests. However, as far as frontal dummy goes, worldwide accepted and detailed test procedures adapted to the physical characteristics of the frontal dummies and their specific landmarks are still needed for some tests. This is clear for the head and neck tests and should be easy for thorax tests 1 and 2, which are well-accepted standard tests. It should be relatively easy for the abdomen tests 1, 2 or 5 for which the major positioning criterion is that the rigid impacting bar or belt should only load the soft abdomen, i.e. neither the ribs nor the pelvis hard parts. However, a more precise procedure could be achieved by defining the height of the impact point with respect to the dummy H-point. For the other impact tests, some work is expected to achieve a worldwide consensus on test procedures adapted to any 50th percentile frontal dummy.

Overview

The present paper and its companion paper [1] provide a complete set of biofidelity targets to assess the biofidelity of the upper body and the lower body [1] of a 50th percentile male human surrogate. The test configurations are summarized in Table 11.

TABLE 11
Test configurations selected to assess the biofidelity of a 50th percentile human surrogate in frontal impact.

Body segment	Test #	Test Nature	Normalization Technique	Biofidelity target
Head	1	Rigid impactor test	Eppinger	Figure 1
Neck	1	Flexion test (mini-sled)	None	Figure 2
Thorax	1	Rigid Impactor Low Speed Impact at the 4th costal interspace	Mertz	Figure 3
	2	Rigid Impactor High Speed Impact at the 4th costal interspace	Mertz	Figure 4
	3	Rigid Impactor Oblique Impact at the 8th rib	Eppinger	Figure 5
	4	Sled Test using belt restraint without load limiting	Eppinger	Figure 6
Abdomen	1	Rigid Bar Low Speed Impact at L3	Mertz	Figure 7
	2	Rigid Bar High Speed Impact at L3	Mertz	Figure 8
	3	Rigid Steering Wheel Rim Impact at L2	Mertz	Figure 9
	4	Rigid Steering Wheel Rim Impact at T12	Mertz	Figure 10
	5	Belt loading at L2	none	Figure 11
KTH	1	Knee Impact, Large Impactor, Low Speed	none	In the companion paper [1]
	2	Knee Impact, Large Impactor, Medium Speed	none	
	3	Knee Impact, Large Impactor, High Speed	none	
	4	Knee Impact, Molded Face Large Impactor, Low Speed	none	
	5	Knee Impact, Small Impactor, Low Speed	none	
	6	Antero-Posterior Knee Drawer test	none	
Lower leg	1	Tibia Axial Loading	none	In the companion paper [1]
	2	Ankle Dorsiflexion Test	none	
	3	Ankle Inversion/Eversion Test – 0° Dorsiflexion	none	
	4	Ankle Inversion/Eversion Test – 30° Dorsiflexion	none	

The selected test configurations are issued from an extensive literature review and selected according to clear criteria defined by an international group of experts. An effort has been made to harmonize the data processing and to present the biofidelity targets in the same way: using a mean response curve with ± one standard deviation tolerance band. Some biofidelity targets that have already been published were updated in that way. The update could also concern other stages of the data processing such as the time 0 determination (abdomen test 3), the normalization (thorax tests 1, 2 and 4, abdomen tests 1, 2, 3, and 4), or the account for muscle tension (thorax tests 1 and 2). Some updated targets included additional PMHS tests, such as for the thorax tests 1 and 2 (as compared to the Neathery analysis [38]) and KTH test 6 (as compared to [7]). However, some targets were not updated and were added to the data set in their original state such as for the neck test 1 [22] or the KTH test 5 [45]. Lastly, nine new impact test specifications were constructed from available data in the literature. This is the case for the thorax test 4, the abdomen tests 4 and 5, the KTH tests 1, 2, 3 and 4, and the lower leg tests 1 and 2.

The interest of presenting the biofidelity targets as a mean response curve with ± one standard deviation tolerance band is that it allowed carrying out an objective and quantitative biofidelity assessment using the DCV/CCV technique [51],[52] or the CORA software [53]. Note that these techniques do not use the standard deviation tolerance band as corridor bounds. If biofidelity targets in a shape of a corridor are wished, then it should be useful to tighten the bounds around the mean curve. The bounds could be defined by taking a percentage of the maximum values of the mean response curves [17],[38], or by going back to the set of processed responses of the test sample [18].

Future work (upper body)

Five items were identified as future work, listed in order of priority.

1. Precise test procedures that are applicable to any dummy should be defined for every test.
2. The reproducibility of the thorax test 4, and abdomen tests 3 should be enhanced by acquiring the lacking key data.
3. New biofidelity tests using airbag loading for the upper body and using belt loading for the abdomen and thorax should be developed, performed, and incorporated into the set of tests and response data presented here.
4. The effect of the muscle tension on the abdomen should be investigated.
5. It would be useful to apply more recent normalization methods to all of the body region data to enhance the grouping of the response curves and the accuracy of the biofidelity targets.

V. CONCLUSIONS

The data presented provides a reasonable set of 50th percentile male frontal biofidelity response targets to be used to assess the performance of crash test dummies, component test devices, and human body computer models. The data used to create the targets was rigorously examined and decisions were made by a diverse group of vehicle crash biomechanics professionals to select accurate and well documented tests and response data. The data was normalized when appropriate and re-processed when necessary to allow for the calculation of means and standard deviations for the time history data. The data was also cross plotted when appropriate to obtain force versus deflection plots and one standard deviation tolerance bands were calculated using the ellipse error technique. The resulting biofidelity targets are shown in plotted format for the head, neck, thorax, abdomen in this paper, and the knee/thigh/hip complex and the lower leg in a companion paper [1]. The digital data is available in the supplementary material IRCOBI archive and on the NHTSA database.

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