A Frontal Response Specification for Assessing the Biofidelity of an Anthropometric Test Dummy Part 2 - Lower 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 knee/thigh/hip complex and the leg 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 head, neck, thorax, and abdomen. 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, lower 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 lower body. The upper 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

None of the data of the lower body tests were normalized.

Biofidelity targets

Different proposals can be found in the literature to define and compute biofidelity targets [12]-[16]. The most common is a corridor approach. 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. The standard deviation around the mean curves reflects the variance of the tested PMHS. 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. The two dimensional targets, such as a force versus deflection response, were developed using the "ellipse technique" described in [15]. 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. When the time history curves were not available then the force versus deflection corridor was created by computing the standard deviation of the force for each deflection value.

Knee Thigh Hip (KTH) Tests 1, 2, and 3 – Large impactor, low speed, medium speed, and high speed impact on both knees

Data from a series of tests performed at the University of Michigan Transport Research Institute (UMTRI) were selected for inclusion as three KTH frontal biofidelity targets [17]. The subject was seated on a Teflon sheet with the thighs extended horizontally, the knees bent at 90^{o}, and the feet supported on a platform. The torso was vertical with no back restraint and was supported from above with only the buttocks on the Teflon sheet. Both knees were struck simultaneously by a 275kg mass pendulum impactor at speeds of 1.2 m/s, 3.5 m/s, and 4.9 m/s. For the 1.2 m/s impact the impactor face is covered by a 38 mm thick, 50 durometer (Shore OO scale) layer of Sorbothane padding (Sorbothane Inc., Kent, Ohio). For the 3.5 and 4.9 m/s impacts the impactor face was covered by two 25 mm layers of Sorbothane padding, 70 and 50 durometer respectively, with the 50 durometer outer layer contacting the knee. The resulting sub-injurious loads spanned the range of knee loading conditions produced in FMVSS 208 and NCAP tests.

Biofidelity Target -- The proposed biofidelity targets are the impactor X-axis force at the knee interface, the femur Z-axis force (along the axis of the femur) at the acetabulum, and the pelvis H-point X-axis acceleration versus time. Note that the applied force calculated using the pendulum acceleration and mass should be divided by two.

For 50th percentile male surrogates that do not have an effective mass similar to that of the tested PMHS, the biofidelity target would be a ratio of 54±1.3% for the peak femur Z-axis force at the acetabulum divided by the peak impactor X-axis force applied at the knee interface.

Data processing – The body responses were processed as in the original paper [17] and transmitted by UMTRI in a numerical format. The filter classes were not specified. A summary of the data processing of [17] is given hereafter. A total of 250 knee impacts using 5 PMHS in 5 various states of dissection at three speeds were performed. Configurations ranged from intact whole body to isolated lower body without the thigh flesh with a load cell implanted in the femur shaft and included intermediate states such as whole body without the thigh flesh. For each impact configuration (1 cadaver, 1 dissection state, 1 speed), the test was repeated between three and five times leading to an extensive test matrix. These 250 impact responses measured in various configurations were used to develop and validate a computational model.

The responses of the five whole body cadaver tests were used to compute the biofidelity targets for the impactor X-axis force applied at the knee interface and for the pelvis H-point X-axis acceleration. The PMHS features are given in Table 1. For each impact speed configuration, the responses of the repeated tests were first averaged for each PMHS (within-subject average). Then the mean responses ± one standard deviation were computed from the five within-subject responses.

The computational model developed and validated by Rupp et al. [17] was used to compute the biofidelity target for the femur Z-axis force at the acetabulum. For each impact speed configuration, five different impactor applied force inputs (the within-subject average force of the five PMHS) were first applied to the computational model representing the whole body. Then, the five proximal femur Z-axis force outputs were averaged and the standard deviation was computed to build the biofidelity target.

TABLE 1
KTH tests 1,2, and 3. Details of the PMHS sample [17].

Test Series / Subject ID	Sex	Age	Height (cm)	Whole body weight (kg)	Thigh weight (kg)	Lower leg weight (kg)
0709	M	61	183	86	7.65	4.20
0710	M	67	175	91	7.20	2.60
0711	M	87	175	82	6.50	2.95
0712	M	46	183	91	9.55	3.65
0713	M	77	178	82	7.35	2.55
Mean		*67.6*	*178.8*	*86.4*	*7.65*	*3.19*

KTH Test 4 – Molded Face Large Impactor, Low Speed impact onto the knee

Data from twenty lower extremities from eleven PMHS impacted by a padded sliding piston driven by a large mass mini-sled were selected for inclusion as a KTH frontal biofidelity target [18]. The mini-sled was a 250kg sliding mass which strikes the piston at 1.2 m/s with an energy absorbing layer between the sled mass and the piston and with a molded knee shaped interface at the knee. The leg was flexed at 105°. The lower extremities should be separated from the pelvis at the hip and the femoral ball rigidly supported in an acetabulum shaped cup. The setup represents modern vehicles with energy absorbing knee blocker restraints and distributes load at the knee over the patella and femoral condyles.

Biofidelity Target – The proposed biofidelity targets are the applied force and knee deflection time histories and the force versus deflection.

TABLE 2
KTH test 4. Details of the PMHS test sample [18].

Test IDs	PMHS N°	Sex	Age	Height (cm)	Weight (kg)
19LF / 19RF	1	M	75	180	81
22LF / 22RF	2	M	41	176	91
24LF / 24RF	3	M	60	178	82
25LF / 25RF	4	F	86	168	68
26LF	5	M	62	183	91
27LF / 27RF	6	M	71	183	77
28LF / 28RF	7	F	65	163	82
30LF / 30RF	8	M	45	185	75
31LF / 31RF	9	F	79	165	91
32LF / 32RF	10	M	54	178	109
33RF	11	M	52	183	109
Mean			*63*	*177*	*87*

Data processing – The details of the PMHS sample used to develop the biofidelity targets are shown in Table 2. The response curves were processed exactly as described in [18]. UMTRI provided the processed measurements in numerical format. All forces and displacements were low-pass filtered using a 4th order Butterworth filter with a cutoff frequency of 300 Hz. Mean curves and a one standard deviation data tolerance band were calculated from the force and deflection versus time responses and the force versus deflection target was constructed using the ellipse technique.

KTH Test 5 – Small impactor low speed impact onto the knee

Data from twenty-four knee impacts performed on two cadavers using a pendulum with a rigid face [19] were selected as a frontal biofidelity target for KTH test 5. The subject was seated with buttocks on a horizontal plane with no back support (free back). The thighs were horizontal forward and the feet rest on a support. The knee flexion angle was between 90° and 105°. The mass of the pendulum ranged from 0.24 kg to 5 kg and its face diameter ranged from 38 mm to 76 mm. The impactor struck the knee along the femoral longitudinal axis at the center of the knee. The drop height ranged between 0.1 m and 0.8 m.

Test procedure – Reference [6] proposed to use a 5 kg mass impactor pendulum with a 75 mm diameter flat face to replicate the test. The impact speeds were 2 m/s and 3 m/s, respectively. Both tests had to be used for this target.

Biofidelity target – The proposed biofidelity target is a two dimensional corridor for the peak force applied at the knee plotted against the effective energy. The effective energy is calculated using either of the following two equations:

$$E_e = h \cdot \frac{m_p \cdot m_d}{(m_p + m_d)} \quad , \tag{1}$$

$$E_e = \frac{v^2}{2.g} \cdot \frac{m_p \cdot m_d}{(m_p + m_d)}, \tag{2}$$

where h is the drop height, v is the impactor speed before contact, g is gravity, m_p is pendulum mass and m_d is the 50th percentile male surrogate effective mass. The 50th percentile male surrogate effective mass is computed by using the results of the two impact tests (2 m/s and 3 m/s): first, the two impactor peak applied forces are cross-plotted with the corresponding femur peak accelerations. Second, a straight line (function f=a•x) is fitted to those points. The slope "a" of the straight line is the dummy effective mass used in equation (1) or in equation (2). Then the effective energy E_e is computed for each impact speed and cross-plotted with the related impactor peak forces. Both data points should lie within the corridor for peak knee force versus effective energy.

TABLE 3
KTH test 5. Details of the PMHS sample [19].

N°	Sex	Age	Height (cm)	Whole body weight (kg)	Effective mass (kg)
3150	M	54	180	71	2.02
3281	M	52	175	71	1.55

TABLE 4
Response data (n=15) of the left knee of the cadaver 3281 in the whole body impact conditions.

Pendulum					
Mass (kg)	Diameter (mm)	Drop Height (m)	Peak force (N)	Femur Peak Acc. (g)	Effective energy (kg.m)
0.5	51	0.1	445	24	0.038
0.5	51	0.225	947	63.6	0.085
0.5	51	0.4	1361	96.7	0.151
0.5	51	0.6	2019	160	0.227
0.5	51	0.8	2526	210	0.302
1.5	51	0.1	1050	51.9	0.076
1.5	51	0.225	2010	126	0.172
1.5	51	0.4	2878	194	0.305
1.5	51	0.6	3683	242	0.457
1.5	51	0.8	3816	253	0.610
5	76	0.1	1712	72.8	0.118
5	76	0.225	2887	146	0.266
5	76	0.4	4012	242	0.473
5	76	0.6	4893	300	0.710
5	76	0.8	5774	399	0.947

TABLE 5
Response data (n=9) of the right knee of the cadaver 3150 in the whole body impact conditions.

Pendulum					
Mass (kg)	Diameter (mm)	Drop Height (m)	Peak force (N)	Femur Peak Acc. (g)	Effective energy (kg.m)
0.24	38	0.15	187	15	0.032
0.24	38	0.25	258	25	0.054
0.24	38	0.41	347	38	0.088
0.76	38	0.15	411	15	0.083
0.76	38	0.25	598	22	0.138
0.76	38	0.41	956	55	0.226
2.96	38	0.15	1041	35	0.180
2.96	38	0.25	1532	55	0.300
2.96	38	0.41	2284	120	0.492

Data processing – Two knees from two intact PMHS (whole body condition) were impacted several times as indicated in Table 5 and Table 4. The characteristics of each cadaver are given in Table 3. For each cadaver, the

KTH effective masses were computed by fitting a straight line between peak knee impact force and peak femur acceleration. The force and acceleration signals were filtered at a frequency that equated to the CFC 1000. The effective energy was then computed for each impact test using equation (1). Lastly, for each cadaver a function $F = a.E^b$ was fitted for the peak applied force at the knee (F) and the effective energy (E_e) pairs of points.

KTH Test 6 – Antero-posterior Knee Drawer test

The antero-posterior knee drawer motion test was performed on PMHS knee specimens by General Motors (GM) laboratories [21]-[23], and the Wayne State University (WSU) [24]. The motion was applied on the excised knees flexed at 90° using a servo-controlled actuator driven at 1.8 m/s approximately. The actuator pushed either the femur forward with the tibia fixed [21]-[23] or the tibia rearward with the femur fixed [24].

Biofidelity target – The proposed biofidelity target is the force recorded behind the femur shaft versus the tibial plateau displacement.

Data processing – The data of sixteen tests that resulted in a posterior cruciate ligament rupture or avulsion was used. Tests that resulted in solely tibial fracture were excluded. Details on the PMHS features, knee specimens' preparation, and post-test injuries are summarized in Table 6. The data of the sample from [24] were provided by WSU in numerical format and filtered CFC180 for the displacement and CFC600 for the force. The force versus deflection response curves of the other tests [21]-[23] were digitized from hard copies of a GM Laboratories internal reports [22]-[23]. No information was available on the filtering procedure used for the GM data.

To get rid of the natural slack that exists in the knee joint and align the signals, the tibia displacement was set to zero when the femur load reached 50 N. This implied to shift the original force versus deflection curves as shown in Table 6. The force versus deflection curves were then resampled at a 0.05 mm constant displacement step and the mean and standard deviation of the force were computed at each displacement step.

Test procedure – An alternative test procedure is proposed for this biofidelity target. Current frontal dummies have a knee slider connection between the proximal tibia and the distal femur that is tested with a pendulum impact on the slider assembly without the leg. The dummy knee slider test is performed with a 12 kg pendulum at 2.7 m/s. This test procedure was exposed in [4] and detailed in the GM Hybrid III Manual [31].

TABLE 6
KTH test 6. Details of the PMHS knee specimen test sample [21][24].

Sample	Specimen n°/Side	Sex	Age	Height (m)	Weight (kg)	Knee preparation*	Post test injury	Shift# (mm)
[21]-[22]	20817/L†	M	45	1.7	55	LE	Posterior cruciate ligament central tear	+ 0.1
[21]-[22]	20881/R†	M	69	1.71	75	LE	Posterior cruciate ligament central tear	+ 0.1
[21]-[22]	20827/L†	M	78	1.79	89	LE	Posterior cruciate ligament avulsion and tibial fracture at potting	+ 0.1
[23]	20998/R	M	NA	NA	NA	PCL only	PCL Rupture	- 3.1
[23]	21030/L	M	67	NA	61	LE	PCL Rupture	- 0.3
[23]	21059/R	F	55	NA	66	LE	PCL Rupture	- 2.9
[23]	21059/L	F	55	NA	66	PCL only	PCL Rupture	- 4.4
[23]	21076/R	M	65	NA	79	PCL only	PCL Avulsion	- 2.2
[23]	21118/L	F	78	NA	71	LE	PCL Avulsion	- 4.4
[23]	21118/R	F	78	NA	71	PCL only	PCL Avulsion	- 2.8
[24]	WSU507/6R	F	53	1.69	54.4	Intact	PCL mid-substance rupture	- 0.5
[24]	UM31222/4L	F	58	1.625	90.7	PCL only	PCL avulsion at tibial insertion	- 1.9
[24]	UM31234/5L	M	58	1.755	57.6	PCL only	PCL mid-substance rupture	- 2.1
[24]	WSU571/7R	M	40	1.83	122.5	PCL only (+ RT)	PCL mid-substance rupture	- 1.9
[24]	WSU571/7L	M	40	1.83	122.5	PCL only (+ RT)	PCL mid-substance rupture	- 0.2
[24]	UM31490/8R	M	84	1.74	54.4	PCL only (+ RT)	PCL avulsion at the tibial insertion with partial articular fracture of the lateral plateau	- 0.7
	Mean		*61.5*	*1.74*	*75.7*			

* **PCL only**: Only the PCL and meniscus were left intact ; **PCL only + RT**: Reinforced Tibia shaft in addition to PCL only conditions; **LE**: Only the joint capsule, collateral ligaments, cruciate ligaments and meniscus remained after the dissection ; **Intact**: all the muscular and ligamentous structures were intact

† These knee specimens were harvested on PMHS previously tested using a flat 15cmx15cm square 55.9 kg impactor covered with a ~6cm padding (3.2 KN/cm stiffness, 112 kg/m3 density) propelled at 6m/s approximately onto the tibia (20881/R) or onto the knee and the tibia together (20817/L and 20827/L). No damage was observed on the specimen before the antero-posterior knee drawer test.

Positive values mean shift-to-right and negative values mean shift-to-the left of the F/D curves.

Lower Leg Test 1 – Tibia axial loading

A leg axial load biofidelity target was derived from the PMHS test series of [25] performed at the University of Virginia (UVa). A 33 kg pendulum impactor was used to strike a 6.54 kg linear padded transfer piston with a plate contacting the foot plantar surface. The lower extremities were excised above the knee and a force cell was implanted in the tibia shaft. The lower leg was flexed 90° at the knee and constrained above the knee along the tibia longitudinal axis with the tibia in a horizontal position and the anterior surface facing upward. The ankle was in a "neutral" position and two plies of 9.5 mm thick padding were between the footplate and the plantar surface of the foot. The knee reaction surface and the foot plate surface appear to be parallel with the foot at 90^o to the anterior tibia surface in the setup drawing provided. The load was delivered onto the entire plantar surface of the foot through a 2kg flat plate attached to the transfer piston (the total mass of the padding-transfer piston-foot plate-padding assembly was 6.54 kg). The flat plate was in contact with the foot prior to the impact. The pendulum was propelled at 7 m/s and struck the padded transfer piston in horizontal translation to a maximum of 16 cm in the tibia longitudinal axis direction.

Biofidelity Target – The proposed biofidelity target is the Z force versus time measured in the tibia shaft and the Z force versus the foot-plate displacement. The foot-plate displacement versus time is the input requirement.

Data processing – The data from fifteen PMHS tests were selected for the biofidelity target and the details are shown in Table 7. Most tests resulted in a foot or ankle fracture except one. The tests that resulted in solely a tibia fracture were excluded. The response data were provided by UVa in numerical format. All the response signals were filtered CFC180 and truncated at 19 msec. Time zero was defined as the time when the impactor struck the transfer piston. Mean curves and a one standard deviation tolerance band were derived from the force and displacement responses versus time and the force versus displacement target was constructed using the ellipse technique.

TABLE 7
Lower leg test 1. Details of the PMHS test sample [25].

Test N°	PMHS N°†	Sex	Age	Height (cm)	Weight (kg)	Post-test injury
3B	99-EF-104-L	F	67	163	63.6	Foot/ankle fracture + injury at the tibia plateau
3D	97-EM-76-L	M	47	178	52.3	Foot/ankle fracture + injury at the tibia plateau
4B	99-FF-17-L	F	74	160	60	Foot/ankle fracture
4C	99-FF-17-R	F	74	160	60	Foot/ankle fracture + artifactual tibia shaft fracture
4F	99-EF-104-R	F	67	163	63.6	Foot/ankle fracture
4G	98-FF-100-R	F	42	168	71.4	Foot/ankle fracture + artifactual tibia shaft fracture
5A	97-EM-88-L	M	59	170	47.7	Foot/ankle fracture + injury at the tibia plateau
5B	97-EF-77-R	F	63	160	55.9	None
5C	99-FF-101-R	F	62	168	52.3	Foot/ankle fracture + injury at the tibia plateau
5D	97-EM-88-R	M	59	170	47.7	Foot/ankle fracture
5F	99-FF-101-L	F	62	168	52.3	Foot/ankle fracture + injury at the tibia plateau
5G	99-EM-93-R	M	67	191	80.5	Foot/ankle fracture
5H	99-EM-93-L	M	67	191	80.5	Foot/ankle fracture
5I	99-FM-102-R	M	65	188	84.1	Foot/ankle fracture + injury at the tibia plateau
5J	99-FM-102-L	M	65	188	84.1	Foot/ankle fracture + injury at the tibia plateau
	Mean		*62.7*	*172.4*	*63.7*	

†The first of the two letters in the middle of the specimen ID denotes whether the specimen was embalmed (E) or fresh frozen (F). The authors of [25] used an in-house embalming mixture known to not alter significantly the tissue properties

Lower Leg Test 2 – Ankle dorsiflexion test

The dorsiflexed foot axial load biofidelity target was derived from eighteen PMHS lower extremities (see Table 8) excised above the knee and tested in dynamic axial load using a pendulum impactor and linear transfer piston and foot plate configuration [26]. The test set-up was similar as that of the lower leg test 1 [25] except that the footplate was replaced by a pedal shape and that the load was applied at the ball of the foot (first metatarsal joint). As in Lower Leg Test 1 the foot is approximately positioned at 90^o with respect to the anterior tibia surface but "variability among the specimens required the initial position specifications to only be loosely adhered to" [26]. Additionally, the lower leg specimens were instrumented with load cells in the fibula in addition to the one implanted in the tibia shaft and accelerometers were placed on the tibia shaft and the calcaneus. The transfer piston was allowed to displace up to 17 cm.

Biofidelity Target – The proposed biofidelity target is the reaction moment at the ankle joint versus time and versus the ankle rotation. The applied ankle rotation versus time corridor is the input requirement.

Data processing – The data were processed as in the original paper [26]. The ankle rotation was acquired via tracking on the video image of the test and the ankle moment was calculated from sensor measurements and the geometric and mass properties, i.e. moment of inertia. The data were filtered to SAE J211-prescribed filter classes. The processed data were provided by UVa in numerical format. Mean curves and a one standard deviation tolerance band were derived from the ankle moment and angle response versus time and the moment versus angle biofidelity target was constructed using the ellipse technique.

TABLE 8
Lower leg test 2. Details of the PMHS test sample [26].

Test n°	Specimen n°	Sex	Age	Height (cm)	Weight (kg)
32 37	01-L 01-R	M	41	183	87
33 36	03-L 03-R	M	57	178	86
34 35	113-L 113-R	M	71	175	78
41 44	147-L 147-R	F	63	160	45
42 46	143-L 143-R	F	29	180	85
43 45	151-L 151-R	M	63	183	84
51 53	152-L 152-R	M	70	180	79
52 54	141-R 141-L	M	65	178	75
55 56	180-L 180-R	F	79	168	41
	Mean		*59.8*	*176.1*	*73.3*

Lower leg tests 3 and 4 – Ankle inversion/eversion test

The ankles of nineteen PMHS lower extremities, excised above the knee and were dynamically tested in inversion and eversion by [27]. A specially designed test apparatus (plans are provided in the supplementary material attached to this paper) applied a pure inversion or eversion moment about the ankle at approximately 1000°/sec. Two dorsiflexion test configurations were selected [27] at 0° and 30° with an axial load of 2000 N applied at the proximal tibia. Rotation of the footplate was applied by a pneumatic impactor striking a guided cam on one side of the footplate with the opposite side controlled by 2 kN honeycomb crushed by a piston. The amount of footplate rotation was either 25° or 48° and controlled by the size of the cam used. An initial ankle moment was induced by axially preloading the ankle. In some cases the ankle was initially positioned at 14º of inversion or eversion to allow for large angular rotations under loading and injury. In this biofidelity test the initial position of the foot/ankle should match the target initial target position specification as closely as is possible while recognizing that the target has a tolerance of one standard deviation.

Biofidelity Target – The proposed biofidelity targets for each test configuration are the ankle rotation and moment versus time and the ankle moment versus rotation.

Data processing – Details on the specimen test sample are given in Table 9 and Table 10 for the neutral and 30° dorsiflexion configuration respectively. The data in numerical format were provided by UVa and processed as described in [27]. The moment and rotation response data were digitally filtered to SAE J211 channel class 180. Mean curves and a one standard deviation tolerance band were derived from the ankle moment and rotation responses versus time, and the moment versus angle targets were constructed using the ellipse technique.

TABLE 9

Lower leg test 3. Details of the PMHS specimen test sample [27].

Specimen ID #	Age	Sex	Height (cm)	Mass (kg)	Test #	Final rotation		Axial Load (N)	Failure M_{cr} (N.m)	Failure Angle	Peak M_{cr} (N.m)	Angle at peak M_{cr}	Injury description†
7-L	66	M	183	95	501	-48º	Inv	2467	-63	-37º	-68	-47º	Lateral ligament tears
116-L	69	M	163	92	503	-48º		2633	-64	-32º	-64	-32º	OC fx's, lateral ligament tears
120-L	59	F	168	80	701	-39º		2372	/	/	-76	-41º	/
					702	-62º		2182	-87	-59º	-87	-59º	Lateral ligament tears
127-L	54	F	163	50	705	-62º		1998	-62	-33º	-62	-33º	Bimaleolus fx's, lateral ligament avulsion
146-R	70	M	168	73	805	-62º		2120	-117	-58º	-117	-58º	Lateral ligament tears
Mean	*63.6*		*169*	*78*		*-53.5°*		*2295*	*-78.6*	*-43.8°*	*-79*	*-45°*	
120-R	59	F	168	80	502	48º	Ev	1820	/	/	79	48º	*No injury*
116-R	69	M	163	92	703	62º		1460	150	42º	150	42º	Medial maleolus fx
114-R	66	F	163	60	704	62º		1484	39	27º	57	45º	Bimaleolus fx's
144-L	64	M	173	119	803	11º		1564	/	/	46	11º	/
					804	62º		2567	238	56º	238	56º	Medial ligament tears
Mean	*64.5*		*166.8*	*87.8*		*49°*		*1779*	*142.3*	*41.7°*	*114*	*40.4°*	

†"OC" stands for Occipital Condyle, "Calc." stands for calcaneus, "LPT" stands for Lateral Process of the Talus.

TABLE 10

Lower leg test 4. Details of the PMHS specimen test sample [27].

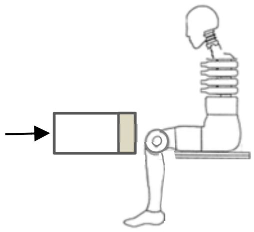
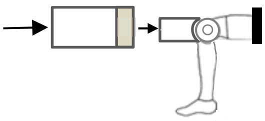
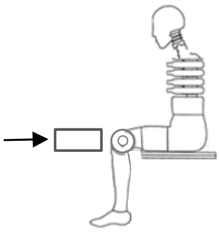
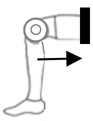
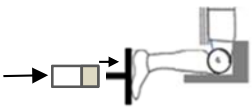
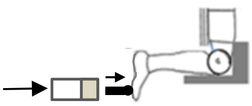
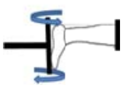
Specimen ID #	Age	Sex	Height (cm)	Mass (kg)	Test #	Final rotation		Axial Load (N)	Failure M_{cr} (N.m)	Failure Angle	Peak M_{cr} (N.m)	Angle at peak M_{cr}	Injury description
112-L	55	M	173	85	504	-48º	Inv	2679	/	/	-115	-48º	*No injury*
112-R	55	M	173	85	602	-62º		3035	-96	-30º	-112	-61º	OC fx's, Lateral ligament tears
146-L	70	M	168	73	707	-62º		1549	-54	-31º	-64	-62º	Calc. fx, Lateral ligament tears
137-R	75	F	168	68	807	-11º		1937	/	/	-40	-11º	/
					808	-62º		1913	-35	-37º	-64	-47º	OC and calc. fx's, Lateral ligament tears
Mean	*63.8*		*170.5*	*77.8*		*-49°*		*2223*	*-61.7*	*-32.7°*	*-79*	*-45.8°*	
119-R	59	M	183	108	505	48º	Ev	2074	200	45º	200	45º	OC and talus fx's
6-R	66	F	165	67	506	48º		3208	176	38º	195	44º	LPT fx
6-L	66	F	165	67	601	62º		2647	182	45º	182	45º	LPT fx, medial ligament tears
119-L	59	M	183	108	603	62º		2250	114	40º	117	50º	LPT fx, medial ligament tears
144-R	64	M	173	119	706	62º		2207	99	30º	110	49º	LPT fx, medial ligament tears
137-L	75	F	168	68	806	62º		1833	68	43º	83	50º	LPT fx, medial ligament tears
Mean	*64.8*		*172.8*	*89.5*		*57.3°*		*2370*	*139.8*	*40.2°*	*147.8*	*47.2°*	

†"OC" stands for Occipital Condyle, "Calc." stands for calcaneus, "LPT" stands for Lateral Process of the Talus.

III. RESULTS

The Table 11 provides a summary of the proposed biofidelity tests for the lower 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 11. 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 11
SUMMARY OF THE PROPOSED BIOFIDELITY TESTS FOR THE LOWER BODY

Test Name	Test schematic	Test Description	Ref.	Biofidelity targets
KTH Test 1		Pendulum impact Seated subject Both knees Padded interface 275 kg, 1.2 m/s	[17]	Impactor X force at the knee interface vs time, Femur Z force at the acetabulum vs time, Pelvis H-point X acceleration vs time, (targets are shown in Figure 1, Figure 2, and Figure 3 for the three impact tests respectively). Minimal requested target: ratio of 54±1.3% for the peak femur Z force at the acetabulum divided by the peak impactor X force applied at the knee interface.
KTH Test 2		Pendulum impact Seated subject Both knees Padded interface 275 kg, 3.5 m/s	[17]	
KTH Test 3		Pendulum impact Seated subject Both knees Padded interface 275 kg, 4.9 m/s	[17]	
KTH Test 4		Pendulum impact with transfer piston Fixed lower extremity One knee Rigid molded interface 250 kg, 1.2 m/s	[18]	Applied force vs time, knee deflection vs time, Applied force versus KTH deflection. (Figure 4)
KTH Test 5		Pendulum impact Seated subject One knee Rigid interface 5 kg, 2 and 3 m/s	[19]	Peak force applied at the knee vs effective energy. (Figure 5)
KTH Test 6		Knee Drawer Test Fixed lower extremity 1.2 m/s servo actuator or HIII knee slider impactor test (12 kg, 2.7 m/s)	[21] [22] [23] [24]	Femur force vs tibial plateau disp. (Figure 6)
Lower Leg Test 1		Tibia Axial Test Pendulum test with transfer piston 33 kg, 7 m/s 16 cm max. stroke Input: piston displacement vs time (Figure 7)	[25]	Z tibia force vs time, Z tibia force vs piston disp. (Figure 7)
Lower Leg Test 2		Ankle Dorsiflexion Test Pendulum test with transfer piston 33 kg 17 cm max. stroke Input: ankle rotation vs time (Figure 8)	[26]	Ankle joint Y moment vs time, Ankle joint Y moment vs ankle rotation. (Figure 8)
Lower Leg Test 3		Ankle Inversion/Eversion Test Pure moment, 1000 °/s Neutral position (no dorsiflexion) Tibia axial preload	[27]	Ankle joint X moment vs time, Ankle joint X moment vs ankle rotation. (Figure 9)
Lower Leg Test 4		Ankle Inversion/Eversion Test Pure moment, 1000 °/s Dorsiflexed 30° Tibia axial preload	[27]	Ankle joint X moment vs time, Ankle joint X moment vs ankle rotation. (Figure 10)

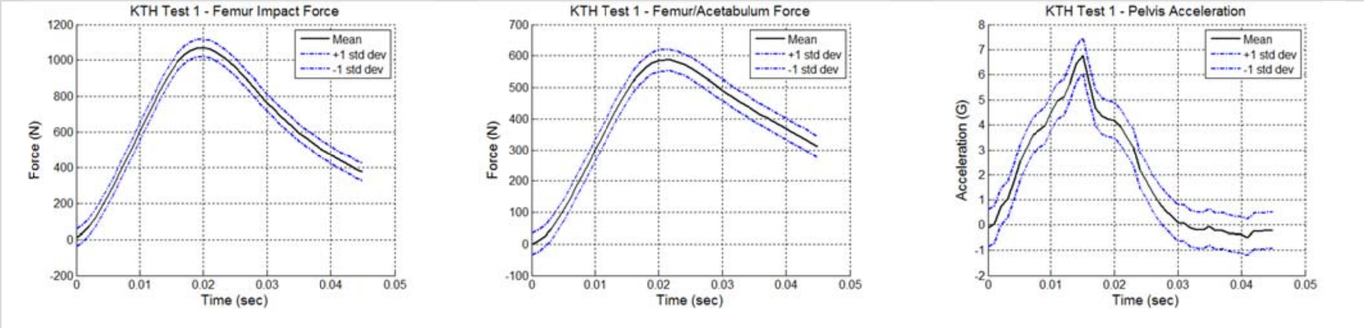


Figure 1. KTH test 1 – Whole body. Biofidelity targets for the 1.2 m/s large impactor knee impact.

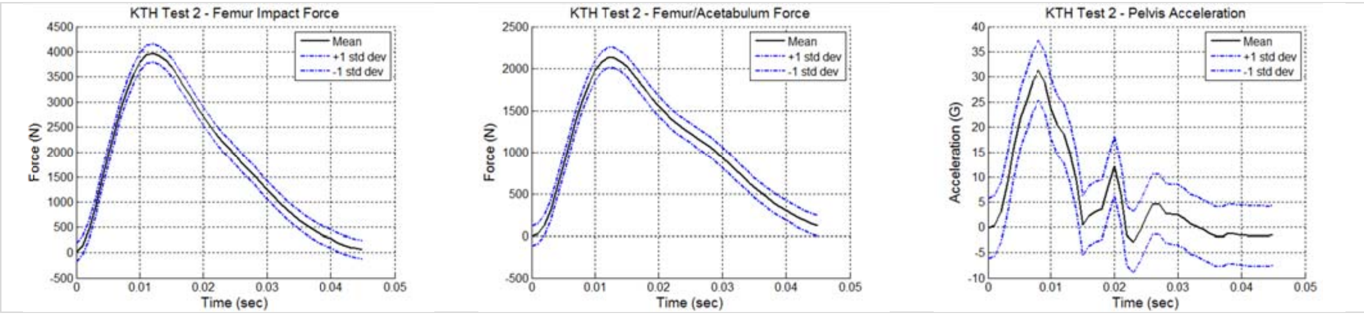


Figure 2. KTH test 2 – Whole body. Biofidelity targets for the 3.5 m/s large impactor knee impact.

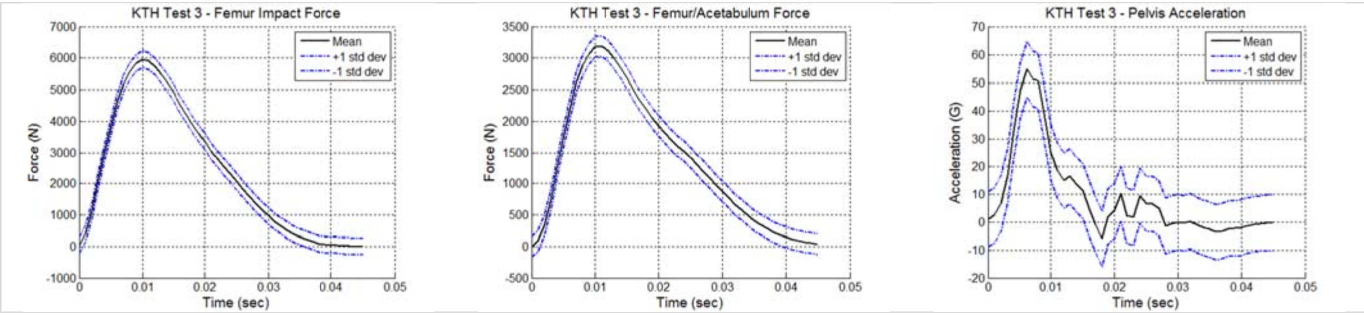


Figure 3. KTH test 3 – Whole body. Biofidelity targets for the 4.7 m/s large impactor knee impact.

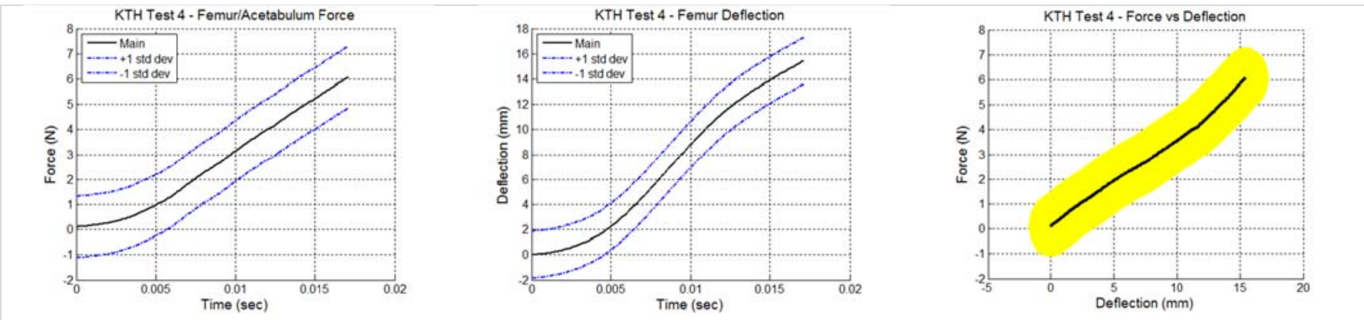


Figure 4. KTH test 4 – Isolated leg. Biofidelity targets for the 1.2 m/s molded face - large impactor knee impact.

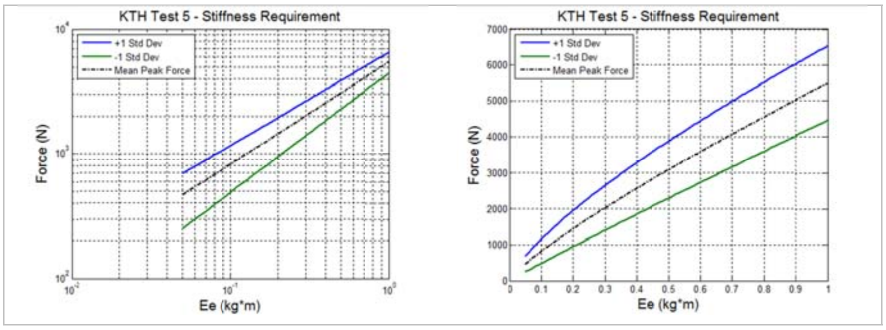


Figure 5. KTH test 5 – Whole body. Biofidelity target for the small impactor knee impact.

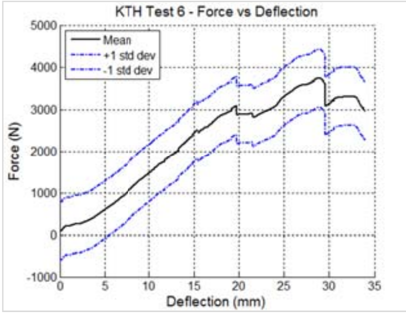


Figure 6. KTH test 6 – Biofidelity targets for the antero-posterior knee drawer test.

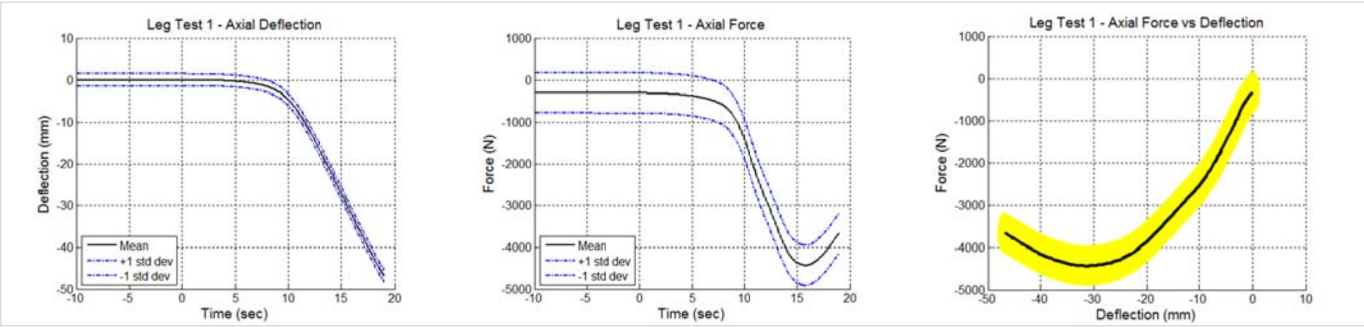


Figure 7. Lower leg test 1 – Biofidelity targets for the tibia axial loading.

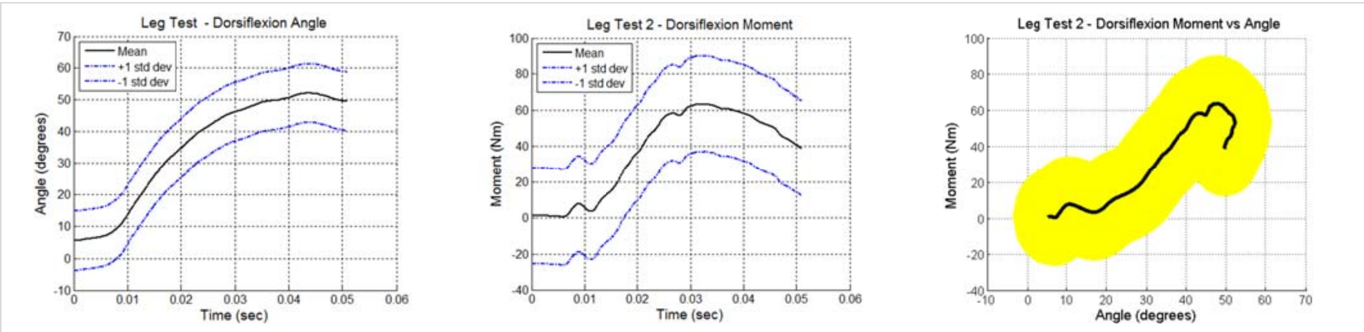


Figure 8. Lower leg test 2 – Biofidelity targets for the ankle dorsiflexion.

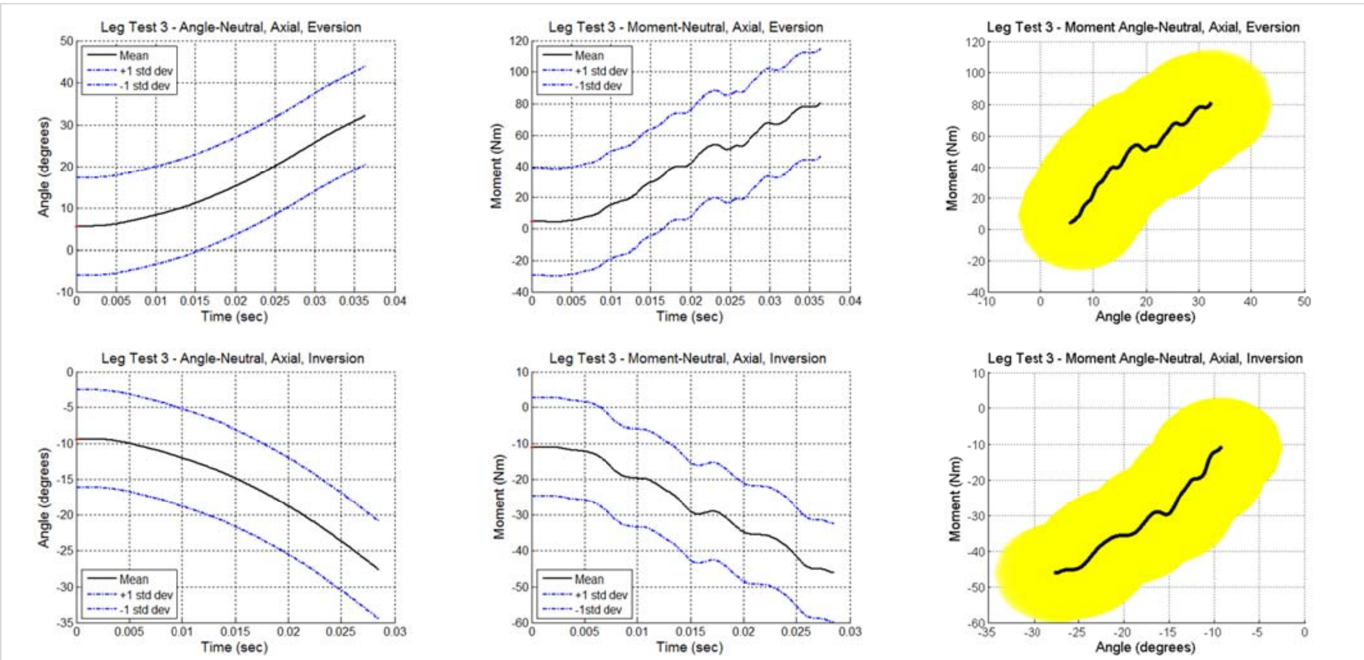


Figure 9. Lower leg test 3 – Biofidelity targets for the ankle eversion (top row) / inversion (bottom row) at 0° dorsiflexion.

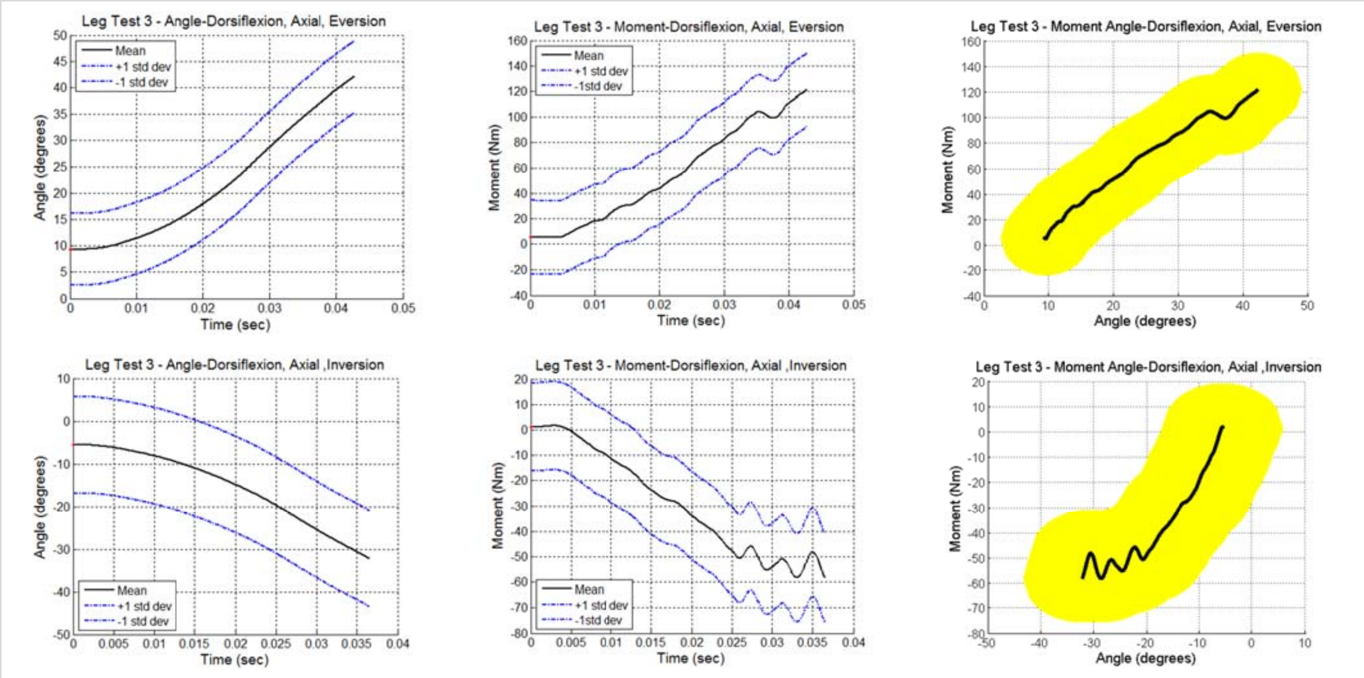


Figure 10. Lower leg test 3 – Biofidelity targets for the ankle eversion (top row) / inversion (bottom row) at 30° dorsiflexion.

IV. DISCUSSION

Relevance of the test configurations

The biofidelity target of the KTH test 5 allows assessing the stiffness of the KTH complex whatever the effective mass of the 50th male surrogate. The use of a small impactor makes the test configuration easy to implement. However the biofidelity target was developed using only two tests (two legs from two PMHS). Further, the relevance of the test may be questioned because the light-mass impactor strike induces a short pulse which is not typical in real world crashes. KTH test 5 is balanced by the larger mass impacts of KTH tests 1 to 4 which were designed to represent the KTH loading conditions produced in FMVSS 208 and NCAP tests.

For the KTH test 6, the test set-up of the original studies used an actuator to induce a drawer motion at a constant speed of 1.8 m/s. The authors of [24] recalled that the response of knee ligaments was shown to be relatively insensitive to small variations of strain rate (observation made on rabbit's ligament). As this drawer test was primarily designed to assess the stiffness of the posterior cruciate ligament (PCL), the test response should also be representative of higher impact speed.

Some previously-existing response corridors in the literature were reviewed, but ultimately not included in this biofidelity suite. The impact configurations of the lower leg test 1 [25] and test 2 [26] were preferred over those of [36] and in [37] for several reasons. The musculature of the leg and the tibia/fibula natural motion at the knee joint was left intact by severing the leg above the knee. The authors of [38] attempted to evaluate the artifact caused by disarticulating the leg at the knee joint and potting the tibia and the fibula together. However, only one specimen severed above the knee was available for comparison of the responses, which was deemed not sufficient by the authors of the present paper. In addition, the nature of the test used by [36], which used a quasi-rigid pendulum to directly impact the foot, differs from what happens in a real world car crash where the foot is in a shoe and is already in contact with the pedal when it begins to be loaded. Actually, the test configuration used in [36] and in [37] was derived from a certification test designed for the skin of the plantar surface of the dummy foot.

Besides, the test set-up of [26] and [27] were designed after considering the experience of previous studies [39]-[42]. Thus, for the lower leg tests 2 (ankle dorsiflexion), 3 and 4 (ankle inversion/eversion), the newest test series [26]-[27] were preferred over the oldest [39]-[42] because it was estimated that the repeatability of the newer test set-up was optimum. Nonetheless, the initial angle of the foot plantar surface with respect to the anterior tibia surface varied in all of these test configurations due to human variation. The calculation of a mean minimized these variations in the target plots. Further, in Lower Leg Tests 3 and 4 the moment-angle response of the subtalar joint was calculated from leg instrumentation and moments were not always equal to zero at time zero due in part to instrument drift between the time load cell offsets were recorded and the beginning of the test. Further, there were 14^o offsets in some initial inversion and eversion angles in order to attain sufficient angular rotation to cause injury. In performing the biofidelity tests these angles should be duplicated to the extent possible.

Data processing

For KTH tests 1 to 3, the acetabulum force biofidelity target is actually the result of a 1D lumped parameter model based on the test data. However, this target is important because it is the basis for an injury risk curve [43] for the hip and hip injury represents a large portion (50%) of the KTH injuries [44]. Furthermore, it should be noted that this lumped parameter model is more sophisticated than a simple two masses one linear spring model and was developed and validated using an extensive set of tests.

Normalization

More data in a numerical format were available for the lower body tests as compared to the data available for the upper body tests [1]. This would be expected to result in decreased variance of the biofidelity targets. However, substantial standard deviation tolerance bands are still in evidence. An attempt to normalize the leg data using the Eppinger technique was performed in [17] and in [18] but resulted in increased scattering of the response curves in each test series. The leg response data and biofidelity targets may benefit from an improved normalization technique to tighten the ± one SD databand.

Two more recent normalization techniques have been proposed by [28] and [29] 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 not to use these newer, and more sophisticated, normalization approaches. They will be examined by the authors in the future.

Muscle tensing

The muscle tension in the lower leg and at the knee is known to play an important role in dynamic response and injury results. The relevance of the biofidelity targets of lower leg test 1 (tibia axial loading) and KTH test 6 (antero-posterior knee drawer test) may be enhanced by using the results of [32] and of [30] respectively.

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 KTH tests 1 to 4, Rupp et al. provided references for the padding material and some dynamic response characteristics for the padding but not at all speeds. Further characterization of the padding material would be required to guarantee the reproducibility of these test configurations over time.

For the lower leg tests 1 and 2, the reproducibility could be facilitated by knowing the characteristics of the padding between the impactor and the transfer piston.

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.

For the KTH test 5 (low speed – light impactor test against the knee), a precise test procedure taken from the literature [6] could be used. For the KTH test 6 (antero-posterior knee drawer motion), an alternative test procedure of a 12kg – 2.75 m/s impactor test has been proposed. This test is thought to be more convenient for laboratory testing. The impact speeds are close and the energy of the impactor test should drive a dummy knee slider over a reasonable distance. Although no direct comparison of these test modes was found in the literature on the same surrogate, it is believed that this test procedure could be used with reasonable level of confidence. For the other lower body test configurations, precise test procedures for dummies remain to be established.

Overview

The present paper and its companion paper [1] provide a complete set of biofidelity targets to assess the biofidelity of the lower body and the upper body [1] of a 50th percentile male human surrogate. The targets are summarized in Table 12.

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 [34]) 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 [45] or the KTH test 5 [20]. 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.

TABLE 12
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	In the companion paper [1]
Neck	1	Flexion test (mini-sled)	None	
Thorax	1	Rigid Impactor Low Speed Impact at the 4th costal interspace	Mertz	In the companion paper [1]
	2	Rigid Impactor High Speed Impact at the 4th costal interspace	Mertz	
	3	Rigid Impactor Oblique Impact at the 8th rib	Eppinger	
	4	Sled Test using belt restraint without load limiting	Eppinger	
Abdomen	1	Rigid Bar Low Speed Impact at L3	Mertz	In the companion paper [1]
	2	Rigid Bar High Speed Impact at L3	Mertz	
	3	Rigid Steering Wheel Rim Impact at L2	Mertz	
	4	Rigid Steering Wheel Rim Impact at T12	Mertz	
	5	Belt loading at L2	none	
KTH	1	Knee Impact, Large Impactor, Low Speed	none	Figure 1
	2	Knee Impact, Large Impactor, Medium Speed	none	Figure 2
	3	Knee Impact, Large Impactor, High Speed	none	Figure 3
	4	Knee Impact, Molded Face Large Impactor, Low Speed	none	Figure 4
	5	Knee Impact, Small Impactor, Low Speed	none	Figure 5
	6	Antero-Posterior Knee Drawer test	none	Figure 6
Lower leg	1	Tibia Axial Loading	none	Figure 7
	2	Ankle Dorsiflexion Test	none	Figure 8
	3	Ankle Inversion/Eversion Test – 0° Dorsiflexion	none	Figure 9
	4	Ankle Inversion/Eversion Test – 30° Dorsiflexion	none	Figure 10

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 [46]-[47] or the CORA software [48]. 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 [13],[34], or by going back to the set of processed responses of the test sample [14].

Future work (lower 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 lower leg tests 1 and 2 should be enhanced by acquiring the characteristics of the transfer padding.

3. We may consider developing additional biofidelity targets for the ankle (dynamic plantarflexion and dynamic internal/external rotation).
4. The relevance of the ankle and knee drawer tests may be enhanced by incorporating the effect of muscle tension.
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 knee/thigh/hip complex and the lower leg in this paper, and the head, neck, thorax, abdomen in a companion paper [1]. The digital data is available in the supplementary material IRCOBI archive and on the NHTSA database.

VI. ACKNOWLEDGEMENT

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