

# BIOFIDELITY OF FORCE RESPONSES OF DIFFERENT TYPES OF HUMAN SURROGATES IN OBLIQUE SIDE IMPACTS

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## ABSTRACT

In order to determine the biofidelity responses of anthropomorphic test devices, also called dummies, used in crashworthiness studies and develop injury criteria for trauma assessment devices, studies using post mortem human subjects (PMHS) are often necessary. From the perspective of side impacts, many studies are available on these issues when the applied load vector is pure lateral. Injuries, injury metrics, and injury criteria have been advanced for the current ES-2re device using matched-pair tests. Similar studies are needed for oblique loading as this mode is recognized in modern vehicle environments as an important vector for inducing trauma. Thus, the present study was designed to compare differences in the design of load-walls between different types of pure lateral tests, review literatures to determine the need to conduct oblique side impact sled tests and present a detailed methodology to gather region-specific data (such as force-time curves) which can be used to accurately evaluate the local responses of PMHS and dummies, ES-2re and WorldSID. The consolidated graphs overlaying PMHS and the two dummy responses serve as a first step in the assessment of dummy biofidelity.

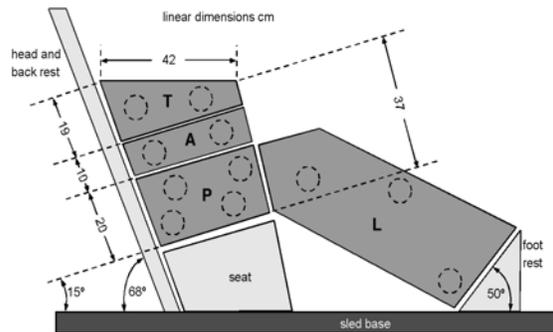
## INTRODUCTION

Matched-pair sled tests with PMHS and dummies have been used to evaluate the responses of different surrogates under predetermined initial and boundary conditions in a laboratory environment [1-9]. Such tests have also been used to develop dummy-specific injury criteria and advance motor vehicle safety standards around the world. For example, the current United States side impact standards FMVSS No. 214 are based on PMHS tests and matched ES-2re experiments [10, 11].

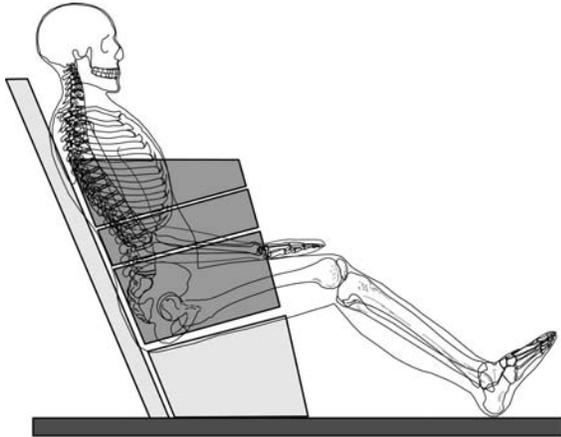
With regard to the application of the dynamic loading in side impacts, pure lateral loading (corresponding

to the clock positions of nine for the driver and three, for the passenger in the United States) has been commonly used as the direction of the loading vector for the evaluation of biomechanics and motor vehicle crashworthiness [2, 5, 8, 12, 13]. Previous studies aimed at determining the biomechanics of nearside impacts consisted of a flat one-unit rigid load-wall attached to the platform of a deceleration sled [13]. These PMHS sled experiments were done in Heidelberg, Germany.

In a series of later studies conducted in the United States, a similar load-wall design (Figure 1) was used by researchers at the Medical College of Wisconsin and elsewhere wherein the dimensions approximated a mid-size sedan [2, 5, 14, 15]. Figure 2 shows the schematic of the PMHS used in these tests with the targeted impact locations in relation to the load-wall, based on the mid-size male anthropometry. A similar segmented load-wall was used by other researchers to determine region-specific responses including dynamic forces applied to the PMHS occupant [12, 16].



**Figure 1: Schematic of the load-wall used to subject human surrogates to pure lateral nearside impact. T, A, P and L respectively represent the load-wall plates for the thorax, abdomen, pelvis and lower leg. The experimental bench seat is also shown.**



**Figure 2: Targeted impact locations from three plates on the PMHS specimen corresponding to the mid-size male anthropometry**

Database analyses using the United States National Automotive Sampling System and Crash Injury Research and Engineering Network (NASS and CIREN) have identified the oblique loading as an important vector associated with trauma in real-world side impacts [17]. Because the impact vector is oblique, deflection patterns, occupant kinematics, injuries and injury mechanisms differ from those induced by the pure lateral vector, and the heterogeneous complex three-dimensional anatomy of the human torso also contributes to this effect. Recognition of this oblique vector and quantification of biomechanical data require sled tests with PMHS in simulated environments. The present study is designed to develop a methodology to apply dynamic forces along an oblique vector to both biological and physical models using an anthropometry-specific custom load-wall design and the results are presented from PMHS, ES-2re and WorldSID surrogates to show the feasibility of the experimental design.

## METHODS

**PMHS specimen preparation:** Medical records of an unembalmed PMHS were obtained. The PMHS was screened for HIV, and Hepatitis A, B and C. The surrogate was prepared as follows for conducting sled tests. Anthropomorphic data and pretest x-rays were obtained according to established procedures [5]. All specimens were dressed in tight-fitting leotards and a mask covered the head/face. The prepared surrogates were placed on a custom Teflon-coated bench seat, fixed to the platform of an acceleration sled (Seattle Safety, Seattle, WA, USA). The sled was configured with an impacting load-wall

to simulate nearside impacts. The impacting load-wall is described later. The experimental bench seat (not a production one) was 1.3 meter in length. It was reinforced below the seat pan at mid-length. The dimensions of the bench seat used for all sled tests are given (Table 1) and schematically shown in figure 1.

**Table 1: Details of the experimental bench seat used in the present study**

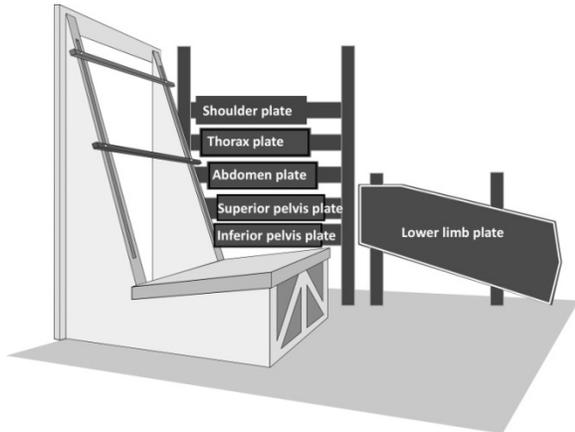
Description	Value
Width (mm)	1220
Length (mm)	410
Height in the front (mm)	290
Height in the back (mm)	195
Seat back height (mm)	930
Seat bottom angle (deg)	13
Seat back angle (deg)	22

**Impacting load-wall:** The load-wall used in these studies was scalable and modular. In other words, the design allowed for positioning different surrogates based on individual anthropometry. The load-wall had six plates. Plates were made a priori with different height dimensions (used 12.5 mm increments) to accommodate varying region-specific specimen anthropometry. The first five metal plates consisted of the shoulder, thorax, abdomen, and superior and inferior pelvis (corresponding to the location of the ipsilateral iliac crest and greater trochanter) plates. A schematic of the load-wall showing the five plates is depicted in figure 3.

The positions of the five plates were adjustable in the frontal plane, that is, adjustments could be made along the vertical, superior-inferior and lateral, left-to-right directions to ensure contact of each plate with the intended specific body region. All these five plates were rigidly attached to a vertical fixture and the fixture was securely connected to the platform of the acceleration sled equipment (Figure 3). A gap was allowed between each of the plates to extract region-specific forces during impact.

A separate sixth plate was used to contact/load the lower limb during side impact (Figure 3). It was mounted to a second vertical fixture, also secured rigidly to the platform of the acceleration sled equipment. The two vertical fixtures allowed for independent positioning of the torso-pelvis and lower limb regions of the surrogate. The vertical height and

lateral positioning of the fixtures were adjusted based on the anthropometry of each surrogate.

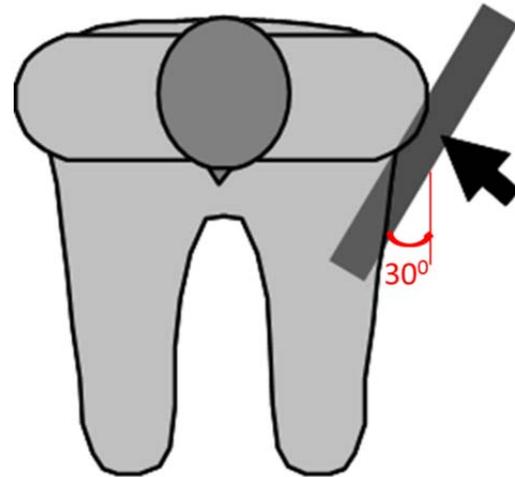


**Figure 3: Schematic of the five metal plates (corresponding to the shoulder, thorax, abdomen, superior pelvis and inferior pelvis) attached to the vertical fixture. The lower limb, i.e., sixth plate attached to another vertical fixture is also shown. The reinforced experimental bench seat is shown.**

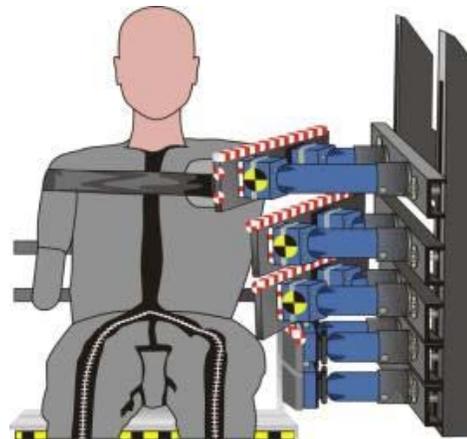
In order to simulate oblique side impact loading, the shoulder, thorax and abdomen plates of the load-wall were oriented at thirty degrees antero-medially with respect to the ipsilateral side of the specimen. Figure 4 shows a schematic of the orientation as viewed from the top.

To ensure simultaneous contact of all torso regions, the individual shoulder, thorax, abdomen and pelvis plates were positioned based on the PMHS specimen anthropometry using the modular and adjustable features of the load-wall design. The shoulder plate was positioned first by moving the upper arm horizontally and rotating antero-medially to the same obliquity as the plate. This ensured contact with the shoulder plate. The resulting position of the shoulder plate was secured to its vertical fixture. The positioning of the shoulder plate is illustrated in figure 5.

Subsequently, the thoracic plate was positioned by moving the plate laterally to contact the thorax at the fourth rib level on the lateral-most aspect of the PMHS specimen and the resulting position of the plate was secured to its vertical fixture. The positioning of the thoracic plate is illustrated in figure 6.



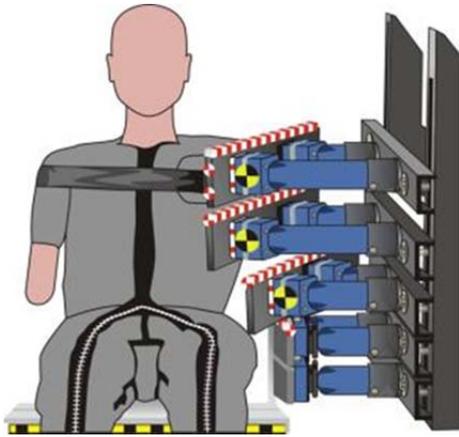
**Figure 4: Overhead view showing the alignment of the plates for oblique left side impact.**



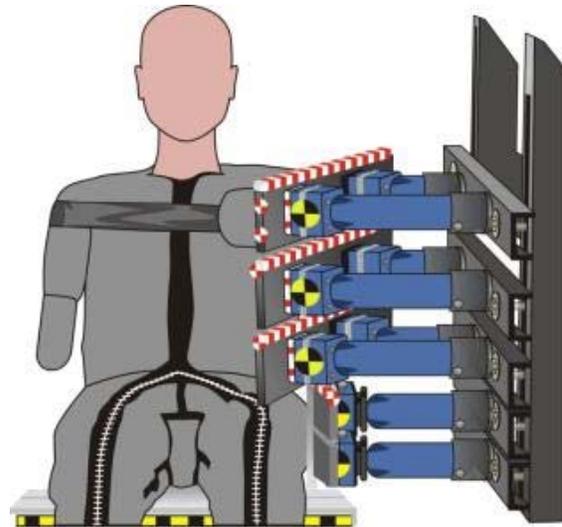
**Figure 5: Alignment and positioning of the shoulder load plate with the shoulder.**

A similar process was used for the abdomen plate with alignment focusing on the tenth rib of the PMHS specimen. The positioning of the abdomen plate is illustrated in figure 7.

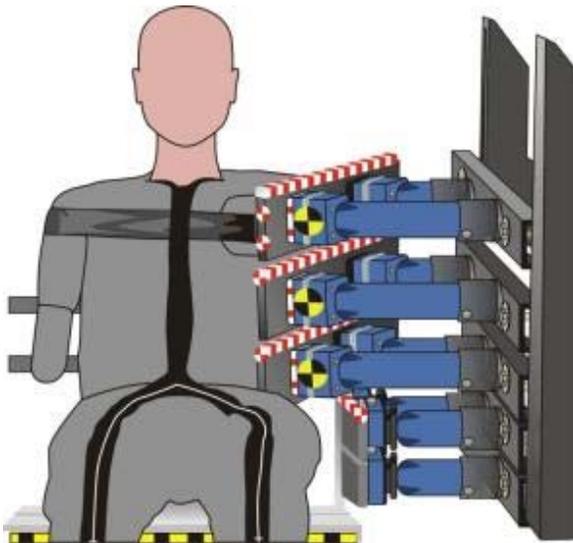
The two pelvic plates were then brought into contact with the lateral protuberances of the iliac crest and greater trochanter regions of the PMHS specimen. The positioning of the pelvis plates is illustrated in figure 8.



**Figure 6: Alignment and positioning of the thorax load plate with the thorax.**



**Figure 8: Alignment and positioning of the pelvis load plates with the pelvis regions.**



**Figure 7: Alignment and positioning of the abdomen load plate with the abdomen**

To simulate normal driving position, the left arm was held parallel to the shoulder plate and rotated inferiorly by 45 degrees in the sagittal plane before the start of the experiment.

**Anthropomorphic tests device preparation:** Two dummies were used in the study to demonstrate the feasibility of the modular scalable load-wall to conduct oblique nearside impact tests with the acceleration sled. The ES-2re dummy was clothed and positioned according to or procedures used in the New Car Assessment Program (NCAP) in the United States.

The shoulder plate of the load-wall was positioned by moving the upper arm of the ES-2re dummy horizontally and rotating medially by an angle of 30 degrees to contact the dummy shoulder. The resulting position of the shoulder plate was secured to the vertical fixture. This process was similar to those used in the positioning of the biological surrogate.

The thoracic plate was positioned by moving the thoracic plate laterally to contact the second thoracic rib region of the ES-2re dummy and the resulting position of the plate was fixed as before, again corresponding to methods used for positioning the PMHS. The abdomen plate was also similarly positioned.

Similar to the positioning of the biological surrogate, pelvic plates in the ES2-re dummy were brought into contact with the pelvic region and in addition, the left lower extremity contacted the lower limb plate. The arm was positioned parallel to the plate in the driving posture similar to the PMHS tests and before applying the side impact pulse.

For the positioning of the WorldSID, while all procedures were identical, because of the smaller dimensions of the dummy, only one pelvic plate was used instead of two used in the PMHS and ES-2re tests.

**Side impact loading and instrumentation:** The following methods are common to all three

surrogates. An acceleration sled was used to conduct the tests at a change in velocity of 24 km/h. The sled equipment was instrumented with a uniaxial accelerometer to record the input side impact acceleration pulse from which the change in velocity was computed in the time domain.

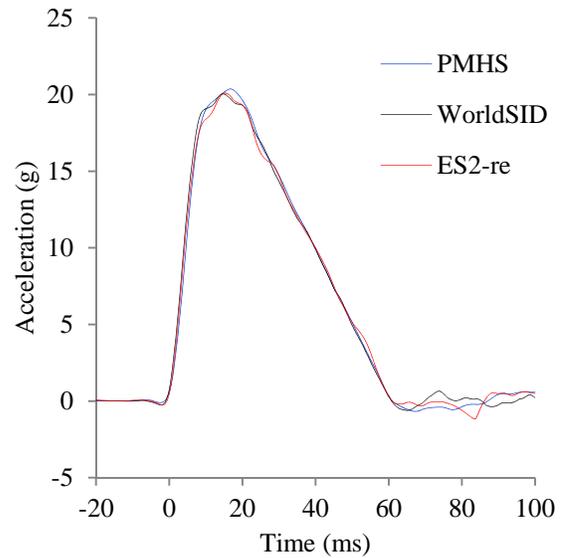
The segmented load-wall with the six plates was instrumented with tri-axial load cells. All load cells were located approximately at the mid-height of each plate and one-third distances from the fore and aft edges to obtain generalized force histories corresponding to different body segments.

**Biomechanical data:** Data were gathered according to the Society of Automotive Engineers specifications [18]. To obtain body region-specific impact force histories, the individual force-time signals from respective load cells were summated for the specific load-wall plate. The biomechanical force data from the biological surrogate were scaled based on the equal velocity, equal mass approach [19]. This methodology has been used in earlier side impact studies [1, 2, 8, 12, 20]. The times of attainment of five percent of the peak force on the pelvis were used as the origin to align force signals from all load-wall plates to ensure consistent extraction of the peak loads on various body regions from all the three surrogates. The maximum forces and the times of attainments of the respective peak amplitudes were obtained for each body region. Plots of the sled acceleration, forces from the shoulder, thorax, abdomen, pelvis and lower limb plates are presented in the results section below for the PMHS, ES-2re and WorldSID surrogates.

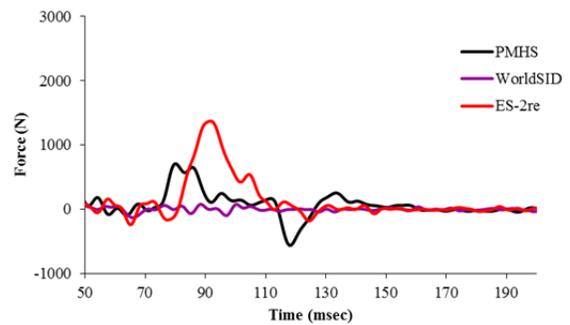
## RESULTS

Figure 9 shows the sled acceleration applied to the PMHS and the two surrogates. The pulse was unimodal and was such that the change in velocity was 24 km/h. For the shoulder, the peak forces and times of occurrence for the PMHS and ES-2re were: 0.7 kN occurred at approximately 80.0 ms, and 1.4 kN occurred at approximately 91.7 ms. Forces were low (less than 100 N) for the WorldSID device. These data are shown (Figure 10).

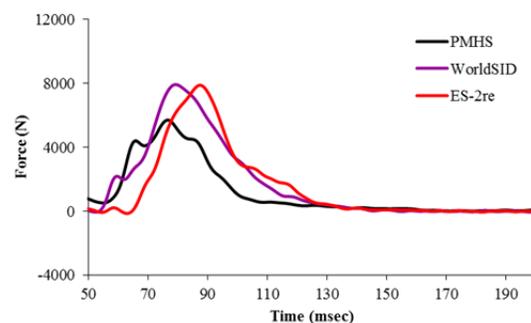
Figure 11 compares the force-time histories for the thorax for all surrogates. Forces were considerably greater than those encountered by the shoulder. The peak force of 5.8 kN occurred at approximately 76.7 ms for the PMHS, 7.9 kN occurred at approximately 87.5 ms for the ES-2re, and 7.9 kN occurred at approximately 79.3 ms for the WorldSID.



**Figure 9: Sled pulse used for all surrogates**



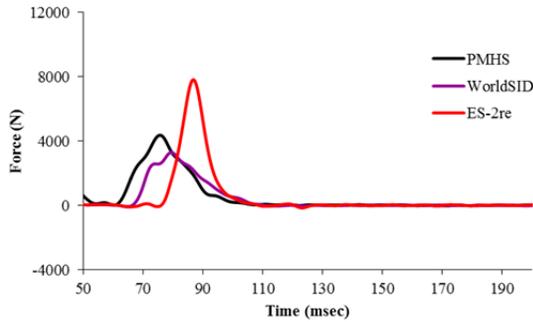
**Figure 10: Shoulder force histories.**



**Figure 11: Thorax force histories.**

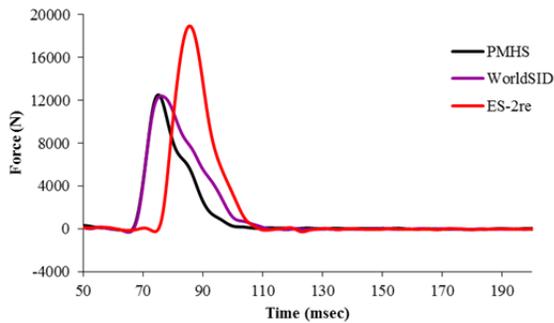
Figure 12 compares the force-time histories for the abdomen for all surrogates. The peak force of 4.4 kN occurred at approximately 75.7 ms for the PMHS, 7.8 kN occurred at approximately 86.9 ms for the ES-2re,

and 3.3 kN occurred at approximately 79.69 ms for the WorldSID.



**Figure 12: Abdomen force histories.**

Figure 13 compares the force-time histories for the pelvis for all surrogates. The peak force of 12.5 kN occurred at approximately 75.1 ms for the PMHS, 18.9 kN occurred at approximately 85.6 ms for the ES-2re, and 12.4 kN occurred at approximately 76.2 ms for the WorldSID.



**Figure 13: Pelvis force histories.**

## DISCUSSION

As indicated in the introduction, the objective of the present study was to compare differences in the design of load-walls between different types of pure lateral tests, review literatures to determine the need to conduct oblique side impact sled tests and present a detailed methodology to gather region-specific data (such as force-time curves) which can be used to accurately evaluate the local responses of PMHS and dummies, ES-2re and WorldSID. The consolidated graphs overlaying PMHS and the two dummy responses serve as a first step in the assessment of dummy biofidelity.

This was accomplished by using a scalable modular load-wall capable of isolating forces on the shoulder,

thorax, abdomen, superior and inferior pelvis regions, and the ipsilateral lower limb of all surrogates. The load-wall was configured such that it was angled to induce oblique loading antero-medially to the PMHS, WorldSID and ES2-re surrogates, simulating nearside dynamic contact loading to the driver or passenger.

The chosen velocity of 24 km/h has been used in previous studies with pure lateral loading [2, 5, 10, 20]. Thus, it is possible to evaluate the present oblique loading data with the data from the other vector. Extending the present methodology to include additional PMHS tests and repeat dummy tests would render such evaluations possible, and this is considered as future research. As forces are extracted from different body region, with additional tests it should also be possible to evaluate regional biofidelity responses of the two dummies, and to accomplish these goals, methods are available in the literature [21, 22].

The load-wall configuration used in these oblique loading tests included multiple segmented plates to individually contact the shoulder, thorax, abdomen, pelvis and lower limb on the ipsilateral side of each surrogate. Allowing gaps between the torso plates facilitated the isolation of forces in the respective body regions. However, this was not the sole determinant to extract region-specific forces from the three surrogates. This is because the same dimension/geometry, non-anthropometry specific load-wall cannot be used for all surrogates. It is well known that the seating heights of the mid-size male 50<sup>th</sup> percentile side impact dummies are not identical [6, 23]. Further, the overall seating and region-specific heights of biological surrogates vary. From this perspective, it is imperative to accommodate a scalable and modular load-wall in the experimental design so that the individual body regions can be positioned such that the plate contacts only those respective regions to extract forces. This feature was also included in the present study. Thus, the biomechanical metrics from this study represent the true region-specific information.

The surrogates were placed at a distance from the load-wall such that impact occurred at the end of the acceleration pulse during the region of constant velocity. Due to the nature of the servo sled control mechanism, this zone is relatively large. Thus, timing of the initial impact with the load-wall with the specimen was not critical. Therefore, surrogates may have contacted the load-wall at different times during the region of constant velocity. To accurately compare signals between surrogates, it was necessary to determine the timing of initial impact with the

load-wall. The pelvis plate was chosen for this process because it was parallel to the mid-sagittal plane of the surrogate and consistently demonstrated unimodal response. The close agreement in the times of attainments of peak forces (within 5, 9 and 7 ms for the PMHS, WorldSID and ES-2re) shows that the modular load-wall is effective in delivering region-specific impact loads uniformly in all surrogates.

The alignment of the signals using this method with respect to the close times of attainments of the peak forces in all surrogates show that the modular load-wall is capable of delivering the impact forces within the same time domain, thereby assisting in a better evaluation of dummy biofidelity.

Energy absorbing materials exist in real-world motor vehicle environments. However, no such materials were used in the present study, i.e., the load-wall plates were not covered with padding components. While rigid load-wall tests have been used in sled tests in previous studies, it should be noted to cover the full spectrum of research paralleling those conducted for pure lateral tests, it would be necessary to extend the present series of tests to other initial/boundary conditions. This includes offset (abdomen and pelvis) conditions and probably other angulations to determine the most practically feasible detriment obliquity condition to understand the mechanism of injuries, injury tolerance and injury criteria. It should be possible to conduct such studies based on earlier research used for the development of ES-2re pure lateral injury criteria [1, 10]. Another area of potential application is postero-lateral loading which has been recognized as another oblique loading vector for injuries to organs such as the spleen and kidneys [24]. It should be possible to reorient the angulations of the different plates to induce postero-lateral oblique loading and conduct similar tests with different surrogates to determine injuries, injury mechanisms, regional biomechanical metrics, injury criteria and dummy biofidelity. These are considered as future research and dissemination topics.

## CONCLUSIONS

- a) The present study compared differences in the design of load-walls between different types of pure lateral tests, reviewed literatures to determine the need to conduct oblique side impact sled tests and presented a detailed methodology to gather region-specific data (such as force-time curves) which can be used to accurately evaluate the

local responses of PMHS and dummies, ES-2re and WorldSID.

- b) A scalable modular load-wall was developed for conducting oblique side impact studies.
- c) The load-wall design included segmentation of forces to the shoulder, thorax, abdomen, superior and inferior pelvis, and ipsilateral lower limb.
- d) To demonstrate the feasibility of using the developed methodologies, tests were conducted using the PMHS, a biological surrogate; the ES-2re, the currently federalized dummy for side impact crashworthiness in the United States according to FMVSS No. 214 and NCAP protocols; and the WorldSID, a dummy under development which has different designs for the shoulder, thorax, abdomen and pelvic regions.
- e) Force-time histories were compared for each of the various body regions on surrogate-by-surrogate bases by conducting sled tests at a velocity of 24 km/h.
- f) Peak forces and the time of occurrences of these metrics for all surrogates and body regions were also presented.
- g) It should be possible to extend these studies with additional samples, boundary/initial conditions and velocities similar to those used in pure lateral side impact studies for the derivation of injury criteria/probability-based risk functions and assessment of dummy biofidelity responses on a regional basis.
- h) The provided consolidated graphs overlaying PMHS and dummy response serve as a first step in the overall biofidelity goals.

## ACKNOWLEDGMENTS

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