

TEST METHODOLOGY FOR EVALUATING THE RECLINED SEATING ENVIRONMENT WITH HUMAN SURROGATES

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Paper Number 19-0243

ABSTRACT

Automated vehicles introduce the potential for non-traditional seating postures, including various degrees of recline. To date, there have been no human surrogate studies in the literature describing reclined occupant response in frontal or other crashes, which suggests that new biofidelity reference targets are needed to evaluate anthropomorphic test device (ATD) and human body model (HBM) predictions. The goal of this study was to develop and demonstrate a methodology for performing biofidelity reference tests for reclined occupants that incorporate methods for capturing these complex kinematics and kinetics. The test methodology developed here is demonstrated with a frontal impact sled test performed with one post mortem human surrogate (PMHS). A simplified, generic, semi-rigid seat pan and minimal back support (at 50 degrees reclined with the vertical) was used to support the occupants as they underwent a 50 km/h crash pulse while restrained with a three pretensioner force-limited seat-integrated belt restraint. Occupant kinematics, seat deflections, belt spool-in and spool-out, and buck motion were collected with an optoelectronic motion tracking system and lumbar spine and pelvic load timing were collected with additional instrumentation. Boundary conditions are critical for finite element (FE) model validation. The forces beneath the seat pan, toe pan and buckle were measured in 6 degrees of freedom (DOF). Additionally, the forces at the lap belt and shoulder belt were measured.

This is the first effort in the field to develop and evaluate a methodology for reclined occupant biofidelity reference testing, which can (and will) be used for: i) additional PMHS testing to generate biofidelity reference targets for assessing the performance of occupant models in reclined postures; and can also be extended to: ii) generate reference data for other reclined configurations and iii) to assess the performance of new and novel restraint system designs.

INTRODUCTION

Highly automated vehicles (HAVs) may bring the potential for alternative seating postures, as the driver may be able to hand over control to the vehicle for extended periods of time. One of these potential postures is reclined seating— while this posture is achievable in current vehicles, the prevalence of occupants seated in recline is

expected to grow as HAVs are introduced. In one CIREN study, reclined seating postures are linked to a higher degree of mortality in motor vehicle collisions, with a high rate of spinal compression and flexion injuries for fatal and nonfatal cases [2]. Limited studies have been performed to assess occupant kinematics and restraint interactions in reclined seating postures; those that exist are predominantly computational studies [3] [4] [5].

Current efforts to model and predict injury risk for reclined occupants are hampered by a lack of fundamental reference data with which to assess model biofidelity. Of particular concern are motion of the pelvis and the lumbar spine. Due to the initial rearward-rotated orientation of the pelvis and the upper body, reclined occupants may be more likely to submarine, with the lap belt translating over the pelvis and into the abdomen [4]. This type of submarining behavior, combined with a greater excursion of the upper body as it pitches forward from recline, may result in substantial flexion in the lumbar spine [5]. Thus, efforts to develop restraint solutions for reclined occupants will require occupant models (physical or computational) that can replicate the interaction of the pelvis with the lap belt and seat, and the kinematics of the spine. Thus, refining and evaluating such models requires detailed reference information (e.g., from tests with post mortem human surrogates, PMHS) describing lumbar spine and pelvis motion (among other factors) in a well-defined test environment instrumented to capture kinetic and kinematic information at all loading boundaries.

Such testing presents unique challenges for reclined occupants. First, to preserve lines of sight for 3D motion tracking of the spine and pelvis, the tests should be performed without a seatback. This requires developing a methodology to suspend a PMHS in a reclined posture (on a sled) without a seatback, in a manner that will not interfere with motion during a test. Second, given the importance of the lumbar spine to kinematics and injury risk for reclined occupants, it is pertinent to quantify motion of the lumbar spine in greater detail (e.g., at more locations) than has typically been performed in past testing [12]. This requires new strategies for instrumentation and motion capture for tracking the spine kinematics. Third, the goal of any fundamental biofidelity reference study should be to utilize a testing environment that can be readily defined, described, and replicated in future modeling or biofidelity assessment experiments. Thus, components such as the seat, toe pan, and belt system anchors should be generic, simplified, rigidized, and well-defined, yet should be representative enough of a typical vehicle environment as to retain significance of the results. These components should also be instrumented to the extent possible to capture all boundary forces applied to the occupant, as well as recording detailed kinematics of any boundary components that move.

The goal of this study was to develop a methodology for performing frontal-impact biofidelity reference sled tests for reclined occupants that incorporate methods to address the concerns described above. All necessary information to perform detailed computational simulations of the test, as well as to make detailed comparisons to dummy response, was captured. This methodology was then demonstrated with the first in a series of sled tests with a 50th percentile male PMHS.

METHODS

The PMHS was obtained and treated in accordance with the ethical guidelines established by the Human Usage Review Panel of the National Highway Traffic Safety Administration, and all testing and handling procedures were reviewed and approved by the Center for Applied Biomechanics and an institutional review board at the University of Virginia (Charlottesville, VA, USA). The subject (age: 66, height: 177.8 cm, weight: 74.4 kg) was seated on a semi-rigid seat and reclined to a 50-degree angle with the vertical using three tethers that were routed through overhead bars on the buck (see Figure 1). The minimal profile and placement of these tethers allowed for full visibility of posterior instrumentation. At time 0, the tethers released via a drop-release mechanism. A net was placed behind the seat to catch the subject on rebound. The subject's feet were placed on a toe pan and fully constrained. To aid in subject positioning, straps were tied around the shins and attached to a support fixture at the front of the buck. The subject's arms were placed in an initial position that allowed for full visibility of the lap belt. As boundary conditions are critical for HBM validation, the forces at the boundary of the occupant, i.e. beneath the seat pan, toe pan, buckle, and at the lap belt and shoulder belt, were measured.

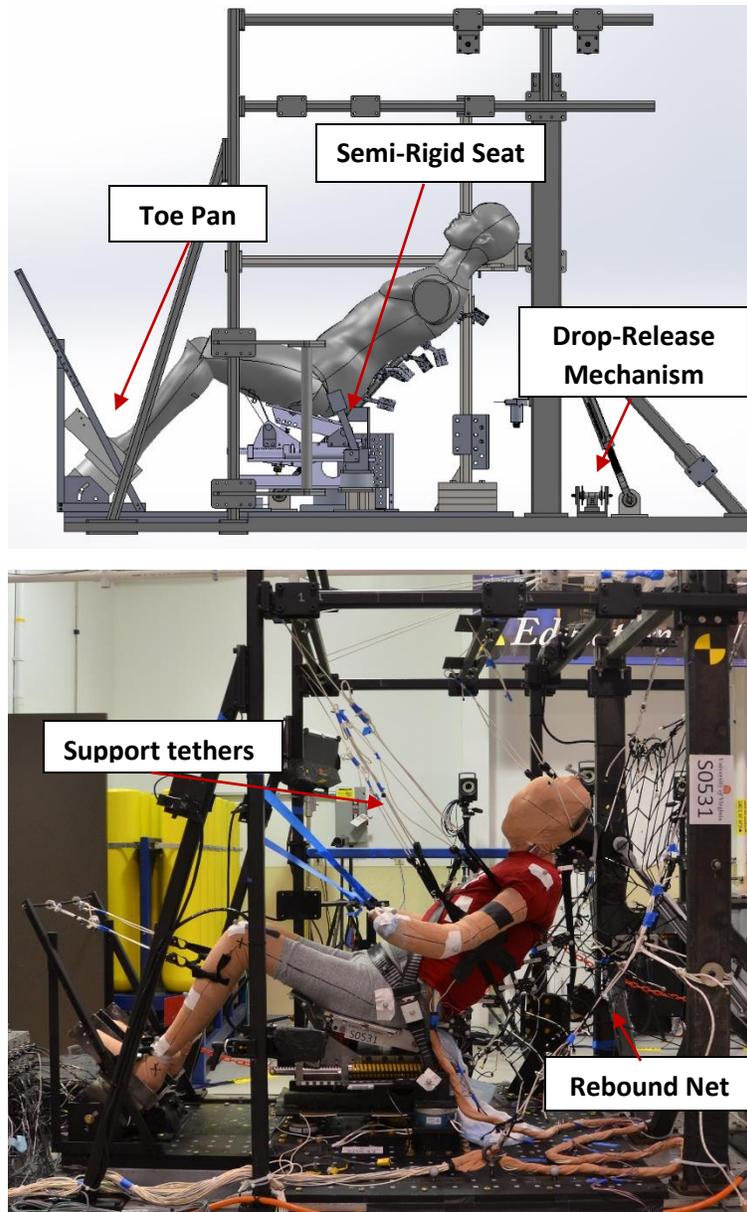


Figure 1. The CAD design of buck setup (top). The experimental setup (bottom).

Test Environment

Semi-rigid seat: The subject was seated on a semi-rigid seat (see Figure 2). The semi-rigid seat used in this test was based on a design developed by [14] to perform biofidelity sled reference tests with PMHS [10] [13]. The seat, consisting of two articulated rigid aluminum plates (see Figure 3), has been designed to reproduce the behavior of a real seat [10] [14]. The angular stiffness of each aluminum plate is generated by means of springs. The stiffness of the springs represents a front seat configuration for this test. This seat pan is angled at approximately 15° from the horizontal. The second articulated aluminum plate, positioned in front of the seat pan, represents an anti-submarining ramp angled at approximately 30° from the horizontal. Upon deflection of the seat pan and anti-submarining pan, an anti-rebound locking mechanism maintains the springs in a compressed state and thereby reduce the level of elastic energy returned into the subject by the seat on rebound.

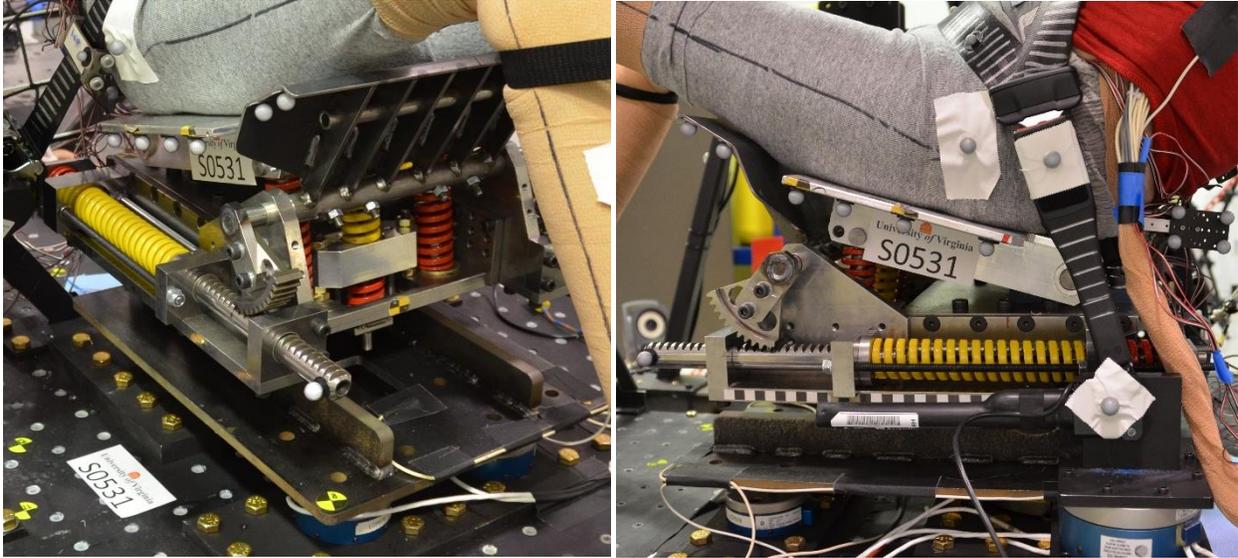


Figure 2. Oblique view of the semi-rigid seat in the experimental test setup (left). Lateral view of the semi-rigid seat (right).

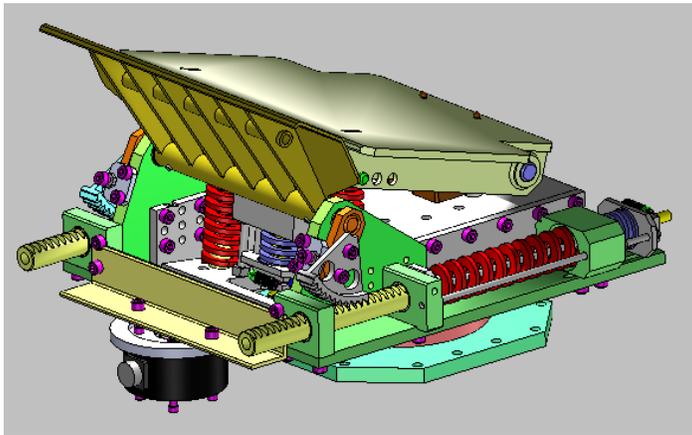


Figure 3. CAD model of the semi-rigid seat.

Belt: The belt system used in this study was designed to increase engagement of the pelvis, reducing the risk of submarining for reclined occupants. This consisted of a 3-point belt equipped with dual lap-belt pretensioners and a shoulder-belt pretensioner. Additionally, the belt system included a crash locking tongue that obstructed webbing transport from shoulder-belt to lap-belt and a shoulder-belt load limiter of approximately 3 kN. The D-ring was positioned to simulate the approximate position of a seatback-integrated D-ring, with an angle of approximately 12° as the belt leaves the shoulder. The shoulder belt crossed the shoulder at approximately mid-clavicle.

Pulse: These tests were performed on a Seattle Safety Systems 1.2 MN ServoSled acceleration sled system. The pulse (see Figure 6) used in this test was developed by [14] and has been used in previous sled tests to assess PMHS submarining [10] [13]. The Delta-v for this pulse is 51 kph.

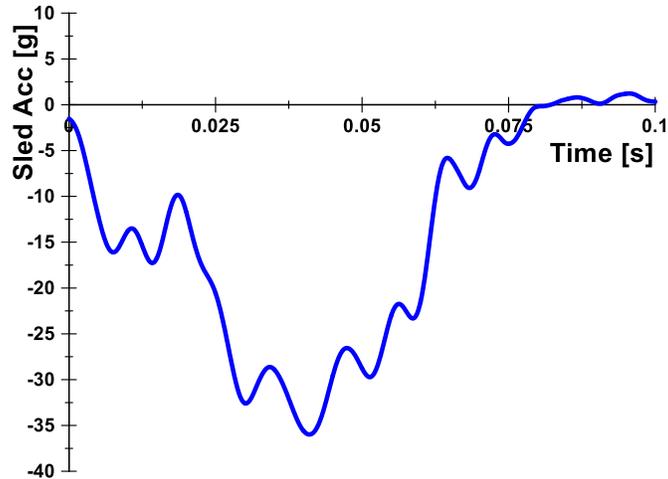


Figure 4. Sled acceleration pulse (CFC 60).

Positioning

The occupant was positioned in a 50-degree recline (measured as the angle the line connecting the H-point to the acromion made in the sagittal plane) with respect to the vertical, using three support straps for the upper- and mid-torso, and head (see Figure 1). Due to the sensitivity of the pelvis position's effect on submarining, the pelvis angle was measured based on targets developed from data on volunteers in 23, 33, 43, and 53 degrees of recline [9]. The methods used by [9] included digitizing the subject's ASIS and PSIS landmark locations, estimating the subject-specific pelvis geometry using an estimate flesh margin at the ASIS based on the adjustment for BMI [8] and utilizing an optimization method described in [7] to find the pelvis position and rotation around the lateral axis that best matches the subject's lumbar and thigh segment lengths. These methods produced pelvis angles measured from the ASIS to the pubic symphysis in the sagittal plane for each degree of recline, each with a set degree of standard deviation. Interpolating the measured pelvis angle between the 43- and 53-degree seatback recline angles resulted in a target of 61.35 degrees with respect to the vertical, with a standard deviation of approximately 15 degrees.

The positioning support straps were routed through overhead bars and attached to a drop-release located at the rear of the buck (see Figure 1). Two straps were routed behind the torso of the subject for both lumbar and thoracic support and positioning (see Figure 5, right). These straps allowed for fine tuning adjustability, individually at the lumbar and thoracic regions, to reach the appropriate torso angle. Similarly, a separate head support strap was used to adjust head angle. The drop release incorporated redundant mechanisms (one electromechanical and one pyrotechnic) with independent triggering pathways to minimize risk of failure and ensure proper release. The support straps were released at time 0. Following the test, during the deceleration phase of the sled, the subject's motion was arrested by a catch net mounted on the sled behind the initial position of the subject.

Three-Dimensional Kinematic Motion Tracking

Spine and pelvis motion tracking: A reclined seating posture introduces a higher likelihood of lap-belt submarining, a phenomenon where the belt is properly placed across the anterior superior iliac spines (ASIS) initially, but then, as a result of interaction with the soft tissue in the area, the belt becomes disengaged from the bony pelvis allowing it to move vertically upward relative to the occupant to load the abdomen [6]. As a result, tracking the motion of the spine and pelvis throughout the full excursion is of importance for this test mode. Kinematic data were collected at 1000Hz using an optoelectronic motion capture system consisting of 20 cameras (Vicon MX™, VICON, Centennial, CO, USA) that tracked the position of retro reflective spherical markers in a calibrated 3D space lying within the cameras' collective field of view. Four-marker clusters were secured to selected anatomical locations including the head, spine, sternum, and pelvis to facilitate the determination of the position and

orientation of the corresponding bone using rigid body mechanics and coordinate transformations at each time step. This method has been used in previous sled test studies [12].

For sled tests with occupants seated in traditional upright postures, posterior reflective marker cluster hardware are mounted at T1, T8, L2, and the sacrum (see Figure 5, left). In such studies, marker arrays for spine tracking have been oriented to be visible from the posterior of the subject. With a reclined position however, the visibility of the posterior aspect of the subject is limited and is not conducive for rear-facing marker arrays. Additionally, a thorough examination of spine kinematics requires the installation of mounts at more vertebrae locations than has been traditionally studied. Accounting for both the limited space and obscured view posterior of the subject along the spine, novel marker cluster hardware for the vertebrae and pelvis were developed for this test (see Figure 5, right).

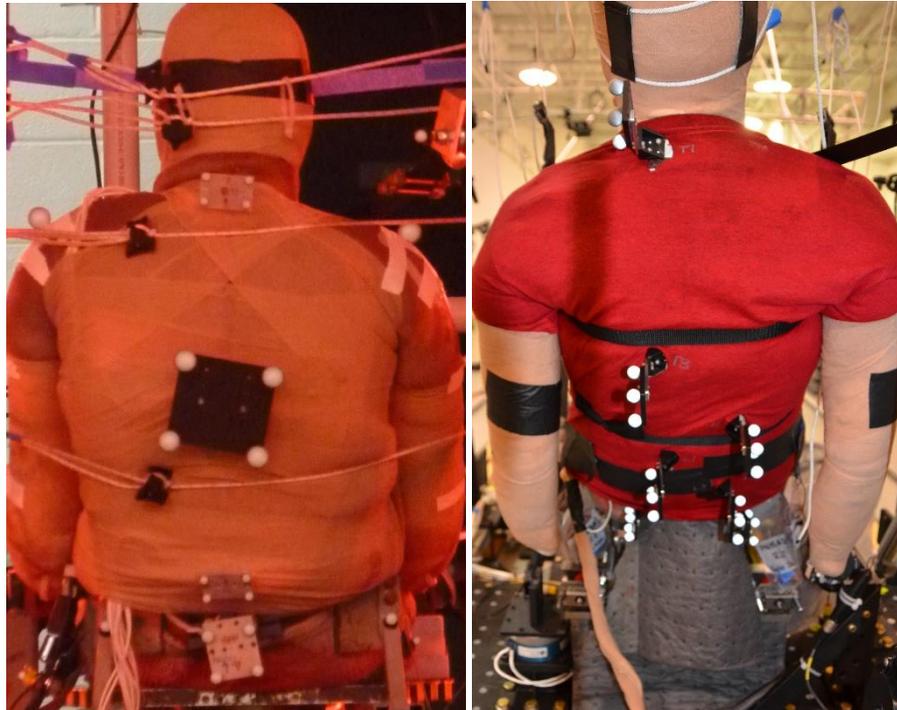


Figure 5. Traditional posterior motion-tracking instrumentation, located at T1, T8, L2, and the sacrum (left) [1]. Novel posterior motion-tracking instrumentation, located at T1, T8, T11, L1, L3, and the pelvis (right).

The main component of the spinal hardware consisted of an aluminum “horseshoe” shaped mount that was flushed against the spinous process of each chosen vertebrae location and drilled in posteriorly with $2\frac{3}{4}$ ” screws. Spine mounts were mounted at the T1, T8, T11, L1 and L3 locations (see Figure 6). This instrumentation was installed under X-Ray guidance to ensure that the screws did not bridge adjacent vertebrae. On the side of the “horseshoe” mount, a 6 D.O.F. cube was installed to track acceleration and angular rate local to each chosen vertebra. Superior to this, a 3D-printed carbon fiber L-bracket was installed, attaching an aluminum pivot arm to allow for longitudinal adjustability. The marker clusters were arranged on flat 3D-printed carbon plates, adding minimal weight to each chosen vertebra. This hardware allowed visibility of the reflective spherical markers in the lateral plane (see Figure 7). To maximize the available longitudinal space, the plates were staggered facing the left and right lateral planes.



Figure 6. CT Scan of spinal hardware installed on PMHS (head and pelvis hardware also visible).

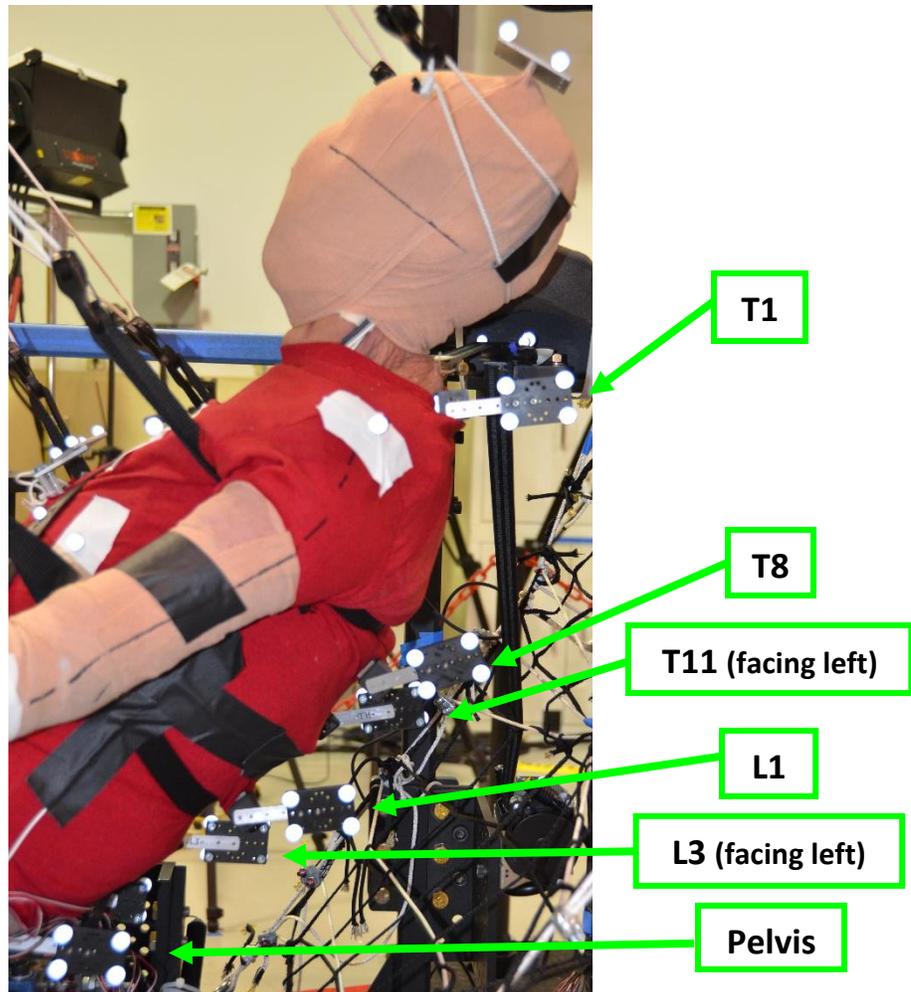


Figure 7. Posterior 3D Motion Tracking Instrumentation.

The pelvis mount included a lateral aluminum bar bilaterally into the posterior superior iliac spine (PSIS) using 1” screws (Figure 11). Upon installation, the screws were angled outward from the pelvis to avoid either fusing the iliac wings to the sacrum or drilling through the iliac wings. The pelvis mount consisted of two Vicon clusters, each facing outward from the center of the subject.

Other motion tracking: Vicon marker arrays were also attached to the skull and sternum (Shaw et al. 2009), and surface markers were placed at various locations on the chest, and extremities. Markers were also attached to track motion of the belt, seat pan, and buck.

Other Instrumentation

6 D.O.F. Cubes: Inertial measurement sensor packages consisting of sets of three mutually perpendicular linear accelerometers and three mutually perpendicular angular rate sensors (6 D.O.F. cubes) were attached to the vertebral mounts, pelvis mount and head mount to track acceleration and angular rate local to the anatomical locations. The sternum acceleration was tracked with a uniaxial accelerometer in the X-direction.

Disc Pressure Transducers: For this test, Model 060S pressure sensors (Precision Measurement Company, Ann Arbor, MI) were inserted in the intervertebral discs at three locations: T12/L1, L2/L3, L4/L5. This sensor, designed for medical applications, is the smallest pressure sensor commercially available today (3 mm L x 1.5 mm W, thickness 0.3 mm). The pressure transducers were inserted into the intervertebral disc posteriorly with a bore

needle gauge apparatus. The end of the bore needle gauge was inserted into the center of the nucleus. After this location was confirmed using X-ray (both posteroanteriorly and laterally), the needle was removed, leaving the pressure sensor in place.

Pelvis Strain Gauges: Two strain gauge rosettes were installed on each iliac wing at the exterior portion of the ilium, between the ASIS and AIIS locations (see Figure 8). The central axes of these gauges were aligned with the anterior portion of the pelvis to measure strain directly resulting from the lap belt load.

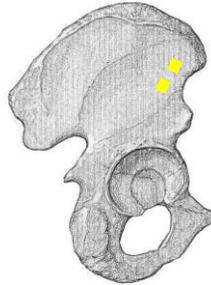


Figure 8. Pelvis strain gauge locations.

Belt Force Sensors: Belt gauges were placed on both the lap belt at the outer anchorage location, as well as on the shoulder belt between the occupant's shoulder and the integrated seatback "d-ring" location. The load was also measured beneath the buckle with a 6-axis load cell.

Seat and Toe Pan Load Cells: Loads were measured beneath the seat using an array of three load cells: a 6-axis load cell in the rear and two 3-axis load cells in the front.

RESULTS

Spine Kinematics: The novel Vicon instrumentation installed to track both spine and pelvis kinematics was proven to be fully visible throughout the occupant's full excursion (see Appendix I). The torso began to accelerate forward at 40 ms. At approximately 70 ms, the torso center-of-gravity was directly over the pelvis. Peak torso excursion occurred at 117 ms.

Pelvis Kinematics: The pelvis first began to slide forward at 26 ms, reaching peak excursion at 70 ms (see Appendix I). The seat pan deformed as a result of this forward excursion, however the anti-submarining pan deflected only slightly, without enough deflection to activate the anti-rebound device for this pan.

Pressure Transducer Signals: Initial testing of the pressure transducers indicated that the magnitude of the load signal was highly sensitive to the positioned location of the gage, and as a result, the magnitude of the recorded pressures did not seem to correlate with pressure readings at other levels. However, the sensors accurately captured loading timing including maximum loading timing. The pressure transducer located at the T12/L1 disc recorded a maximum pressure at 64 ms (see Figure 16, top). The L2/L3 pressure transducer recorded a maximum pressure at approximately the same time, 63 ms. The pressure transducer installed at the L4/L5 disc failed prior testing.

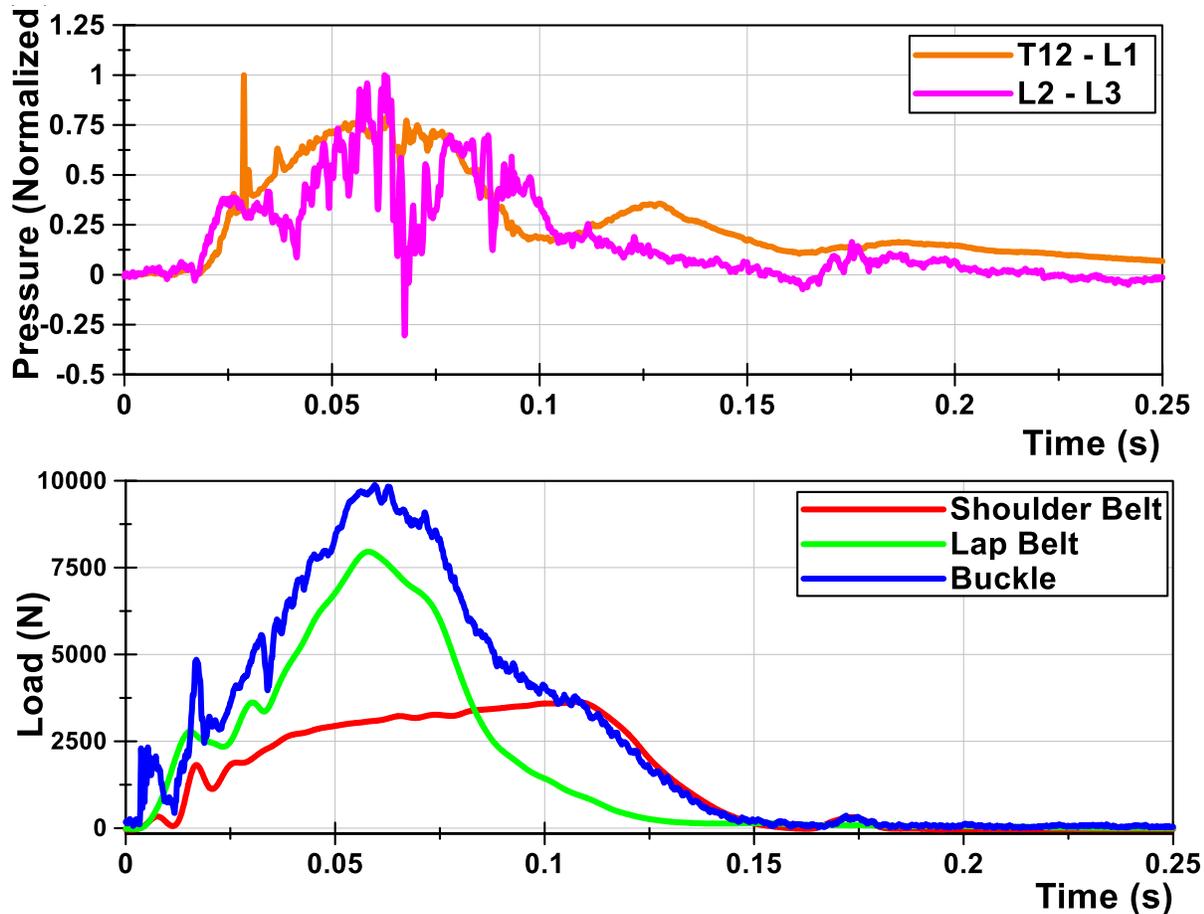


Figure 9. Lumbar pressure transducer signals (top): Normalized signals, filtered at CFC 1000. Belt Forces (bottom): Shoulder belt and lap belt forces filtered at CFC 60; Buckle resultant filtered at CFC 1000.

Belt Forces: The buckle force (resultant) recorded a peak force of 9.88 kN at 59.5 ms (Figure 9, bottom). The lap belt recorded a peak force of 7.96 kN at 58 ms. The shoulder belt recorded a peak force of 3.63 kN at 107.5 ms. The signals from the strain gauges on the pelvis correlated with peaks in lap belt and buckle loads, peaking at 63 ms for the gauges on the right iliac.

DISCUSSION

This setup is the first of its kind to test PMHS in a reclined seating configuration. The novel Vicon mounts have been proven to successfully track the spine and pelvis, whose kinematics play a critical role in the likelihood of submarining-related injuries. At approximately 70 ms, the torso's center-of-gravity was directly over the pelvis. This is estimated to be the time in which the lumbar spine was in its highest degree of compression prior to the forward pitch of the torso, where the lumbar spine is loaded under combined compression and bending (seen at 86 ms). At approximately 70 ms, a peak in intervertebral disc pressure is measured by the T12/L1 pressure sensor (64 ms) and the L2/L3 pressure sensor (63 ms).

These peaks in disc pressure occur shortly after the peak lap belt force, measured via both the lap belt and the buckle resultant force (Figure 9). The peak lap belt forces measured by the belt gauge and buckle load cell are 8 kN and 9.9 kN respectively and occur at approximately 60 ms. The peak shoulder belt load was 3.6 kN and occurred at 108 ms. The pressure at the T12/L1 location again increased following the peak shoulder belt load, with a local maximum of 219 psi occurring at 129 ms.

The pressure transducer signals indicate peak pressure occurs at the stage of maximum spinal compression, before going into bending. Since the pressure transducer is in the center of the intervertebral disc at the nucleus, it does not account for the pressure due at the most anterior landmark of the disc, wherein a high level of pressure is likely seen during flexion. Therefore, a diagnosis of when injury is most likely to occur during frontal impact in a reclined seating posture cannot necessarily be taken from the pressure transducer signal. From the overall kinematics, the spine goes into a high degree of flexion. Future studies should be conducted to determine injury thresholds of the spine in combined compression and bending.

At 70 ms, the pelvis reaches full excursion, however the anti-submarining pan is not deflected enough to engage the anti-rebound device. From the video, it appears that this is not a function of the stiffness of the anti-submarining pan, but rather it is due to the amount of tissue on the subject's femurs. This subject did not have enough soft tissue to engage the anti-submarining pan in order to allow it to articulate about its axis.

The lap-belt maintained contact with the pelvis during the full test and the subject did not appear to submarine (Figure 10). During the pelvis excursion, the pelvis was seen to rotate forward.

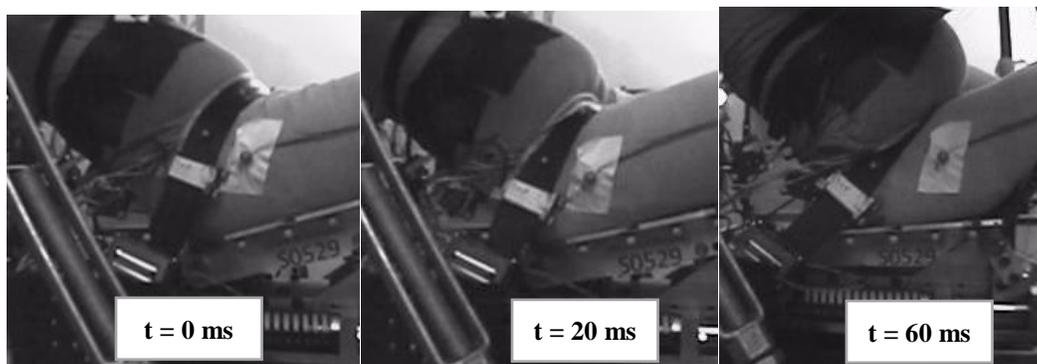


Figure 10. Pelvis excursion time stills from onboard camera view.

The double lap belt pretensioner combined with a shoulder belt pretensioner places a high amount of load on the subject's pelvis. Fractures and soft tissue injuries for this test will be thoroughly investigated.

While the visible tracking of the lap belt is lost due to the abdomen covering the pelvis during forward torso excursion, the data from the belt loads and the pelvis strain gauges clarify that the belt remains engaged with the ASIS AHS area throughout the test. Therefore, no submarining occurred; however, to prove this restraint configuration is successful in restraining the pelvis, it must be validated through the testing of more subjects. This test setup has proven to be successful in testing a PMHS in a reclined seating configuration, with a high success rate of entirely novel sensors. This methodology will be used for at least 3 additional PMHS tests in this condition. The resulting data from these tests can be used to validate HBM simulations in reclined seating postures. To further validate the restraint configuration, and to further investigate reclined occupant kinematics, this test setup can be used to explore a variety of pulses, degrees of recline, and anthropometries in the future.

CONCLUSIONS

A methodology was developed to test occupants in a reclined seating configuration in frontal impact scenarios, and an example test was performed. A reclined seating posture introduces the likelihood of submarining and combined compression and flexion loading in the lumbar spine, therefore lumbar spine and pelvis kinematics are of great interest. This methodology allows for the visibility of pelvis and spine kinematics in this posture, a strain time history of the pelvic iliac wings, and the timing and severity of lumbar loading. This data will be used to perform detailed computational simulations of the test, as well as to make detailed comparisons to dummy response.

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APPENDIX I

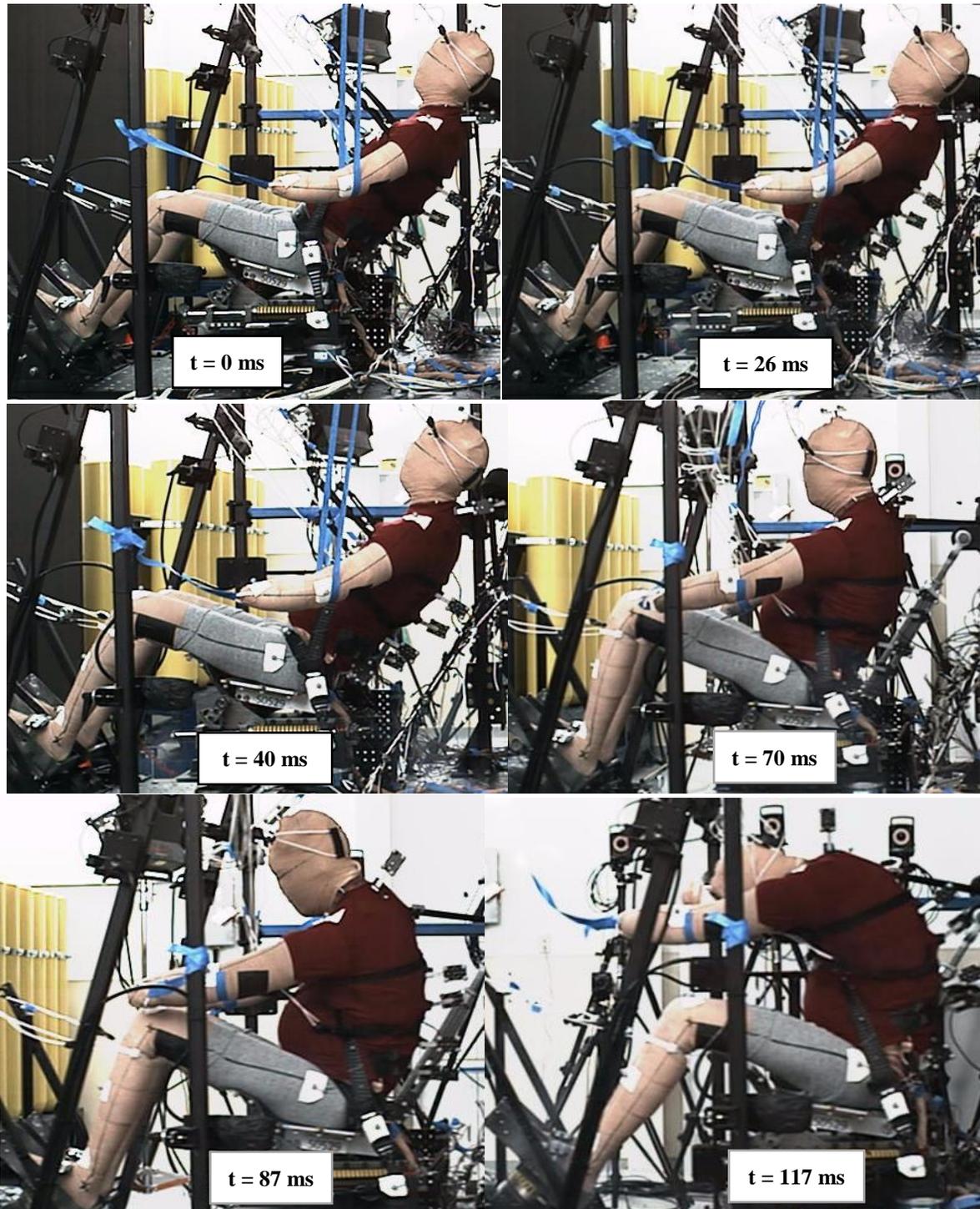


Figure 8. Video stills from sled test.