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Evaluation of Anthropomorphic Test Devices for Testing Aviation Seating Systems at 30° and 45° with Respect to the Aircraft Centerline

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12. Abstract

The Federal Aviation Administration (FAA) has established test procedures and standards for evaluating forward-facing and side-facing seats. As transport category aircraft continue to evolve, airlines have proposed (and subsequently installed) oblique-facing seats, which are defined as 18°-80° with respect to the aircraft centerline. The currently available Anthropomorphic Test Devices (ATDs) are designed to be loaded either in the frontal or lateral direction, and their ability to measure injury criteria in an oblique-facing environment is unknown. The FAA Civil Aerospace Medical Institute evaluated four ATDs to determine their ability to accurately measure injury risk for oblique-facing seats. The ATDs evaluated were the Hybrid II, FAA-Hybrid III, ES-2re, and THOR-NT. The testing involved both static and dynamic evaluations. The ES-2re and THOR-NT were eliminated after the static evaluation due to concerns regarding structural or hardware failures that could occur due to the high forward flail expected in dynamic tests. The Hybrid II and FAA-Hybrid III were determined to be structurally robust enough to withstand testing, but only the FAA-Hybrid III had the required instrumentation to fully evaluate the injury risk. Dynamic testing was performed with both ATDs. A total of seventeen tests were run, three with the Hybrid II and fourteen with the FAA Hybrid III. The testing variables included different combinations of two configurations (a seat with a half wall to simulate an interior feature and a seat with no wall), two angles (30° and 45°), and three belt systems (lap belt-only, shoulder belt, and lap belt inflatable restraint). Lap belt-only tests produced injury measures exceeding the limits for both the lumbar spine and neck. Tests with a shoulder belt did not exceed the lumbar spine limits. Tests with the lap belt inflatable restraint produced results near the newly proposed combination of the lumbar spine tension, flexion moment, and lateral bending moment. The FAA Hybrid III was the only ATD evaluated that could perform in the oblique-facing environment (up to 45°) and is recommended for use in horizontal certification testing.

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List of Abbreviations

ATD	Anthropomorphic Test Device
AWS	Amazon Web Services
CAMI	Civil Aerospace Medical Institute
DOI	Digital Object Identifier
DOT	Department of Transportation
FAA	Federal Aviation Administration
HIC	Head Injury Criteria
NHTSA	National Highway Traffic Safety Administration
Nij	Neck Injury Criterion
PMHS	Postmortem Human Subjects
THOR	Test Device for Human Occupant Restraint
US	United States

BACKGROUND

The Federal Aviation Administration (FAA) has standards and regulations that are intended to protect aircraft occupants in the event of a civil aircraft crash (Emergency Landing Dynamic Conditions, 14 CFR §25.562; Seats, Berths, Safety Belts, and Harnesses, §25.785, 2023). These standards primarily focus on providing protection for forward-facing seats. Additional rules have been implemented for aft-facing seats, e.g., SAE Aerospace Standard 8049C section 3.2.10 (SAE International, 2015), and purely side-facing seats, i.e., seats installed 90° with respect to the aircraft centerline (FAA, 2012). Transport category passenger seats continue to evolve, with a recent development being a partially enclosed (pod) seat that is oriented obliquely with respect to the aircraft centerline in what is commonly referred to as a "herringbone" arrangement. This orientation exceeds the standard 18° of a forward-facing seat but is not purely side-facing. Seats between 18° and 80° are generally referred to as oblique-facing, with FAA policy and an SAE International Aerospace Standard currently limited to seats installed from 18° to 45° (FAA, 2018; SAE International, 2017).

Oblique-facing seats are used primarily in transport category aircraft. The seating system regulations require two dynamic tests that are carried out at different levels of acceleration and duration (Emergency Landing Dynamic Conditions, 14 CFR §25.562). One of the two tests required for this installation is a horizontal impact test with a minimum impact velocity of 44 ft/s with a peak acceleration of 16 g. The Anthropomorphic Test Device (ATD) used for the testing is based on the seat installation angle. If it is considered a forward-facing seat, the test requires the use of the 50th percentile male-sized Hybrid II or its equivalent. The only ATD currently approved as an equivalent to the Hybrid II is the FAA-Hybrid III (Jones, 2000). With these two ATDs, the principal measurements are the risk of injury to the head using the Head Injury Criteria (HIC) and the risk of injury to the upper leg (Emergency Landing Dynamic Conditions, 14 CFR §25.562).

For side-facing seats, FAA Policy Statement PS-ANM-25-03-R1 defines the criteria for evaluating the seat to provide an equivalent level of safety to forward-facing seats. This policy draws on occupant protection information adopted by the automotive industry, particularly the use of the ES-2re and injury criteria referenced in 49 CFR §571.214 (Side Impact Protection, 49 CFR §571.214, 2022). The ES-2re is an ATD with specialized instrumentation for assessing injuries in a side-facing configuration. The injury criteria that are used with this ATD include a limit on neck tension, rib displacement, and assorted loads throughout the torso.

Oblique-facing seats present a novel off-axis loading environment that may permit significant flailing due to the unique orientation. The Hybrid II, Hybrid III, and ES-2re ATDs used for crash testing were developed and codified by the automotive industry and designed to perform in a relatively confined environment (i.e., automotive interiors with three-point harnesses). In addition, the Hybrid II and Hybrid III were designed to be loaded in the forward direction, while the ES-2re was designed to be loaded in the lateral direction. An additional ATD called the Test Device for Human Occupant Restraint (THOR) is under development by the automotive community. This ATD "incorporates major advancements in biofidelity and sensing, with significantly expanded instrumentation and improved user handling" (Humanetics, n.d.).

Beginning in fiscal year 2011, the Biodynamics Research Team at the Civil Aerospace Medical Institute (CAMI) was tasked with providing research to support the development of an FAA policy for the approval of oblique-facing seats. The intent of this policy is to ensure that occupants of oblique-facing seats are afforded the same level of protection currently provided to occupants of conventional seats. To achieve this, an ATD capable of evaluating injury risks due to combined forward and lateral loads is required. This paper details a series of evaluations of the Hybrid II, FAA-Hybrid III, ES-2re, and the THOR-NT ATDs for use with oblique-facing seats.

Injury Measures

Neck

The FAA prohibits concentrated loading on the neck in addition to the use of performance-based requirements. For frontal impacts, the Neck Injury Criterion (N_{ij}), which has a limit of 1.0, evaluates the loads in the neck for tension/compression and flexion/extension (Occupant Crash Protection, 49 CFR §571.208, 2022). There are also limits on pure tension and compression, where tension is limited to 937 lb. and compression to 899 lb. For oblique loading that results primarily in flexion/extension, N_{ij} should be valid. The FAA injury criteria for lateral impacts limit neck tension and compression to 405 lb. (FAA, 2012). This is significantly lower than the forward-facing limits because lateral bending of the neck reduces its tolerance to tension. The side-facing policy also limits the bending torque (M_x) to 1018 in.-lb. and the transverse plane shear (F_{xy}) to 186 lb. The FAA side-facing seat policy does not define the amount of lateral bending necessary to reduce the neck tolerance, but for purely side-facing seats, it seems prudent to assume that the bending precondition is met. The effect of lateral bending on the tension/compression neck limits has not been quantified between pure frontal and lateral loading. Thus, for oblique-facing seats, the installation angle where the lateral bending of the neck begins to reduce the neck's tolerance to tension/compression is unknown.

Lumbar Spine

At the beginning of this project, unique injury risks associated with oblique-facing seats were unknown. As such, initial testing was primarily used to evaluate the ATD kinematics to support future biomechanical testing that would determine the most likely injuries. Between the initial testing in 2012 and the second phase of testing in 2016, a preliminary injury criterion was used in FAA special conditions starting in 2014 and adopted by FAA policy in 2018 (FAA, 2014 and PS-ANM-25-27). The criterion, which limits lumbar spine tension to 1200 lb., was based on matched pair testing of Postmortem Human Subjects (PMHSs) and the FAA-Hybrid III (Humm et al., 2015). Since none of the 2012 tests produced a lumbar spine tension below the preliminary limit, additional testing was conducted in 2016 to determine if an effective shoulder harness could meet this limit. By the time of the final testing phase in 2023, a more robust injury criterion, FAA-LL_{tb}, was proposed (Karthik et al., 2022). The FAA-LL_{tb} is a combination of the lumbar spine tension, flexion moment, and lateral bending moment, as defined by equation 1.

$$FAA - LL_{tb} = \frac{F_z}{F_{z(int)}} + \frac{M_y}{M_{y(int)}} + \left|\frac{M_x}{M_{x(int)}}\right|$$

Equation 1: FAA-LL_{tb}

F_z is the peak axial tensile load, F_{int} is the critical axial load (2832.6 lb.), M_y is the peak flexion moment, $M_{y(int)}$ is the critical flexion moment (2717.2 in.-lb.), M_x is the peak lateral moment, and $M_{x(int)}$ is the critical lateral moment (3071.2 in.-lb.). The peaks are selected irrespective of the time of occurrence. The flexion moment (M_y) is taken in the direction of occupant motion, while the lateral moment (M_x) is the absolute peak, regardless of polarity.

Thoracic

The FAA-Hybrid III and THOR-NT have optional thoracic load cells in the area between the ATD's spine box and the top of the rubber lumbar spinal column. The thoracic load cell was added for this test series to evaluate potential injury to the thoracic region of the back. Currently, there is no injury limit for this load cell, and the data were collected for information purposes only.

Shoulder Belt

Seats installed at an angle greater than 18° require a shoulder belt or energy-absorbing fixture, such as a back rest or padded wall, to create additional support for the head and torso (Seats, Berths, Safety Belts, and Harnesses, 14 CFR §25.785, 2023). When single-strap shoulder belts are utilized, the measured load should not exceed 1750 lb. (Emergency Landing Dynamic Conditions, 14 CFR §25.562). CAMI performed tests both with and without a shoulder belt as part of this test series. The tests with a shoulder belt measured the load in the upper and lower attachment points and the belt payout distance.

Soft-Tissue Injuries

The abdomen is not protected by bony structures, and injuries to internal organs can be fatal. Researchers were concerned with the possibility of soft-tissue damage resulting from an intrusion of the seat or surrounding structure into the abdomen. While abdominal instrumentation is ideal for evaluating potential soft-tissue injuries, kinematic analysis can also be used to detect abdominal contact with surrounding structures. In that case, the requirement for soft-tissue injuries is to prohibit contact between the occupant's abdomen and any part of the seat or interior structure.

METHODS

CAMI conducted a project to evaluate the use of current ATDs for oblique-facing seats. The evaluation methods included two phases. The initial phase was a static structural examination of each ATD to determine if it could withstand off-axis impacts and loads. The latter phase was to conduct dynamic tests with seats placed at 30° and 45° with respect to the aircraft centerline to determine which ATD was most capable of measuring the expected injury risks.

Static Evaluation

Hybrid II

The Hybrid II is a 50th percentile mid-sized male defined by 49 CFR §572 Subpart B. It has limited instrumentation, with accelerometers in the head and pelvis and load cells in the lumbar spine and femur. The concern with the Hybrid II is that with such limited instrumentation, it would be unable to assess injuries in the thorax or any loading in the neck. However, due to the robust nature of the ATD and the availability of spare parts, this ATD was tested first to assess gross occupant kinematics.

FAA-Hybrid III

The FAA-Hybrid III is a mixture of the Subpart B Hybrid II and Subpart E Hybrid III ATDs, as specified in Gowdy et al. (1999). The modification consists of several Hybrid II parts substituted into the Hybrid III structure, including the straight lumbar spine, abdominal insert, chest jacket, and upper leg linkage. It includes accelerometers in the head and pelvis and load cells in the lumbar spine and femur, like the Hybrid II. The FAA-Hybrid III also includes load cells in the neck, thorax, and lower leg. Based on the risk of neck injuries observed in side-facing seat tests and the possibility of airbags being used as a mitigation strategy (which requires the measurement of neck loads to assess), the FAA Hybrid III is a better option than the Hybrid II for oblique-facing seats that are primarily forward-facing.

ES-2re

The ES-2re ATD is specially designed to evaluate injury in test conditions with significant lateral loading and is defined by 49 CFR §572 Subpart U. This ATD is cited in FAA policy PS-ANM-25-03-R1 for side-facing seats and 49 CFR §571.214 for use in automotive side-impact tests. The ES-2re was designed for pure lateral loading and, therefore, excluded from the dynamic test series due to concerns about permanent damage to rib sliders and the abdomen with forward flexion of the torso. This was deemed to be a particular concern for the dynamic tests where the torso was unrestrained. Its performance instead was evaluated numerically in a separate project (Moorcroft, 2013).

THOR-NT

As early as the 1980s, the National Highway Traffic Safety Administration (NHTSA) saw the need for a more advanced ATD that could be used in conjunction with newer restraint systems and with more advanced instrumentation to better understand emerging injury patterns. This prompted the development of the THOR (Haffner et al., 2001). The THOR contains an extensive array of instrumentation, particularly in the thoracic and abdominal regions. However, the THOR was developed for use in compact automotive environments, and a visual inspection revealed that extensive damage to the instrumentation and the lumbar spine element would likely occur in tests with significant lateral bending or forward flexion of the torso.

Figure 1A shows the THOR-NT in a fully flexed position. Figure 1B shows where metallic structures in the spine could pinch wires in the abdomen, thus damaging them. Figure 1D shows the rigid structures interacting with the softer abdominal instrumentation as the THOR-NT is fully flexed. Any interaction of this nature would likely damage or otherwise alter the readings received from the instrumentation. Therefore, the THOR-NT was excluded from horizontal impact testing.

The Hybrid II and FAA-Hybrid III lumbar spine have a simple cylindrical design, which gives them strength to withstand significant torso flexion. The THOR-NT lumbar spine element has a more complex design, with several stress concentration points that would likely fail with excessive loading. Figure 1C and Figure 2 show the stress concentration points on the THOR-NT lumbar spine.

At the time of the static evaluation, the THOR-NT was the current version. Since 2012, the THOR-K and THOR-M versions have been released. As of this writing, the United States has not codified the THOR. However, the THOR-50M is called out by the European and Australian new car assessment programs.

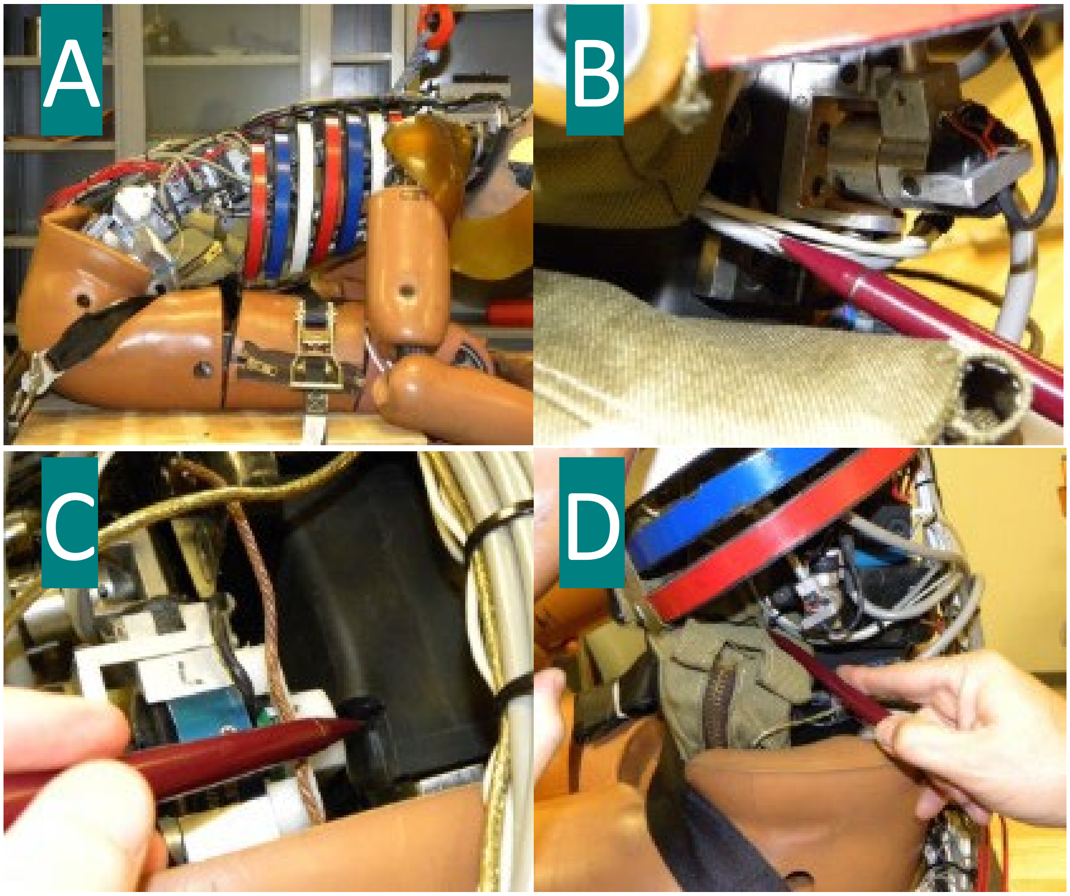

Figure 1: THOR-NT Hardware Interactions

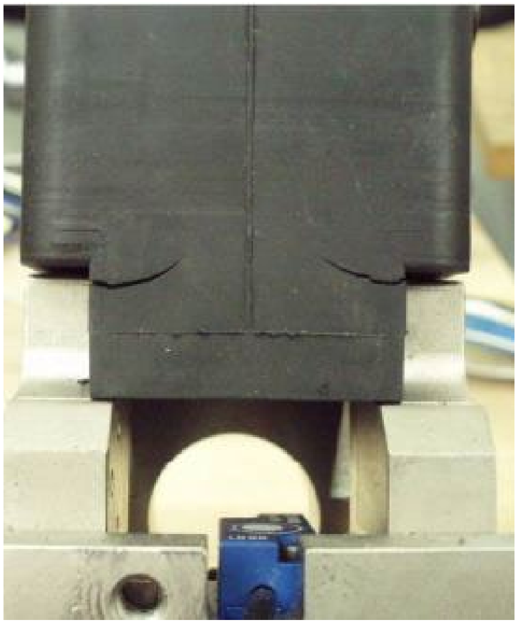
Figure 2: Posterior View of THOR Lumbar Spine

Dynamic Evaluation

At CAMI's request, the SAE Seat Committee conducted an informal industry survey to determine the typical orientation for oblique-facing seats. Based on the information received, a rigid couch was configured to reflect four seat configurations and permit orientation at 30° and 45° with respect to the aircraft centerline (Figure 3). Tests were completed with the 16 g, 44 ft/s impact severity defined in 14 CFR 25.562. For a detailed drawing of the rigid couch setup, see Appendix B. The seat had a flat seat bottom, a 13° back angle, 4-inch soft foam (DAX 47) cushions with a leather covering, and the armrest was padded with 1 in. of stiff foam (IV3). The cushions were rectangular in shape and covered in upholstery-grade, smooth leather. The cushions were attached to the seat with hook-and-loop fastener material to prevent sliding.

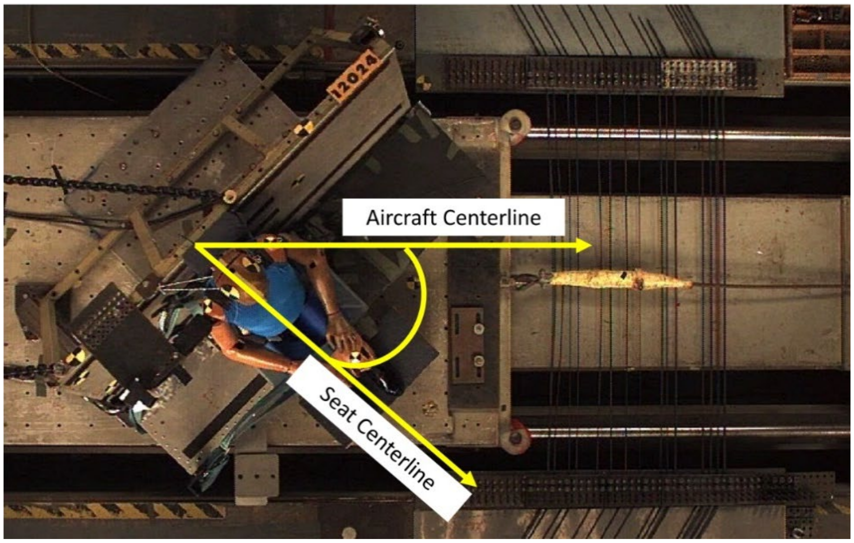

Figure 3: Seat Orientation

ATD

The Hybrid II and FAA-Hybrid III ATDs were selected for dynamic testing based on the initial static evaluation. Due to its robust construction and the availability of parts, the Hybrid II was initially used to measure gross kinematics. After the initial kinematic evaluation with the Hybrid II, the FAA-Hybrid III was used to measure loading in the neck, thoracic spine, lumbar spine, and legs.

Seat Configuration 1

The first configuration emulated a scenario where an occupant is seated next to an interior feature that is rigid below the armrest level and frangible above it (Figure 4). The interior feature was emulated by a rigid half wall with the legs restrained laterally at the ankles with belt webbing. This was to simulate features where the legs are contained by the surrounding structure.

Three belt setups were used for this test configuration (see Table 1). In the first setup, the ATD was constrained solely using a conventional lap belt to simulate a worst-case scenario for occupant flail where the shoulder belt was ineffective (Figure 4). The second setup added an effective shoulder belt to reduce flail (Figure 5). For the shoulder belt tests, the ATD pelvis was restrained using both a conventional lap belt and a body-centered lap belt (Figure 6) (a body-centered lap belt helps reduce forward flail in seating configurations with a significant lateral installation angle). The third setup used only a lap belt inflatable restraint (Figure 7). The inflatable scenario was initially tested twice. The ATD–airbag interaction was inconsistent with developmental tests run by Amsafe, Inc. The researchers decided to modify the setup to match the developmental tests more closely. The largest change was moving the ATD about 2-3 in. closer to the armrest. Additional notes are in Appendix C.

Table 1: Belt Setups for Seat Configuration 1

Test Number	Conventional Lap Belt	Body-Centered Lap Belt	Shoulder Belt	Inflatable Restraint
A12021	X	None	None	None
A12025	X	None	None	None
A12026	X	None	None	None
A16034	X	X	X	None
A16035	X	X	X	None
A16038	X	X	X	None
A16039	X	X	X	None
A23051	None	None	None	X
A23052	None	None	None	X
A23056	None	None	None	X
A23057	None	None	None	X

Figure 4: Configuration 1 with Lap Belt Only

Figure 5: Configuration 1 with Shoulder Belt

Figure 6: Configuration 1 Belt Routing, Highlighting Conventional and Body-Centered Lap Belts (Arrows)

Figure 7: Configuration 1 with Inflatable Lap Belt Restraint

Seat Configuration 2

The second configuration emulated a scenario where the occupant is seated next to an interior feature that only restricts the motion of the legs (Figure 8). For the lap belt-only tests, the ATD legs were restrained laterally at the thighs and ankles with belt webbing. For the shoulder belt tests, the legs were only restrained at the ankles.

Two belt setups were used for this test configuration (see Table 2). In the first setup, the ATD was constrained solely by using a conventional lap belt to simulate a worst-case scenario for occupant flail. This represents a scenario where the shoulder belt was ineffective (Figure 8). The second setup added a shoulder belt to reduce flail and represent an effective shoulder belt (Figure 9).

The ATD pelvis was restrained using both a conventional lap belt and a body-centered lap belt for both the lap belt-only and shoulder belt configurations (Figure 10). A body-centered lap belt helps reduce forward flail in seating configurations with a significant lateral installation angle. (Figure 10).

Table 2: Belt Setups for Seat Configuration 2

Test Number	Conventional Lap Belt	Body-Centered Lap Belt	Shoulder Belt
A12022	X	X	None
A12023	X	X	None
A12024	X	X	None
A12027	X	X	None
A16036	X	X	X
A16037	X	X	X

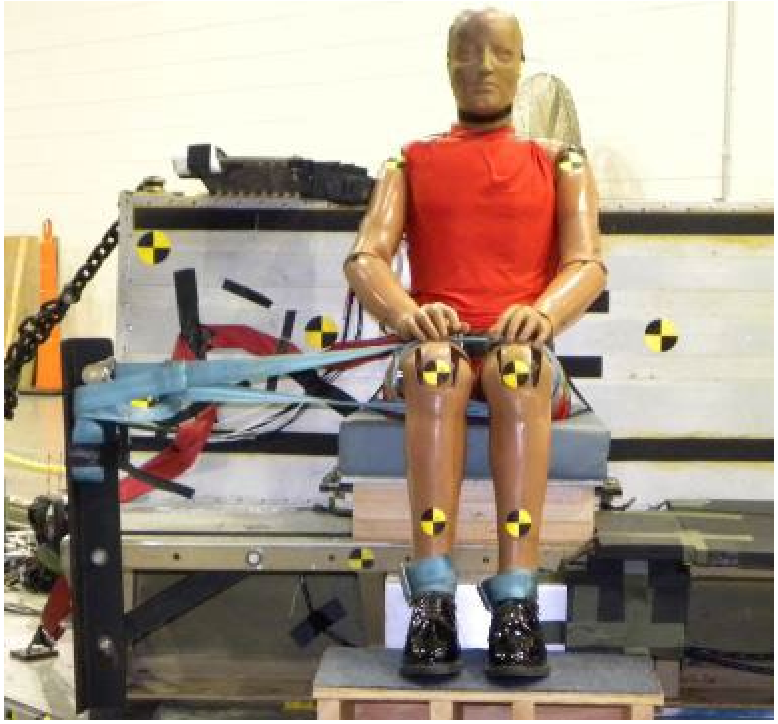

Figure 8: Configuration 2 with Lap Belt Only

Figure 9: Configuration 2 with Shoulder Belt

Figure 10: Configuration 2 Belt Routing, Highlighting Conventional and Body-Centered Lap Belts (Arrows)

ATD Seating Method

The ATD was seated according to a procedure developed at CAMI that results in a consistent fore/aft position and initial pelvis angle (Moorcroft, 2010). This procedure involves suspending the ATD above the seat cushion by approximately 1 in. A rigid bar is then inserted under the thighs just aft of the knees and used to elevate them slightly so as not to interfere with the ATD self-aligning. A force gauge is used to press on the sternum of the ATD with approximately 20 lb. of force while the ATD is lowered into full contact with the seating surface. The ATD is rocked from side to side and allowed to rest for five minutes to settle into the seat. A video of this procedure is currently available at https://www.youtube.com/watch?v=TNNjpzTQ4sQ.

Test Conditions

Each configuration used the 16 g, 44 ft./s impact condition defined in 14 CFR 25.562. Between the initial test series in 2012 and the second series in 2016, the deceleration sled at CAMI was upgraded to an acceleration sled. Representative pulses for the accelerator sled, decelerator sled, and ideal theoretical pulse are shown in Figure 11.

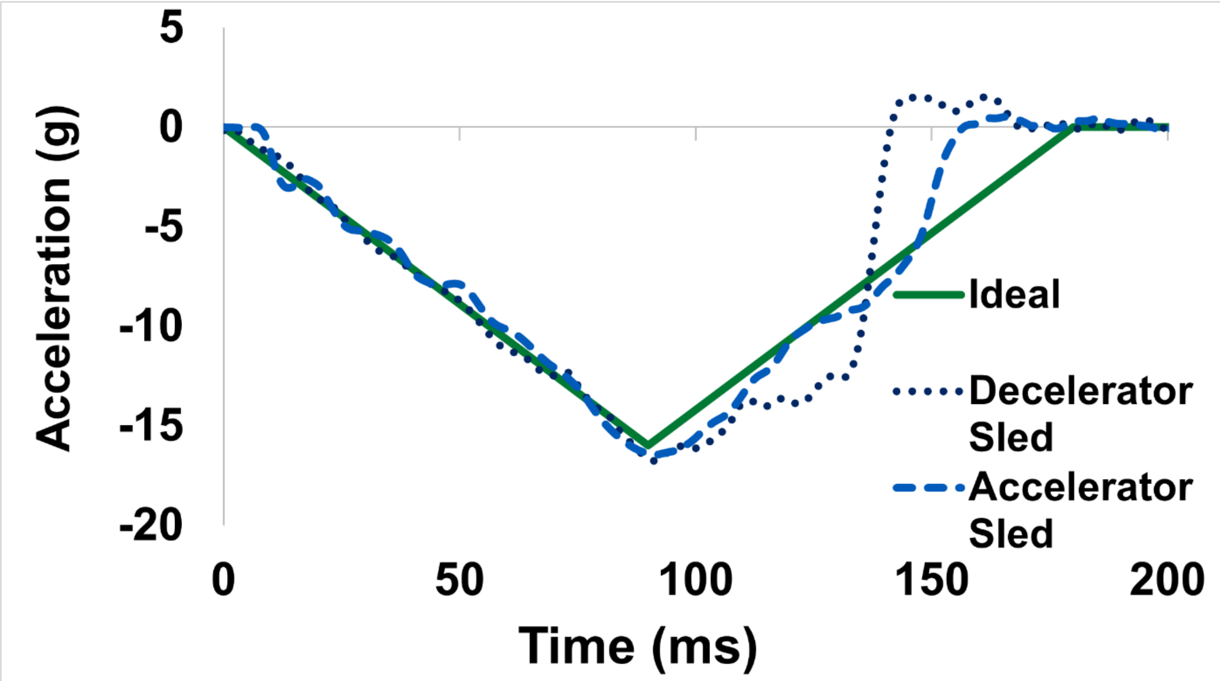

Figure 11: Representative Sled Pulses

Instrumentation

Electronic Instrumentation

The ATDs were instrumented to collect the data necessary to evaluate potential injury risk for occupants in oblique-facing seats. Each ATD has different instrumentation; Appendix A details the full list of instrumentation for each ATD. Six-axis load cells were installed at the anchor points for the lap belt, and webbing transducers were installed on the shoulder harness, one on either side of the shoulder belt guide (Figure 12). All electronic instrumentation was gathered according to SAE J211/1, which includes a channel filter class of 180 for the angular rate sensors (SAE International, 2014). The shoulder harness included a retractor with an inertia reel. When the belt is suddenly pulled, such as during an impact event, the reel locks, causing the retractor to act as a rigid anchor point. To measure shoulder belt payout, a simplified string pot was constructed with a piece of string attached to the belt and then passed through a small block of dense foam fixed to the seat near the inertia reel (Figure 13). By measuring the length of string pulled through the foam block, the maximum webbing payout during each test was estimated.

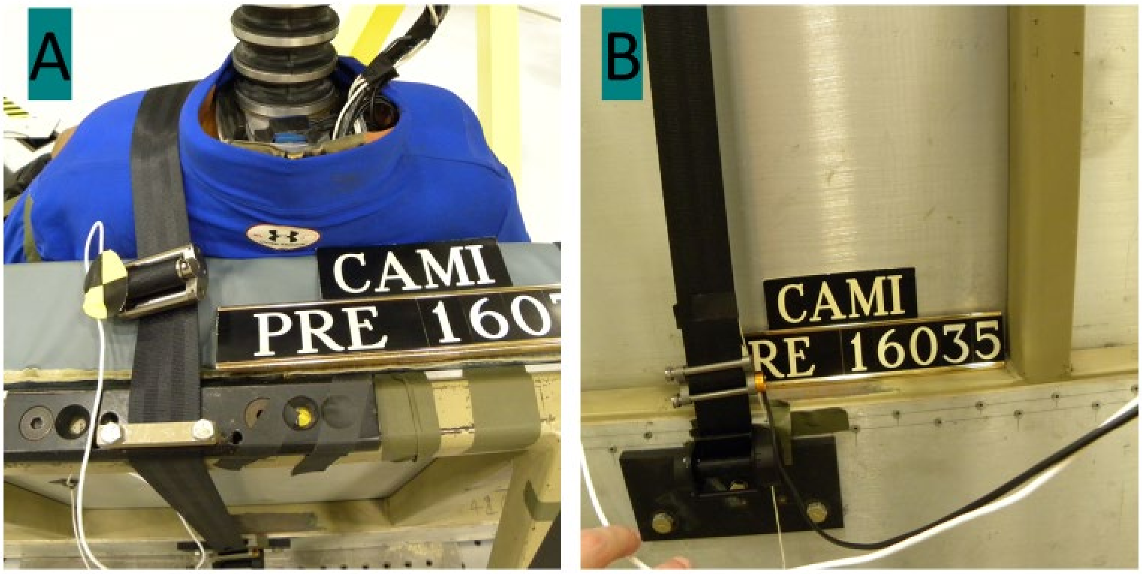

Figure 12: Upper (A) and Lower (B) Belt Webbing Transducers

Figure 13: Shoulder Belt Showing String in Foam and Lower Webbing Transducer

Video Coverage

Cameras aimed perpendicular to the sled's travel captured high-speed (1000 frames/s), high-resolution (1024 x 768 pixels) color video from the side and overhead directions. Rectilinear targets were placed on the ATD, the seat belt, and the seat structure for possible future motion analysis. Targets were also placed on rigid structures for scaling and validation.

Test Matrix

Seventeen tests were conducted to gather kinematic and kinetic data. Table 3 summarizes the variables evaluated for each test in this study. These included the ATD, seat installation angle, seat configuration, and belt type.

Table 3: Test Matrix

Test Number	ATD	Seat Conf.	Angle	Belt
A12021	Hybrid II	1	45°	Lap
A12022	Hybrid II	2	45°	Lap[1]
A12023	Hybrid II	2	45°	Lap[1]
A12024	FAA-Hybrid III	2	45°	Lap[1]
A12025	FAA-Hybrid III	1	45°	Lap
A12026	FAA-Hybrid III	1	30°	Lap
A12027	FAA-Hybrid III	2	30°	Lap[1]
A16034	FAA-Hybrid III	1	45°	Shoulder
A16035	FAA-Hybrid III	1	45°	Shoulder
A16036	FAA-Hybrid III	2	45°	Shoulder
A16037	FAA-Hybrid III	2	30°	Shoulder
A16038	FAA-Hybrid III	1	30°	Shoulder
A16039	FAA-Hybrid III	1	30°	Shoulder
A23051	FAA-Hybrid III	1	45°	Inflatable
A23052	FAA-Hybrid III	1	45°	Inflatable
A23056	FAA-Hybrid III	1	45°	Inflatable
A23057	FAA-Hybrid III	1	45°	Inflatable

RESULTS

Notes on each test, including still shots to show the ATD kinematics during the test, are detailed in Appendix C.

Head

Since there was no head contact with the surrounding structure, HIC was not evaluated. While the ATD's head did contact the knee in at least one test, the FAA does not require HIC to be evaluated for body-to-body contact.

Neck

There are no established criteria for neck loading with oblique-facing seats. Depending on the loading environment, either frontal loading or lateral loading criteria could be valid. Because of this, the data to support either criterion were recorded and can be found in Table 4. Loads that only failed the frontal load limits are red and bold and loads that failed the lateral load limits are green and italic.

No tests exceeded the N_{ij} limit of 1. However, the lap belt-only tests with a half wall (A12025 and A12026) produced values close to the limit (0.96 and 0.87, respectively). Both tests exceeded the pure tension limit of 937 lb. For the shoulder belt and lap belt inflatable restraint scenarios, the

[1] Lap belt-only tests in Configuration 2 included a body-centered belt in addition to the conventional lap belt.

tests yielded much lower N_{ij} numbers (all but one under 0.5). In addition to the two tests with neck tension above the fore-aft limit, seven tests exceeded the tension limit for side-facing seats. All the lap belt tests and five out of six of the shoulder belt tests exceeded the shear limit. Two of the tests with a lap belt inflatable restraint were close to the shear limit (179 lb. vs 186 lb. limit). Further research is required to determine the proper neck limit for oblique-facing seats. The M_y channel failed in test A16038, so N_{ij} was unavailable for this test.

Table 4: FAA Hybrid III Upper Neck Readings

Test Number	ATD	Seat Conf.	Angle	Belt	N_{ij}	F_z (lb.)	M_x (in.-lb.)	F_{xy} (lb.)
A12024	FAA-Hybrid III	2	45°	Lap[2]	0.78	*793*	300	*225*
A12025	FAA-Hybrid III	1	45°	Lap	0.96	**1065**	-315	*386*
A12026	FAA-Hybrid III	1	30°	Lap	0.87[3]	**1009**	-273	*305*
A12027	FAA-Hybrid III	2	30°	Lap[2]	0.74	*849*	-510	*290*
A16034	FAA-Hybrid III	1	45°	Shoulder	0.34	354	158	*198*
A16035	FAA-Hybrid III	1	45°	Shoulder	0.35	379	116	181
A16036	FAA-Hybrid III	2	45°	Shoulder	0.34	354	157	*198*
A16037	FAA-Hybrid III	2	30°	Shoulder	0.38	*511*	152	*225*
A16038	FAA-Hybrid III	1	30°	Shoulder	N/A[4]	384	89	*216*
A16039	FAA-Hybrid III	1	30°	Shoulder	0.39	*472*	134	*229*
A23051	FAA-Hybrid III	1	45°	Inflatable	0.41	*492*	622	135
A23052	FAA-Hybrid III	1	45°	Inflatable	0.56	*698*	745	179
A23056	FAA-Hybrid III	1	45°	Inflatable	0.33[5]	294	427	179
A23057	FAA-Hybrid III	1	45°	Inflatable	0.41	*579*	673	129

Lumbar Spine

The FAA-Hybrid III and Hybrid II contain a lumbar load cell, so the load was measured for each test configuration. The resulting loads are reported in Table 5, along with the test number and ATD model. Tests that exceed either the compressive lumbar load limit of 1500 lb., the preliminary tension limit of 1200 lb., or the FAA-LL_{tb} proposed limit of 1.88 are in red and italic. The peak loads in the 3-pt belt tests were compressive, and all were below the 1500 lb. limit, with the highest value being 1245 lb. The peak loads in the lap belt-only tests were tensile, and each was above the 1200 lb. preliminary limit, with the lowest value being 1793 lb. The lap belt-only tests also produced an FAA-LL_{tb} over the proposed limit, with a low of 2.51. For the tests with a lap belt inflatable restraint, the tension loads were lower than the lap belt-only tests but above the 1200 lb. preliminary limit. The first two lap belt inflatable restraint tests exceeded the FAA-LL_{tb} limit, but

[2] Lap belt-only tests in Configuration 2 included a body-centered belt in addition to the conventional lap belt.
[3] The ATD's head struck the knee in test A12026.The injury data for this test utilize data proceeding body-body contact.
[4] The M_y channel failed in test A16038, so an accurate N_{ij} calculation is unavailable for this test.
[5] The ATD's head struck a test fixture in A23056. The injury data for this test utilize data proceeding contact with nonrepresentative structures.

the second two tests, with less space available for the bag to move away from the ATD, were below the proposed limit.

Table 5: Lumbar Load

Test Number	ATD	Seat Conf.	Angle	Belt	F_z (lb.)	M_y (in.-lb.)	M_x (in.-lb.)	FAA-LL_{tb}
A12021	Hybrid II	1	45°	Lap	*3078*	2924	3256	*3.22*
A12022	Hybrid II	2	45°	Lap[6]	*1793*	3308	2728	*2.74*
A12023	Hybrid II	2	45°	Lap[6]	*1969*	3448	4000	*3.27*
A12024	FAA Hybrid III	2	45°	Lap[6]	*2017*	2398	3807	*2.83*
A12025	FAA Hybrid III	1	45°	Lap	*2841*	1953	2416	*2.51*
A12026	FAA Hybrid III	1	30°	Lap	*2374*	3225	1978	*2.67*
A12027	FAA Hybrid III	2	30°	Lap[6]	*2135*	3323	3107	*2.99*
A16034	FAA Hybrid III	1	45°	Shoulder	-803	697	-1245	0.72
A16035	FAA Hybrid III	1	45°	Shoulder	-721	665	-946	0.62
A16036	FAA Hybrid III	2	45°	Shoulder	-974	566	-1032	0.61
A16037	FAA Hybrid III	2	30°	Shoulder	-972	806	-1235	0.76
A16038	FAA Hybrid III	1	30°	Shoulder	-1162	659	-1091	0.68
A16039	FAA Hybrid III	1	30°	Shoulder	-1245	810	-1292	0.80
A23051	FAA Hybrid III	1	45°	Inflatable	*1533*	1807	2674	*2.08*
A23052	FAA Hybrid III	1	45°	Inflatable	*1738*	1745	2621	*2.11*
A23056	FAA Hybrid III	1	45°	Inflatable	*1434*	1484	-1463	1.53
A23057	FAA Hybrid III	1	45°	Inflatable	*1481*	1656	2094	1.81

[6] Lap belt-only tests in Configuration 2 included a body-centered belt in addition to the conventional lap belt.

Thoracic Spine

Table 6 includes the thoracic axial (F_z) load, the positive and negative moments about the x-axis, and the positive and negative moments about the y-axis. There are no established injury criteria for the thoracic spine with oblique-facing seats. Thus, the data recorded in Table 6 are for informational purposes only.

Table 6: FAA-Hybrid III Thoracic Readings

Test Number	Seat Conf.	Angle	Belt	Axial Load (lb.)	Positive M_x (in.-lb.)	Negative M_x (in.-lb.)	Positive M_y (in.-lb.)	Negative M_y (in.-lb.)
A12024	2	45°	Lap	2434	2501	-2391	1786	-1920
A12025	1	45°	Lap	2829	1730	-2718	3387	-1545
A12026	1	30°	Lap	2593	2062	-1641	3011	-2105
A12027	2	30°	Lap	2636	2153	-1854	2276	-1806
A16034	1	45°	Shoulder	-795	1920	-620	2433	-333
A16035	1	45°	Shoulder	-740	1937	-402	2020	-316
A16036	2	45°	Shoulder	-950	1901	-275	1950	-198
A16037	2	30°	Shoulder	-938	1932	-226	2227	-253
A16038	1	30°	Shoulder	-1140	1604	-305	2663	-440
A16039	1	30°	Shoulder	-1191	2093	-267	2651	-408
A23051	1	45°	Inflatable	1511	2021	-2324	988	-925
A23052	1	45°	Inflatable	1722	1489	-2227	1234	-1151
A23056	1	45°	Inflatable	1436	1156	-859	1058	-1057
A23057	1	45°	Inflatable	1399	1390	-1740	1431	-884

While there are no injury criteria for the thoracic region of the spine for oblique-facing seats, the data collected from this load cell had similar trends as the lumbar load cell (Figure 14). Three trends were observed:

1) For tests where the occupant had considerable free flail (i.e., configuration 2, which lacked a half wall, and configuration 1 at 30°), the two loads deviated, with the thoracic producing a higher peak.

2) For the tests with a shoulder belt, the two load cells measure similar values, with the lumbar peak being slightly higher for five of the six tests. This is logical, as there is additional mass loading into the lumbar load cell.

3) For the lap belt inflatable restraint and half wall at 45° tests, where there was significant torso contact with either the airbag or half wall, the two loads did not deviate.

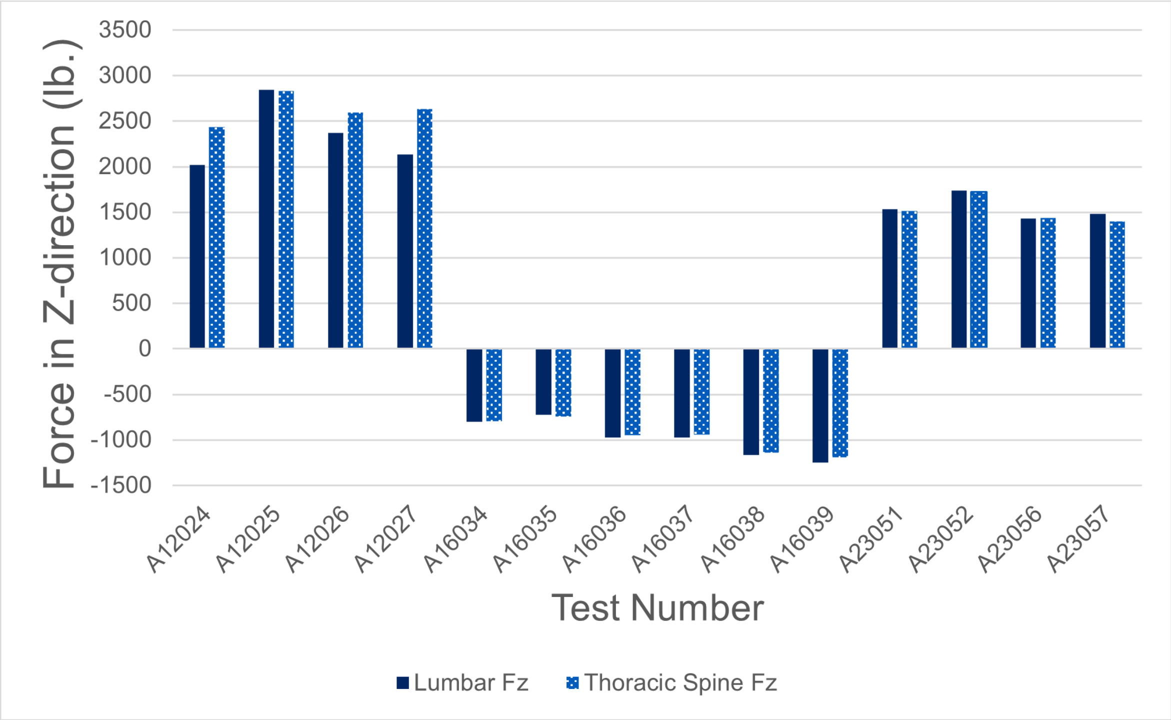

Figure 14: Lumbar F_z vs Thoracic F_z

Shoulder Belt

Table 7 summarizes the shoulder belt webbing loads above and below the belt guide and the payout recorded for tests with a shoulder belt. No tests exceeded the 1750 lb. limit.

Table 7: Shoulder Belt

Test Number	Upper (lb.)	Lower (lb.)	Payout (in.)
A16034	1385	1071	1.4
A16035	1405	1085	1.2
A16036	1390	1030	1.1
A16037	*sensor failure*	1060	1.5
A16038	1400	1059	1.0
A16039	1360	1046	1.1

Soft-Tissue Injuries

As neither the Hybrid II nor the FAA Hybrid III have instrumentation in the abdomen to detect contact, kinematic analysis was required to evaluate potential soft-tissue injuries in an oblique-facing seat. Only minor interaction was noted between the abdomen and the armrest. Still shots and notes are contained in Appendix C.

Hardware failures

Due to the high flail environment of the rigid half-wall testing in configuration 1 and the lack of a shoulder belt in some tests, the Hybrid III experienced multiple structural failures. In test A12025, the left humerus fractured at a weld (Figure 15). In A12026, both clavicles failed at the lightening holes drilled in the cast aluminum part (Figure 16). The estimated failure force for the clavicles is 1350 lb.

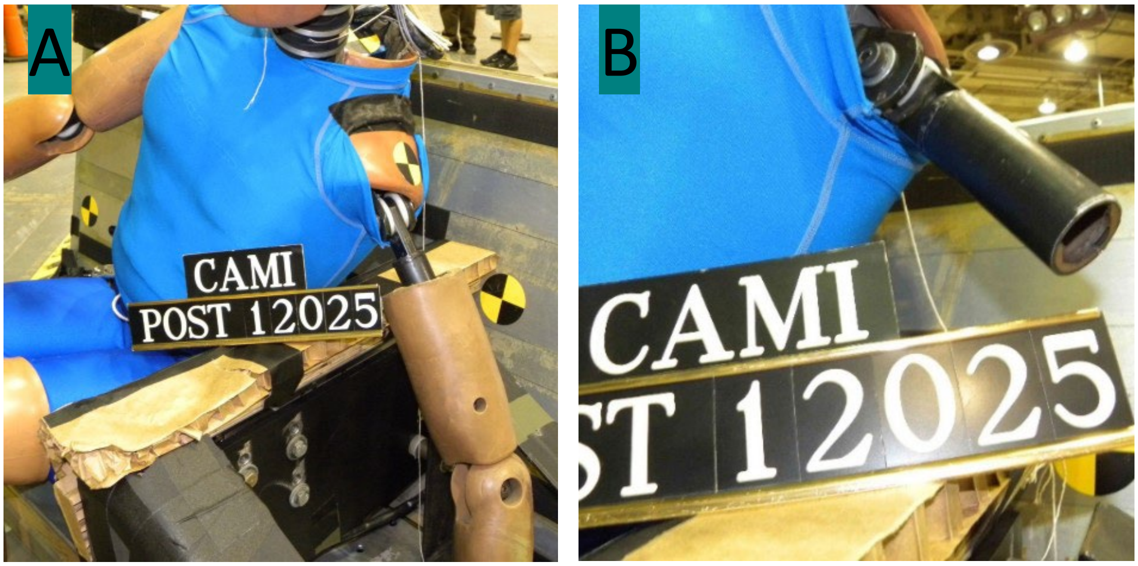

Figure 15: FAA-Hybrid III Broken Humerus (A); Location of Humerus Weld (B)

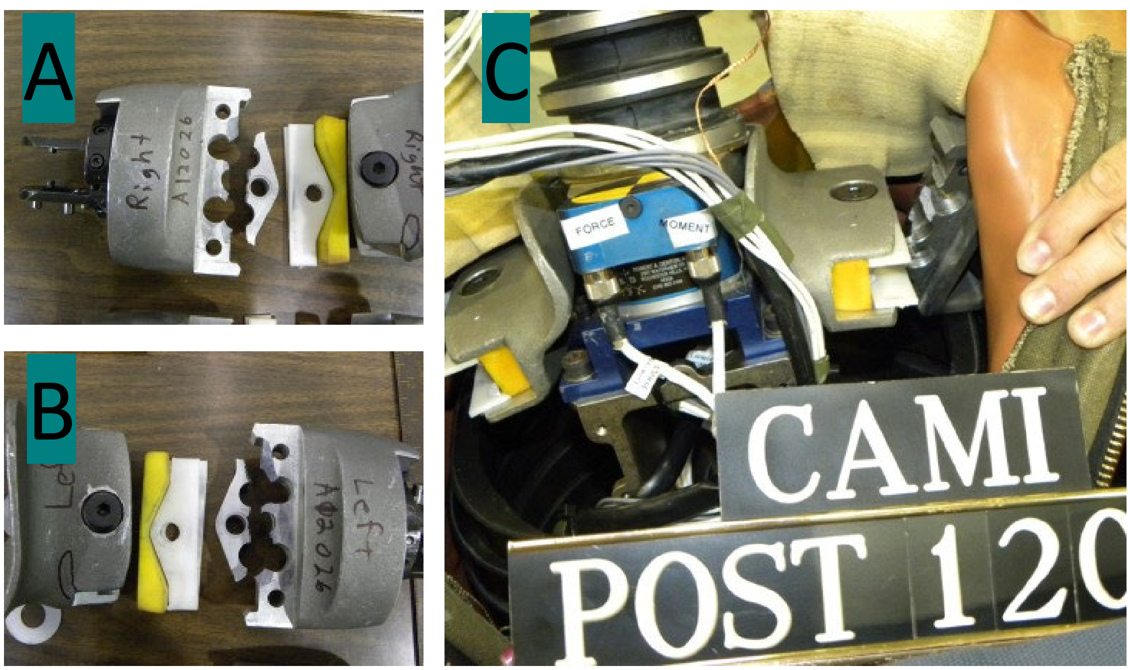

Figure 16: Broken Right Clavicle (A); Broken Right Clavicle (B); Broken Clavicle in ATD (C)

DISCUSSION

Oblique-facing seats present challenges to certification, as they share injury risks with both forward-facing seats and side-facing seats. These challenges include determining the appropriate ATD to use in certification tests and applicable injury criteria. Initially, researchers were primarily concerned with potential soft-tissue injuries resulting from the intrusion of part of the seat into the abdomen. Due to the expanded instrumentation, especially throughout the abdomen, CAMI secured a THOR-NT ATD from NHTSA to evaluate its applicability to oblique seat testing in an aviation environment. However, once CAMI performed a static evaluation, it was anticipated that the THOR-NT would experience instrumentation damage in the abdomen and pelvis and possible failure of the lumbar spine if allowed to flail without a torso restraint. As such, it was excluded from use in the dynamic portion of the testing.

The ES-2re was also considered in the project due to its specialized instrumentation for the certification of side-facing seats. However, this ATD was also excluded after the static evaluation. The rib sliders were designed to be loaded parallel to their motion, and off-axis loading, such as would occur in oblique-facing seats, could bind or damage those sliders. A separate project used computational modeling to evaluate the ATD for potential use in oblique-facing seats with an effective shoulder restraint (Moorcroft, 2013).

Both the Hybrid II and FAA-Hybrid III were deemed robust enough for dynamic testing, and since they include the Hybrid II lumbar spine and have the same weight distribution, similar torso kinematics were expected. The initial tests with the Hybrid II showed limited abdominal contact with surrounding structures. This was later confirmed in PMHS tests performed by the Medical College of Wisconsin, which did not show abdominal injury from oblique-facing seats (Humm et al., 2015). The results of the ATD and PMHS testing indicated serious injuries to the lumbar and neck regions. Soft-tissue injuries resulting from contact with the seat or surrounding structures were unlikely for the configurations tested.

While the Hybrid II has a load cell in the lumbar spine, it cannot measure the loading to the neck. Since the FAA policy (PS-AIR-25-27) requires an evaluation of neck loads and N_{ij}, the Hybrid II is insufficient for certification testing of oblique-facing seats for the horizontal test condition. The lumbar loads measured by the Hybrid II and FAA-Hybrid III in the lap belt-only configuration exceeded the tension limit of 1200 lb. and the FAA-LL_{tb} limit of 1.88 in every test. The lap belt-only testing also had neck tension loads that exceeded either the forward-facing limit or the side-facing limit in every test. Additionally, the excessive flail in the lap belt-only configurations resulted in several ATD structural failures, potentially translating to real-world injuries.

Subsequent testing in 2016 added a shoulder belt to the previous testing setup to reduce flail. This also reversed the direction of the loading in the lumbar spine since the ATDs were restrained from forward motion. With the addition of the shoulder belt, the maximum lumbar compression load was 1245 lb., which was below the 1500 lb. limit. The shoulder belt testing passed the forward-facing neck tension limit in every test and exceeded the lateral limit for neck tension in two of the six tests.

The additional inflatable lap belt restraint testing in 2023 exceeded the tension limit in all four tests but passed the FAA-LL_{tb} limit in two of the four tests. This test series also failed the lateral neck tension limit in three of the four tests.

An occupant restrained solely by a lap belt is at high risk of serious or fatal injury in oblique-facing seats. The results from the shoulder belt and inflatable lap belt tests suggest that existing technology can provide adequate protection from lumbar injuries in oblique-facing seats. Further research is required to determine the proper neck injury criteria for oblique-facing seats.

LIMITATIONS

This research project focused on the longitudinal test condition with the seat installed between 30° and 45° degrees with respect to the aircraft centerline, with the majority of the tests being performed at 45°. The results, along with the recommendation for which ATD to use during certification testing, may not apply to seats installed beyond 45° or for the combined horizontal-vertical test condition. Due to the limited number of tests at 30°, there are insufficient data to determine which angle has higher injury risk. As such, caution should be used when making assumptions about the most critical case to test when selecting between +10° and -10° yaw (relative to installation angle) when certifying an oblique-facing seat.

A limited number of tests were performed with the same wall configuration and belt setup. When the test configuration and belt setup were repeated (i.e., A16034 and A16035), the test data had good agreement. However, the test variance cannot be fully determined since only a few tests with identical configurations and belt setups were repeated.

The lap belt inflatable restraints used in this test series were a developmental design that has not been subjected to certification testing. According to the airbag manufacturer (Amsafe, Inc.), alternative designs, such as structural mounted airbags, are more common in production seats. For the purposes of this test series, the lap belt inflatable restraint was successful in showing a non-shoulder belt configuration that can meet the lumbar combined metric limit.

Due to the direction of ATD travel in oblique-facing seats, multiple camera angles are useful to fully examine the ATD's motion and interaction with surrounding structures. Because the tests conducted in 2012 only used an offboard camera system (perpendicular to sled travel), it was difficult to observe the ATD's interaction with the seat structure. Testing in 2016 and 2023 included four onboard cameras that were close to perpendicular to the sled, providing better coverage. Even with the better angle, the lack of an overhead camera allowed the lap belt inflatable restraint or other test articles to sometimes block the view of the ATD. When testing oblique-facing seats, it is recommended to use a combination of cameras mounted perpendicular to sled travel, perpendicular to the seat, and overhead.

CONCLUSIONS

Testing at CAMI was conducted to evaluate existing ATDs for their ability to capture injury risks in oblique-facing seats up to 45° with respect to the aircraft centerline. Initial static testing indicated that the ES-2re and the THOR-NT might suffer serious damage to their internal structure and instrumentation if exposed to the unrestrained and off-axis flailing of the proposed dynamic tests. The Hybrid II was determined to be structurally sound enough to withstand the dynamic testing to determine gross kinematics. However, because of its limited instrumentation, specifically in the neck, it cannot fully measure potential injury risks. The FAA-Hybrid III was also determined to be able to withstand the potential flailing from dynamic tests. It includes the required instrumentation for measuring potential injury risks. Dynamic testing using the FAA-Hybrid III showed lumbar tension loads and FAA-LL_{tb} well in excess of the proposed limit and structural failures of the ATD in the lap belt-only configuration. With the addition of a shoulder belt, the lumbar spine experienced moderate compression loads and reduced flail. Testing with lap belt inflatable restraints produced results close to the proposed FAA-LL_{tb} limit, with two tests slightly below and two slightly above.

The FAA-Hybrid III was the only ATD evaluated by CAMI capable of measuring all the required injury metrics in an oblique-facing environment (up to 45°) without risk of damage to the sensors and is, therefore, recommended for use in horizontal certification testing.

REFERENCES

Anthropomorphic Test Devices. 49 CFR §572. (2022). https://www.govinfo.gov/app/details/CFR-2011-title49-vol7/CFR-2011-title49-vol7-part572

Emergency Landing Dynamic Conditions. 14 CFR. §25.562. (2023). https://www.govinfo.gov/app/details/CFR-2022-title14-vol1/CFR-2022-title14-vol1-sec25-562

Federal Aviation Administration (2012). *Technical Criteria for Approving Side-Facing Seats*. (Policy Statement No. ANM-25-03-R1). https://drs.faa.gov/browse/excelExternalWindow/FE2C2B5663AC288786257ABC004EDD6E.0001

Federal Aviation Administration (2014). *Boeing Model 777-300ER, Single-Occupant, Oblique (Side-Facing) Seats With Inflatable Lapbelts*. (Special Condition No. 25-569-SC). https://federalregister.gov/a/2014-22781

Federal Aviation Administration (2018). *Technical Criteria for Approving Oblique Seats*. (Policy Statement No. AIR-25-27). https://drs.faa.gov/browse/excelExternalWindow/923EEE252FEFEDB7862582DA0066797D.0001

Gowdy, V., DeWeese, R., Beebe, M., Wade, B., Duncan, J., Kelly, R., Blaker, J. (1999). *A lumbar spine modification to the Hybrid III ATD for aircraft seat tests*. SAE Technical Paper 1999-01-1609. https://doi.org/10.4271/1999-01-1609

Haffner, M.P., Eppinger, R.H., Rangarajan, N., Shams, T., Artis, M., Beach, D. (2001*). Foundations and elements of the NHTSA Thor ALPHA ATD design*. International Technical Conference on Enhanced Safety of Vehicles https://www.nhtsa.gov/document/paper-foundations-and-elements-nhtsa-thor-alpha-atd-design

Humanetics.(n.d.) Thor 50 M https://www.humaneticsgroup.com/products/anthropomorphic-test-devices/frontal-impact/thor-50m/thor-50m

Humm J., Moorcroft D., Yoganandan N., DeWeese R., Taylor A., Pintar F. (2015b). *Preliminary FAA-Hybrid III Spinal Injury Criteria for Oblique-Facing Aircraft Seats*. Proc ASME Intl Mech Engg Congress Exp; Nov 13-15, Houston TX, Paper # IMECE2015-52059.

Jones, James (2000, March 3) *Use of Hybrid III Anthropomorphic Test Dummy in Seat Dynamic Testing* [Memorandum]. Federal Aviation Administration. https://www.abbottaerospace.com/downloads/faa-air-100-3-3-2000-use-of-the-hybrid-iii-anthropomorphic-test-dummy-in-seat-dynamic-testing/

Karthik Somasundaram, John R. Humm, Narayan Yoganandan, David M. Moorcroft, Frank A. Pintar (2022): *Tension-bending risk curves for the ATD lower lumbar spine subjected to oblique impact under FAA emergency landing conditions*, International Journal of Crashworthiness, DOI: 10.1080/13588265.2022.2130611

Moorcroft, D (2010). *Improving Test Repeatability and Methods.* The Sixth Triennial International Fire & Cabin Safety Research Conference; Atlantic City, New Jersey. https://www.fire.tc.faa.gov/2010Conference/files/Crash_Dynamics_III/MoorcroftLumbarLoad/MoorcroftLumbarLoadPres.pdf

Moorcroft, D. (2013). *Performance of a Numerical Model of the ES-2re as a Function of Impact Angle*. The Seventh Triennial International Fire & Cabin Safety Research Conference; Philadelphia, PA.

Occupant Crash Protection. 49 CFR §571.208 (2022). https://www.govinfo.gov/app/details/CFR-2022-title49-vol6/CFR-2022-title49-vol6-sec571-208

SAE International (2014). *Instrumentation for Impact Test - Part 1 - Electronic Instrumentation J211/1_201403* (Surface Vehicle Recommended Practice No: J211-1). Warrendale, PA: SAE International.

SAE International (2015). *Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft* (SAE Aerospace Standard No: AS8049C). Warrendale, PA: SAE International.

SAE International (2017). *Performance Standard for Oblique Facing Passenger Seats in Transport Aircraft* (SAE Aerospace Standard No: AS6316). Warrendale, PA: SAE International.

Seats, Berths, Safety Belts, and Harnesses. 14 CFR. §25.785. (2023). https://www.govinfo.gov/app/details/CFR-2022-title14-vol1/CFR-2022-title14-vol1-sec25-785

Side Impact Protection. 49 CFR §571.214. (2022). https://www.govinfo.gov/app/details/CFR-2022-title49-vol6/CFR-2022-title49-vol6-sec571-214

APPENDIX A: Full List of Recorded Channels

Table 8: Full Instrumentation List

Description	Units	Filter Class	Hybrid II	FAA-Hybrid III
Sled Acceleration (main and aux)	g	60	X	X
Head Acceleration (Ax, Ay, Az)	g	1000	X	X
Head Rotational Acceleration (Rx, Ry, Rz)	deg/s	180	-	X
Upper and Lower Neck Force (Fx, Fy, Fz)	lb.	600	-	X
Upper and Lower Neck Moment (Mx, My, Mz)	in.-lb.	600	-	X
Thorax Spine Acceleration (Ax, Ay, Az)	g	180	X	X
Thorax Rotational Acceleration (Rx, Ry, Rz)	deg/s	180	-	X
Thorax Force (Fx, Fy, Fz)	lb.	600	-	X
Thorax Moment (Mx, My)	in.-lb.	600	-	X
Lumbar Force (Fx, Fy, Fz)	lb.	600	X	X
Lumbar Moment (Mx, My, Mz)	in.-lb.	600	X	X
Pelvis Acceleration (Ax, Ay, Az)	g	180	X	X
Pelvic Rotational Acceleration (Rx, Ry, Rz)	deg/s	180	-	X
Left Belt Anchor Force (Fx, Fy, Fz)	lb.	60	X	X
Center Belt Anchor Force (Fx, Fy, Fz)[7]	lb.	60	X	X
Right Belt Anchor Force (Fx, Fy, Fz)	lb.	60	X	X
Armrest Force (Fx, Fy, Fz)	lb.	60	X	X
Armrest Moment (Mx, My, Mz)	in.-lb.	60	X	X
Upper and Lower Shoulder Belt Force	lb.	60	-	X
Left and Right Femur Force (Fx, Fy, Fz)[8]	lb.	600	-	X
Left and Right Femur Moment (Mx, My, Mz)[8]	in.-lb.	600	-	X
Left and Right Femur Rotational Acceleration (Rx, Ry, Rz)[8]	deg/s	180	-	X
Right Upper and Lower Tibia Force (Fx, Fy, Fz)[8]	lb.	600	-	X
Right Upper and Lower Tibia Moment (Mx, My)[8]	in.-lb.	600	-	X
Head Rotational Displacement (θz)[9]	deg	Calc	-	X

[7] Not available for 2012 armrest tests, as center belt was not installed.
[8] Leg data only available in 2023.
[9] Angle data created by integrating angular velocity. Only calculated for A23051 and A23057.

APPENDIX B: Rigid Couch Dimensions

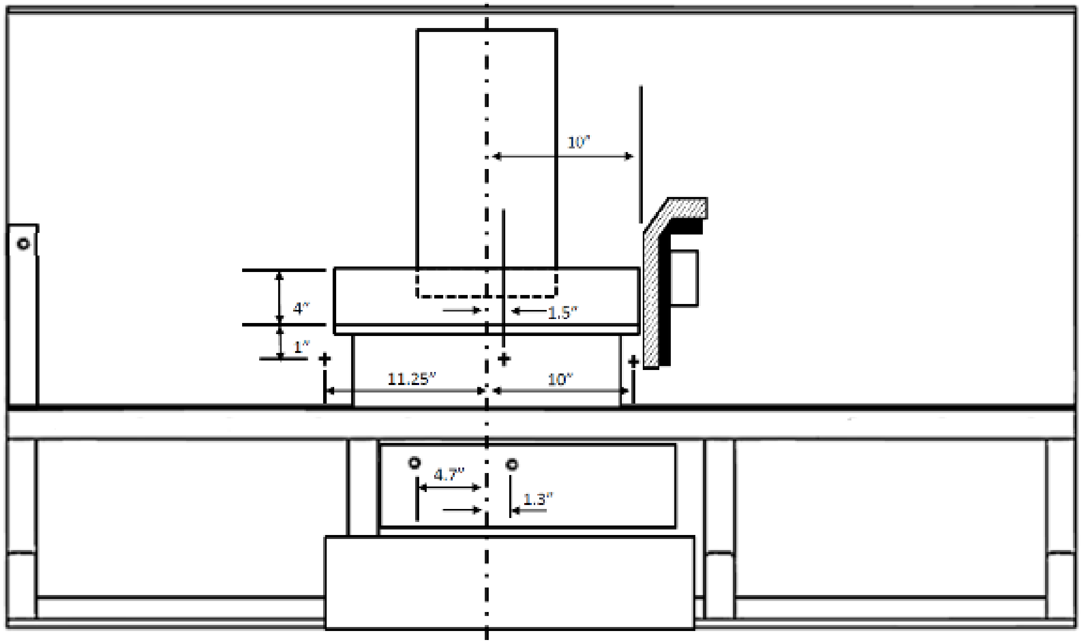

Figure 17: Dimensions from front view of couch

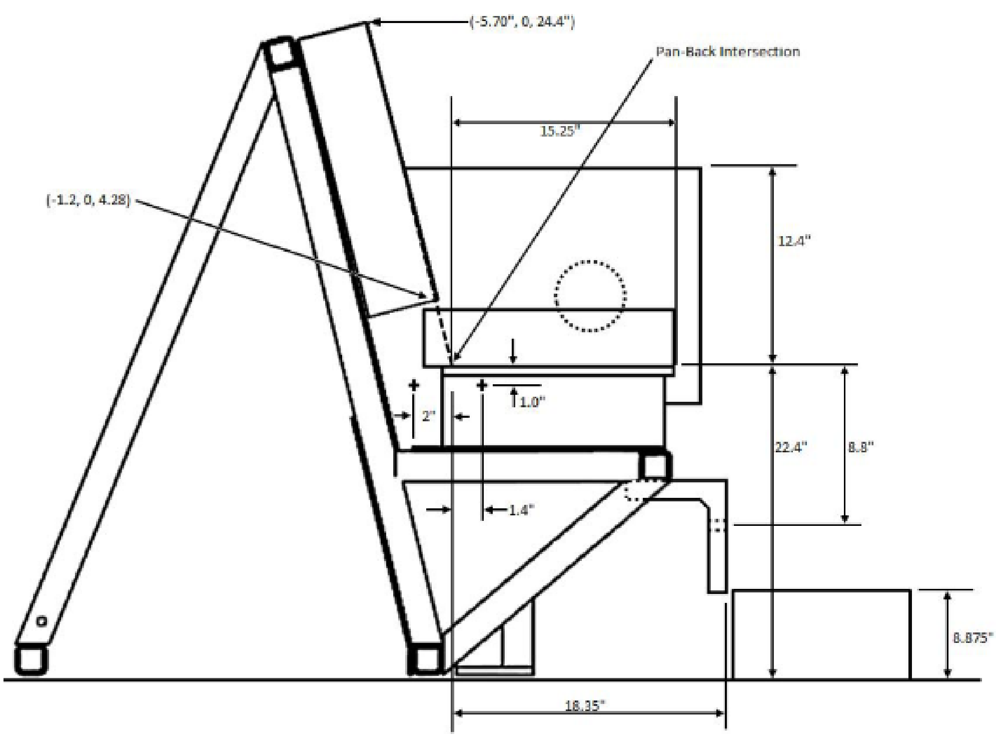

Figure 18: Dimensions from side view of couch

APPENDIX C: Detailed Test Evaluations

A12021 – Hybrid II, 45°, Configuration 1 (body-centered lap belt plus conventional lap belt, with armrest)

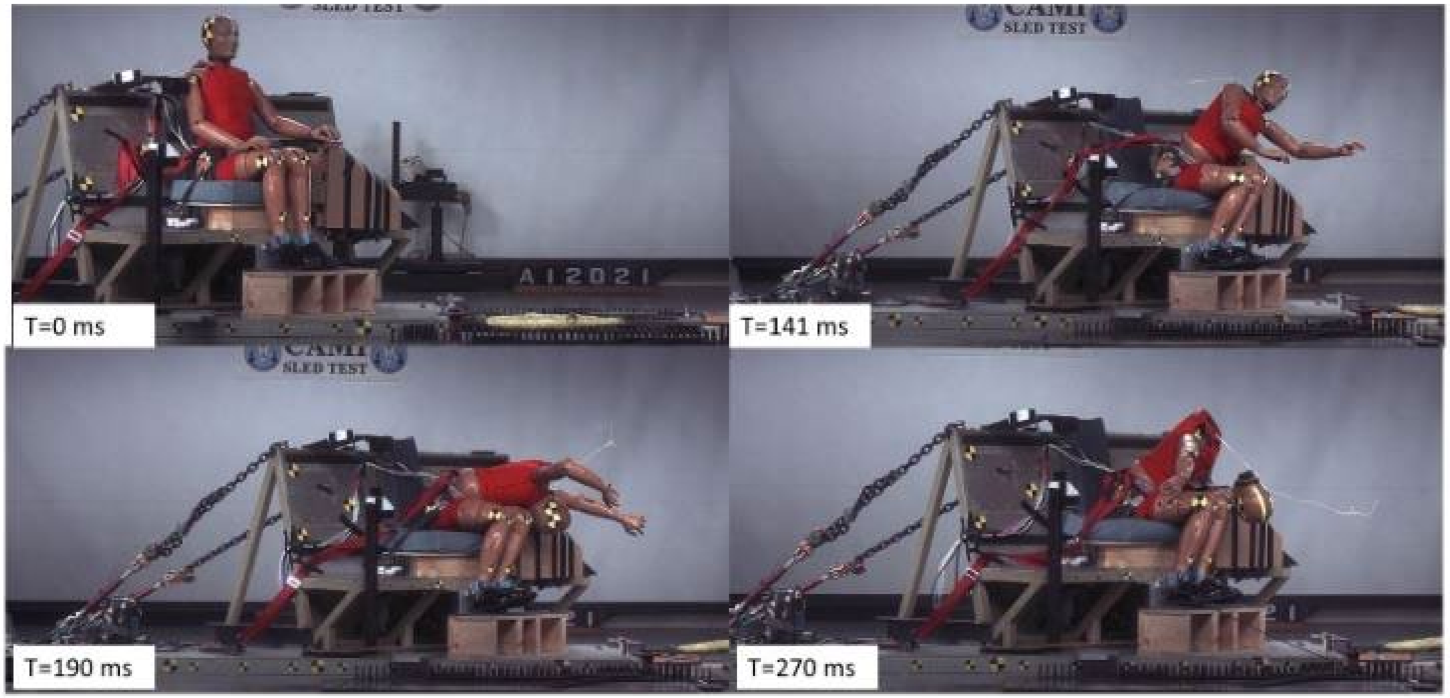

Figure 19: A12021

- Minor interaction between rib cage and top of half wall at 141 ms.
- Head slides between left leg and half wall at.
- Head detaches due to fatigue of rubber neck element.

A12022 – Hybrid II, 45°, Configuration 2 (body-centered lap belt plus conventional lap belt, no armrest)

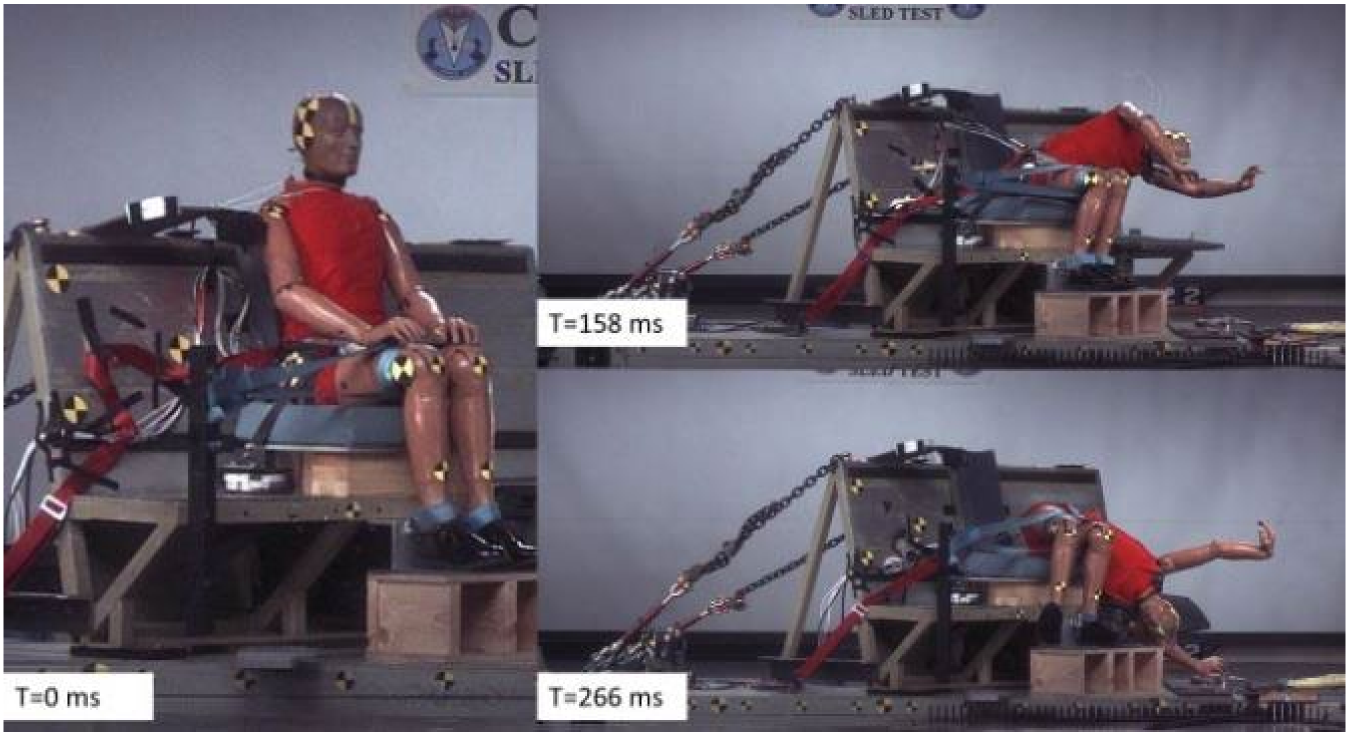

Figure 20: A12022

- Lap belt tears at 158 ms (Figure 18).
- Upper body flails past seat pan, and the pelvis begins to slide off the seat pan.

Figure 21: Lap Belt Tear

A12023 – Hybrid II, 45°, Configuration 2 (body-centered lap belt plus conventional lap belt, no armrest)

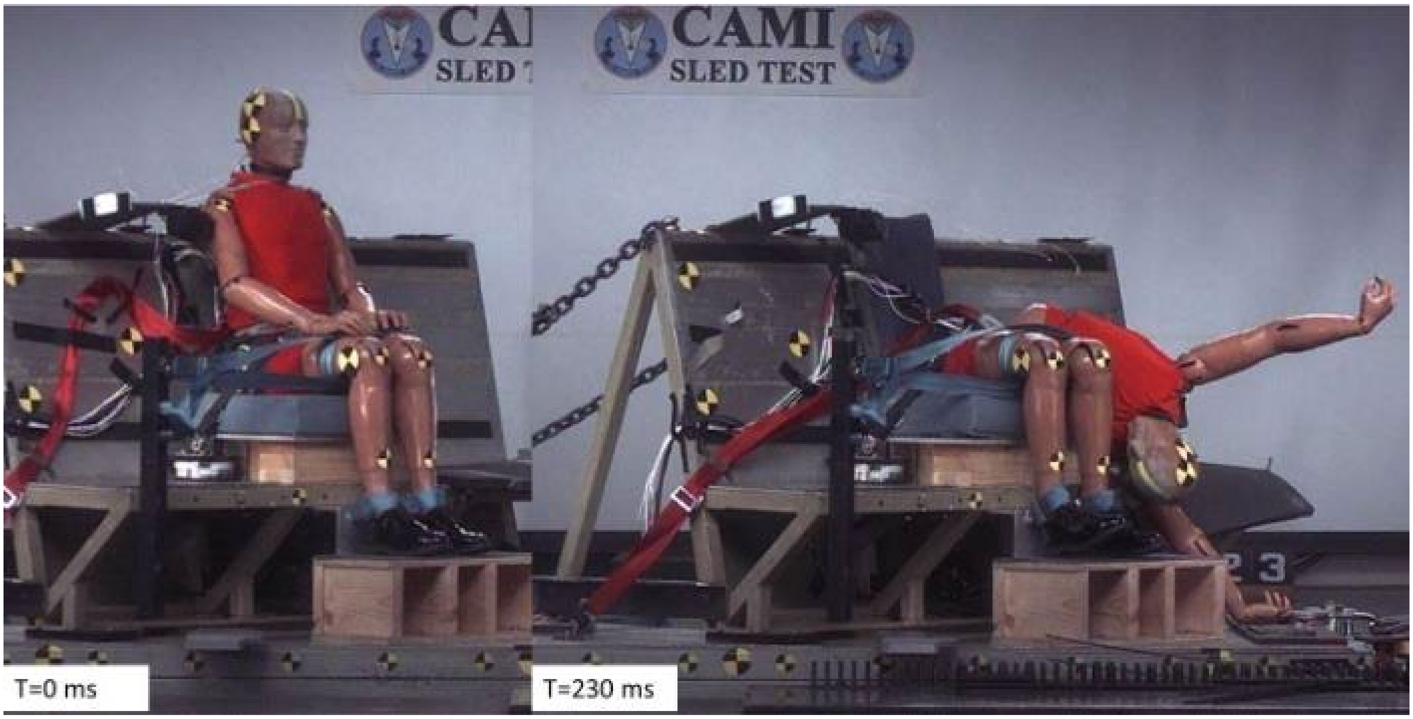

Figure 22: A12023

- Upper body flails past seat pan; wrist hits floor at 230 ms.

A12024 – FAA Hybrid III, 45°, Configuration 2 (body-centered lap belt plus conventional lap belt, no armrest)

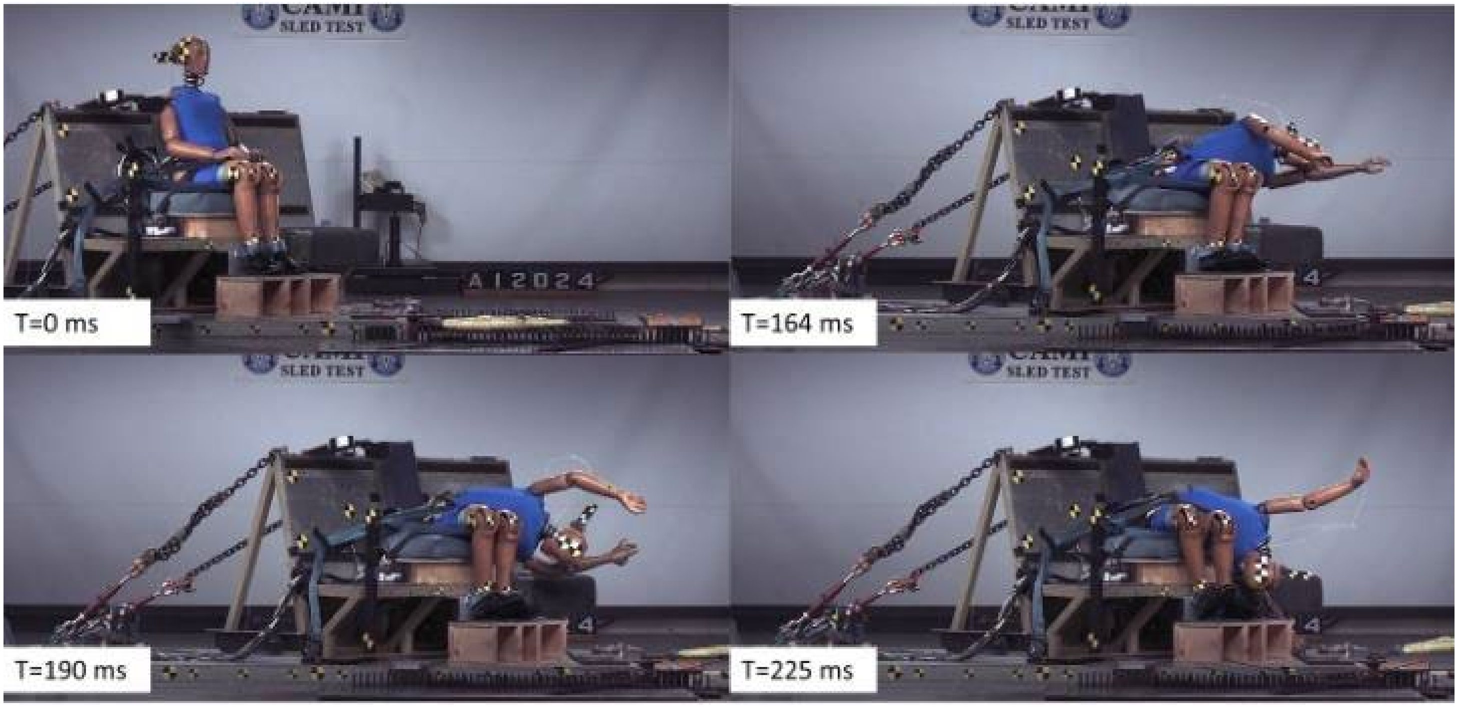

Figure 23: A12024

- ATD head hits left arm at 164 ms.
- Head flails beyond seat pan at 190 ms, but pelvis is retained.
- Wrist hits floor at 225 ms.

A12025 – FAA Hybrid III, 45°, Configuration 1 (body-centered lap belt plus conventional lap belt, with armrest)

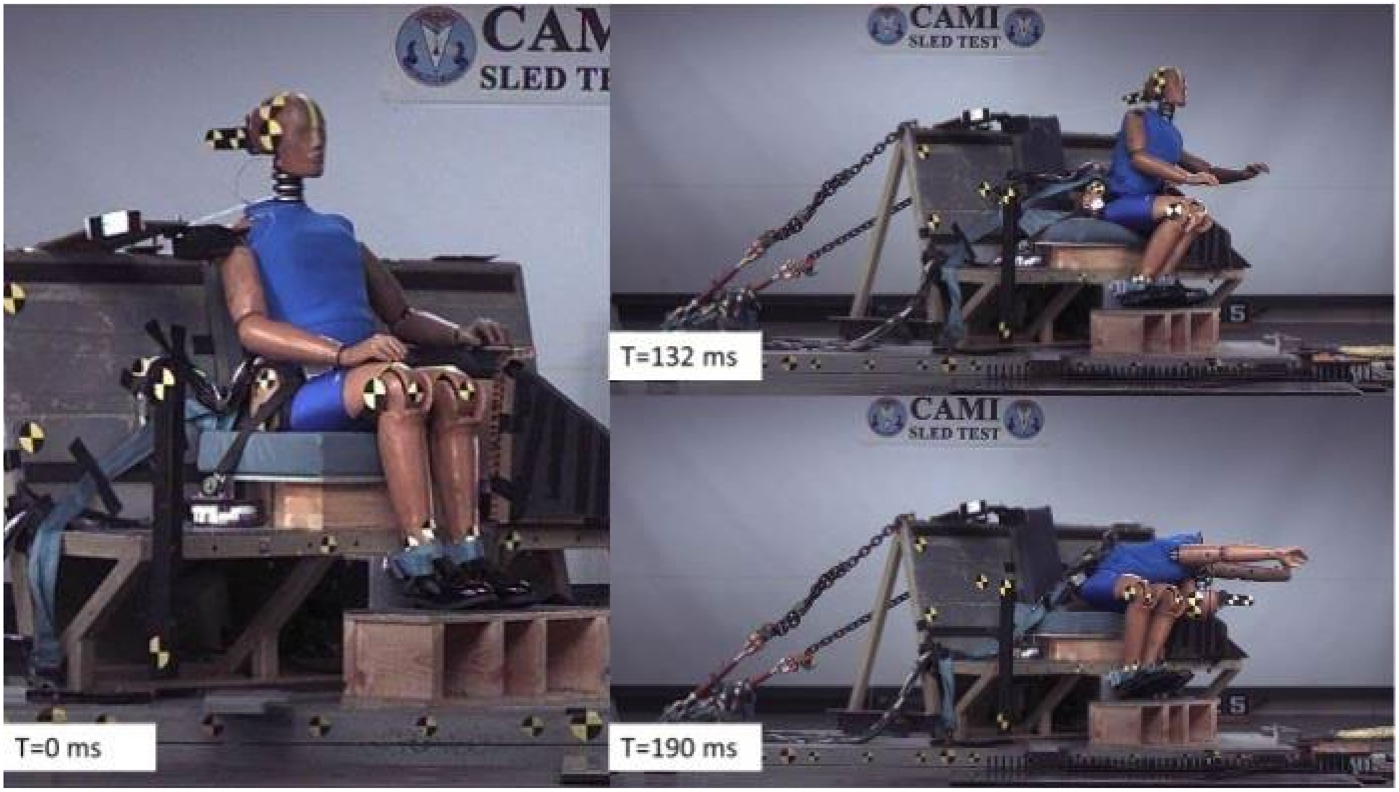

Figure 24: A12025

- Minor rib cage interaction with half wall at 132 ms.
- Head passes between left knee and half wall but does not have a significant. Impact with any seat structure at 190 ms.

A12026 – FAA Hybrid III, 30°, Configuration 1 (body-centered lap belt plus conventional lap belt, with armrest)

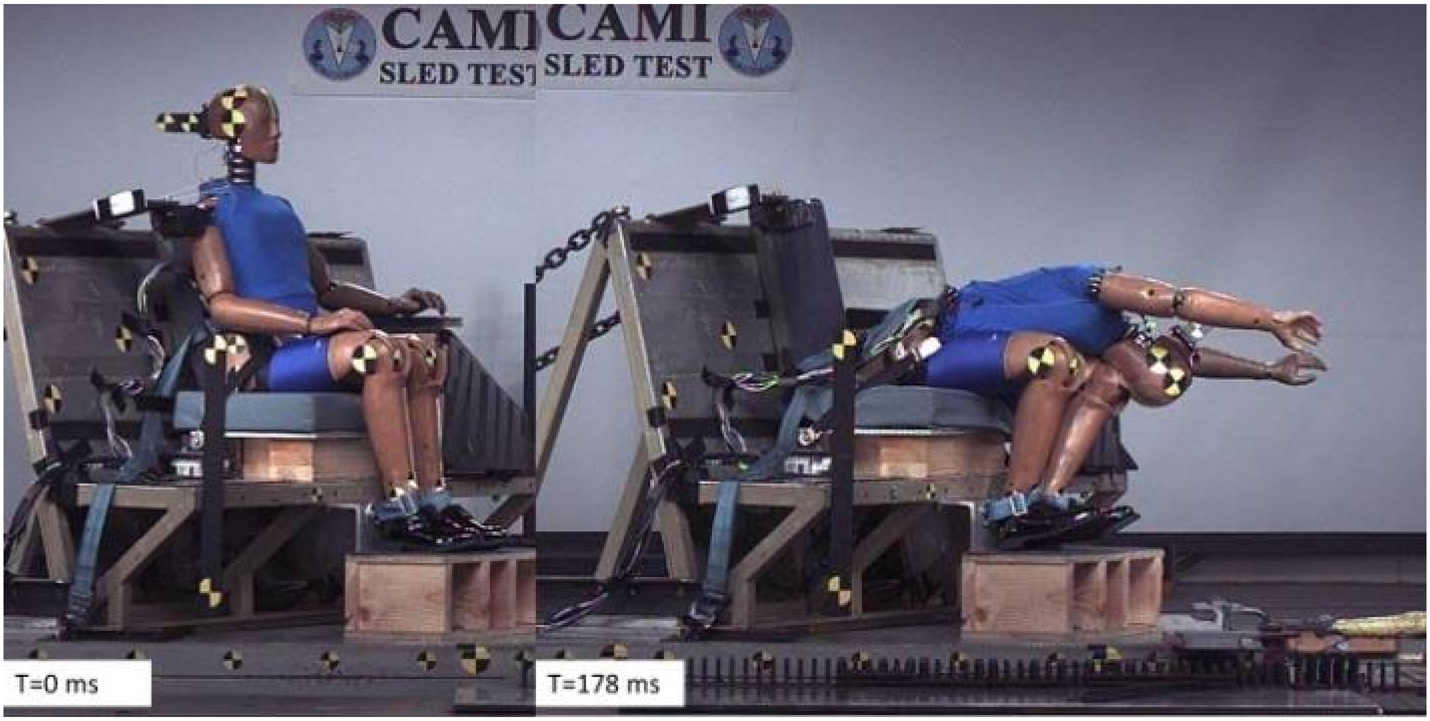

Figure 25: A12026

Figure 26: Rib Cage Wall Interaction Witness Marks

- Significant head strike on knee at 178 ms.
- Minor rib cage contact with front of wall (Figure 24).

A12027 – FAA Hybrid III, 30°, Configuration 2 (body-centered lap belt plus conventional lap belt, no armrest)

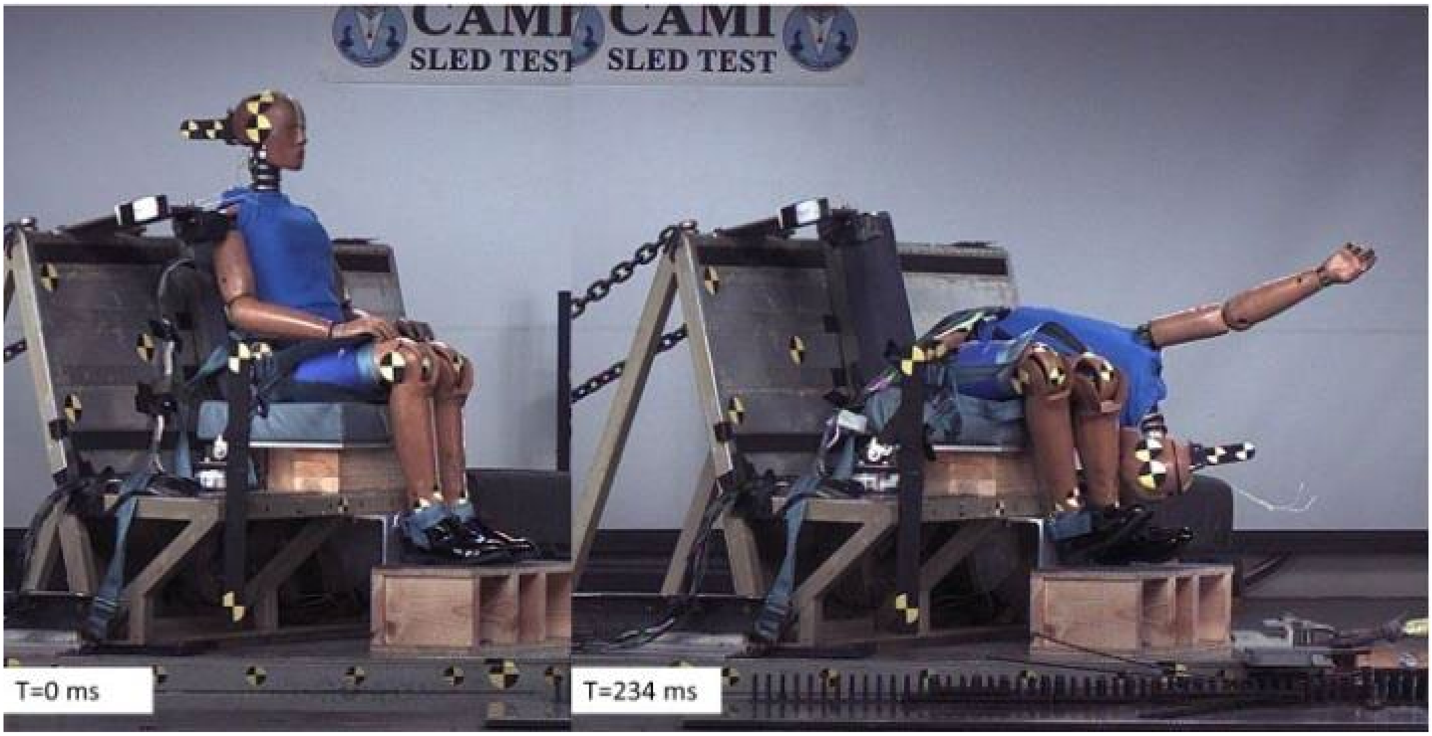

Figure 27: A12027

- Flail past seat pan; wrist hits floor.

A16034 and A16035– FAA Hybrid III, 45°, Configuration 1 (body-centered lap belt plus conventional lap belt and shoulder belt, with armrest)

Figure 28: A16034

- Rib cage contact with half wall at 135 ms.

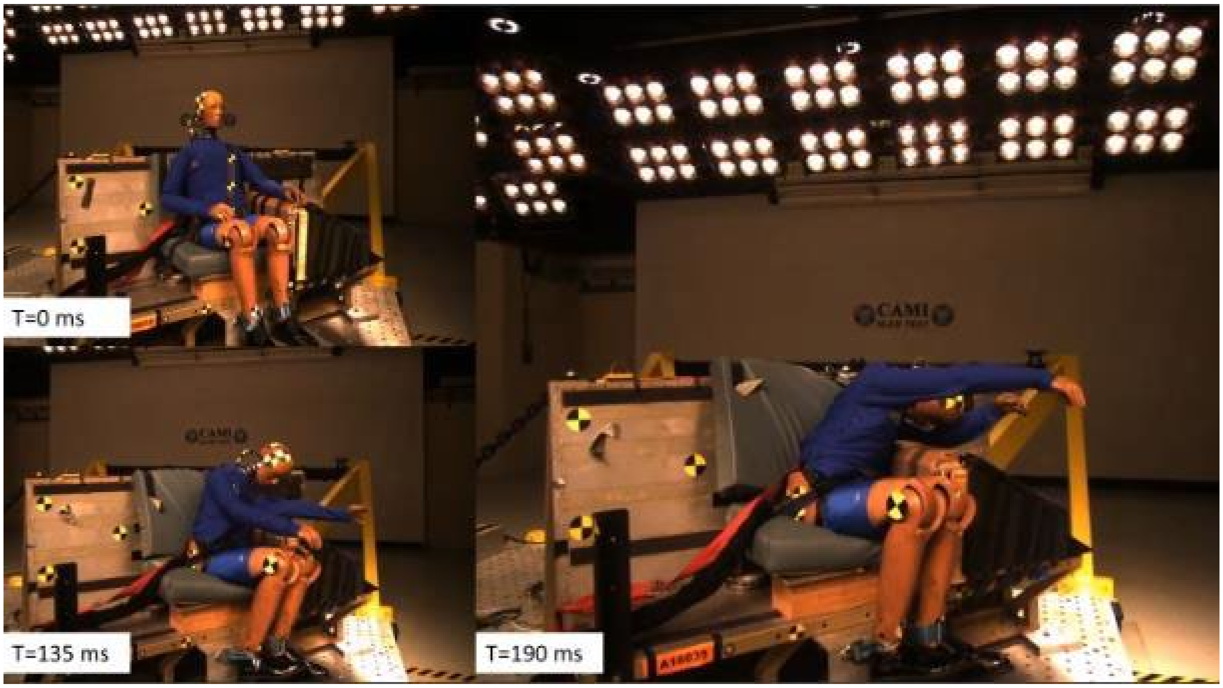

Figure 29: A16035

- Max flail at 190 ms.

A16036 and A16037 – FAA Hybrid III, 45°and 30°, Configuration 2 (body-centered lap belt plus conventional lap belt and shoulder belt, no armrest)

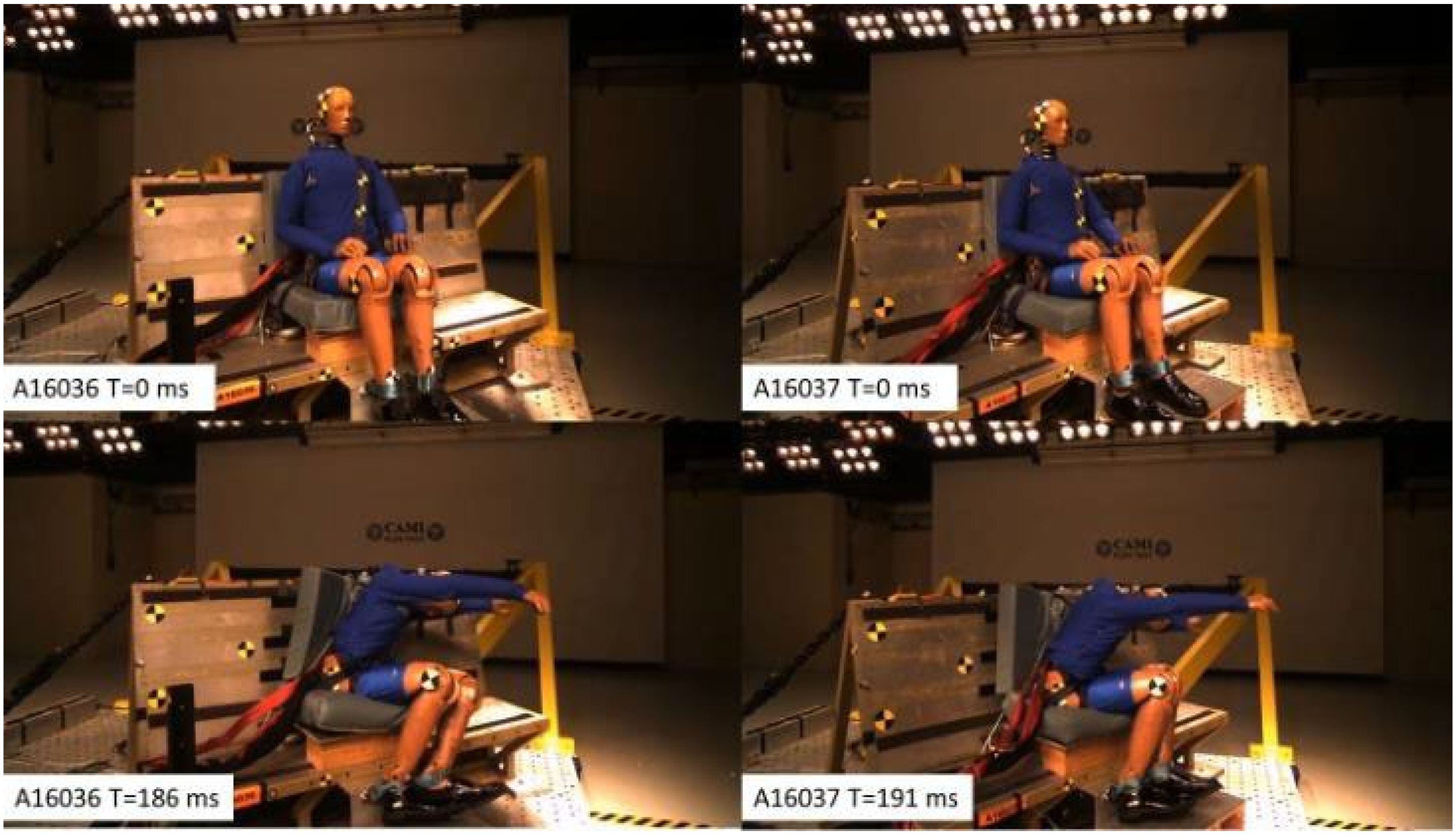

Figure 30: A16036 and A16037

- The three-point restraint has reduced max flail vs. lap belt-only.

A16038 and A16039 – FAA Hybrid III, 30°, Configuration 1 (body-centered lap belt plus conventional lap belt and shoulder belt, with armrest)

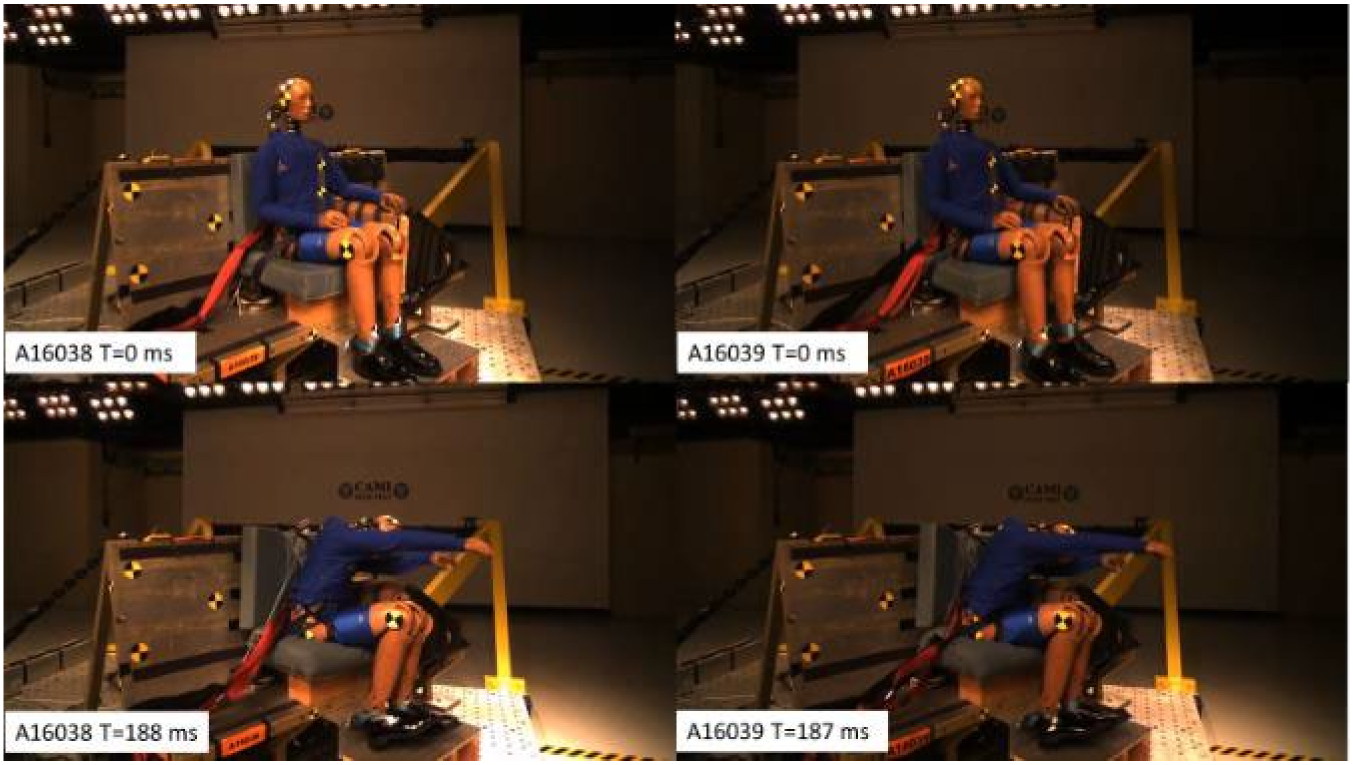

Figure 31: A16038 And A16039

Figure 32: A16038 Knee Strike Witness Mark

Figure 33: A16039 Knee Strike Witness Mark

- Slight thigh contact but no torso contact (Figure 30 and Figure 31).
- Max flail at 187 and 188 ms.

A23051 – FAA Hybrid III, 45°, Configuration 1 (body-centered lap belt plus lap belt inflatable restraint, with armrest)

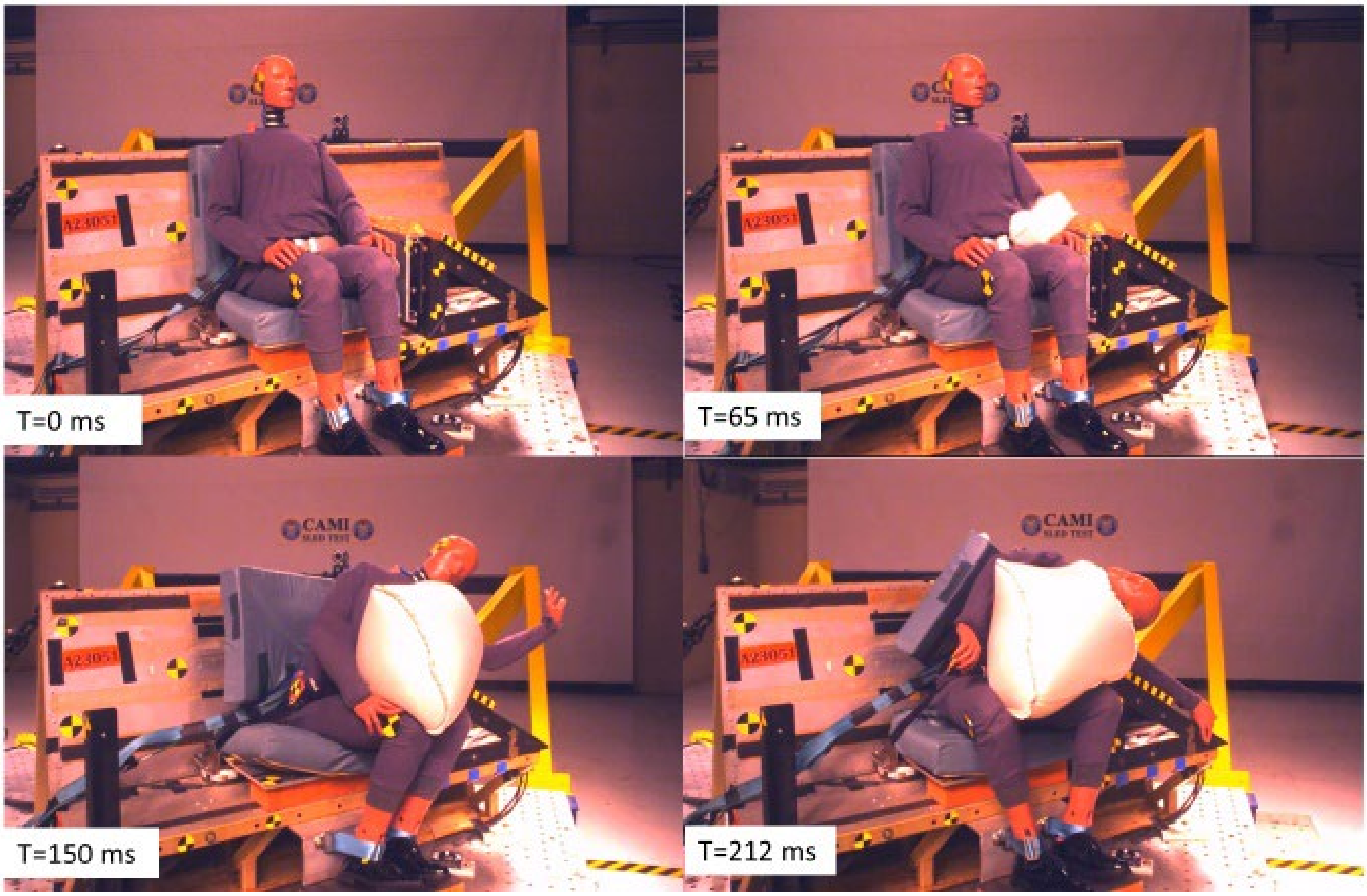

Figure 34: A23051

- **Setup Notes**: Left arm on left leg, no cardboard on wall, basic cushions, buckle attachment centered on ATD (buckle load bar behind centerline).
- Airbag deploys at T = 65 ms.
- Torso slides behind airbag, blocking view of potential torso to wall contact at 150 ms.
- Head twists so ATD's head is looking toward ceiling over right shoulder at 212 ms.
- Airbag blocking view of torso. Head twist about z-axis may exceed 105° limit; however, the camera coverage is insufficient to confirm. Integrating the head angular rate sensor provides an estimated angle for max twist of 77°.

A23052 – FAA Hybrid III, 45°, Configuration 1 (body-centered lap belt plus lap belt inflatable restraint, with armrest)

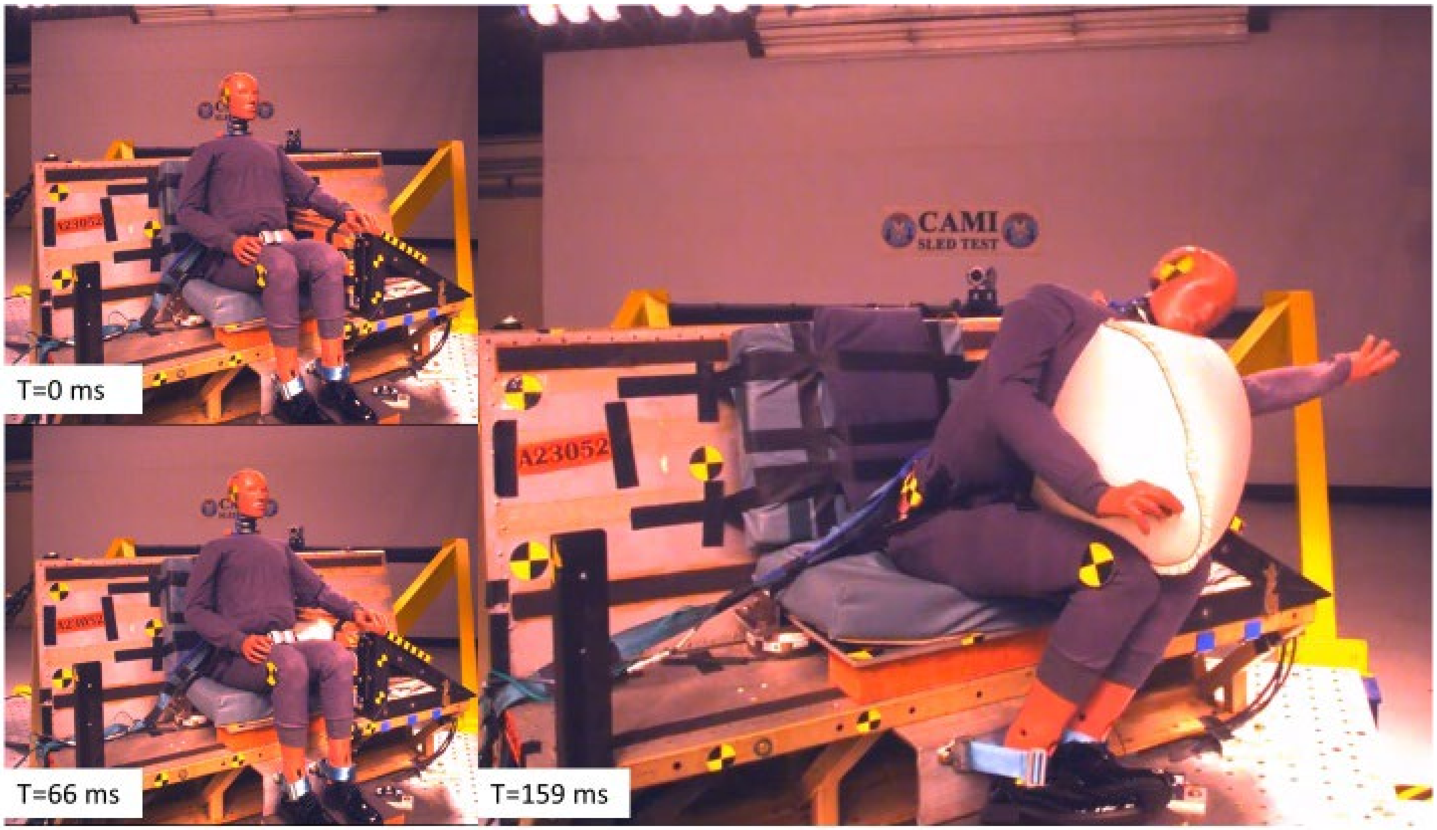

Figure 35: A23052

- **Setup Notes**: Left arm on armrest; added cardboard; shim to move ATD forward to align buckle load bar with seat centerline.
- Airbag deploys at T = 66 ms.
- ATD slides behind airbag less than in previous test.
- Airbag pushes left arm out of the way.

A23056 – FAA Hybrid III, 45°, Configuration 1 (body-centered lap belt plus lap belt inflatable restraint, with armrest)

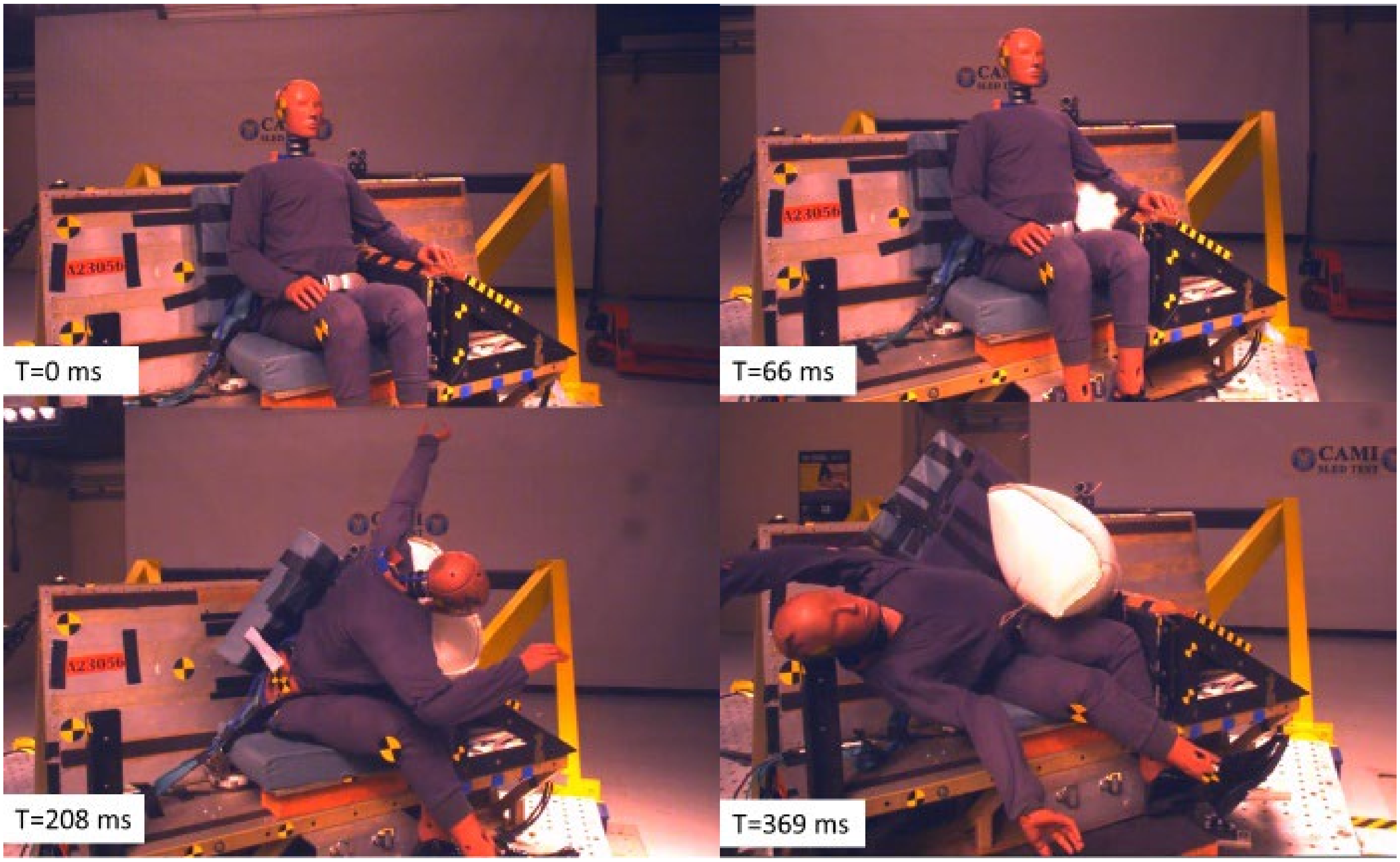

Figure 36: A23056

- **Setup Notes:** Left arm on armrest; black foam on wall; ATD closer to wall (2-3 in.); legs free to flail.
- Airbag deploys at T = 66 ms.
- Initial chest-to-airbag contact stops forward motion.
- ATD rotates counterclockwise, which allows significant flail on rebound.
- Pelvis does not translate off seat place.
- Head contact with metal post (test artifact, not representative of a realistic aircraft installation).

A23057 – FAA Hybrid III, 45°, Configuration 1 (body-centered lap belt plus lap belt inflatable restraint, with armrest)

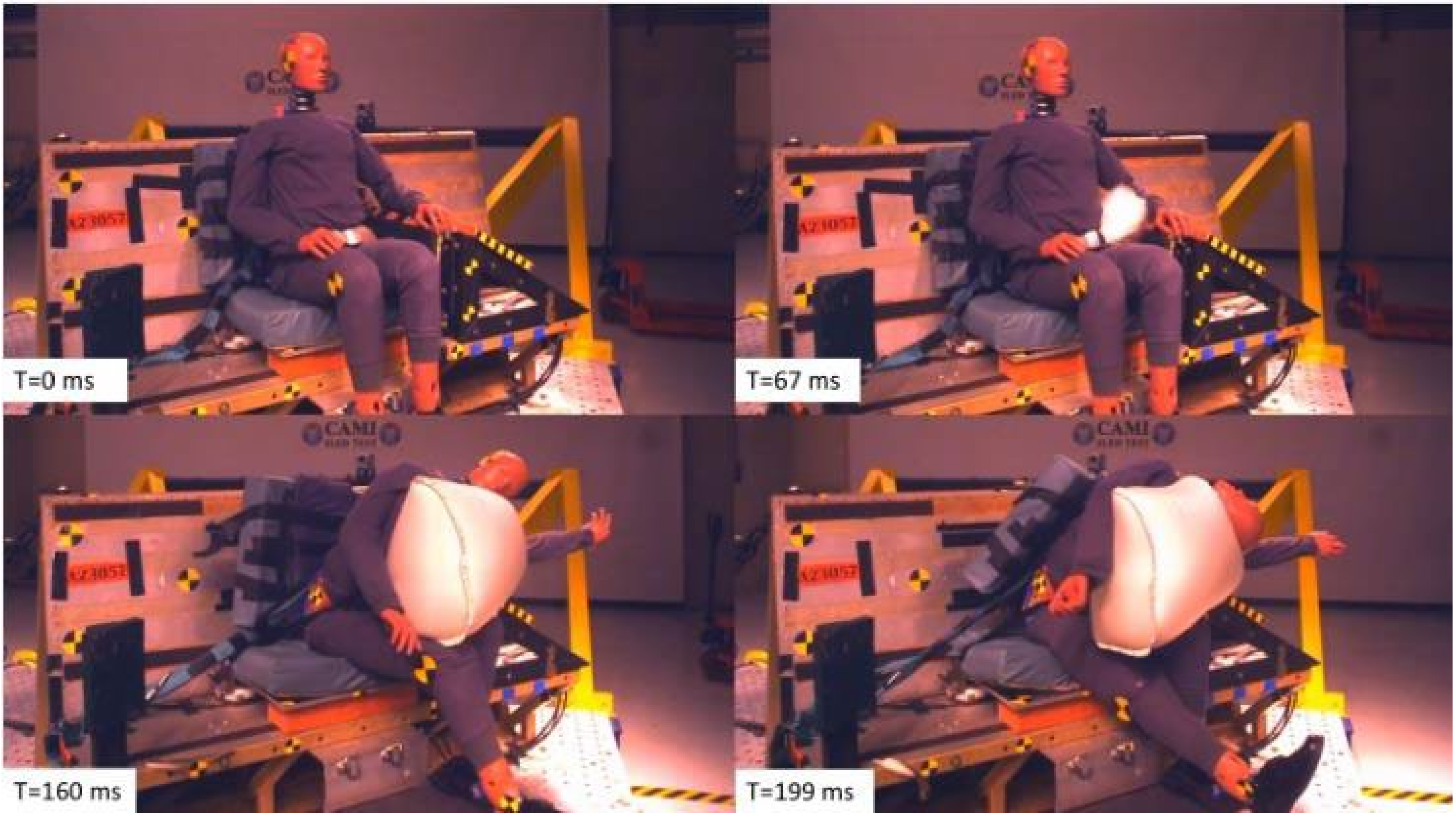

Figure 37: A23057

- **Setup Notes**: Left arm on armrest; black foam on wall; ATD closer to wall (2-3 in.); legs free to flail.
- Airbag deploys at T = 66 ms.
- Torso slides behind airbag, blocking view; similar to A23051.
- Head twists such that ATD is looking over right shoulder.
- Airbag blocking view of torso. Head twist about z-axis may exceed 105° limit; however, the camera coverage is insufficient to confirm. Integrating the head angular rate sensor provides an estimated angle for max twist of 89°.

APPENDIX D: Data Management Plan

Dataset and Contact Information

Title: Injury Criteria for Obliquely Oriented Seats

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https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/aam/cami/

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Persistent link: https://doi.org/10.21949/1529643

Recommended Citation: U.S. DOT, FAA Administration. (2024). Injury Criteria for Obliquely Oriented Seats [datasets]. https://doi.org/10.21949/1529662

Project Abstract

This project will evaluate the unique occupant kinematics and loading that could occur in impacts involving oblique seat installations. The questions involve identifying any loading conditions that cannot be adequately assessed using existing forward or lateral injury criteria and determining the injury mechanisms and human impact tolerance levels and methods of predicting occupant injuries in obliquely facing seats during a survivable crash.

Project start date: 03-16-2013

Project end date: 03-29-2024

Data Description

This dataset contains sled test data of anthropomorphic test devices seated in a rigid seat installed obliquely to the impact vector. This data is created by physical experiments. Sensors include load cells and accelerometers. Data also includes video from high-speed cameras and photos from still cameras. The tests were conducted from 2013 to 2023. No existing data were used for this test series.

It is anticipated that aircraft seat manufacturers and test laboratories will benefit from access to this data as they design and test real aircraft seats and restraints. This dataset will also provide a public record to support potential rulemaking.

Roles & Responsibilities

The FAA Aerospace Medical Research Division (see *Contact Information*) is responsible for generating the data and is also responsible for managing the data initially. This division is also responsible for managing the internal project management processes to ensure adherence to the published data management plan (DMP). This process requires management review and sign-off at project start and close-out.

This dataset is hosted by the NHTSA in the biomechanics test database at:

https://www.nhtsa.gov/research-data/research-testing-databases#/biomechanics

Standards Used

The dataset complies with the NHTSA Test Reference Guide available at https://www.nhtsa.gov/databases-and-software/entree-windows. The data files collected are saved in common file formats, including ascii text, .xls, .jpg, .avi, and .mp4. The file formats can be opened using commonly available software such as text editors, picture viewers, and video viewers. .xls files can be opened with Microsoft Excel or freely available software, such as OpenRefine.

Access Policies

These data files are in the public domain and can be shared without restriction. The data files contain no sensitive information.

Sensitive Data Policies

The data files contain no sensitive information.

Sharing Policies

These data are managed by the NHTSA. The data are in the public domain and may be re-used without restriction. Citation of the data is appreciated. Please use the following recommended citation: US DOT, FAA. (2024). Injury Criteria for Obliquely Oriented Seats [datasets]. https://doi.org/10.21949/1529662.

Archiving and Preservation Plans

The dataset will be archived in the NHTSA Biomechanics Test Database at: https://www.nhtsa.gov/research-data/research-testing-databases#/biomechanics. Prior to archiving, the data are stored on the secured FAA networks and drives, which are backed up nightly. The US DOT systems are secured from outside users and backed up daily. The NHTSA

Crash Test Database (which includes Vehicle, Biomechanics, and Component databases) is stored in the Amazon Aurora PostgreSQL database. The database is hosted in the DOT managed Amazon Web Services (AWS) cloud environment. Automated full database backups are taken daily, leveraging AWS relational database service backups. The retention period for the backups is 14 days. The database is secure and only accessible to selected DOT users while only on the DOT network.

The dataset will be retained in perpetuity.

FAA staff will mint persistent Digital Object Identifiers (DOIs) for each dataset stored in the Biomechanics Test Database. These DOIs will be associated with dataset documentation as soon as they become available for use.

The DOIs associated with this dataset include: https://doi.org/10.21949/1529662

The assigned DOI resolves to the repository landing page for the "Injury Criteria for Obliquely Oriented Seats" dataset so that users may locate associated metadata and supporting files.

The Biomechanics Test Database meets all the criteria outlined on the "Guidelines for Evaluating Repositories for Conformance with the DOT Public Access Plan" page: https://ntl.bts.gov/publicaccess/evaluatingrepositories.html

Applicable Laws and Policies

This data management plan was created to meet the requirements enumerated in the US DOT's 'Plan to Increase Public Access to the Results of Federally-Funded Scientific Research' Version 1.1 (https://doi.org/10.21949/1520559) and guidelines suggested by the DOT Public Access website (https://doi.org/10.21949/1503647), in effect and current as of March 03, 2024.