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Effect of Passenger Position on Crash Injury Risk in Transport-Category Aircraft

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Revised 11/19/2015 (see erratum page, inside cover)

Final Report

NOTICE

ERRATA

This report, as originally published, contained errors, all of which have been corrected and eliminated from the revised report. The authors regret the oversight. Below is a list of corrections.

1. In the original version of this report, Tables 3,4,5,and 6 contained a typographical error. The Criteria Limit for the Negative Right Femur My (in-lb) and the Negative Left Femur My (in-lb) should have been 2655, not 2265.
2. Page A1: Third bullet, last sentence, change “exceeded the limit” to “was relatively high.”
3. Page A2: Third bullet, last sentence, change “exceeded the limit” to “was relatively high.”
4. Page A3: Third bullet, second sentence, change “exceeded the limit” to “was relatively high.”
5. Page A6: Third bullet, last sentence, change “which exceeded the limit” to “that was relatively high.”
6. Page A7: Third bullet, last sentence, change “both of which were greater than the limit” ” to “The TI exceeded the limit and the Y-Axis moment was relatively high.”
7. Page A8: Third bullet, next to last sentence, change “which exceeded the limit” to “that was relatively high.”
8. Page A9: Third bullet, 4th sentence, change “Y-Axis” to “positive Y-Axis” and change “above the limit” to “relatively high.”
9. Page A10: Third bullet, next to last sentence, change “exceeded the limit” to “was relatively high.”
10. Page A11: Third bullet, last sentence, change “exceeded the limit” to “was relatively high.”
11. Page A13: Third bullet, last sentence, change “below the criteria limit” to “relatively low.”
12. Page A14: Third bullet, last sentence, change “below the limit” to “relatively low.”
13. Page A15: Third bullet, last sentence, change “below the criteria limit” to “relatively low.”
14. Page A16: Third bullet, last sentence, change “well below the criteria limit” to “relatively low.”
15. Page A17: Third bullet, last sentence, change “well below the limit” to “relatively low.”

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This work is to support the Fire & Cabin Safety Technical Community Representative Group Project: Prevention of Injuries That Impeded Egress, Project 2011-05/2012-06.

16. Abstract

In the event of an accident, one action that an occupant can take to contribute to their survival is to assume an appropriate “brace-for-impact” position. This is an action in which a person pre-positions their body against whatever they are most likely to be thrown against, significantly reducing injuries sustained. Occupants in the US Airways flight 1549 sustained shoulder injuries that they attributed to the brace position; therefore, the NTSB recommended that the position be re-evaluated.

The Federal Aviation Administration investigated this by conducting a series of 17 sled impact tests, 15 with two rows of transport category forward facing passenger seats and two with a bulkhead configured to represent the types of seats currently in use. Head, neck, upper and lower leg injury risks were evaluated using an advanced test dummy and injury criteria from current FAA regulations, Federal Motor Vehicle Safety Standards, European auto safety regulations, and applicable research findings.

The current brace position, head against the seat back with hands on top of the seat back, was only successful in reducing head injury risk for locked-out seat backs. However, for full break-over and energy absorbing seat backs, this position increased the severity of the head impact. There was, however, no evidence that the anthropomorphic test device interaction with any of the seatback types resulted in hyper-extension of the shoulder joint. Significant lower leg injury potential was not observed in this study, and therefore adopting lower leg injury criteria at this time does not appear to be a benefit. Even in the worst case test condition, the femur axial compressive force was below the regulatory limit, indicating that the femur compression criteria currently cited in FAA regulations is not likely to be exceeded in passenger seat dynamic qualification tests. To reduce detrimental interaction between the occupant’s arms and the seatback, the current position was modified by placing the hands down by the lower legs instead of on the seat back. This alternate position was successful in significantly reducing head and neck injury risk for all of the seat back types evaluated. This research has led to the determination that as seat technology has evolved, the most effective brace position has as well, and the current positions recommended in AC 121-24B may need some adjustment to provide an equivalent level of safety for all passenger seat back types.

17. Key Words
Brace for Impact, Passenger Position, Leg Injury Criteria, Neck Injury Criteria, Head Injury Criteria, Femur Compression, Femur Bending

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BACKGROUND

It is a common misconception that if an airplane crashes, all occupants will likely perish. While in reality, according to the National Transportation Safety Board (NTSB), from 1983 to 2000, 96% of occupants survived [1]. One action that occupants can take to contribute to their survival is to assume an appropriate "brace for impact" position. Descriptions of this type of position have been in passenger briefings for decades. The goal is to reduce the risk of injuries from a secondary impact, with the primary impact being between the airplane and the ground, and the secondary impact being between the occupants and the inside of the airplane. "Brace for impact" is an action in which occupants pre-positions their body against whatever they are most likely to impact, and thereby significantly reducing impact forces and the resulting injuries.

While the positive benefits of bracing seem somewhat obvious, public interest in the purpose and effectiveness of the brace position persists. The position that will protect the maximum range of occupants has long been one of the most frequently asked questions of crash safety researchers [2]. During the 1980s, brace position effectiveness was investigated using the then-new dynamic impact test techniques and the recommendations were adjusted to reflect the findings. By the late 1980s, the effort to develop crashworthy seats resulted in a large amount of data concerning the flail response of occupants seated in a variety of configurations. These data were used to develop specific brace recommendations for many potential seating configurations [3].

Many of these recommendations formed the basis of the brace positions cited in Advisory Circular (AC) 121-24B Appendix 4 (Fig.1). Subsequent crash investigations have resulted in new recommendations concerning brace positions [4]. These new recommendations, as well as Federal Aviation Administration (FAA) guidance and previous research findings, were used as the basis of the brace recommendations contained in SAE Aerospace Recommended Practice 4771 [5].

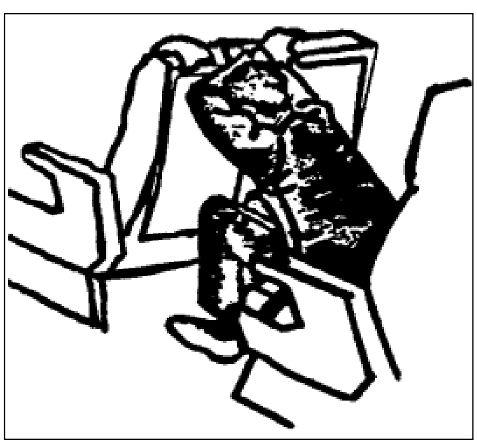

Figure 1. Passenger Brace Positions in AC 121-24B

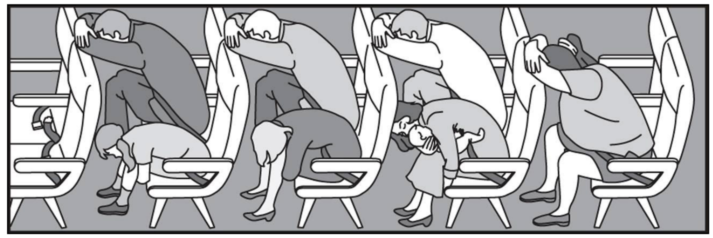

Figure 2. Passenger Brace Position Shown in the US Airways Safety Information Card

On January 15, 2009, US Airways flight 1549, an Airbus A320, ditched in the Hudson River approximately 8.5 miles from LaGuardia Airport. Four passengers sustained serious injuries attributed directly to the impact; two passengers sustained similar shoulder injuries. Both described assuming similar "brace for impact" positions in which they placed their arms on the seat back in front of them and leaned over placing their head on the back of their hands. This is a similar position to the one depicted in the US Airways safety card (Fig. 2).

As a result of this accident, the NTSB issued several safety recommendations to the FAA, one of which stated, "Conduct research to determine the most beneficial passenger brace position in airplanes with non-break over seats installed. If the research deems it necessary, issue new guidance material on passenger brace positions" [6]. Injuries sustained by occupants, passenger confusion as to the proper brace position, and newer technology used in seats brought to the forefront a need to review brace position effectiveness to determine if the recommended positions were still appropriate for the widest range of occupants. Some recent research data were available but did not specifically address the effect of the seat back folding over [7].

While complying with the NTSB call to evaluate the "most beneficial passenger brace position in airplanes with non-break over seats installed," the Civil Aerospace Medical Institute (CAMI) completed a more thorough project that evaluated passenger brace position for the three most common types of seat-hinge mechanisms: locked-out (also known as non-break over), full break-over, and energy absorbing break-over. This evaluation included a comprehensive assessment of occupant injury risk, comprising current regulatory criteria and additional criteria that may be informative, and also is a component of a FAA Aviation Safety research task to study injuries that could impede egress after a crash. Head and leg injuries are considered to have the greatest effect on the ability to self-evacuate, and we decided to evaluate leg injury risks simultaneously with the brace position research, since the necessary test configurations were similar for both projects.

METHODS

We investigated brace positions by conducting a series of sled impact tests with two rows of forward-facing passenger seats, and a bulkhead wall configured to represent the types of seats in use. The factors investigated were: seat back type, occupant position (braced and un-braced), the spacing between rows, occupant stature, and interaction with interior walls. Leg injury risk was investigated during the same series of tests. The factors investigated were leg initial position, the spacing between rows, occupant stature, contact surface stiffness, and interaction with the floor. Seventeen tests were completed using the deceleration sled at CAMI with the 16 G, 44 feet per second impact severity defined in the Code of Federal Regulations (CFR) 14 CFR Part 25.562. Figure 3 shows a typical deceleration pulse for this series. To reduce test-to-test variability and enable direct comparison, no yaw or floor deformation was included in the experimental design.

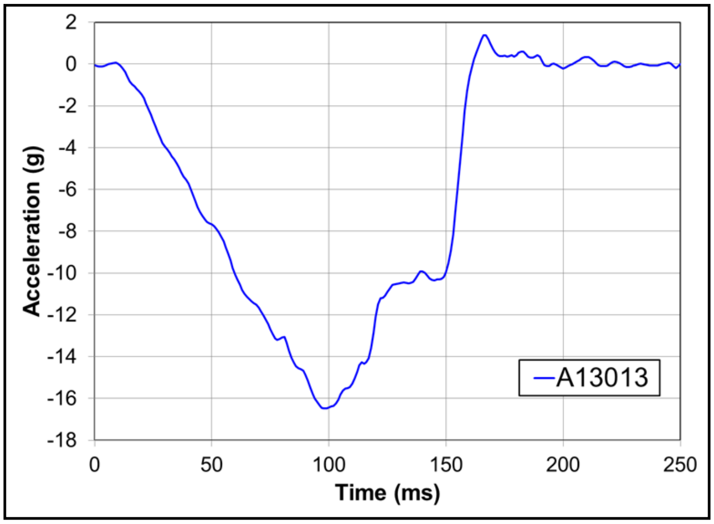

Figure 3 – Typical Sled Deceleration Pulse

Test Device

The Anthropomorphic Test Device (ATD) used to assess injury was a fiftieth percentile male FAA Hybrid III. This ATD differs from the standard Hybrid III used in automotive testing because it has been modified to better emulate the more upright posture of an occupant in an airliner seat and provide kinematic and vertical response equivalent to the Hybrid II [8]. The Hybrid II or an equivalent (such as the FAA Hybrid III) is currently required for certification tests of aviation seats. The modification consists of several Hybrid II parts substituted into the structure, including the lumbar spine, abdominal insert, chest jacket, and upper leg bone (Fig. 4).

The FAA Hybrid III ATD was selected in part because of its capability to measure neck and lower leg loads. This ATD used for the study had load cells at both the upper and lower neck positions and instrumented lower legs installed. The instrumented lower legs have two 5-axis load cells, one in the upper and one in the lower part of the tibia, which records forces and moments.

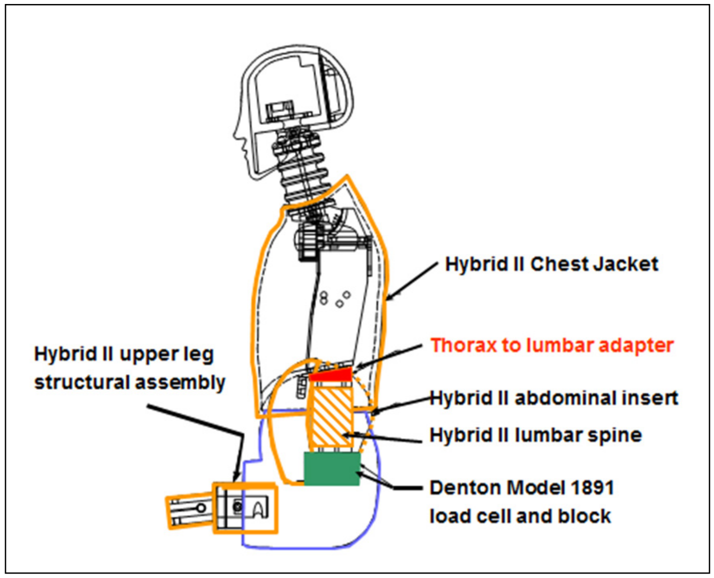

Figure 4. FAA Hybrid III, Orange-Outlined Parts are Hybrid II

Impact Surfaces

Three types of seat backs, in addition to a rigid wall and knee plate, were chosen for evaluation:

Locked-out seat back

A locked-out seat back, also referred to as non-break over, has a simple nut-and-bolt connection in the linkage that connects the seat back to the seat frame. When loaded by inertial forces or when struck from behind, the amount of forward flexion of the seat back is dependent on the strength and stiffness of the seat back structure only, as the nut-and-bolt connection does not permit rotation of the seat back frame. Significant loading by an occupant of the row behind usually results in some initial forward motion due to elastic deformation, followed by permanent deformation to the seat back structure. Seat backs of this type are primarily found in aircraft that are not required to meet the head impact protection requirements of § 25.562 (c) [9].

Full break-over seat back

A full break-over seat back is free to fold over about its hinge point, limited only by friction in the hinge joint and contact with the seat bottom or occupant of the seat. All passenger seat backs must resist folding when a force up to 25 lb is applied at the top of the seat back, as defined in AC 25-17A section 25.785 81.b paragraph d [10]. This is necessary so that seat backs can provide an effective hand-hold for passengers walking down the aisle. This resistance is typically provided by an adjustable friction mechanism in the hinge joint. To ensure consistent folding force during these tests, a shear pin was installed in the hinge linkage in lieu of a friction device. The pin was sized to shear when the force at the top of the seat back exceed 35 lb. This force accounts for in-service adjustment tolerance on the 25 lb minimum force. This type of seat back was common on older seat designs that are being replaced by newer ones and would only be found in aircraft that are not required to meet the head impact protection requirements of § 25.562 (c) [9].

Energy absorbing (EA) break-over seat back

An energy-absorbing break-over seat back is designed so that when the aft surface of the seat back is struck by the occupant behind it, the surface moves forward at a rate that limits the magnitude and duration of the occupant's head acceleration. This controlled motion is usually provided by a combination of local deformation of the seat back surface and overall stiffness provided by the folding action of the seat back about the hinge at its base. The local stiffness of the back depends on its construction (i.e., video screen, tray table, literature pocket) and can vary significantly. The overall stiffness of the seat back depends on the folding resistance of the hinge mechanism and the height of the impact point above the hinge. In general, the closer the impact point is to the hinge, the greater the overall stiffness due to the decreased leverage. The controlled motion provides head impact protection for occupants of transport category passenger seats equipped with lap belts.

The EA seat back used for this study controlled its forward-folding with a combination of friction washers and dual shear pins in the hinge mechanism. The shear pins are sized to limit the contact force produced when the head of the occupant strikes the seat back from behind. This allows the seat to absorb some of the occupant's energy prior to folding over. In this case, each pin would shear sequentially when a force of approximately 220 lb was applied horizontally at the top of the tray table, 19 in above the hinge point. During a crash, the first bolt shears due to inertial forces acting on the seat back. The second bolt then shears when the occupant comes into contact with the seat back. The resisting force provided by this energy-absorbing mechanism is considered typical for seat backs designed to limit head injury potential [11].

The seat back friction washers were adjusted to provide 35 lb of resistance to a force applied at the top of the seat tray table. This force corresponds to the maximum applied force permitted when retuning a seat back upright for evacuation clearance evaluation after a dynamic test, as stated in SAE Aerospace Standard (AS) 8049b paragraph 3.5.5 [12]. In-service seats are similarly adjusted to ensure compliance with this requirement. Once the friction washers were adjusted, the shear pins were installed into the hinge mechanism to complete the setup. This dual shear type of energy absorber has a stiffness that falls between the break-over seat back and locked-out seat back.

Seats utilizing EA seat backs are typically found in aircraft designed since 1988 that must meet 14 CFR 25.562, although they can be installed as replacements in other aircraft as well. Since FAA regulations require that seats meeting § 25.562 be installed in all newly manufactured transport aircraft operated in passenger carrying operations after October 27, 2009, EA seat backs will eventually be the prevalent seat back type in service as newer aircraft are added to the fleet.

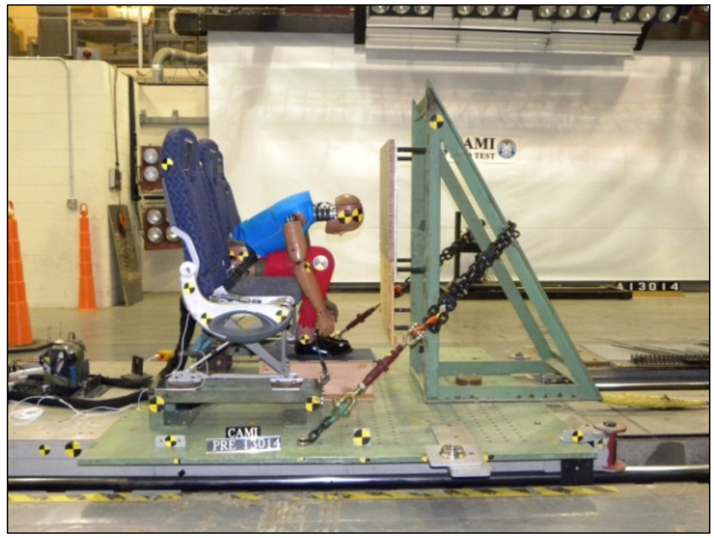

Figure 5. Rigid Wall with Honeycomb Panel

Figure 6. Knee Plate

Bulkhead

To evaluate a worst case axial neck loading, a nearly rigid wall was constructed to emulate a seat just aft of a bulkhead. The wall consisted of a 1-in thick fiberglass faced Nomex® honeycomb core panel of the type used in typical aircraft interior walls, which was rigidly supported by a 0.5-in aluminum plate (Fig. 5).

Solid knee plate

To determine the likely maximum worst case axial loading into the femur, a rigid plate was attached to the seat frame where the knee would contact (Fig. 6).

ATD positions

The ATD position was varied to assess the different injury risks for each scenario. Some of the tested positions were intended to emulate the currently recommended brace positions.

However, the actual positions varied somewhat from the guidance illustrations due to limitations of the ATD construction and articulation capability. For this study, the positions tested are defined in terms of torso, hand, and leg positions.

Torso positions

- Upright: The nominal seated position. This position is used for qualification tests.
- Braced: Leaned forward with the head touching the seat back. A cord over the back was necessary to maintain this initial position.
- Pike: Leaned all the way over until the neck was horizontal and the chest was touching the tops of the thighs. (Fig. 7) This position was used to assess the worst case axial loading in to the neck. To achieve this position, it was necessary to remove the abdominal insert from the ATD and hold the torso down with a frangible string over the back (designed to break immediately after the test began).

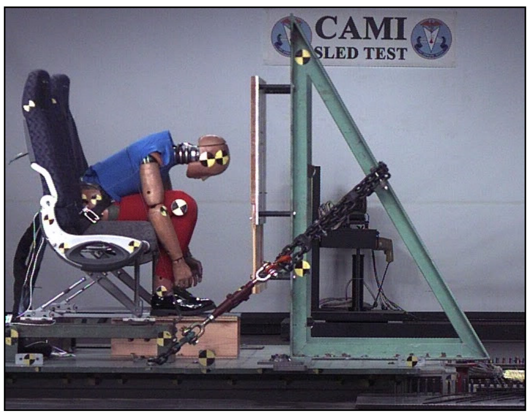

Figure 7. Pike Position Behind a Rigid Wall

Hand positions

- Top of thighs: the nominal position used for qualification tests
- Top of seat back: resting on seatback, taped lightly in place
- Back of head: hands placed on head and taped together to stay in position
- Side of legs: arms straight with hands just below knees

Leg positions

- Vertical: the nominal position used for qualification tests (Fig. 8)

Figure 8. Lower Leg "Vertical" Position

Figure 9. Lower Leg "Forward" Position

Figure 10. Lower Leg "Aft" Position

Figure 11. Unsupported Leg Position (No Floor)

- Forward: the feet placed as far forward as possible while remaining flat on the floor (Fig. 9)
- Aft: feet placed as far back as possible, but limited by contact with the baggage bar (Fig. 10) This position has been previously proposed as a means to reduce leg injury [4]
- Unsupported: no floor installed at that seat place. Intended to simulate a short stature occupant whose legs do not touch the floor, and thus will swing forward unimpeded from an initial vertical position (Fig. 11)

Seat Pitch

The seat pitch used for most of the tests was about 30.5 in, which reflects one of the narrowest pitches currently used by major US air carriers (Fig. 12). This was chosen as a near worst case for evaluating brace effectiveness, since at close pitch, a braced occupant would initially be more upright than at a longer pitch. This more upright position would allow occupants more space to generate differential velocity between their head and the seat back, resulting in higher injury risk. This close pitch was also considered worst case for leg impact since the chance of leg interaction with the seat in front was greater. Longer pitches were used to investigate specific leg and head injury risks. A wall was used for two tests and was placed at 35 in from the Seat Reference Point (SRP) of the launch seat (Fig. 13). Thirty-five in was chosen because that position is just beyond the nominal head strike zone defined in AC 25-17A section 25.785 81.b paragraph d [10] and is therefore a commonly used installation dimension.

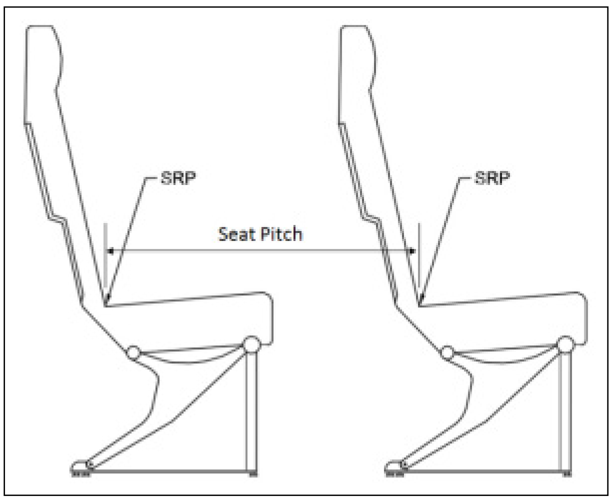

Figure 12. Seat to Seat Configuration

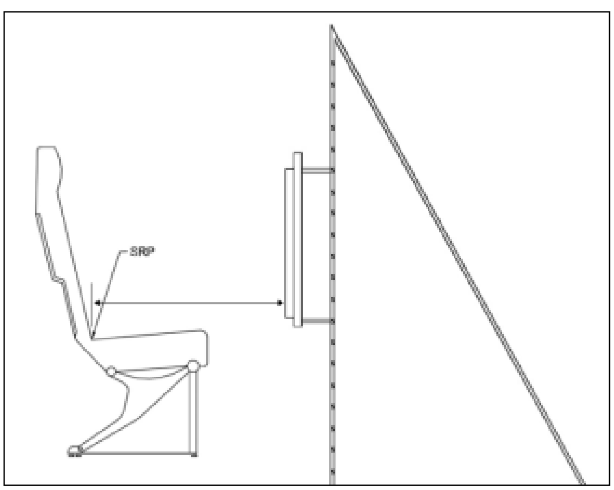

Figure 13. Seat to Wall Configuration

Instrumentation

Electronic instrumentation

ATDs were instrumented as shown in Tables 1a-c. For this project, lower leg injury potential was measured with two Denton-type lower legs recording both upper and lower tibia forces and moments. The tensions on both sides of the lap belt were measured between the pelvis of the ATD and the belt anchor with webbing transducers. The forces applied to the floor attachments of the target seat were also measured using 3-axis 10,000 lb load cells. The test data were gathered and filtered per the requirements of SAE J211/1 [13]. The sign convention of the recorded signals conformed to SAE J1733 [14].

Video coverage

High-speed (1,000 frames per second), high-resolution (1024 x 512 pixels) color video was captured from both side directions by Phantom cameras (Vision Research), aimed perpendicular to the sled travel. Rigidly mounted targets were affixed to the ATD's knee and ankle with the center of the target representing the center of the joint to facilitate motion analysis. Targets were also placed on the hip point, head center of gravity, seat cross-tubes, and seat backs. The position and velocity of selected targeted points were derived from the videos using procedures complying with the requirements of SAE J211/2 [15].

Table 1a. Instrumentation Summary

Ch. Num	Description	Filter Class	Range	Units	Rack
1	Sled X Acceleration	60	25	G	1
2	Left Belt Strap	60	3000	lb	1
3	Head Ax	1000	2000	G	1
4	Head Ay	1000	2000	G	1
5	Head Az	1000	2000	G	1
6	Head Rx ARS18K	180	18000	Deg/Sec	1
7	Head Ry ARS18K	180	18000	Deg/Sec	1
8	Head Rz ARS18K	180	18000	Deg/Sec	1
9	Upper Neck Fx	600	2000	lb	1
10	Upper Neck Fy	600	2000	lb	1
11	Upper Neck Fz	600	3000	lb	1
12	Upper Neck Mx	600	2500	in-lb	1
13	Upper Neck My	600	2500	in-lb	1
14	Upper Neck Mz	600	2500	in-lb	1
15	Lower Neck Fx	600	3000	lb	1
16	Lower Neck Fy	600	3000	lb	1
17	Lower Neck Fz	600	3000	lb	1
18	Lower Neck Mx	600	4000	in-lb	1
19	Lower Neck My	600	4000	in-lb	1
20	Lower Neck Mz	600	4000	in-lb	1
21	Thorax Ax	600	2000	G	1
22	Thorax Ay	600	2000	G	1
23	Thorax Az	600	2000	G	1
24	Thorax Rx ARS12K	180	12000	Deg/Sec	1
25	Thorax Ry ARS12K	180	12000	Deg/Sec	1
26	Thorax Rz ARS12K	180	12000	Deg/Sec	1
27	Thoracic Fx	600	3000	lb	1
28	Thoracic Fy	600	3000	lb	1
29	Thoracic Fz	600	4500	lb	1
30	Thoracic Mx	600	5000	in-lb	1

Table 1b. Instrumentation Summary (continued)

Ch. Num	Description	Filter Class	Range	Units	Rack
31	Thoracic My	600	8000	in-lb	1
32	Pelvis Ax	600	500	G	1
33	Pelvis Ay	600	500	G	1
34	Pelvis Az	600	500	G	1
35	Pelvis Rx ARS12K	180	12000	Deg/Sec	1
36	Pelvis Ry ARS12K	180	12000	Deg/Sec	1
37	Pelvis Rz ARS12K	180	12000	Deg/Sec	1
38	Lumbar Fx	600	3000	lb	1
39	Lumbar Fy	600	3000	lb	1
40	Lumbar Fz	600	5000	lb	1
41	Lumbar Mx	600	10000	in-lb	1
42	Lumbar My	600	10000	in-lb	1
43	Lumbar Mz	600	4000	in-lb	1
44	Right Femur Fx	600	3000	lb	1
45	Right Femur Fy	600	3000	lb	1
46	Right Femur Fz	600	5000	lb	1
47	Right Femur Mx	600	3000	in-lb	1
48	Right Femur My	600	3000	in-lb	1
49	Right Femur Mz	600	4000	in-lb	1
50	Right Upper Tibia Fx	600	2500.1	lb	1
51	Right Upper Tibia Fy	600	2500.1	lb	1
52	Right Upper Tibia Fz	600	2500.1	lb	1
53	Right Upper Tibia Mx	600	3500.5	in-lb	1
54	Right Upper Tibia My	600	3500.5	in-lb	1
55	Right Lower Tibia Fx	600	2500.1	lb	1
56	Right Lower Tibia Fy	600	2500.1	lb	1
57	Right Lower Tibia Fz	600	2500.1	lb	1
58	Right Lower Tibia Mx	600	2500.1	in-lb	1
59	Right Lower Tibia My	600	2500.1	in-lb	1
60	Right Knee String Pot	180	1.417323	in	1

Table 1c. Instrumentation Summary (continued)

Ch. Num	Description	Filter Class	Range	Units	Rack
61	Left Femur Fz	600	5000	lb	1
62	Left Femur My	600	3000	lb	1
63	Left Knee String Pot	180	1.417323	in	1
64	Right Belt Strap	60	3000	lb	1
65	Sled X Accelerometer	60	25	G	2
66	Front Left Floor Load Cell Fx	60	10000	lb	2
67	Front Left Floor Load Cell Fy	60	10000	lb	2
68	Front Left Floor Load Cell Fz	60	10000	lb	2
69	Front Right Floor Load Cell Fx	60	10000	lb	2
70	Front Right Floor Load Cell Fy	60	10000	lb	2
71	Front Right Floor Load Cell Fz	60	10000	lb	2
72	Rear Left Floor Load Cell Fx	60	10000	lb	2
73	Rear Left Floor Load Cell Fy	60	10000	lb	2
74	Rear Left Floor Load Cell Fz	60	10000	lb	2
75	Rear Right Floor Load Cell Fx	60	10000	lb	2
76	Rear Right Floor Load Cell Fy	60	10000	lb	2
77	Rear Right Floor Load Cell Fz	60	10000	lb	2
78	Left Leg Upper Tibia Fx	600	2500	lb	2
79	Left Leg Upper Tibia Fy	600	2500	lb	2
80	Left Leg Upper Tibia Fz	600	2500	lb	2
81	Left Leg Upper Tibia Mx	600	3500	in-lb	2
82	Left Leg Upper Tibia My	600	3500	in-lb	2
83	Left Leg Lower Tibia Fx	600	2500	lb	2
84	Left Leg Lower Tibia Fy	600	2500	lb	2
85	Left Leg Lower Tibia Fz	600	2500	lb	2
86	Left Leg Lower Tibia Mx	600	2500	in-lb	2
87	Left Leg Lower Tibia My	600	2500	in-lb	2
88	Left Leg Knee Clevis Left	600	2000	lb	2
89	Left Leg Knee Clevis Right	600	2000	lb	2
90	Right Leg Knee Clevis Left	600	2000	lb	2
91	Right Leg Knee Clevis Right	600	2000	lb	2

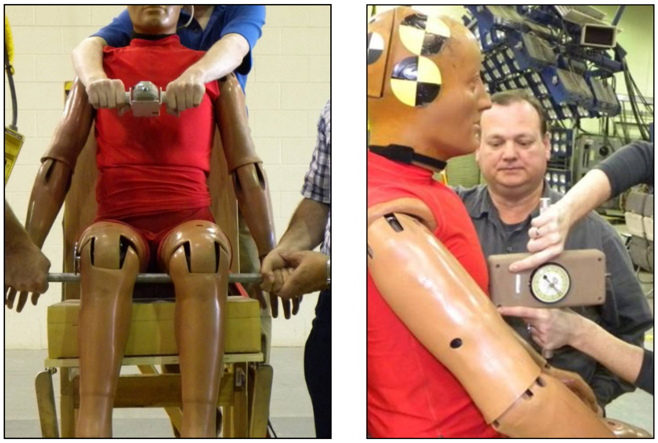

Figure 14. Seating Procedure

Seating Procedures

For this study, the ATD was seated in accordance with a procedure developed at CAMI that results in a consistent fore/aft position and initial pelvis angle [29]. This procedure involves suspending the ATD above the seat cushion just enough to insert a flat hand (approximately 1 in) between the bottom of the pelvis and the cushion. A 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 (Fig. 14). A force gage 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 to fully settle it into the seat. Once seated, the lap belt was tightened "two finger tight," as specified in SAE AS 8049b [12].

To generate the brace and pike positions, the initial seating procedure was the same as the upright position; however, once the ATD was seated and its lap belt tightened, the ATD was bent over into position and parachute chord was utilized to hold its torso in place. The parachute chord was routed to become slack immediately upon occupant forward motion so as not to interfere with ATD kinematics or loading. The pike position required removal of the abdominal insert to allow full bending at the lumbar spine. Two strands of frangible string were used to hold the torso in the pike position.

After the ATD was positioned, a three-dimensional portable measuring arm was used to take multiple points on the sled, seat, and ATD. The sled points included the center of the seat tubes, belt anchor location, and seat back location. The ATD anatomical points included the hip point, head center of gravity, knee joint, and ankle joint. The angle of the leg, with respect to the vertical, was calculated from the measured location of the knee and ankle targets; the angle of the torso, with respect to the vertical, was calculated from the measured location of the head center of gravity and hip point targets.

Restraints

Sixteen of the 17 tests used a conventional 2-point nylon lap belt, and one test used a polyester Y-belt. A Y-belt is a type of lap belt that has two attachment hooks on each end. These belts typically attach to a pair of anchor points on each side of the occupant, one at the conventional location and another at a higher point. This type of belt provides a more horizontal restraint path than a conventional belt to reduce forward excursion.

Data Analysis

Some injury criteria such as Head Injury Criteria (HIC), Normalized Neck Injury Criterion (N_{ij}), and Tibia Index (TI) are derived from test data mathematical calculations. Instructions for calculating them can be found in the regulations that cite the criteria and in a useful summary report published by the Data Processing Vehicle Safety Workgroup [16].

Head Injury Criteria (HIC)

HIC is used to evaluate head injury risk and has a pass/fail limit of 1,000; this corresponds to a 23%risk of an Abbreviated Injury Scale (AIS) AIS-3 or greater (serious) head injury or a 47% risk of an AIS-2 or greater (moderate) head injury [17]. The AIS, developed by the Association for the Advancement of Automotive Medicine, provides a means of quantifying the severity (or threat to life) of a specific injury [18]. The HIC calculation cited in 14 CFR 25.562 differs from the automotive version in that the duration is unlimited but only includes the resultant head acceleration after head contact. Body-to-body contact is excluded from this calculation due to the undamped resonant response that can occur when relatively rigid parts of the ATD strike each other, which would give an artificially high HIC value.

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right\}_{max}$$

t_1 is the initial integration time in seconds
t_2 is the final integration time in seconds
a(t) is the total acceleration vs. time curve for the head in units of gravity

Note: The values of t_1 and t_2 are selected such that the HIC value is the maximum possible for the time period being evaluated.

Neck injury

To limit the potential for neck injury in forward automotive crashes, 49 CFR 571.208 defines the criteria for neck tension and compression, as well as a criterion that combines the effect of the neck-bending moment and axial force, called N_{ij}. This is not currently a pass/fail criterion in aviation, but a limit of 1.0 is called for automotive testing [19]. The N_{ij} calculation uses force and moment data measured with an upper neck load cell (projected to the occipital condyle location). The automotive compression limit is 899 lb and the tension limit is 937 lb [19].

$$Nij = \frac{F_z}{F_{zc}} + \frac{M_{OCy}}{M_{yc}}$$

F_z is the force at the transition from the head to neck
F_{ZC} is the critical force (1,530 lb)
M_{OCy} is the total moment
M_{yc} is the critical moment (1,200 in-lb)

Shoulder injury

The FAA Hybrid III ATD does not have instrumentation to measure forces on the shoulder. Since the NTSB had identified shoulder injury as a potential risk for a braced occupant, a means of determining that injury risk was needed for this study. Hyper-extension of the shoulder joint in the sagittal (X-Z) plane was a possible injury mechanism for brace positions that place the hands on the seat back. To determine if it occurred during testing, the bolt securing the FAA Hybrid III's shoulder rotation stop block was narrowed down to 0.133 inches to lower its shear strength to 660 lb (Fig. 15). This would allow the stop block to fail if the torque on the shoulder joint (in the x-z plane) exceeded 990 in-lb. A post-test range of motion and visual inspection indicated whether the bolt had been sheared. This assessment was used to determine if there was potential for shoulder injury, but the torque required to shear the bolt has not been correlated to a specific injury severity.

Figure 15. Shear Bolt for Shoulder Injury Evaluation

Upper leg injury

The limit for axial compressive load in the femur is 2,250 lb, per § 25.562, which represents a 15% risk of serious injury to the knee-thigh-hip complex [20]. In addition to axial loading, excessive bending moments can cause serious injuries. European regulations for protection of pedestrians cite a femur bending limit of 4,514 in-lb and a monitoring value of 2,655 in-lb [21]. The 2,655 in-lb limit has been proposed by the European Enhanced Vehicle Safety Committee (EEVC) for pedestrian impacts and corresponds to a 20% risk of moderate injury to the femur [22]. Application of this criteria to other impact cases is limited because it was scaled using a dynamic multiplier against existing quasistatic femur-bending tolerance data, then scaled to the pedestrian leg form tester [23]. The pedestrian leg form is different than the femur used for the FAA Hybrid III in that the pedestrian leg form is designed to be used vertically to assess a car bumper's interaction with a pedestrian. The FAA Hybrid III femur is designed to be used in a seated position to assess bending and axial loading in the upper leg. The two leg forms differ in their non-metallic parts and knee joint, as well.

Appropriate application should also consider the loading case for which the limit was derived, specifically, a force applied perpendicularly to the femur mid-shaft, generating negative bending moments. In this study, this type of loading is produced when the lower legs are free to flail forward, and pelvis-forward rotation forces the femur down against the seat frame at approximately the femur mid-point. Alternately, if the lower legs do not flail and support the distal end of the femurs, forward flailing of the upper torso applies forces and moments to the ATD pelvis causing it to rotate forward and generate significant positive bending moments in the femur due to internal contact between the pelvis bone and femur. This means that the EEVC limit may be usful as a reference value for the load cases involving contact loading of the femur, but may not be valid for the other loading cases where ATD articulation creates the femur-bending moments.

Knee injury

Tibia-Femur displacement is used as an indicator of knee injury risk in auto crashes. A limit of 0.6 in is cited in European regulations for protection of occupants in frontal collisions and corresponds to partial ligament failure in humans [21]. Significant displacement can occur when the tibia (rather than the patella) becomes the load path between the occupant and structure in a forward impact.

Lower leg injury

Lower leg injury potential is evaluated with the Tibia Index (TI), which combines the bending moments and axial forces in the lower leg. For each leg, one Tibia Index is calculated from the lower instrumentation and a separate TI is calculated from the upper instrumentation. European regulations for protection of occupants in frontal collisions call out a TI limit of 1.3, and a tibia compressive force limit of 1,800 lb [21]. According to Mertz, a TI reading less than 1.0 indicates that injury is unlikely [24]. To protect against tibia plateau fracture, he also proposed a supplemental compressive force limit of 1,800 lb in addition to the TI. Lower leg injuries are not current pass/fail criteria in aviation seat testing.

$$TI = \left|\frac{M_R}{(M_C)_R}\right| + \left|\frac{F_Z}{(F_C)_Z}\right|$$

with:

$$M_R = \sqrt{(M_x)^2 + (M_y)^2}$$

M_x is the bending moment around the x-axis
M_y is the bending moment around the y-axis
$(M_c)_R$ is the critical bending moment (1,991 in-lb)
F_z is the axial compression in the z-direction
$(F_c)_Z$ is the critical compression force in z-direction (8,071 lb)

Test Matrix

Table 2 summarizes the variables evaluated for each test in this study. These include the seat pitch, seat back or impact surface type, belt type, ATD torso, hand, and leg positions, and whether a simulated floor was included.

RESULTS

Tables 3 through 6 summarize the test results grouped by impact surface type; the values shown in red exceeded the injury criteria. The top seven rows contain the details of the test condition, and the remaining rows contain the values for the injury criteria introduced in the Data Analysis section. A detailed evaluation of each test setup, including discussion, and video stills showing the initial condition and other times of interest, are provided in Appendix A. All tests met the pulse requirement defined in AC 25.562 [25].

Locked-Out Seat Back

The locked-out seat back configuration was evaluated with six tests. Two tests with an unbraced occupant (A12037 and A12038) had HIC scores greater than 1,000, while a third test with an upright occupant (A13010) had a low HIC, but an N_{ij} value 50% higher than the limit due to an unusual interaction with the tray table. Conversely, the braced condition (A12036) produced a very low HIC, and Nij value less than half the limit. The leg injury criteria were generally favorable, although multiple tests resulted in high positive bending moment in the right femur.

Full Break-Over Seat Back

The full break-over seat back configuration was evaluated with four tests, including one specifically designed to generate worse-case femur compression. The HIC scores for all these tests were below the limit, although two were over 900, suggesting a limited margin of safety. Test A13002 produced a high N_{ij} value when the tray table deployed and caught beneath the ATD's chin. The Tibia Index was exceeded in test A13001, in which the lower legs were initially forward.

Test A13007 included a rigid plate mounted to the forward seat at the location of probable knee strike. This test produced high femur compression; however, it did not exceed the limit (1,950 lb measured vs. 2,250 lb limit). This test also resulted in an artificially high Tibia Index due to impingement on the knee plate, and therefore should be considered an anomaly and not included in the analysis. All other leg injury parameters were less than the limits.

Table 2. Test Matrix

Test #	Torso	Hand	Legs	Seat Back	Seat Pitch	Belt Type
A12036	Braced	Top of fore seat back	Back	Locked out	30.4	2-point
A12037	Upright	Top of thighs	Back	Locked out	30.4	2-point
A12038	Upright	Top of thighs	Vertical	Locked out	30.5	2-point
A13001	Braced	Top of fore seat back	Forward	Full break-over	30.5	2-point
A13002	Upright	Top of thighs	No Floor	Full break-over	30.3	2-point
A13003	Braced	Top of fore seat back	Back	EA break-over	30.4	2-point
A13004	Upright	Top of thighs	Vertical	EA break-over	30.3	2-point
A13005*	Braced	Top of fore seat back	Back	EA break-over	30.4	2-point
A13007	Upright	Top of thighs	Back	Knee Plate	30.9	2-point
A13008	Braced	Back of head	Back	EA break-over	29.9	2-point
A13009	Pike	Back of head	Back	Locked out	37.8	2-point
A13010	Upright	Top of thighs	No Floor	Locked out	33.6	2-point
A13011	Braced	Side of legs	Back	EA break-over	30.3	2-point
A13012	Braced	Side of legs	Back	Full break-over	30.3	2-point
A13013	Braced	Side of legs	Back	Locked out	30.3	2-point
A13014	Pike	Side ankles	Back	Nomex Wall	35.6	2-point
A13015	Pike	Side of legs	Back	Nomex Wall	34.8	y-belt

*Occupant in the Front Seat

Table 3. Locked-out Seat Back Test Summary

Test parameter	Criteria Limit	Test Number					
		A12036	A12037	A12038	A13009	A13010	A13013
Torso Position		Braced	Upright	Upright	Pike	Upright	Braced
Hand Position		Seat Back Top	Thigh Top	Thigh Top	Down by legs	Thigh Top	Down by legs
Leg Position		Back	Back	Vertical	Back	No Floor	Back
Restraint		Lap belt	Lap belt	Lap belt	Lap belt	Lap belt	Lap belt
Seat Pitch		30.4	30.4	30.5	37.8	33.6	30.3
Impact Velocity (ft/s)		45.2	45.1	45.2	44.7	44.7	44.9
Impact Acceleration (g)		17.1	17.1	17.4	16.7	16.8	16.5
HIC	1000	335	***1004***	***1285***	262	520	167
Nij	1.0	0.45	0.83	0.85	0.63	***1.57***	0.52
Upper Neck Tension (lb)	937	368	652	768	359	893	305
Upper Neck Compression (lb)	-899	-110	-42	-137	-258	-27	-182
Knee Slider (in)	0.6	0.0	0.0	0.1	0.0	0.1	0.0
Right Tibia Compression (Upper) (lb)	-1800	-626	-784	-810	-639	-199	-435
Right Tibia Compression (Lower) (lb)	-1800	-639	-806	-789	-650	-119	-433
Left Tibia Compression (Upper) (lb)	-1800	-25	-41	-108	-56	-474	-39
Left Tibia Compression (Lower) (lb)	-1800	-19	-29	-138	-52	-390	-36
Right Leg TI (Upper)	1.0	0.59	0.50	0.37	0.88	0.84	0.58
Right Leg TI (Lower)	1.0	0.69	0.83	0.32	0.62	0.83	0.34
Left Leg TI (Upper)	1.0	0.24	0.40	0.72	0.60	0.67	0.30
Left Leg TI (Lower)	1.0	0.11	0.18	0.43	0.23	0.31	0.18
Peak Knee Velocity (ft/s)		11.3	12.8	12.3	12.9	25.2	13.7
Right Femur Compression (lb)	2250	-21	-103	-567	-256	-98	-16
Left Femur Compression (lb)	2250	-28	-340	-509	-71	-110	-25
Positive Right Femur My (in-lb)	unknown	2480	3334	2718	2373	998	1682
Negative Right Femur My (in-lb)	2655	-141	-116	-656	-303	-1855	-113
Positive Left Femur My (in-lb)	unknown	873	1165	1667	1654	531	942
Negative Left Femur My (in-lb)	2655	-162	-133	-1014	-219	-1821	-144

Table 4. Full Break-Over Seat Back Test Summary

Test parameter	Criteria Limit	Test Number			
		A13001	A13002	A13007*	A13012
Torso Position		Braced	Upright	Upright	Braced
Hand Position		Seat Back Top	Thigh Top	Thigh Top	Down by legs
Leg Position		Forwards	No floor	Back	Back
Restraint		Lap Belt	Lap Belt	Lap Belt	Lap Belt
Seat Pitch		30.5	30.3	30.9	30.3
Impact Velocity (ft/s)		45.4	45.3	45.4	44.9
Impact Acceleration (g)		17.0	17.6	17.4	16.7
HIC	1000	965	436	920	408
Nij	1.0	0.79	***1.39***	0.74	0.43
Upper Neck Tension (lb)	937	410	741	790	378
Upper Neck Compression (lb)	-899	-513	-2	-146	4
Knee Slider (in)	0.6	0.1	0.1	0.2	0.0
Right Tibia Compression (Upper) (lb)	-1800	-793	-87	-353	-547
Right Tibia Compression (Lower) (lb)	-1800	-554	-46	-348	-536
Left Tibia Compression (Upper) (lb)	-1800	-69	-78	-110	-21
Left Tibia Compression (Lower) (lb)	-1800	-57	-110	-51	-22
Right Leg TI (Upper)	1.0	**1.06**	0.59	0.70	0.58
Right Leg TI (Lower)	1.0	**1.00**	0.29	0.21	0.43
Left Leg TI (Upper)	1.0	0.79	0.72	***1.16***	0.37
Left Leg TI (Lower)	1.0	0.57	0.32	0.27	0.16
Peak Knee Velocity (ft/s)		10.7	12.0	11.9	9.4
Right Femur Compression (lb)	2250	-878	-75	-1337	-157
Left Femur Compression (lb)	2250	-692	-305	-1949	-10
Positive Right Femur My (in-lb)	unknown	1480	635	3135	1847
Negative Right Femur My (in-lb)	2655	-1256	-959	-133	-124
Positive Left Femur My (in-lb)	unknown	67	609	2568	976
Negative Left Femur My (in-lb)	2655	-692	-1422	-122	-137

* Knee Plate

Table 5. Energy Absorbing Seat Back Test Summary

Test parameter	Criteria Limit	Test Number				
		A13003	A13004	A13005*	A13008	A13011
Torso Position		Braced	Upright	Braced	Braced	Braced
Hand Position		Seat Back Top	Thigh Top	Seat Back Top	Back of Head	Down by legs
Leg Position		Back	Vertical	Back	Back	Back
Restraint		Lap Belt	Lap Belt	Lap Belt	Lap Belt	Lap Belt
Seat Pitch		30.4	30.3	30.4	29.9	30.3
Impact Velocity (ft/s)		45.5	45.4	44.4	44.6	44.9
Impact Acceleration (g)		18.0	17.9	16.6	16.6	16.8
HIC	1000	***1095***	743	760	411	224
Nij	1.0	0.83	0.87	0.90	0.66	0.51
Upper Neck Tension (lb)	937	705	623	495	403	327
Upper Neck Compression (lb)	-899	-49	-4	-158	-91	-6
Knee Slider (in)	0.6	0.0	0.2	0.0	0.0	0.0
Right Tibia Compression (Upper) (lb)	-1800	-652	-815	-611	-533	-531
Right Tibia Compression (Lower) (lb)	-1800	-660	-843	-616	-535	-523
Left Tibia Compression (Upper) (lb)	-1800	-28	-139	-34	-29	-32
Left Tibia Compression (Lower) (lb)	-1800	-27	-137	-33	-29	-31
Right Leg TI (Upper)	1.0	0.56	0.63	0.58	0.70	0.66
Right Leg TI (Lower)	1.0	0.68	0.28	0.67	0.53	0.41
Left Leg TI (Upper)	1.0	0.40	***1.37***	0.39	0.28	0.29
Left Leg TI (Lower)	1.0	0.41	0.70	0.33	0.18	0.15
Peak Knee Velocity (ft/s)		14.3	13.3	14.7	12.7	N/A
Right Femur Compression (lb)	2250	-5	-28	-19	-13	-7
Left Femur Compression (lb)	2250	-9	-564	-17	-17	-29
Positive Right Femur My (in-lb)	unknown	2572	3518	2650	2516	1498
Negative Right Femur My (in-lb)	2655	-144	-34	-203	-138	-82
Positive Left Femur My (in-lb)	unknown	2104	1370	2243	1709	800
Negative Left Femur My (in-lb)	2655	-117	-165	-165	-199	-112

*Occupant in the Front Seat

Table 6. Bulkhead Test Summary

Test Parameter	Criteria Limit	Test Number	
		A13014	A13015
Torso Position		Pike	Pike
Hand Position		Down by legs	Down by legs
Leg Position		Back	Back
Restraint		Lap Belt	Y-Belt
Seat Pitch (in)		35.6	34.8
Impact Velocity (ft/s)		45.0	45.2
Impact Acceleration (g)		16.4	16.6
HIC	1000	211	106
Nij	1.0	***2.02***	0.50
Upper Neck Tension (lb)	937	96	303
Upper Neck Compression (lb)	-899	***-2399***	-28
Knee Slider (in)	0.6	0.0	0.0
Right Tibia Compression (Upper) (lb)	-1800	-289.0	-206.0
Right Tibia Compression (Lower) (lb)	-1800	-258.0	-185.0
Left Tibia Compression (Upper) (lb)	-1800	-52	-21
Left Tibia Compression (Lower) (lb)	-1800	-51	-24
Right Leg TI (Upper)	1.0	0.37	0.28
Right Leg TI (Lower)	1.0	0.21	0.11
Left Leg TI (Upper)	1.0	0.43	0.30
Left Leg TI (Lower)	1.0	0.23	0.17
Peak Knee Velocity (ft/s)	N/A	12.9	-
Right Femur Compression (lb)	2250	-19	-5
Left Femur Compression (lb)	2250	-30	-16
Positive Right Femur My (in-lb)	unknown	730	765
Negative Right Femur My (in-lb)	2655	-422	-145
Positive Left Femur My (in-lb)	unknown	666	828
Negative Left Femur My (in-lb)	2655	-419	-148

Energy Absorbing (EA) Break-Over Seat Back

The energy absorbing break-over seat back configuration was evaluated with five tests. As expected, the HIC scores for the upright occupant were below the limit. However, the HIC value for the occupant in the current brace condition (A13003) exceeded the limit. Subsequent tests with an occupant in the front seat (A13005) and two tests with modified hand positions (A13008 and A13011) produced HIC values below the limit. All tests produced neck loads below the limits. The leg injury criteria were generally favorable, although multiple tests resulted in high positive bending moment in the right femur, one test (A13004) produced a high Tibia Index in the upper portion of the left tibia.

Bulkhead

Two tests were run with the occupant behind a bulkhead. The initial test (A13014) positioned the occupant slightly beyond the minimum allowable distance of 35 in and included a standard lap belt. While the HIC value was quite low (211), extreme neck compression was observed. Subsequently, a test was run incorporating a Y-belt, which is common for this seating configuration. The Y-belt reduced the forward motion of the occupant, while nearly eliminating the neck compression. Both tests produced low values for all of the leg parameters, in part because the knees did not contact the bulkhead.

DISCUSSION

Injury Risk Evaluation

The current injury criteria required for certification of an airplane seat were based upon the data and instrumentation available in the 1980s, when the regulations were implemented. These regulations did not specifically address all potential neck and leg injury mechanisms. To analyze whether the current certification injury criteria and test device are adequate to evaluate the potential injury for the evolving seat designs, newer leg injury and neck injury criteria were evaluated, in addition to the existing criteria.

Neck Injury

In the row-to-row tests, all but two of the test configurations, including the configurations with the occupant upright, had neck injury values below limits. The two row-to-row cases that had high neck loads were produced by an unusual loading scenario.

Figure 16. Chin of ATD Catching on Tray Table

In three of the tests, the tray table deployed in a manner that caused it to catch under the ATD's chin. In one case, the table released prior to head impact, and in the other two, the ATD's head struck the tray table latch, freeing the table (Fig. 16). This interaction momentarily interrupted the forward travel of the ATD, resulting in very high neck loads. The combined neck bending-tension criteria Nij were exceeded in two cases, and it was below the criteria in the third. One of these tests also nearly exceeded the neck tension criteria. Catching the chin on the tray table can produce serious injury. The Hybrid II ATD, typically used in dynamic tests conducted to qualify new seat designs, cannot directly measure the interaction with a tray table that has deployed, leaving conservative qualitative assessments as the only means to ensure the safety of the interaction. The neck instrumentation in the FAA Hybrid III can assess the risk of cervical spine injury due to applied forces, but neither ATD can measure contact forces that could cause serious soft tissue injury such as a collapsed larynx. In the absence of a soft tissue injury assessment method, avoiding impingement onto hard structures may be the best means of preventing neck injury.

The test matrix also included a rigid wall to assess the axial loading in the neck. In the first test, the standard two-point belt was installed, resulting in head impact with the wall. This contact lead to high compressive loading in the cervical spine, as well as a value of the neck injury criteria that was over double the regulatory limit. In the second test, a Y-belt restraint was installed, which reduced the distance that the ATD traveled sufficiently to prevent contact of its head with the rigid wall. Without contact, the neck forces were primarily tensile due to inertial loading, resulting in a neck injury value that was only half the regulatory limit.

Shoulder injury

Based on the injuries seen in the Hudson River ditching, shoulder injury was evaluated. Hyper-extension of the shoulder joint in the sagittal plane was a possible injury mechanism for brace positions that place the hands on the seat back. There was no indication that the ATD interaction with any of the seatback types resulted in hyper-extension, as observed in the videos and evidenced by inspection of the shoulder stop bolt, which remained intact throughout the study.

Femur compression

Even at a relatively close pitch (30 in), none of the tests of representative seats resulted in significant femur compression. In many cases, the femur load was primarily tension that occurred as the pelvis was constrained by the lap belt before the knee contacted any structure. For one test, a rigid vertical plate was attached to the target seat in front of the aft occupant's knees. This worst case condition still did not produce femur compression that exceeded the injury limit. It is possible that testing in a yaw condition could asymmetrically load the legs and increase the load somewhat, but that increase would have to be over 15% to exceed the injury limit.

Femur bending

In test configurations where the knee vertical motion was constrained by the position of the lower leg, forward rotation of the pelvis produced significant positive femur Y-axis bending. The moments measured were less than the European regulatory limit [21] but exceeded the EEVC limit in cases where the ATD legs were in the aft position and the torso was either upright or in the current brace position. Both the biofidelity of the moment produced and the applicability of the EEVC limit for these loading cases are unknown.

In test configurations where the lower legs flailed forward, the upper legs were forced downward against the front of the seat frame as the pelvis rotated forward, producing a significant negative Y-axis bending moment. The EEVC femur bending criteria may be useful in evaluating the injury risk posed by this loading since it is similar to the loading cases for which that criterion was derived, i.e., a three-point bending scenario. Some injuries in the Kegworth crash were attributed to this type of loading [26]. For the tests that produced significant negative bending, the moment was always less than the EEVC limit.

Tibia-femur displacement

Although in some tests the tibia, rather than the knee, was the primary load path for the interaction with the target seat, the loading generated was not high enough to cause significant tibia-femur displacement in any of the tested configurations.

Tibia compression

The magnitude of tibia compression produced in all test configurations was less than half of the criteria limit, and is therefore not a likely injury mechanism.

Tibia bending-compression combined criteria

The Tibia Index was over the biomechanical limit of 1.0 in only two cases (excluding the knee plate scenario), with one of these also exceeding the EU regulatory limit of 1.3. The legs were positioned forward or vertical in these cases. This initial position allows the tibia to contact the seat frame before or at the same time as the knee. This produced bending in the tibia as the momentum of the leg below the seat frame, and the inertial force of the upper leg, load the ends of the tibia. In the case with a TI over the European limit, the seat cushion slid forward with the pelvis, which apparently caused the ATD to travel further than usual. This motion could help explain why this test produced a TI that was much higher (1.37) than other seat configurations.

The unsupported (no floor) test configurations were specifically set up to evaluate the risk of tibia injury when the occupant's lower legs are free to swing forward and impact the seat frame. Neither of these "worst case" tests resulted in a TI over the limit. Note that interaction between the rigid knee plate and the lower leg also produced high TI values, but this special configuration was not considered a valid evaluation of lower leg injury risk because the plate's shape and stiffness was not representative of an actual aircraft seat. In this test series, the TI results were quite dependent on leg initial position because it affected the orientation of the leg when it interacted with the seat frame structure. This indicates that the TI is sensitive to the shape and stiffness of the forward seat's structure and the seat pitch, since both of these factors could affect where the loads are applied to the tibia and the magnitude of those loads. Given the low injury potential observed in this study, there does not now appear to be a benefit to adopting lower leg injury criteria.

Brace Position Evaluation

Current brace position

The occupants place their hands on the top of the seat back and their head against the seat back, as shown in AC 121-24B. This position was successful in reducing head and neck injury risk in only one scenario, when the seat back in front was a locked-out type. When the seat back in front was the full break over or energy absorbing type, the resulting head injury criteria were near or over the criteria limit, while the neck criterion were below limits. In these cases, the arms pushed the seat back away from the occupant, allowing the head to accelerate relative to the seat back, producing significant relative velocity between the head and seat back. Pushing the seat back away resulted in an impact point lower on the seat back, nearer the hinge joint. This lower point would tend to provide a stiffer response than a point higher up on the seatback. Both the high velocity and the high stiffness of the impact surface tend to increase the severity of the head impact. In one test with an EA seat back, the front row was occupied. This reduced how far the seat back could fold forward, altering the impact point and stiffness with respect to the unoccupied case, decreasing the head injury risk. The interaction with the full break-over and energy absorbing seat backs tended to increase the neck injury risk, but the criteria values did not exceed the limits.

Leg placement

Initial leg position did not appear to have a significant effect on upper torso and head interaction with the seat back and similarly, the upper torso initial position appeared to have little effect on leg injury assessment values. This permitted independent evaluation of each factor.

Vertical position

This position resulted in moderate-to-high TI values. It also produced moderate femur compression values and positive femur Y-axis bending moments.

Forward position

This position resulted in a TI value that was just over the limit. It also produced moderate femur compression values and significant levels of positive and negative femur Y-axis bending moments.

Aft position

This leg position tended to prevent forward translation of the lower legs, which in turn prevented contact with the front seat, significantly reducing loads on the lower leg. This position produced positive Y-axis bending moment, but it prevented femur contact with the front of the seat frame and the associated negative Y-axis bending. Of course, this position will only provide these advantages for occupants whose lower legs are long enough for their feet to firmly touch the floor.

Alternate brace position

The occupants place their head directly on the seat back in front of them, and their hands down by the side of their lower legs. The primary factor affecting the effectiveness of the current brace position was the interaction between the occupant's arms and the seat back. To reduce this interaction, the current position was modified by placing the hands down by the lower legs instead of on the seat back (Fig. 17). Because the arms were positioned to prevent them from pushing the seat back forward during the impact, the head remained in contact, which reduced head and neck injury risk. This "alternate" position was successful in reducing head and neck injury risk for all of the seat back types evaluated. This position (when combined with the "Aft" leg position) prevented lower leg contact with the seat in front and produced negligible femur axial compressive forces, lower (positive) femur Y-axis bending forces, and prevented femur contact with the front of the seat frame . Improving performance

Figure 17. Alternate Brace Position

with the EA seat back was of particular importance since they will eventually be the most prevalent seat back type in service as newer aircraft with dynamically qualified seating systems are added to the fleet.

Pike position

In the current guidance, the pike position is the one where the seat in front is too far away to support the head, or there is no seat in front, as in a bulkhead row. This position was successful in reducing head and neck injury risk in a row-to-row application. The tested configuration used a locked-out seat back to provide a worst case overall stiffness, and a seat pitch (38 in) selected to maximize the head impact velocity. This configuration is representative of a long pitch configuration with an average-size occupant, or a shorter pitch configuration with a shorter statured occupant. During the test, the head contacted the seat back, but the combination of low-impact velocity and relatively soft local compliance of the point on the seat back struck (center of the tray table) contributed to the low HIC and N_{ij} values. When seated behind a wall 35 in from the seat reference point, this position reduced head injury risk but permitted significant neck loading. The compressive load in the upper neck load cell was 2,399 lb and the N_{ij} value was 2.02, both of which are more than double the criteria limits. While these results are concerning, they may not be typical for occupants of seat places behind interior walls. Because of the risk of head injury for occupants of conventional seats placed behind walls at the minimum allowable distance of 35 in, many aircraft meeting the head impact protection requirements of 14 CFR 25.562 (c) have seats at these locations that incorporate "head path reducing features" such as Y-belts, and seat frames designed to flex less under load [27]. To investigate this more likely scenario, the previous test was repeated with the ATD seated in a front row type of seat, restrained by a Y-belt. In this seat configuration, the Y-belt and seat frame stiffness effectively limited the occupant horizontal head excursion to 5 in from the initial position, which did not allow the ATD to contact the wall in front, significantly reducing head and neck injury risk.

LIMITATIONS

Effect of Combined Loading

Being subjected to combined vertical/horizontal loads while in the current or proposed brace positions could alter the spinal injury risk, compared to the upright position due to spinal misalignment. An evaluation of this difference in injury risk requires data relating injury tolerance to spine bending angle, which is currently not available. Since the current and alternate brace positions result in a similar initial torso angle and torso kinematics, a difference in spinal injury risk is not expected.

Seat Back Range of Stiffness

The three types of seat backs used in this study are representative of the range stiffness of seat backs contained in the US fleet. The locked-out and full break-over seat backs are typical for older aircraft that were not required to meet the head impact protection requirements of 14 CFR 25.562 (c) [9]. They represent the stiffest (locked-out) and softest (full break-over) hinge properties. Seats utilizing EA seat backs are typically found in aircraft designed since 1988 that must meet the provisions of 14 CFR 25.562, although they can be installed as replacements in other aircraft as well. Since FAA regulations require that seats meeting §25.562 be installed in all newly manufactured transport aircraft operated in passenger carrying operations after October 27, 2009, EA seat backs will eventually be the prevalent seat back type in service as newer aircraft with dynamically qualified seating systems are added to the fleet. The stiffness of EA seat backs varies between different seat manufacturers and different seat models, but only one type of EA seat back was used for this study. Since the alternate brace position was effective for the range of stiffness evaluated, and EA seat backs, in general, provide a resistance that falls somewhere between the locked-out and the full break-over, the effectiveness of the position should extend to other EA seat backs.

Seat Back Distribution

The percentage of the seats in the fleet with seat back characteristics that tend to reduce the effectiveness of the current brace position (arms on seat back) is unknown. Using data retrieved from the FAA's Safety Performance Analysis System (SPAS) on June 25, 2008, it was estimated that 37% of the fleet met either all the requirements of §25.562 or at least the structural integrity requirements in §25.562 [28]. This total does not include seats on aircraft initially delivered without improved seats, but which had them installed later. The fully compliant seats are assumed to contain EA seat backs. The lack of information makes it difficult to determine the immediate benefit of changing the brace position. However, as the number of EA seats within the fleet increases, the benefit will increase.

Test Repeatability

Due to the limited number of test articles, exact test conditions were not repeated. Previous testing at CAMI yielded HIC variation of less than 100 HIC points on impacts onto EA seat backs, while impacts onto homogenous surfaces had less points [11]. Testing repeatability for the other injury parameters are unknown but should to be of a similar magnitude.

CONCLUSIONS

We conducted research into transport aircraft passenger brace position effectiveness and leg injury risk. The test configurations were derived to evaluate several factors including: seat back resistance to folding over, the currently recommended brace positions and alternate positions, the spacing between rows of seats, occupant stature, and interaction with the floor and interior walls. Injury risks were evaluated using an advanced test dummy and injury criteria from current FAA regulations, Federal Motor Vehicle Safety Standards, European auto safety regulations, and applicable research findings. Analysis of the results led to the following conclusions:

- **Neck injury:** Neck injury was not found to be a significant risk in the row-to-row seating configurations evaluated unless the chin of the ATD catches the top of the tray table.
- **Upper Leg Injury:** Even in the worst case test condition, the femur axial compressive force was below the regulatory limit indicating that the femur compression criteria currently cited in FAA regulations is not likely to be exceeded in passenger seat dynamic qualification tests. While high negative bending moments were not observed in this test series, injuries in the Kegworth crash (attributed to femur bending) suggest that this type of loading may be more useful injury criterion. However additional research is necessary to determine the biofidelity of the moments produced by the ATD and to establish appropriate pass/fail limits before any such criteria could be adopted.
- **Lower Leg Injury:** Given the low injury potential observed in this study, there does not appear to be a benefit to adopting lower leg injury criteria at this time.
- **Current Brace Position:** This position (head against the seat back, hands on top of the seat back) was evaluated for three common types of seat backs. This position was only successful for locked-out type seat backs. For full break-over and energy absorbing type seat backs, the ATD's arms pushed the seat back away, allowing the head to accelerate relative to the seat back, increasing the severity of the head impact. There was, however, no evidence that the ATD interaction with any of the seatback types resulted in hyper-extension of the shoulder joint. The "Forward" and "Vertical" leg brace positions permitted the lower legs to flail forward and contact the seat in front. This contact produced femur bending and compression (below criteria limits), and tibia injury risk in some cases. The "Aft" leg brace position reduced lower leg flailing and prevented femur contact with the front of the seat frame. This position resulted in low femur and tibia injury assessment values; however, it is only achievable for occupants whose lower legs are long enough for their feet to firmly touch the floor.
- **Alternate Brace Position:** To reduce the detrimental interaction between the occupant's arms and the seatback, the current position was modified by placing the hands down by the lower legs instead of on the seat back. This "Alternate" position was successful in reducing head and neck injury risk for all of the seat back types evaluated.
- **Pike Position:** This position is currently recommended when the seat in front is too far away to support the head, or there is no seat in front, as in a bulkhead row. It was successful in reducing head and neck injury risk in the row-to-row scenario, as long as the struck seat back has a relatively soft local compliance at the point of impact. When seated behind a bulkhead, the effectiveness of the pike position was dependent on whether the head of the occupant struck the bulkhead. "Head-path-reducing features," such as Y-belts, prevented head contact at the typical 35-in setback.

This study used an idealized impact condition to evaluate the dynamic performance of seats and occupants. While these types of tests are useful for comparison purposes, they cannot predict brace position performance or injury risk in all possible impact scenarios. The observations and recommendations made concerning the effectiveness (or ineffectiveness) of the brace positions studied should be applied taking that fact into consideration. These findings are based purely on results of impact tests with ATDs, and further study is necessary to determine whether the Alternate position is practical to implement from a human factors perspective. This research has led to the determination that as seat technology has evolved, the most effective brace position has as well; the current positions recommended in AC 121-24B may need some adjustment to provide an equivalent level of safety for all passenger seat back types.

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APPENDIX A

Test Analysis

Braced position with arms on seat back, locked-out seat back, legs back
(Figures A1 to A3)

Figure A1 – A12036 T=0 ms

Figure A2 – A12036 T=120 ms

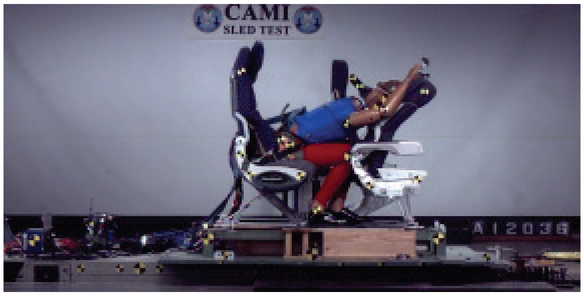

Figure A3 – A12036 T=150 ms

- The ATD is positioned with the torso forward and head against the seat back. The hands are resting on the top of the seat back in front, the legs are back as far as was allowed by the baggage bar.

- The arms place a load on the seat back in front causing it to move forward some, but because the seat back is the locked out type, it does not move significantly away from the ATD's head during the test. The continuous contact maintained between the head and the seat back was one factor in the relatively low HIC of 335.

- The right foot did not slide forward and the left foot slid forward until the lower leg was nearly vertical. The knees translated forward and contacted the seat back. The aft-ward position of the feet appeared to prevent lower leg flailing. No significant femur compression loads were generated; however, the Y-axis positive moment in the right femur (2480 in-lb) was relatively high.

Upright position with a locked out seat back, legs back
(Figures A4 to A6)

Figure A4 – A12037 T=0 ms

Figure A5 – A12037 T=125 ms

Figure A6 – A12037 T=177 ms

- The ATD was positioned with the torso upright and the legs back as far as was allowed by the baggage bar, the hands were placed on top of the thighs.
- The hands come forward in the early stage of the test and begin to push the seat back away from the occupant. This motion permits the head to travel further and hit the seat back at a lower point than if the seat back had remained in the nominal upright position. The high head impact velocity (51 ft/s) relative to the seat and higher overall stiffness of the point on the seat back where the head struck resulted in a HIC of 1004, which exceeds the limit.
- The feet slid forward in unison with the knee excursion. The knees contacted the seatback. The aft-ward position of the feet appeared to prevent lower leg flailing. Low femur compression loads were generated and the positive Y-axis moment in the right femur (3334 in-lb) was relatively high.

Upright position with a locked out seat back, legs vertical
(Figures A7 to A9)

Figure A7 – A12038 T=0 ms

Figure A8 – A12038 T=125 ms

Figure A9 – A12038 T=170 ms

- The ATD was positioned with the torso upright, the legs vertical, and the hands placed on top of the thighs. This is the initial position used for seat qualification tests.

- The hands come forward in the early stage of the test and begin to push the seat back away from the occupant. This motion permits the head to travel further and hit the seat back at a lower point than if the seat back had remained in the nominal upright position. The high head impact velocity (52 ft/s) relative to the seat and higher overall stiffness of the point on the seat back where the head struck resulted in a HIC of 1,285, which exceeds the limit.

- The feet slid forward in unison with the knee excursion until the knees contacted the seatback, generating low compression loads. As the torso and pelvis rotated forward, a positive Y-axis bending torque was generated in the right femur (2718 in-lb) that was relatively high. The lower legs moved forward and made contact with the aft tube of the seat frame but the calculated tibia indices for the legs did not exceed the limit. After swinging forward, the angle of the lower legs permitted the knees to translate downward significantly. This relieved the positive Y-axis moment but resulted in negative femur Y-axis bending (but not close to the limit).

Braced position with arms on seat back, full break over seat back, legs forward
(Figures A10 to A12)

Figure A10 – A13001 T=0 ms

Figure A11 – A13001 T=120 ms

Figure A12 – A13001 T=188 ms

- The ATD is positioned with the torso forward and head against the seat back. The hands are resting on the top of the seat back in front, and the legs are as far forward as possible while still contacting the floor.
- The ATD's elbows pressed against the seat back, pushing it away from the occupant and folding it completely flat just before head contact. This motion permits generation of significant relative velocity between the head and the seat back before it strikes the seat back just below the tray table. The resulting HIC was 965, which nearly exceeds the limit.
- The lower legs translated forward in unison with the knee, which resulted in contact between the tibia and the aft tube of the seat frame. This caused femur compression and positive Y-axis bending (but neither was over the limit). The feet maintained contact with the floor as they continued to slide forward. This generated a combination of axial compression and bending in the tibia that resulted in a tibia index just over 1.0 for the right leg (upper and lower calculations). After swinging forward, the angle of the lower legs permitted the knee to translate downward significantly as the torso and pelvis rotated forward. This placed the femur in significant negative bending (but not over the limit).

Upright position, full break-over seat, legs unsupported
(Figures A13 to A15)

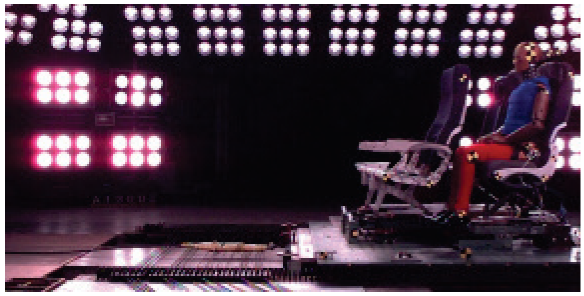

Figure A13 – A13002 T=0 ms

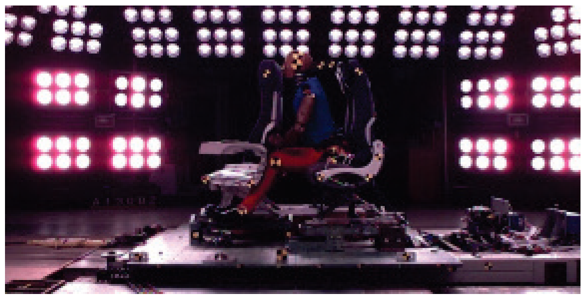

Figure A14 – A13002 T =120 ms

Figure A15 – A13002 T=196 ms

- The ATD was positioned with the torso upright and hands on top of the thighs. No floor was installed, allowing the legs to dangle vertically to emulate a shorter occupant whose feet will not contact the floor.
- The ATD's arms struck the seat back prior to the head, causing the seat back to move away slightly. The head struck the tray table latch shattering it and releasing the tray table. With the tray table loose, the ATD's chin caught on the tray table and hung there as the seat back moved away. This interaction caused tension and bending moments in the neck (N_{ij} of 1.39) which exceeded the combined limit.
- The lower legs translated forward in unison with the knee until the knee contacted the seatback. The lower legs then rotated forward allowing tibia contact with the aft tube of the seat frame. The calculated tibia indices for the legs did not exceed the limit. The angle of the lower legs and the lack of a floor reaction surface permitted the knee to translate downward significantly as the torso and pelvis rotated forward. This placed the femur in significant negative bending (but not over the limit).

Braced position with arms on seat back, energy absorbing seat back, legs back
(Figures A16 to A18)

Figure A16 – A13003 T=0 ms

Figure A17 – A13003 T=130 ms

Figure A18 – A13003 T=180 ms

- The ATD is positioned with the torso forward and head against the seat back. The hands are resting on the top of the seat back in front, and the legs are back as far as was allowed by the baggage bar.
- As the ATD rotated forward, the elbows pressed against the seat back in front, pushing it away from the occupant, folding it completely flat just before head contact. This motion permits generation of significant relative velocity between the head and the seat back before the head strikes the seat back just below the tray table (as in test 13001). The resulting HIC of 1,095 was relatively high.
- The feet slid forward very little and the knees translated forward and contacted the seat back. The seat cushion slipped forward during the test which apparently allowed the ATD to translate forward further than in a similar test (A12036). This additional excursion did not result in significant femur compression loads. The lower legs did not flail forward after contact. As the torso and pelvis rotated forward, a positive Y-axis moment was generated in the right femur (2,572 in-lb), that was relatively high.

Upright position, energy absorbing seat back, legs vertical
(Figures A19 to A21)

Figure A19 – A13004 T=0 ms

Figure A20 – A13004 T=120 ms

Figure A21 – A13004 T=150 ms

- The ATD was positioned with the torso upright and the legs vertical. The hands were placed on top of the thighs. This is the initial position used for seat qualification tests.
- The hands come forward in the early stage of the test and begin to push the seat back away from the occupant slightly. This seat back motion resulted in the head impacting just below the tray table latch and sliding down the seat back as it folded forward. The resulting HIC did not exceed the limit.
- The legs slid forward in unison with the knee translation. The seat cushion slipped forward during the test which apparently allowed the ATD to translate forward further than in a similar test (A12038). This resulted in knee and upper tibia contact with the lower seat back and seat frame, generating low femur compression loads. This interaction prevented the lower legs from flailing forward, but caused significant bending in the left upper tibia (TI of 1.37) and right femur (positive Y-Axis moment of 3,518 in-lb). The TI exceeded the limit and the Y-Axis moment was relatively high.

Braced position with arms on seat back, energy absorbing seat back, legs back, with a front row occupant
(Figures A22 to A24)

Figure A22 – A13005 T=0 ms

Figure A23 – A13005 T=130 ms

Figure A24 – A13005 T=170 ms

- The ATD is positioned with the torso forward and head against the seat back. The hands are resting on the top of the seat back in front, and the legs are back as far as was allowed by the baggage bar. This is the same setup and seat configuration as test A13003, but this test also included a front occupant to assess the interaction between the seat back and the occupant.

- As the ATD rotated forward, the elbows pressed against the seat back in front pushing it away from the rear occupant until the seat back contacted the back of the front row occupant. This interaction limited the seat back forward rotation so the rear occupant hit higher on the seat back than in test A13003. The head hit towards the bottom of the tray table resulting in a HIC of 760 which was significantly less than the HIC of 1095 registered in the test without an occupied front seat (test A13003).

- The feet slid forward very little and the knees translated forward and contacted the seat back but did not result in significant femur compression loads. The lower legs did not flail forward after contact. As the torso and pelvis rotated forward, a positive Y-axis moment was generated in the right femur (2,650 in-lb), that was relatively high. This is a similar response as in test A13003.

Upright position, full break-over seat, legs back, and a rigid knee contact plate.
(Figures A25 to A27)

Figure A25 – A13007 T=0 ms

Figure A26 – A13007 T=100 ms

Figure A27 – A13007 T=190 ms

- The ATD was positioned with the torso upright and the legs back. The hands were placed on top of the thighs, and the legs were as far back as was allowed by the baggage bar. A vertical rigid plate was attached to the back of the front seat frame in the knee strike zone.

- After the knees struck the seat, the tray table was released. As the ATD moved forward, the hands contacted the seat back, pushing it forward some, creating a gap between it and the loose tray table, which remained upright. As the ATD continued forward, the neck contacted the tray table which became caught under the ATD's chin. This interaction produced a significant loading of the neck (N_{ij} = 0.74) but did not exceed the limit. The table interaction did not prevent the ATD's head from impacting the seat back. That impact destroyed the table latch and produced a HIC of 920, which was near the limit.

- The ATD slid forward until the knees impacted the steel strike plate. This produced a high femur compressive force of very short duration followed by a lower oscillating force that continued until the ATD rebounded. After the knee impact, the feet slid forward until the lower legs were vertical. Both legs exhibited similar response, with femur peak loads of 1,337 lb on the right side and 1,949 lb on the left side which were both below the limit. The femur positive Y-Axis moments, however, were relatively high, with the right side producing 3,135 in-lb, and the left side 2,568 in-lb. This interaction with the strike plate prevented lower leg flailing which resulted in high moments in the left tibia. However, lower leg injury was not assessed for this test due to the unrealistic interaction between the lower leg and the knee strike plate.

Braced position with hands on top of head, energy absorbing seat back, legs back
(Figures A28 to A30)

Figure A28 – A13008 T=0 ms

Figure A29 – A13008 T=120 ms

Figure A30 – A13008 T=180 ms

- The ATD is positioned with the torso forward and head against the seat back. The hands are on the back of the head taped together to stay in place, and the legs are back as far as was allowed by the baggage bar.
- As the ATD rotated forward, the elbows pressed against the seat back in front, pushing it away from the occupant. This motion permits generation of significant relative velocity between the head and the seat back before it strikes just below the tray table (as in test A13001 and A13003). This seat back did not fold completely flat before the head impact. This likely provided more compliance in the area struck; resulting in the HIC of 411 which was less that measured in A13001 and A13003, and well below the limit.
- The right foot did not slide forward and the left foot slid forward until the lower leg was nearly vertical. The knees translated forward and contacted the seat back but did not generate significant femur compression. As the torso and pelvis rotated forward, a positive Y-axis moment was generated in the right femur (2,516 in-lb) that was relatively high. This is a similar response as in test A13003.

Pike position with hands on top of head, locked-out seat back, and legs back
(Figures A31 to A33)

Figure A31 – A13009 T=0 ms

Figure A32 – A13009 T=100 ms

Figure A33 – A13009 T=170 ms

- The ATD is positioned with the torso as far forwards as it can go with the abdominal insert removed. This position aligns the neck with the horizontal impact vector. The hands are on the back of the head taped together to stay in place and the legs back as far as allowed by the baggage bar. The seat pitch was increased to 38 inches to provide the necessary space for a 50th percentile occupant to assume this position. This setup was intended to emulate a small occupant that cannot brace against the seat back in front when seats are installed at a typical economy class pitch.

- The ATD's arms and top of head struck the middle of the tray table, forcing the seat back to fold over. The HIC and neck loads were all well below limits.

- The right foot did not slide forward and the left foot slid forward until the lower leg was nearly vertical. The knees translated forward but did not contact the seat back. As the torso and pelvis rotated forward, a positive Y-axis moment was generated in the right femur (2373 in-lb) that was relatively high.

Upright Position, locked-out seat back, no floor
(Figures A34 to A36)

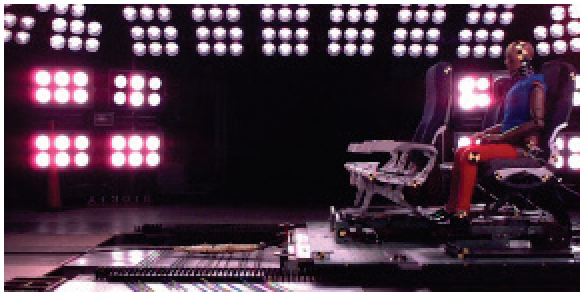

Figure A34 – A13010 T=0 ms

Figure A35 – A13010 T=120 ms

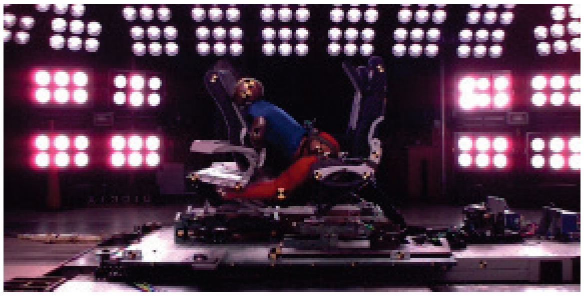

Figure A36 – A13010 T=160 ms

- The ATD was positioned with the torso upright and hands on top of the thighs. No floor was installed, allowing the legs to dangle vertically to emulate a shorter occupant whose feet will not contact the floor. The seat pitch (34 inches) was chosen to maximize the ankle velocity at the time of contact between the lower leg and the seat frame aft cross tube.

- The ATD's arms pushed the seat back slightly away from the occupant, as seen in previous tests, causing the head to strike the tray table latch. This impact released the table allowing it to catch under the ATD's chin. During a typical impact onto a seat back the head slides down after initial impact (as observed in test A12037). In this case, the contact between the ATD's chin and the top of the tray table prevented the sliding action and resulted in significant force applied to the chin. This did not produce a high HIC value but it did result in an upper neck tension of 893 lb which is very near the limit of 937 lb, and a very high N_{ij} value of 1.57, which is well over the limit.

- The lower legs translated forward in unison with the knee until the knee contacted the seatback without generating significant femur compression. The lower legs then flailed forward allowing tibia contact with the aft tube of the seat frame. The angle of the lower legs and the lack of a floor reaction surface permitted the knee to translate downward significantly as the torso as pelvis rotated forward. The calculated tibia indices for the right leg were higher than in test A13002 (which had a smaller, 30 in, seat pitch) while the tibia indices for the left leg were nearly identical to test A13002. All calculated tibia indices did not exceed the criteria limit.

Braced position with arms at side of legs, energy absorbing seat back, legs back
(Figures A36 to A38)

Figure A36 – A13011 T=0 ms

Figure A37 – A13011T =120 ms

Figure A38 – A13011 T=200 ms

- The ATD is positioned with the torso forward and head against the seat back. The hands are down at the side of the legs, and the legs are back as far as allowed by the baggage bar.
- As the ATD and seat back moved forward, the head remained in contact with the seat back. The arms contacted the bottom of the seat back and seat frame but did not appear to influence the motion of the seat back. This interaction produced a very low HIC of 224 and all the other recorded values were below the criteria limits.
- The right foot did not slide forward and the left foot slid forward until the lower leg was nearly vertical. The knees translated forward and contacted the seat back without generating significant femur compression. As the torso and pelvis rotated forward, a positive Y-axis moment was generated in the right and left femurs but both were relatively low.

Braced position with arms at side of legs, full break-over seat back, legs back
(Figures A39 to A41)

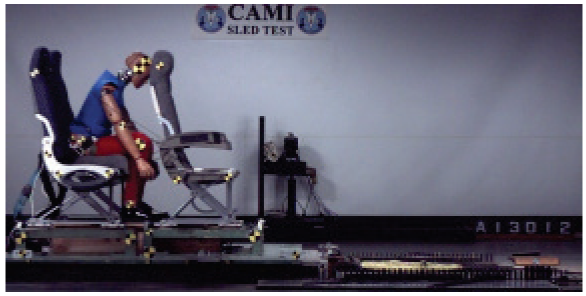

Figure A39 – A13012 T=0 ms

Figure A40 – A13012 T=120 ms

Figure A41 – A13012 T=180 ms

- The ATD is positioned with the torso forward and head against the seat back. The hands are down at the side of the legs, and the legs are back as far as allowed by the baggage bar.

- The ATD head initially remained in contact with the seat back as it folded forward. After the ATD torso reached about a 45 degree angle, the seat back rotated away from the ATD and the head impacted the seat back below the tray table. The arms contacted the bottom of the seat back and seat frame but did not appear to influence the motion of the seat back. Since the head and seat back moved in unison for much of the test, there was less time after the seat back moved away to generate relative velocity. This reduced impact velocity produced a very low HIC of 408 and all the other recorded values were below the criteria limits.

- The right foot did not slide forward and the left foot slid forward until the lower leg was nearly vertical. The knees translated forward and contacted the seat back without generating significant femur compression. As the torso and pelvis rotated forward, a positive Y-axis moment was generated in the right and left femurs but both were relatively low.

Braced position with arms at side of legs, locked out seat back, legs back
(Figures A42 to A44)

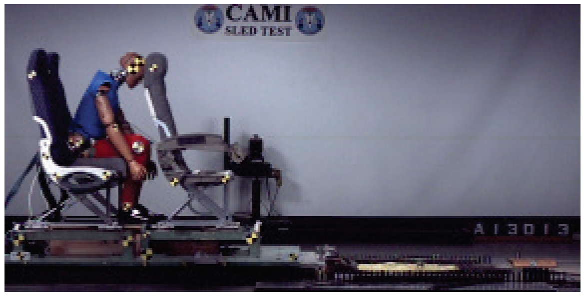

Figure A42 – A13013 T=0 ms

Figure A43 – A13013 T=120 ms

Figure A44 – A13013 T=170 ms

- The ATD is position with the torso forward and head against the seat back. The hands are down at the side of the legs, and the legs are back as far as allowed by the baggage bar.

- As the ATD and seat back moved forward, the head remained in contact with the seat back. The arms contacted the bottom of the seat back and seat frame but did not appear to influence the motion of the seat back. This interaction produced a very low HIC of 167, and all the other recorded values were below the criteria.

- The right foot did not slide forward and the left foot slid forward until the lower leg was nearly vertical. The knees translated forward and contacted the seat back without generating significant femur compression. As the torso and pelvis rotated forward, a positive Y-axis moment was generated in the right and left femurs but both were relatively low.

Pike position with arms down at sides, legs back, rigidly supported fiberglass faced, Nomex® honeycomb wall (Figures A45 to A47)

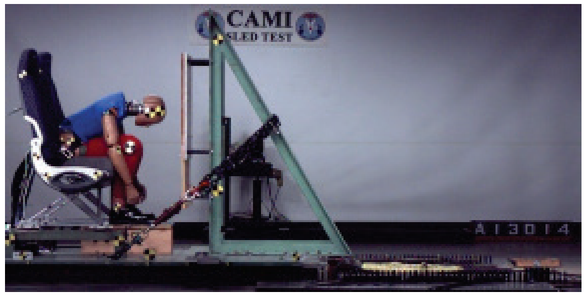

Figure A45 – A13014 T=0 ms

Figure A46 – A13014 T=90 ms

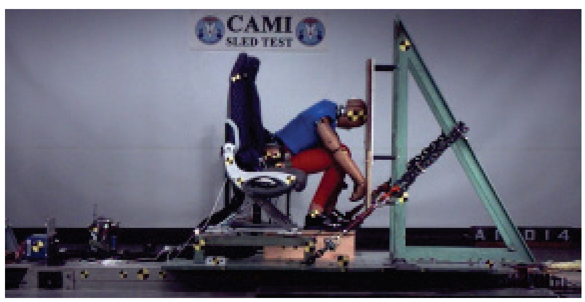

Figure A47 – A13014 T=130 ms

- The ATD is positioned with the torso as far forward as it can go with the abdominal insert removed. This position aligns the neck with the horizontal impact vector. The hands are down at the side of the legs and the legs back as far as were allowed by the baggage bar. A 1.0 in thick fiberglass faced Nomex® honeycomb panel, rigidly supported by a 0.5 in thick aluminum plate, was positioned 35 inches from the SRP.

- The ATD slid forward in the seat until the top of the head contacted the wall. The rest of the body continued to translate forward, compressing the neck visibly. The ATD hit the wall with the neck almost perfectly horizontal (a worst case condition for neck compressive loads). The N_{ij} value was 2.02 and the upper neck compressive force was 2,399 lb, both of which are over twice the criteria limits of 1.0 and 899 lb, respectively. However, the HIC was only 211 due to the very low impact velocity.

- The right foot did not slide forward and the left foot slid forward until the lower leg was nearly vertical. The knees translated forward but did not contact the wall. Y-axis moment in both legs was relatively low. This is likely because the torso was initially flexed forward, reducing the tendency for the pelvis to rotate forward during impact and in-turn induce the femur bending.

Pike position with arms down at sides, legs back, rigidly supported fiberglass faced, Nomex® honeycomb wall, and y-belt type restraint
(Figures A48 to A50)

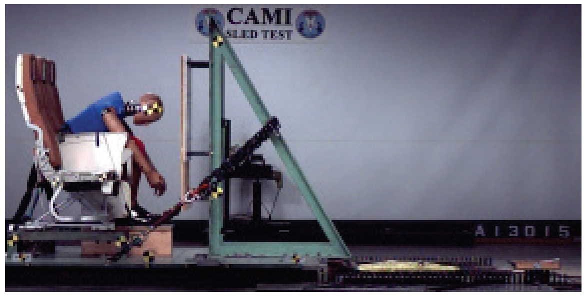

Figure A48 – A13015 T=0 ms

Figure A49 – A13015 T=90 ms

Figure A50 – A13015 T=120 ms

- The ATD is positioned with the torso as far forwards as it can go with the abdominal insert removed. This position aligns the neck with the horizontal impact vector. The hands are down at the side of the legs and the legs back as far as were allowed by the baggage bar. A 1.0 in thick fiberglass faced Nomex® honeycomb panel, rigidly supported by a 0.5 in thick aluminum plate, was positioned 35 in from the seat reference point. The seat belt was a y-belt of the type typically used in front row applications to limit forward translation of the occupant.

- The y-belt effectively limited the occupant horizontal head excursion to five inches from the initial position, which did not allow the ATD to contact the wall in front.

- Neither foot slid forward and the Y-axis moment in both legs was relatively low.