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Lumbar Load Variability in Dynamic Testing of Transport Category Aircraft Seat Cushions

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16. Abstract

The Federal Aviation Administration (FAA) has standards and regulations in place that require aircraft seating systems protect occupants in the event of a crash. These standards require dynamic testing to substantiate the safety of seating systems. In a vertical impact, the seat bottom cushion plays a vital role in controlling the load transferred to the occupant's spine. Repeat testing has identified large test uncertainty. To identify the source and magnitude of the observed uncertainty, existing data was combined with a series of tests specifically designed to evaluate these factors. The analysis identified that a significant amount of irreducible test uncertainty was inherent to the test method and type of Anthropomorphic Test Devices (ATDs). The maximum observed uncertainty was 340 lb and appears to be a function of the specific foam tested. This amount of load uncertainty corresponds to an injury risk probability range of 40%. The testing also identified areas of reducible uncertainty that can be minimized by controlling certain variables. These include ATD initial position, ATD construction consistency and degradation, and ATD interactions with armrests. Reducible uncertainty may have a larger effect on the lumbar load than the irreducible uncertainty. These results highlight the need for a standardized vertical calibration for ATDs used in vertical tests. Analysis of the results led to a better understanding of testing uncertainty and to the development of best practices for minimizing test uncertainty. These best practices are provided as an Appendix to this report.

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BACKGROUND

The Federal Aviation Administration (FAA) has regulations in place that require aircraft seating systems protect occupants in the event of a crash. Dynamic testing is required by these regulations in order to substantiate the safety of seating systems. One of the two dynamic tests required is a primarily vertical impact with a minimum impact velocity of 35 ft/s, a peak acceleration of 14 G and an impact angle of 30° off vertical. In this test, the principal measurement is the compressive load in the lumbar spinal column, which has a regulatory limit of 1500 lb [1]. During this vertical impact, the seat bottom cushion plays a vital role in controlling the load transferred to the occupant's spine, and therefore the risk of injury. When seat cushions wear and need replacement, the original foam is not always available. Foam formulation changes and economic factors may make it necessary to substitute foam materials when producing replacement cushions. The current approach to substantiate the performance of the new multi-layer cushion construction is to repeat the full-scale dynamic test as a system with the seat and new cushion. A simplified means of showing compliance would facilitate both cushion replacement to maintain safety and development of cushions that provide a higher level of safety. One proposed methodology is to compare the replacement cushion with the original cushion on a rigid seat, similar to the existing restraint replacement methodology [2]. The expectation is that the rigid seat tests would show the same lumbar load trend as observed in the real seat tests. That is, if cushion "A" had a larger lumbar load than cushion "B" when tested on a rigid representation of that seat, then the same should be true when tested on a real seat. Rigid seat mockups are often used by researchers to study the performance of seat belts or seat cushions independent of the seat frame flexion that occurs in dynamic tests with real seat assemblies [3, 4, 5]. These studies are predicated on the hypothesis that rigid seat dynamic test results are repeatable, reproducible, and indicate the relative performance between restraint or seat cushions when installed in a real seat. That hypothesis can only be proved when the signal (differences in lumbar load between cushions) is greater than the noise (variability due to other factors). This proposed methodology was evaluated by the FAA Civil Aerospace Medical Institute (CAMI) via a series of sled tests using real and rigid seats and cushions made from a variety of typical aircraft foams. Large test uncertainty thwarted the original goal of this project because the variability obscured the differences between the tested cushions.

Lumbar Spine Injury

During vertical loading, the most vulnerable portion of the body is the lumbar spine. The injuries expected are those resulting from spinal compression and include vertebral disc disruptions and herniations, avulsions, and wedge fractures to the spinal bodies. While some of these may be moderate, some can be serious and cause extensive complications, including impeding the ability to quickly evacuate the aircraft. The lumbar load criteria cited in the regulations is based on the Dynamic Response Index (DRI). The DRI model represents the spinal column of the human occupant as a lumped mass-spring-damper model [6]. Input to the model consists of seat pan accelerations and model output consists of the deflection time history of the DRI system. The maximum value of the DRI response is the parameter of interest. This value was correlated with operational injury data from military ejections (Figure 1). Specific injuries are not reported; instead, the term "detectable injuries" is used. The cadaver injuries are reported as vertebral compression fractures, implying that these curves both represent AIS 2+ injuries [7]. The operational data has a DRI in the range of 16-20, resulting in spinal injury rates of about 1% to 20%. These injury rates are specific to the military pilot population in the seat and restraint systems in use at the time of the study (1960s). The cadaver data is likely based on an older, less healthy population. The trendline for the cadaver data suggests that this population has a higher risk of injury for the same DRI. Recent studies also suggest that modern seat and restraint systems and the modern military pilot population have a higher risk than the original data [8, 9].

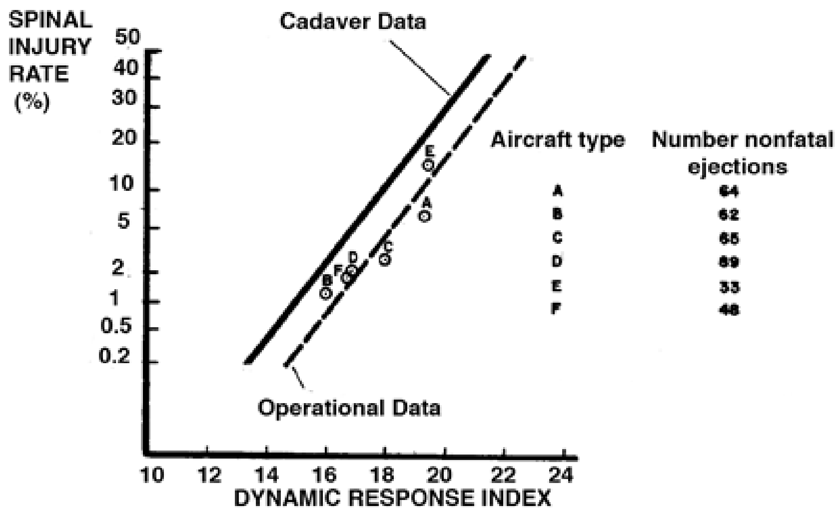

Figure 1 – Spinal Injury vs DRI [6]

The primary limitation of the DRI model is that it was derived for seats with nearly rigid seat pans with only a small amount of firm cushioning and a typical ejection seat restraint system. Therefore, it is not directly applicable to typical aircraft seats that have compliant seat pans and cushions. To address these issues, the FAA developed a lumbar load tolerance value. Since load in the lumbar region is the primary factor causing injuries, it was surmised that a criterion based directly on measured lumbar load response was prudent. To determine the threshold, the FAA conducted a series of dynamic impact tests using aviation-specific pulses [10]. These tests included an energy-absorbing seat with a rigid seat pan and an Anthropomorphic Test Device (ATD) that was modified to collect lumbar loads. For each test, a lumbar load was measured and the DRI of the test condition was calculated (Figure 2). Based upon this correlation, a lumbar load of 1500 lb measured in the Hybrid II ATD was correlated to a DRI of 19, or approximately a 9% risk of a detectable spinal injury in the original military population. By combining the data in Figure 1 and 2, lumbar load can be related directly to the probability of spinal injury for a range of risks (Table 1). Due to the logarithmic nature of the injury rate, small changes in load can have a large effect on the injury risk. The risk is likely larger for the general public, but the specific value is unknown.

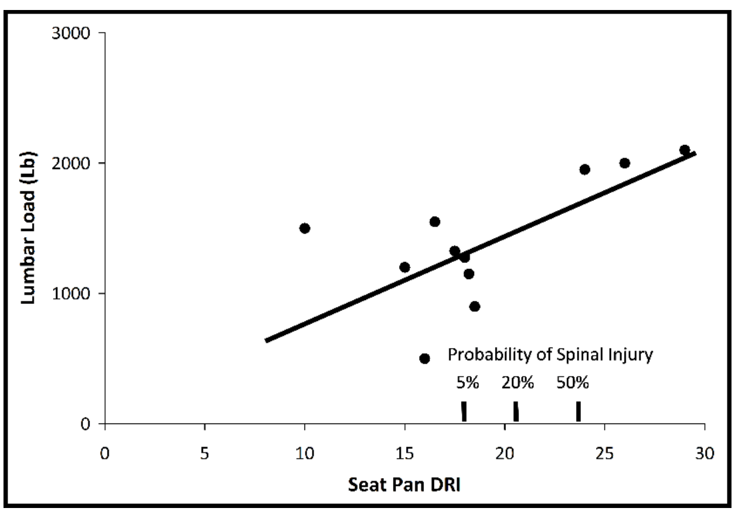

Figure 2 - Lumbar Load vs DRI [8]

Table 1 - Spinal Injury Risk, DRI, and Lumbar Load

Spinal Injury Risk (%)	DRI Operational Trendline	Lumbar Load (lb)
1	16	1330
5	18	1450
9	19	1500
20	20	1580
40	22	1670
50	23	1710

GENERAL METHODS

The original research protocol consisted of a straightforward comparison between tests of cushions on real seats and tests of the same cushions on a rigid representation of the seats. The expectation was that the rigid seat tests would show the same lumbar load trend as observed in the real seat tests. Initial results, however, did not exhibit this trend but, instead, appeared to be somewhat random. Since a source of these inconsistent results is test uncertainty, it was decided to analyze the available data from this and previous research projects to determine the sources and magnitude of the observed uncertainty. The analysis focused on quantifying areas of irreducible uncertainty inherent to the test articles or test devices used and on identifying areas of reducible uncertainty that can be minimized by controlling certain variables.

As new issues were discovered, the test plan was modified to isolate the specific test variables of concern. For example, when testing a three-place seat, significant differences in lumbar load were observed that appeared to be due to ATD contact with the armrests. Following this observation, additional tests were run in which ATD-to-armrest interaction was varied. For most evaluations, three repetitions were used, however, due to a limitation of test articles, some configurations were only run once or twice. For cushions that were tested more than once, the cushion was rotated, and sometimes flipped, to provide a different area for loading by the ischial tuberosities, which are the primary weight bearing points of a seated pelvis. All tests were conducted on the deceleration sled at CAMI. Due to the ad hoc nature of this test series, this report presents the general test methods first and then the specific evaluations and their results in a subsequent section. Because the data from a test could enlighten more than one uncertainty factor, many tests appear in multiple subsections.

Test Device

The Anthropomorphic Test Devices (ATDs) used to assess injury risk were two 50th percentile male sized Hybrid IIs as specified in the regulations for civil aircraft seat tests [1] and one FAA Hybrid III, which is an approved equivalent to the Hybrid II [11, 12]. The two Hybrid II ATDs used for this series were serial number 680 (ATD 1) and serial number 10 (ATD 2). For one uncertainty factor, an FAA Hybrid III was also used. This ATD was serial number 122 (ATD 3).

Seat Types

Rigid Seat Fixture

A rigid seat test fixture with its horizontal (aircraft longitudinal) axis pitched up 30° with respect to the sled vertical was used to emulate the pertinent characteristics of real seats while eliminating as much variability as possible in the test set up (Figure 3). This seat had a seat back with an angle of 13° with respect to the aircraft vertical and a flat seat pan with an angle of 5° with respect to the horizontal. The seat pan was sized to fit the cushion being evaluated. For rectangular block cushions, a simple flat aluminum pan was used. For tests of cushions from seats that did not have a flat seat pan, a rigid pan having the same shape as the real seat pan was used. The shape of the real seat pan was measured when occupied by an ATD applying a 1-G load, then that shape was replicated by adding wood to the rigid seats pan (Figure 4). The rigid seat pan mockup was shaped such that it supported the tested cushion in a uniform manner just as when installed on the real seat and was effectively rigid. This insured that initial force/deflection properties of the cushion would be the same as the real seat. The seat back position of the rigid seat was adjusted by adding a cloth-covered, closed cell foam shim so that the ATD pelvis was in the same fore/aft position relative to the cushion as when seated on the real seat. A floor was included to produce a realistic force distribution between the pelvis and the feet. The simulated floor used with the rigid seat was adjusted so that the distance between the hip point (or H-point) and the center of the ankle was the same as the 1-G seated position, approximately 13 inches. The H-point of the ATD lies on a line passing through the center of both hip ball and socket joints of the ATD.

Figure 3 – Rigid Seat Fixture

Real Seat with Contoured Aluminum Seat Pan

One of the seats being emulated was a triple place, economy class seat with two supporting legs and a contoured aluminum seat pan (hereafter referred to as the contoured seat pan) (Figure 4). The seat pans were stamped aluminum with a compound concave shape, attached at the front and rear to the seat frame cross tubes. The seat legs were placed under the left side of the first seat place and under the left side of the third seat place. This resulted in the first seat place being supported on one side (a cantilevered condition). The center and third seat places were supported at each side but not between them (a partially supported condition). For some comparison tests, the armrests were down, for others, they were folded up out of the way to evaluate the effect of an alternate load path for the ATD.


Figure 4 – Top: Contoured Aluminum Seat Pan, Bottom: Contoured Rigid Pan Mockup

Real Seat with Cloth Seat Pan

Another seat being emulated was a triple place, economy class seat with two supporting legs and a relatively flexible cloth pan. The front of the seat pan was attached to the seat frame front cross tube and the rear of the pan was attached to a small tube behind the rear seat frame cross tube (Figure 5). This pan was initially flat and taut. When occupied by the ATD, the pan deflected 1.1 inches in the middle and assumed a uniformly curved shape. The seat legs were placed under the left side of the first seat place, and under the left side of the center seat place. This resulted in seat places one and three both being supported on only one side (a cantilevered condition). The center seat place was supported on each side (a simply supported condition). The armrests were removed for all comparison tests.

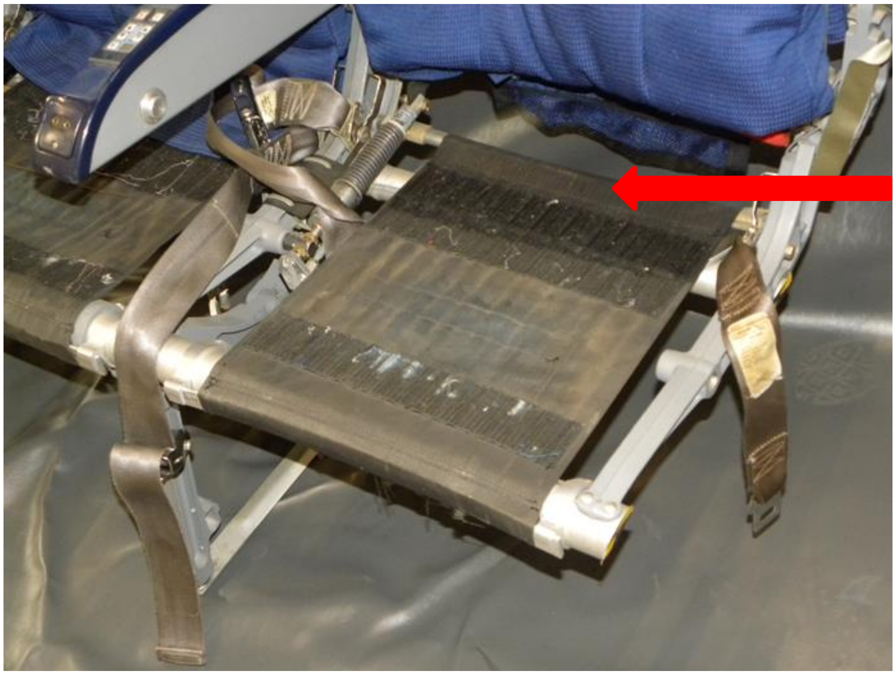

Figure 5 – Flexible Cloth Seat Pan with Small Attachment Tube (arrow)

ATD Seating Method

Both the rigid seat and the real seats used for this series were pitched up at a 60° angle during the test. The nominal upright ATD seated position (1-G position) was determined with respect to the seat cushion for each test article prior to testing. This measurement was made in the real seat, the rigid seat, or a surrogate wooden seat with pan and back angles and floor height identical to the tested seat (Figure 6). The same ATD and cushion was used for this measurement as was used during the dynamic test.

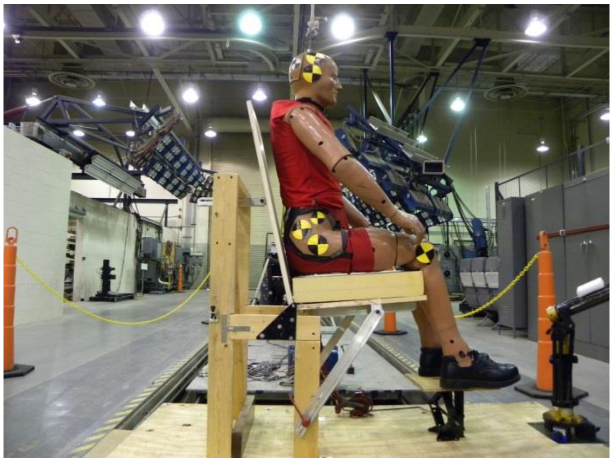

Figure 6 - ATD on Wooden 1-G Seating Fixture

For these tests, target markers centered on the H-point were placed on the surface of the pelvis [13]. Auxiliary targets were placed directly above this target to permit deriving its location when obscured, and to determine the rotation angle of the pelvis (Figure 6). Alternatively, a tool can be used to locate the H-point, and sensors are available that provide a real-time output of ATD body segment angles. A three-dimensional measuring machine was used to record the ATD head center of gravity photometric target, as well as the H-point and vertical pelvis targets. These measurements were used to derive the pelvic angle (i.e. orientation of the pelvis) and torso angle (based on a line between the head CG and H-point). The origin selected for the seating on the rigid seat was the intersection of the rigid seat pan and seat back, which could be easily located on both the rigid test seat and the wooden surrogate. The origin selected for the real seat measurements was a point that was common to both the real seat and the rigid seat replica, such as a point on the seat pan upper surface.

Both the 1-G position and pre-test seating procedures improved as the test series progressed. Initially, the ATD was placed for measuring the 1-G seated location following the basic AS8049B procedure and only the pelvic z location was controlled in the sled test setup (tests A09001 – A10011). In all subsequent tests, the 1-G seating procedure included pushing the ATD rearward with a specific force as it was being lowered. This resulted in a very consistent fore/aft position and initial pelvis angle [13]. For each test condition, the ATD was seated and measured three times, and the average of these values was used as the goal.

The final 1-G seating procedure developed involves suspending the ATD above the seat cushion just enough to insert a flat hand (approximately 1 inch) between the bottom of the pelvis and the cushion. A rigid bar is then inserted under the thighs just aft of the knees and used to elevate them slightly so as not to interfere with the ATD self-aligning. A force 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. The recommended seating method in SAE AS8049C now reflects this procedure [14].

The 1-G position data were then used to place the ATD in the correct fore-aft and vertical position in the pitched up seat. The current laboratory procedure sets an initial goal to meet an inner tolerance of ±0.1 inch for the pelvis H-point (X and Z coordinates), ±1° for the pelvis angle, and ±2° for the torso angle. If this inner tolerance is not met after several attempts, an outer tolerance of ±0.2 inch for the pelvis H-point, ±2° for the pelvis angle, and ±5° for the torso angle is acceptable. If the outer tolerance is not met, the test is normally not run. In 11 of the 43 tests the inner tolerance was not met, however in no test did the z-component of the H-pt goal exceed 0.3 inch. Achieving this initial position required insertion of cloth covered, closed cell foam shim behind the ATD to maintain the fore-aft position and significant tension in the lap belt to maintain the vertical position. Controlling the fore/aft position is important if the cushion is tapered, not homogenous in construction, or if the seat frame does not provide uniform support for the seat cushion along the seat fore/aft axis.

Test Severity

A triangular shaped impact pulse with acceleration and velocity change goals of 14 Gs and 35 ft/s was used (Figure 7). This test severity corresponds to the combined horizontal/vertical tests specified in 14 CFR 25.562 [1].

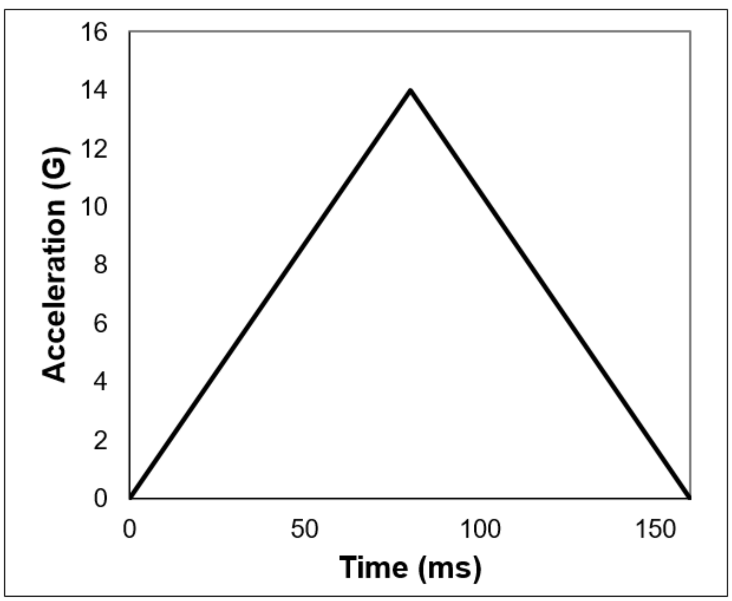

Figure 7 - Ideal 14 G acceleration pulse

Instrumentation

Electronic instrumentation

The sled, ATD, and rigid seat were instrumented as shown in Table 2. For this project, the seat pan was instrumented with a load cell to evaluate the manner in which the ATD loads into the rigid seat. The test data was gathered and filtered per the requirements of SAE J211-1 [15]. The sign convention of the recorded signals conformed to SAE J1733 [16].

Table 2 - Instrumentation List

Description	Filter Class	Range	Units
Sled Acceleration	60	25	G
Aux Sled Acceleration	60	25	G
Lumbar Fx	600	3000	lb
Lumbar Fz	600	5000	lb
Lumbar My	600	10000	in-lb
Thorax Ax	600	2000	G
Thorax Az	600	2000	G
Pelvis Ax	600	500	G
Pelvis Ay	600	500	G
Pelvis Az	600	500	G
Seat Pan Load Cell Fx*	60	10000	lb
Seat Pan Load Cell Fy*	60	10000	lb
Seat Pan Load Cell Fz*	60	10000	lb
Seat Pan Load Cell Mx*	60	25000	in-lb
Seat Pan Load Cell My*	60	25000	in-lb
Seat Pan Load Cell Mz*	60	25000	in-lb

* Rigid seat only

Video coverage

High-speed (1000 frames per second), 512 x 1024 resolution color video was captured from each side by cameras aimed perpendicular to the sled (Phantom 5 series, Vision Research, Wayne, NJ). Targets were placed on the ATD at the head center of gravity, the side of the pelvis at the hip joint, two auxiliary H-point locations, and on a rigid plate mounted to the knee joint. Targets were also placed on rigid structures for scaling and for subtracting relative motion between the sled and the camera.

Restraint

A standard 2-point lap belt was used to restrain the ATD as well as hold the ATD in the nominal 1-G seating position. For rigid seat tests that did not have corresponding real seat tests, the belt anchors were 4.25 inch forward and 1.0 inch below the pan/back intersection. This location is further forward than typical for aircraft seats but was chosen to facilitate observation of pelvis motion and to provide a means to maintain the necessary initial ATD preload into the cushion. For rigid seat tests intended to emulate a real seat configuration, the anchor location for rigid seat tests was in the same relative location with respect to the seat cushion as on the real seat. This was done because the combined vertical/horizontal test has a significant horizontal component and the anchor location may affect pelvis rotation and horizontal translation.

Cushions

For generic rigid seat tests, the cushion was made up from rectangular blocks of foam. For rigid seat tests emulating a specific real seat, entire seat cushion assemblies, complete with dress cover, were used. Table 3 summarizes the construction of these cushion assemblies. Cushions B, C, and D were constructed with materials commonly used for aircraft seat bottom cushions. The P and R cushions were original equipment manufacturer (OEM) for the seats. The specifics of their construction is unknown. The intent was to test a set of cushions that provided a range of lumbar loads in order to detect trends in the results. Rate-sensitive foams were not evaluated.

Table 3 – Real Seat Test Cushion Construction

Cushion	Description
B	2-inch thick top layer of medium density, high resiliency foam + 2 inch thick bottom layer of high density, progressive stiffness foam (Firm-PS).
C	3-inch thick top layer of medium density, high resiliency foam + 0.5-inch thick bottom layer of closed cell flotation foam, 2.2 lb/cu ft.
D	2-inch thick top layer of medium density, high initial stiffness foam (Med-HIS) + 2-inch thick bottom layer of closed cell flotation foam 2.2 lb/cu ft.
P	An OEM prototype cushion of unknown construction for the real seat with the cloth seat pan.
R	An OEM prototype cushion of unknown construction for the real seat with the contoured aluminum seat pan.

Data Processing

The lumbar loads were gathered and filtered using CFC 600 and normalized to the test goal G-peak as allowed in AS8049C [14]. This procedure adjusts the recorded lumbar load value by multiplying it by the ratio of the acceleration goal divided by the measured peak acceleration occurring prior to the lumbar load peak. This adjustment is done to compensate for small differences in test severity when comparing results. In some cases, the lumbar load peak occurred prior to the sled acceleration reaching the 14 G peak goal. For those cases, no normalization was done. Seat pan loads were tare corrected to eliminate the inertial effect of the fixture and internal load cell mass.

SPECIFIC EVALUATIONS AND RESULTS

Irreducible Test Uncertainty Quantification

Real world systems always contain uncertainty. This inherent uncertainty is formally called aleatory uncertainty and is considered irreducible because no matter how much data is gathered, the variability will always remain. A common example of irreducible uncertainty is variability of material properties. The following section quantifies some of the irreducible uncertainty associated with running a combined horizontal-vertical impact test.

Test Uncertainty Due to the Test Method

To assess lumbar load variability that results from the test method, tests were run with the same physical cushion and the same ATD. In between tests, the cushion was rotated, and sometimes flipped, to provide a different area for loading by the ischial tuberosities, which are the primary weight-bearing surfaces of a seated pelvis. This method removes sources of variability such as variation from one foam sample to another and ATD differences. By normalizing the lumbar load by the measured peak acceleration when necessary, the impact of the test pulse variation is reduced. Table 4 shows a cushion that produced a small range of peak lumbar load.

Table 4 - Test Method Uncertainty – 4.0" Thick Low Density, Progressive Stiffness Foam (Soft-PS)

	H-point X position (in)	H-point Z position (in)	H-point Angle (deg)	Sled Pulse Peak (g)	Lumbar Fz Normalized (lb)	Group Range (lb)
Goal	3.35	4.81	-11.0	14.0	-	-
A11024	3.15	4.85	-11.0	15.3	1292	63
A11025	3.15	4.90	-10.6	15.1	1270	
A11026	3.25	4.83	-10.8	15.6	1229	

Table 5 shows the cushion that produced the largest range of peak lumbar load. The test with the highest load had the lowest sled peak and the test with the lowest load had the highest sled peak, suggesting that, if anything, the data normalization increased the apparent scatter. Also, the test with the greatest deviation in H-point Z position relative to the goal produced a lumbar load in the middle of the range. The tests with the highest and lowest loads had very similar ATD initial positioning, only differing in pelvic angle (less than 1.5 degrees). Taken together, these two tables suggest that test variability is a function of the specific cushion and that well-controlled repeated tests can vary as much as 340 lb.

Table 5 - Test Method Uncertainty - 3.5” Thick, Medium Density, High Initial Stiffness Foam (Med-HIS)

	H-point X position (in)	H-point Z position (in)	H-point Angle (deg)	Sled Pulse Peak (g)	Lumbar Fz Normalized (lb)	Group Range (lb)
Goal	3.28	7.19	-12.0	14.0	-	-
A10002	3.49	7.13	-11.5	15.4	1599	342
A10003	3.54	6.90	-11.5	14.7	1865	
A10004	3.45	7.13	-12.9	14.5	1941	
A10005	3.49	7.15	-11.7	14.5	1908	

Test Uncertainty Due to Test Method Across Cushion Foam Types

Based on the above results, a series of repeated rigid seat tests were analyzed to determine how much the test method uncertainty varied across cushion foam types (Table 6). As in the previous group, these tests were conducted using one cushion article and one ATD. In between tests, the cushion was rotated, and sometimes flipped, to provide a different area for loading by the ischial tuberosities. For this evaluation, only cushions with a thickness of 4 inches to 4.5 inches were included in order to remove cushion thickness as a variable. The observed variability ranged from 63 lb to 197 lb.

Table 6 – Test Method Uncertainty by Foam Type

Test	ATD	Cushion	Thickness (inches)	Lumbar Fz Normalized (pounds)	Group Avg	Group Range
A09001	1	Firm-PS	4.60	1042	1011	63
A09004	1	Firm-PS	4.60	979		
A09005	1	Med-PS	4.50	1433	1381	84
A09006	1	Med-PS	4.50	1360		
A09007	1	Med-PS	4.50	1349		
A11024	1	Soft-PS	4.00	1292	1264	63
A11025	1	Soft-PS	4.00	1270		
A11026	1	Soft-PS	4.00	1229		
A10009	1	Med-HIS	4.50	1796	1887	197
A10010	1	Med-HIS	4.50	1873		
A10011	1	Med-HIS	4.50	1993		

Test Uncertainty Due to Test Method Across Cushion Foam Thickness

Next, the effect of cushion thickness on the observed variability was analyzed (Table 7). As before, the same physical cushion and the same ATD were used for each group of tests. In between tests, the cushion was rotated, and sometimes flipped, to provide a different area for loading by the ischial tuberosities. The observed variability ranged from 157 lb to 342 lb, with no clear trend indicated.

Table 7 – Test Method Uncertainty by Foam Thickness

Test	ATD	Cushion	Thickness (inches)	Lumbar Fz Normalized (pounds)	Group Avg	Group Range
A10009	1	Med-HIS	4.50	1796	1887	197
A10010	1	Med-HIS	4.50	1873		
A10011	1	Med-HIS	4.50	1993		

Test	ATD	Cushion	Thickness (inches)	Lumbar Fz Normalized (pounds)	Group Avg	Group Range
A10002	1	Med-HIS	3.50	1599	1828	342
A10003	1	Med-HIS	3.50	1865		
A10004	1	Med-HIS	3.50	1941		
A10005	1	Med-HIS	3.50	1908		
A10006	1	Med-HIS	2.00	1526	1537	157
A10007	1	Med-HIS	2.00	1621		
A10008	1	Med-HIS	2.00	1464		

Test Uncertainty Due to Test Method With and Without Leather Dress Cover

To assess lumbar load variability relative to whether a foam is bare or covered, one cushion type was tested with and without a leather dress cover (Table 8). The same physical cushion and the same ATD were used for each group of tests. In between tests, the cushion was rotated, and sometimes flipped, to provide a different area for loading by the ischial tuberosities. The observed variability ranged from 85 lb for the bare foam to 60 lb for the covered foam.

Table 8 – Test Method Uncertainty With and Without Leather Dress Cover

Test	ATD	Cushion	Thickness (inches)	Lumbar Fz Normalized (pounds)	Group Range
A09005	1	Med-PSUncovered	4.50	1433	85
A09006	1	Med-PSUncovered	4.50	1360	
A09007	1	Med-PSUncovered	4.50	1348	
A09008	1	Med-PSCovered	4.50	1178	60
A09009	1	Med-PSCovered	4.50	1238	
A10001	1	Med-PSCovered	4.50	1194	

Test Uncertainty Due to Cushion Variation

To assess lumbar load variability due to the inherent variability in cushion articles, rigid seat tests were conducted with a variety of OEM cushions and built-up cushions made from commonly used foam materials (Table 9). For each test, a fresh cushion test article was used. It is unknown whether the foams were from a single batch or multiple batches. Within the cushion group, the same ATD was used for each test, however, two different ATDs were used to complete these tests. The "B" and "C" cushion buildups, and the "R" OEM prototype cushion showed low variability (less than 14 lb variation). The "D" cushion buildup and the "P" OEM prototype cushion showed large variability (over 158 lb). This data suggests that lumbar load variability can be quite different for each cushion material and combination of materials. However, cushion "D" provides a useful reminder that the reported values may not be the true variability. If only tests A12007 and A12010 were analyzed, then the range would be reported as 13 lb (similar to the value for cushion "R"). The inclusion of test A12008 increased the range to 126 lb even though the pelvic initial positions differed by only 0.06" in Z. Considering that the three cushions with the smallest range are also the three cushions that were only tested twice, it is important to note that there should be low confidence in the cushion variability observed from a limited sample. The true variation due to the cushion is potentially higher than what can be observed by three tests or less.

Table 9 - Cushion Variability (values in pounds)

Test	ATD	Cushion #	Lumbar Fz Normalized	Group Avg	Group Range
A11040	1	R1	1936	1929	14
A11042	1	R3	1922		
A11049	1	P1	1690	1776	158
A11050	1	P2	1790		
A11051	1	P3	1848		
A11052	1	C4	1989	2002	25
A11053	1	C5	2014		
A12005	2	B4	1346	1356	19
A12009	2	B5	1365		
A12007	2	D4	1594	1628	126
A12008	2	D5	1708		
A12010	2	D6	1581		

Reducible Test Uncertainty Quantification

In addition to irreducible uncertainty, a lack of knowledge of the process under study can also contribute to uncertainty. This knowledge uncertainty is formally called epistemic uncertainty and is considered reducible because additional data can, in theory, decrease the amount of variability. A common example of reducible uncertainty is control of initial conditions. The following section provides data on some sources of reducible test uncertainty.

Test Uncertainty Due to ATD Initial Position

To evaluate how much ATD initial compression affects lumbar load, tests were compared where the ATD was preloaded into the cushion correctly (i.e. the same as when seated upright) with tests where the ATD was seated 1 inch higher (preloaded less). Cushions consisting of a relatively soft 4.0 inch thick, low density, progressive stiffness foam with no cover were used for these tests. The same ATD (number 1) was used to determine the 1-G position and for all dynamic tests. Each test condition was run three times with the same cushion sample. The 1-inch preload difference had a considerable effect on the lumbar load with the incorrectly seated test having 399 lb higher average lumbar load than the tests with the correctly seated ATD (Table 10). This difference is over twice the cushion variability (151 lb).

Table 10 – Test Uncertainty Due to ATD Initial Position

Test	ATD	Cushion	Thickness (inches)	Lumbar Fz Normalized (pounds)	Group Avg	Group Range	Fz Difference (pounds)
A11024	1	Soft-PS	4.00	1292	1264	63	399
A11025	1	Soft-PS	4.00	1270			
A11026	1	Soft-PS	4.00	1229			
A11023	1	Soft-PS+1	4.00	1640	1663	151	
A11033	1	Soft-PS+1	4.00	1599			
A11034	1	Soft-PS+1	4.00	1750			

Test Uncertainty Due to ATD Differences

The effect that ATD differences can have on test uncertainty was assessed by testing three custom built up cushions on the rigid seat using two ATDs, applying an H-point goal specific to each ATD and cushion test article. For all three cushions, ATD 1 produced a higher lumbar load than ATD 2 (Table 11). The difference in peak lumbar load ranged from 196 lb to 394 lb and exceeds the expected load variability due to the documented variability for each cushion assembly (Table 9). To investigate the cause, the ATDs' 1-G position when seated on the cushions and a flat plate was compared (Table 12).

Table 11 – Test Uncertainty Due to ATD Differences (values in pounds)

Test	ATD	Cushion #	Lumbar Fz Normalized	Group Avg	ATD Diff
A12003	1	B7	1750	1750	394
A12005	2	B4	1346	1356	
A12009	2	B5	1365		
A11052	1	C4	1989	2002	379
A11053	1	C5	2014		
A12006	2	C7	1623	1623	
A12002	1	D7	1824	1824	196
A12007	2	D4	1594	1628	
A12008	2	D5	1708		
A12010	2	D6	1581		

The height of the H-point above the pan was about 0.5 inch greater for ATD 1 than ATD 2 for all conditions. The thickness of foam and rubber on the bottom of the pelvis is not regulated in the Hybrid-II specifications and the factory tolerance for this dimension is relatively large (±0.2 inch).[1] Since the pelvis foam is quite soft, this height difference could be the primary source of the load difference. The thicker foam could be considered analogous to being seated with insufficient preload into the cushion, which has been shown to result in higher lumbar loads.

Table 12 – ATD H-point Height Variance (values in inches)

Cushion	ATD	H-point Height	Group Difference
No Cushion	1	3.94	0.47
No Cushion	2	3.47	
Cushion B	1	8.23	0.43
Cushion B	2	7.80	
Cushion C	1	8.13	0.53
Cushion C	2	7.60	
Cushion D	1	8.40	0.41
Cushion D	2	7.99	

In addition to initial product variability, the ATD pelvis will also degrade with use, which will affect the 1-G height. The degradation appears to be a softening of the foam inside the pelvis rubber and can be observed via a change in ATD H-point height with respect to a flat rigid surface. In 2011, ATD 1 had an H-point sitting height of 3.9 inches, and when it was measured again in 2016, the H-Point height was 3.7 inch. During that five year period, ATD 1 was used in 81 tests. ATD 2 had a 3.5-inch H-point height in 2011 and a 3.4-inch height in 2016. During that five year period, ATD 2 was used in 15 tests. This degradation means that a 1-G seating to determine initial position for the combined vertical/horizontal test must be done not only with the same ATD that the testing will utilize, but the ATD should not see significant use between the measurement and the test to avoid detrimental changes.

Test Uncertainty Due to ATD Interaction with the Armrests

During tests of a fully occupied real seat (the real seat with contoured aluminum seat pan described previously), it was observed that the arms of the center ATD contacted the armrest significantly, generating enough force to damage the armrests (Figure 8).

[1] The factory tolerance is for a measure of the H-point height with 75 lb applied load. The values in Table 11 are of the H-point height under approximately 130 lb load.

Figure 8 – Left: Test A11020 Arm interaction, Right: Armrest Damage

To investigate this interaction, four tests were conducted. In two tests, the armrests were down (A11019 and A11020) and in two tests the armrests were up (A11021 and A11022). In the first three tests, the seat was fully loaded; the last test only had an ATD in the center seat place (Table 13). With the armrests up, the lumbar load was consistent regardless of the presence of other ATDs in the seat (load range of 13 lb). This is similar to the variability seen when the "R" cushion from this seat was tested on the rigid seat with a Hybrid II (Table 9). When the armrests were down, the lumbar load was reduced by roughly 500 lb when there was limited interaction and by about 1200 lb when there was enough interaction to cause the armrest to break. Figure 9 shows the data traces for the three tests with full occupancy.

Table 13 - Effect of ATD-Armrest Interaction on Lumbar Load

Test	ATD	Cushion	Seat Position	Armrest Config.	Occupancy	Lumbar Fz Normalized
A11019	3	R	Center	Down	Full	1362
A11020	3	R	Center	Down	Full	669
A11021	3	R	Center	Up	Full	1869
A11022	3	R	Center	Up	Single	1856

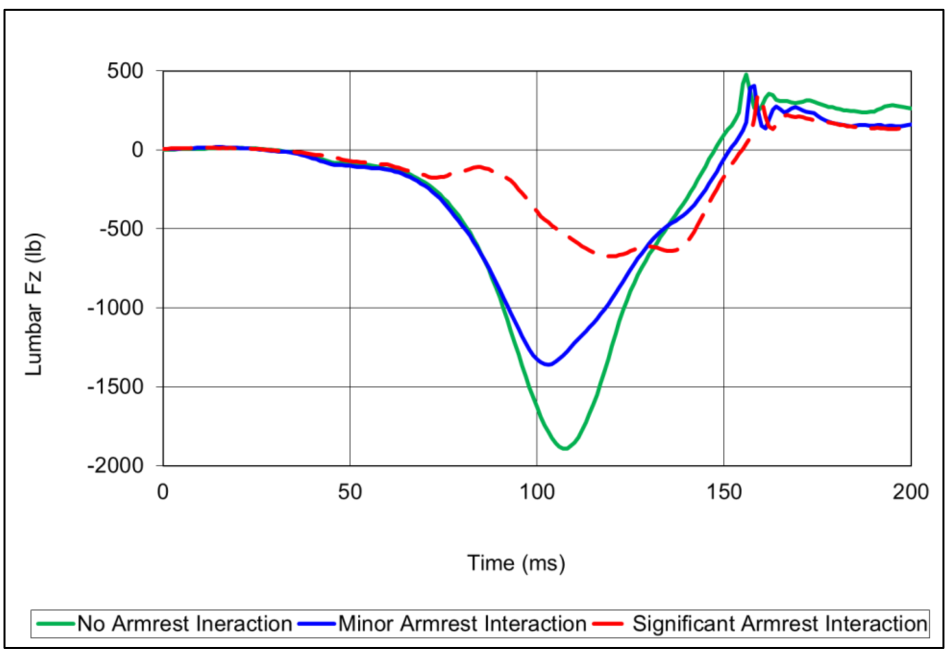

Figure 9 - Lumbar Load with and without Armrest Interaction

Test Uncertainty Due to Test Article Configuration

The tests of a medium density, progressive stiffness foam with and without a dress cover illustrated that the cover can have an effect on lumbar load (Table 14). A tight, non-permeable cover tends to restrict airflow out of the cushion as the cushion is compressed. This affects the dynamic stiffness of the cushion and therefore the lumbar load produced. For these tests, the cover reduced the average lumbar load by about 180 lb, which is about double the irreducible error (Table 8). For this reason, it is necessary to use complete cushion assemblies when conducting comparison tests of cushions.

Table 14 - Test Article Configuration Effect on Lumbar Load

Test	ATD	Cushion	Thickness (inches)	Lumbar Fz Normalized (pounds)	Group Avg
A09005	1	Med-PS Uncovered	4.50	1433	1380
A09006	1	Med-PS Uncovered	4.50	1360	
A09007	1	Med-PS Uncovered	4.50	1348	
A09008	1	Med-PS Covered	4.50	1178	1203
A09009	1	Med-PS Covered	4.50	1238	
A10001	1	Med-PS Covered	4.50	1194	

DISCUSSION

The large amount of variability present in tests of some seat foams, cushion build-ups, and ATDs has significant implications for not only development of seat cushion replacement methods, but also for dynamic seat development testing and certification tests of dynamically qualified seats. The magnitude of uncertainty present in some cases may obscure the actual differences resulting from design changes in cushions or seat frames. Some of the test uncertainty is inherent to the cushion material/design and varied widely, with some cushion repeated test results having a range of only 14 lb and others having a range of 342 lb. For a hypothetical worst-case acceptable seat system (certification lumbar load of 1499 lb), given a 340 lb cushion variability centered on the observed load (1499 ± 170 lb), the "true" value could fall between 1330 lb and 1670 lb. This implies that the "true" injury risk could range from 1% to roughly 40% risk of injury (for the military population that formed the basis of the risk curve).

In addition to the irreducible uncertainty, several other factors contributing to the test uncertainty were identified that are reducible. These factors are discussed below and best practices intended to minimize testing uncertainty are provided in Appendix 1.

- Preloading the ATD into the seat incorrectly was shown to affect results significantly. Correct initial position is crucial for any type of lumbar load comparison. While the large scale effect is known, the finer effect has not been quantified. CAMI selected the most stringent tolerance goals for this research (±0.1" on the pelvis X and Z position, ±1° for the pelvis angle, and ±2° for the torso angle) that could be practically achieved. The tight tolerance on the test setup allows for high confidence that the test results will not be greatly affected by the variation in these positions. However, excessively stringent positioning tolerances add unnecessary time and complexity to test setup, therefore a parameter sensitivity study could be useful in establishing appropriate position tolerances. For qualification tests, insufficient initial compression is a worst-case condition since it is very likely to produce higher lumbar loads.

- The significant difference in nominal H-point height between the two Hybrid II ATDs used in this project makes it clear that the same ATD used for 1-G seating measurement should also be used for the corresponding dynamic tests. The source of the difference may be production variability since the factory tolerance for this dimension is a relatively large ±0.2 inch. The difference may also be due to wear of the pelvis foam from usage or compression of the foam from improper storage. The significant differences in test results that are likely related to the ATD differences highlight the need for a vertical calibration standard for ATDs used for vertical testing. Further research is necessary to develop such a standard. Development of an ATD pelvis specifically for aviation use could also decrease the inherent test uncertainty associated with current pelvis designs. The FAA Hybrid III specifications control pelvis compressed height and that dimension has much tighter tolerances (±0.07 inch vs. ±0.2 inch for the Hybrid II). Until a calibration method or aviation optimized pelvis design is available, use of the FAA Hybrid III should reduce variability of test results due to ATD differences. Since the pelvis dimensional differences appear to be the main source of the ATD test uncertainty, installation of a Hybrid III pelvis on a Hybrid II ATD should provide a similar reduction in test variability. Although the Hybrid III pelvis is functionally interchangeable with the Hybrid II (other than some minor attaching hardware differences), a deviation may be required if used for seat qualification tests. Also, regular inspection of the H-point height of ATDs used for vertical testing may be useful to ensure that the pelvis still meets the design specifications.

- ATD interaction with seat armrests can significantly affect measured lumbar load. The biofidelity of this interaction is unknown, but considering that the ATD arm is made of steel and the shoulder joint vertical range of motion is limited, the stiffness of this load path is likely multiple orders of magnitude higher than a human's. This results in an unrealistic alternate load path, which reduces the measured lumbar load. Because the degree of interaction that would occur with a human occupant is unknown, arm interaction should be avoided or minimized during qualification tests, in order to gather lumbar load data that is representative of the worst case loading condition. If possible, the armrests should be folded out of the way or removed. For seats with fixed armrests, the ATD should be positioned to minimize arm interaction with them.

- Significant differences in measured lumbar load were observed between tests with and without a leather dress cover. Only one cushion was evaluated in this set, so it is unknown whether the variation would be the same for other types of cushions and covers. Dynamic comparisons of cushions should use complete cushion assemblies because of the effect that the covering can have on cushion dynamic stiffness and lumbar load.

- Seat cushion designers have little control over, or insight into, the inherent material variability associated with particular foams or combinations of foams used in a seat cushion design. It may be useful for product developers to conduct some carefully controlled repeated testing to estimate the uncertainty of their designs. This would provide the designers with the information they need to properly interpret comparison test results. Future research efforts to develop cushion replacement methods should include the quantification of test uncertainty to support data interpretation.

LIMITATIONS

The limited availability of some test articles prevented accomplishment of more repeated tests. This could result in an underestimation of the actual variance for those conditions.

The same ATD was used for many tests in this series. While this limited variability due to ATD differences, the effect of pelvic wear on the lumbar loads produced was not quantified. If the loads produced are affected by ATD pelvis wear, then that could limit the validity of comparing test results conducted early in the study with those conducted later. Additionally, most of the ATD variability is assumed to originate in the pelvis, so replacing the pelvis during the test series would likely have the same effect as using a second ATD.

CONCLUSION

The FAA Civil Aerospace Medical Institute undertook a project to evaluate potential methods to qualify replacement elements for worn seat cushions used in transport category seats. Large test uncertainty thwarted the primary goal of this project. While measures were taken to minimize this uncertainty, it was found that a significant amount of variability is associated with seat foams, cushion build-ups, and ATDs. To move forward towards the original goal, it was necessary to first determine the sources and magnitude of the observed uncertainty. The data analysis revealed several sources of significant test uncertainty that have implications for seat and cushion development as well as seat qualification testing. Irreducible test uncertainty is inherent in dynamic testing and was quantified for the seat foams, cushion designs, and test devices assessed in this project. The maximum observed variability was 340 lb. For a design that produces a load close to the regulatory limit, this amount of variability implies a 40% uncertainty in the predicted probability of injury risk. Other sources of test uncertainty were identified that can be controlled including ATD initial position, ATD construction consistency and degradation, and ATD interactions with armrests. These findings highlight the need for a standardized vertical calibration for the ATD. In light of these issues, careful attention to test setup, ATD condition, and an understanding of test uncertainty may be necessary to ensure that seat cushions installed on dynamically qualified seats provide consistent vertical impact performance.

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Appendix: Testing Best Practices

The following practices have been found to maximize the predictability of testing in the combined horizontal-vertical test condition:

- Use an FAA-Hybrid III ATD
  - This ATD has a production tolerance on the height of the H-point, while the Hybrid II does not. This should lead to a more consistent response from ATD to ATD.
  - If an FAA-Hybrid III is not available, it is physically possible to mount a Hybrid III pelvis into the Hybrid II. This should lead to the same consistency; however, a deviation may be needed for certification testing.
- Measure the height of the H-point on a flat, rigid surface and document. This measurement should be redone periodically.
  - The ATD sitting height fixture is a convenient tool to use for this measurement.
  - A reduction in H-point height compared to new indicates pelvis flesh wear.
- When taking 1-G measurements, use the same ATD, same seat place, and same seat bottom cushion as the tested condition.
  - This will account for ATD-to-ATD variability and seat place variability.
  - Conducting repeated seatings and averaging the measurements can increase confidence in the result.
- After the seat is pitched up, place the ATD into the 1-G position following the procedure listed in AS 8049C, paying attention to the X and Z positions of the H-point as well as the angle of the pelvis and the angle of the torso. [Pelvis marking is addressed in reference 8]. The following tolerances on position are recommended:
  - Research & Development tolerance: ±0.1 inch for the pelvis H-point, ±1° for the pelvis angle, and ±2° for the torso angle.
  - Qualification tolerance: ±0.2 inch for the pelvis H-point, ±2° for the pelvis angle, and ±5° for the torso angle.
- When feasible, lift the armrests up and secure them out of the way. Removal of fixed armrests is recommended if permitted.

- Arm/hand placement – For vertical testing, the goal of arm/hand placement is to eliminate or minimize arm interaction with armrests, other horizontal seat features, and any adjacent ATDs. One position that appears to minimize interaction is to make the arms mostly straight (but don't lock the elbow) and place the hands on top of the knees as far forward as possible. The hand position should allow them to slide forward easily to prevent interference with torso forward rotation. In multi-place seats, the ATD should be placed with the shoulders and arms aligned as shown in Figure A1 (not staggered fore/aft or vertically). For narrow seats, this may require leaning the outer ATDs outward.

Figure A1 – Example of ATD Arm Placement