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Supplemental Injury Risk Considerations for Aircraft Side-Facing Seat Certification

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16. Abstract

Application of FAA Policy Statement PS-ANM-25-03-R1, Technical Criteria for Approving Side-Facing Seats, has revealed a need for additional guidance regarding risk of leg injury, protection of occupants during crashes that are not severe enough to deploy inflatable restraints, and risk of injury due to submarining (belt sliding up onto the abdomen) during rebound. FAA sponsored research has shown that serious leg injury can occur in side-facing aircraft seats during an emergency landing scenario. This research also showed that lower velocity tests are unlikely to result in serious leg injuries, suggesting that the injuries were the result of the inertial force of the unrestrained lower leg. The Civil Aerospace Medical Institute reviewed existing literature and conducted a series of sled tests to provide recommendations addressing questions regarding leg injuries, airbag threshold pulses, and risk of injury during submarining. Based on research data, leg injuries are unlikely to occur for any input acceleration that produces energy below the 28.5 ft/s test case and therefore the 35° leg rotation limit could be exempted for these tests. For the 44 ft/s certification sled test, the maximum femur rotation angle limit should be applied to both the leading and trailing legs, but only during the loading phase as long as the method of mitigation does not return excessive energy to the legs during rebound. The current policy states that the lap belt must remain on the pelvis during both the impact and rebound phases. This has the effect of prohibiting contact between the lap belt and the ATD abdomen. In some seat configurations, the occupant kinematics during the rebound phase of the test result in the belt sliding up onto the abdomen (submarining). Due to the low energy typical of rebound, a lap belt tension limit of 250 lb was identified as a conservative value to limit injury risk as an alternate to the prohibition of contact. These observations may be useful for developing new guidance to address these side-facing seat certification issues.

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Contents

Supplemental Injury Risk Considerations for Aircraft Side-Facing Seat Certification

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BACKGROUND

Federal Aviation Administration (FAA) Policy Statement PS-ANM-25-03-R1 defines the technical criteria for approving side-facing seats that provides an equivalent level of safety to forward facing seats [1]. This policy drew on occupant protection information adopted by the automotive industry, particularly the anthropomorphic test device (ATD) and injury criteria referenced in 49 CFR 571.214 [2]. Testing by the FAA Civil Aerospace Medical Institute (CAMI) concluded that the ES-2 ATD functioned well in transport category aircraft seat tests, the injury criteria provided the same level of protection to occupants in aircraft as for occupants in motor vehicles, and the injury criteria could be met with a combination of seat design features and advanced restraint systems [3]. The automotive regulations cite the ES-2re ATD; however, these early FAA tests were conducted with the ES-2 ATD since the ES-2re was not codified at the time [3]. The FAA report noted that high neck loads measured in some seat configurations emphasized the need for appropriate lateral neck injury criteria. Follow-on research by the Netherlands Organisation for Applied Scientific Research and the Medical College of Wisconsin (MCW) provided those criteria, proposing limits on ES-2 upper neck tension, compression, shear, and bending moment [4, 5]. The MCW research also revealed that significant leg injuries can occur to occupants of side-facing seats. Since publication of the FAA policy in 2012, industry feedback has highlighted that additional guidance is needed for some aspects of the side-facing seat policy, specifically regarding risk of leg injury, protection of occupants during crashes that are not severe enough to deploy inflatable restraints, and risk of injury due to submarining during rebound.

Leg Injury

The intent of the femur axial compression force limit in 14 CFR 25.562 is to reduce the chance of leg injuries that could impede egress after an emergency landing [6]. The orientation of side-facing seats makes exceeding the compressive limit during a forward impact very unlikely. However, in tests of aircraft side-facing seats, postmortem human subjects (PMHS) have sustained serious leg injuries that would not only have impeded egress but could also be life threatening [4, 8]. During the loading portion of the test, the motion of the thighs was constrained to primarily axial rotation due to contact with the armrest (i.e. the thigh did not translate or bend in the direction of the sled pulse). This constraint appears to have generated high axial moments in the femur produced by inertia forces acting on the lower leg. This assumption is supported by the injury patterns, specifically spiral fractures (Figure 1), which indicate that excessive torque on the femur is the most likely cause of injury.

In an FAA sponsored research project, the Medical College of Wisconsin conducted rigid seat tests that loaded the PMHS in a pure lateral configuration. Two tests using a 41.0 ft/s rectangular-shaped pulse resulted in serious injuries to the leading leg in each test [4]. Leg injury did not occur in two tests using a 28.5 ft/sec rectangular pulse (Figure 2). The moment in the femur produced by the lower leg during the lower velocity test was evidently not enough to cause a detectable injury. Since the project was focused on neck injury, the test protocol did not include measuring the PMHS femur torque or the specific rotation angle that initiated injury.

Therefore, there is currently insufficient data to determine the specific impact severity at which serious leg injuries begin to occur.

Figure 1. Spiral Fracture from Test FNSC 110 (x-ray courtesy of MCW)

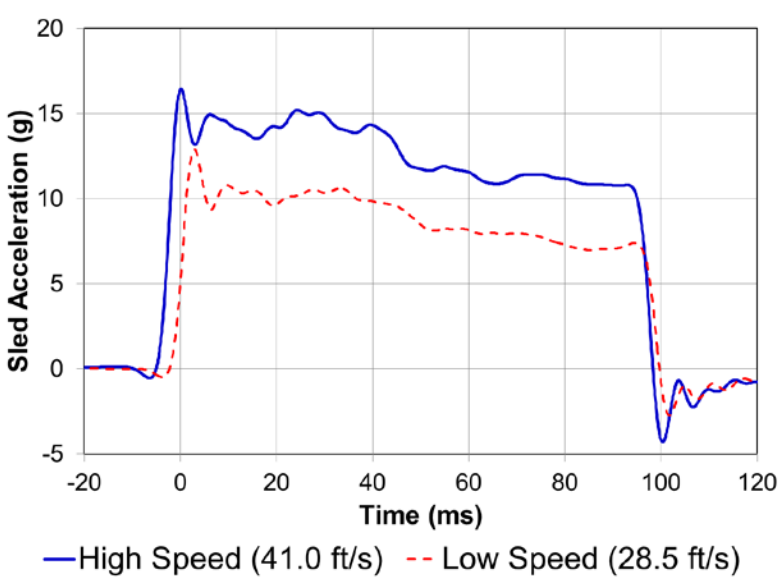

Figure 2. Rectangular Pulses from MCW Test Series [4]

Since the injury patterns indicate that excessive torque on the femur shaft is the most likely cause, and that axial torque is created when the lower leg rotates laterally (i.e. in the frontal/coronal plane), the most effective way to limit injury is to limit the amount of leg flail. This is confirmed by the tests referenced above in which the PMHS that sustained serious leg injuries exhibited about 30° more leg flail angle than the PMHS that had uninjured legs, with a peak angle of 89° vs 55-59° for the uninjured legs [8]. The specific relationship between femur torque and dynamic lower leg flail angle in humans is unknown, but the torque likely increases as the rotation increases.

Replicating the above tests with the ES-2 ATD revealed that the ES-2 leg flail in the lateral direction is not biofidelic; the maximum ATD leg rotation was identical for both impact severities, unlike the human response [8]. The ES-2 also demonstrates poor coupling between torque and the amount of rotation, as shown in Figure 3 [3]. Therefore neither the amount of rotation, nor the torque produced in the ATD femur, is expected to be proportional to leg injury risk. However, because the ES-2 legs have the same weight distribution and the same or greater joint articulation range as a mid-size adult male, it is useful for assessing the effectiveness of leg flail mitigation strategies.

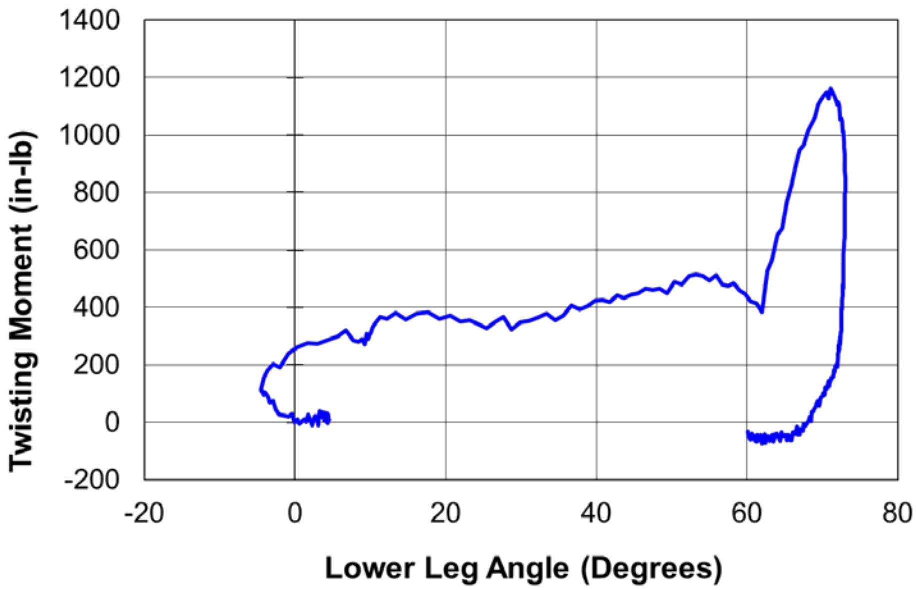

Figure 3. ES-2 Forward Leg Motion during 16g Test (A05076) [3]

Current side-facing seat policy limits leg injury risk by ensuring that ATD leg flail is limited during seat qualification tests to an angle known to be non-injurious for the average person under static loading conditions [1]. The range of motion for a seated occupant's internal and external rotation ranges from 18° for the least flexible persons (the male population's 5th percentile rotation value) to 45° for the most flexible persons (the female population's 95th percentile rotation value) [7]. ATD tests in the same seat configuration as the PMHS tests showed that the ES-2 leg will rotate at least 60° in this loading scenario [8]. In the absence of an available criteria relating rotation angle to a specific risk of injury, limiting upper leg axial rotation with respect to the pelvis to 35° from the nominal seated position (approximately the 50th percentile range of motion for both genders) should also limit the risk of serious leg injury. One means of determining the amount of relative upper leg rotation is by observing the amount of lower leg flailing in high-speed video of the dynamic tests. This method assumes that the legs rotate in a single plane. A combination of a body-centered lap belt and adjacent support structures tends to prevent significant lateral rotation of the pelvis (in the coronal plane), thus the motion of the lower leg with respect to its initial position is sufficient to derive the upper leg relative rotation with respect to the pelvis. Alternately, angular rate sensors (ARS) can be mounted to the femur and the output can be integrated to calculate the femur rotation as a function of time. Over numerous discussions, industry has asked for a standardized method to calculate leg rotation from ARS data and additional guidance on injury risks to the leg during rebound and risks to the trailing leg.

Airbag Threshold Tests

A common means of providing occupant protection in a side-facing seat is the use of airbags. Current airbag Special Conditions require that the airbag not deploy when it is not needed, in part so that the airbag is available to deploy in the event of a subsequent, more severe impact [9]. To meet this condition, the airbag is designed to only deploy when a design-specific threshold is exceeded. The Special Conditions also state that it "must be shown that the [airbag] will deploy and provide protection under crash conditions where it is necessary to prevent serious head injury or head entrapment" [9]. To demonstrate compliance to this condition, a low-G test is included in seat qualification programs to demonstrate that the seat system does not pose an injury risk for impacts with a severity just above the threshold at which inflatable restraints would deploy. The threshold for deployment is application specific and defined by the airbag manufacturer. All injury criteria in the side-facing policy are evaluated during this test. Since leg injury seemed to occur as a result of inertial loading and leg injuries did not occur in the lower severity PMHS research tests, leg injury due to flailing is not likely in threshold tests if the impact severity is similar to or less than those research tests. In those cases, leg injury assessment (i.e. measurement of leg flail angle) should not be necessary to show compliance. In the absence of test data, some inferences concerning the relative severity of two test pulses could be made using published research results. However, the most direct way of comparing the severity of a threshold test pulse with the referenced low-G PMHS test severity would be to conduct both tests and compare the ATD responses.

Submarining

The current occupant retention and support requirements in PS-ANM-25-03-R1are:

> *g. Occupant (ES-2re ATD) retention: The pelvic restraint must remain on the ES-2re ATD's pelvis during the impact and rebound phases of the test. The upper-torso restraint straps (if present) must remain on the ATD's shoulder during the impact.*
>
> *h. Occupant (ES-2re ATD) support: (1) Pelvis excursion: The load-bearing portion of the bottom of the ATD pelvis must not translate beyond the edges of its seat's bottom seat-cushion supporting structure.*

The requirement for the belt to remain on the pelvis and for the pelvis to remain supported during the rebound phase was included in the policy because during some development tests, the ATD rebounded with enough momentum to travel rearward off the end of the seat. Since that motion could produce injuries due to contact forces and belt loading into soft tissue, requirements were added that were intended to prevent it.

Recent development tests have produced occupant kinematics during the rebound phase that were not anticipated by the FAA when formulating the current safety requirements. In seat places without surrounding structure, as the torso rebounds rearward, the legs have enough momentum to travel forward and in an upward arc resulting in the ATD lying on its back on the seat with the legs nearly vertical (Figure 4). This typically results in lap belt partially bearing on the ATD abdomen (a position currently prohibited). For the reviewed development tests, by the time the lap belt moves up off the pelvis during rebound, the belt loads had dropped significantly. Development of a means to directly assess the injury risk in these cases could permit approval of some failing designs that otherwise meet all safety requirements.

Report Overview

This paper documents test data that directly compares the occupant kinematics of the ATD in the non-injurious PMHS test condition to two proposed airbag threshold test conditions. The discussion section addresses the other injury concerns and includes data from the literature on risk of injury due to submarining. The appendix provides a method for the calculation of leg rotation from ARS data.

Figure 4. Illustration of submarining during rebound

METHODS

A series of sled tests were conducted to investigate the potential for injuries to passengers seated in a purely side-facing seat during impacts when those impacts are below the threshold for deployment of airbags. The test setup matched the CAMI tests from the original 2005 project (tests A05075 and A05076), which is also identical to the seat configuration used by the Medical College of Wisconsin (MCW) for the PMHS tests [3, 4]. The seat has a flat seat bottom and a 13° back angle, along with an armrest that extends 12” above the seat bottom (Figure 5). The seat has 4-inch soft foam (DAX 47) cushions with a leather covering and the armrest was padded with 1-inch of stiff foam (IV3). A body-centered polyester belt with a shoulder harness was used to restrain the ATD. The ATD was placed in the seat in the manner prescribed in the FAA side-facing seat policy [1].

Figure 5. Pre-test Photos Showing Seat and ATD

Sled Pulses

Currently, the FAA does not have a single, defined airbag threshold test pulse, in part because the threshold for deployment is application specific. Additionally, there is no guidance specifying the shape for the threshold pulse. For this project, two generic pulse shapes were selected, each based on a different feature of the standard 16g isosceles triangle pulse [10]. The "slope" pulse is an isosceles triangle that follows the slope of the 16g pulse until a given G is reached and then returns to zero (Figure 6). The "duration" pulse is an isosceles triangle that matches the duration of the 16g pulse (180 ms). For this test series, a G peak of 10g was selected for both pulses. This value was selected to be conservative with respect to the limited publically available data, e.g. 8g, reported by Barth [11]. An additional test was run using the low velocity MCW rectangular pulse, hereafter called the research pulse.

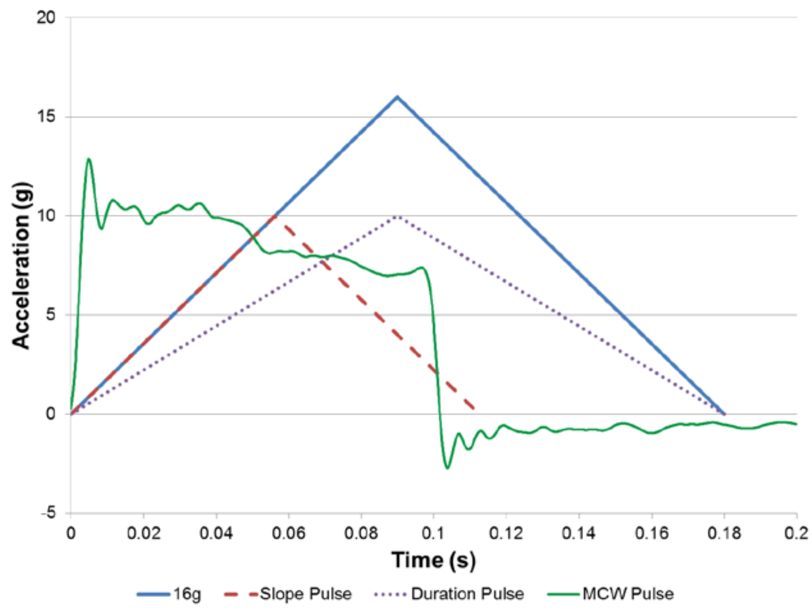

Figure 6. Sled Pulses

One way to define the severity of an impact is the velocity change during the test. The standard Part 25 16g pulse is required to have a velocity change of at least 44 ft/s [12]. The tests conducted at MCW resulted in 28.5 ft/s velocity change. The 10g duration pulse has approximately 29 ft/s velocity change, while the 10g slope pulse has about 18 ft/s velocity change. Evaluation of the ES-2re injury measures and kinematics will provide a more granular evaluation of severity for these three impacts.

Test Device

The ES-2re ATD is specially designed to evaluate injury in test conditions with significant lateral loading. This ATD is cited in FAA policy PS-ANM-25-03-R1 for side facing seats and 49 CFR 571.214 for use in automotive side impact tests [1, 2]. The dummy exhibits good biofidelity when used to evaluate typical aviation seat configurations except for femur torque [3]. The original 2005 tests at CAMI and MCW used an ES-2 build level E2.AI. The subsequent work used the ES-2re (49 CFR Part 572 subpart U), which is the version of the ATD cited in the FAA policy and automotive regulation referenced above [13]. The ES-2re has a set of rib extensions that extend from the ends of the ribs to the back plate, filling a gap that had existed in the previous version. These extensions improved the consistency of the interaction with contoured seat back upholstery common in automobiles [14]. Since the back upholstery used in the FAA research test seats was not contoured, it is unlikely that using the ES-2re produces a different response than the original ES-2.

Instrumentation

The ATD was instrumented to collect all the data necessary to evaluate occupant injury per the FAA side-facing seat policy [1]. Angular rate sensors (ARS) were installed in both femurs to allow for lower leg angle to be determined based on the method defined in Appendix A (Figure 7). Six-axis load cells were installed at the anchor points for the lap belt, and webbing transducers were installed on the shoulder harness (one on either side of the shoulder belt guide). All electronic instrumentation was gathered according to SAE J211/1, which includes a 180 channel filter class for the angular rate sensors [15].

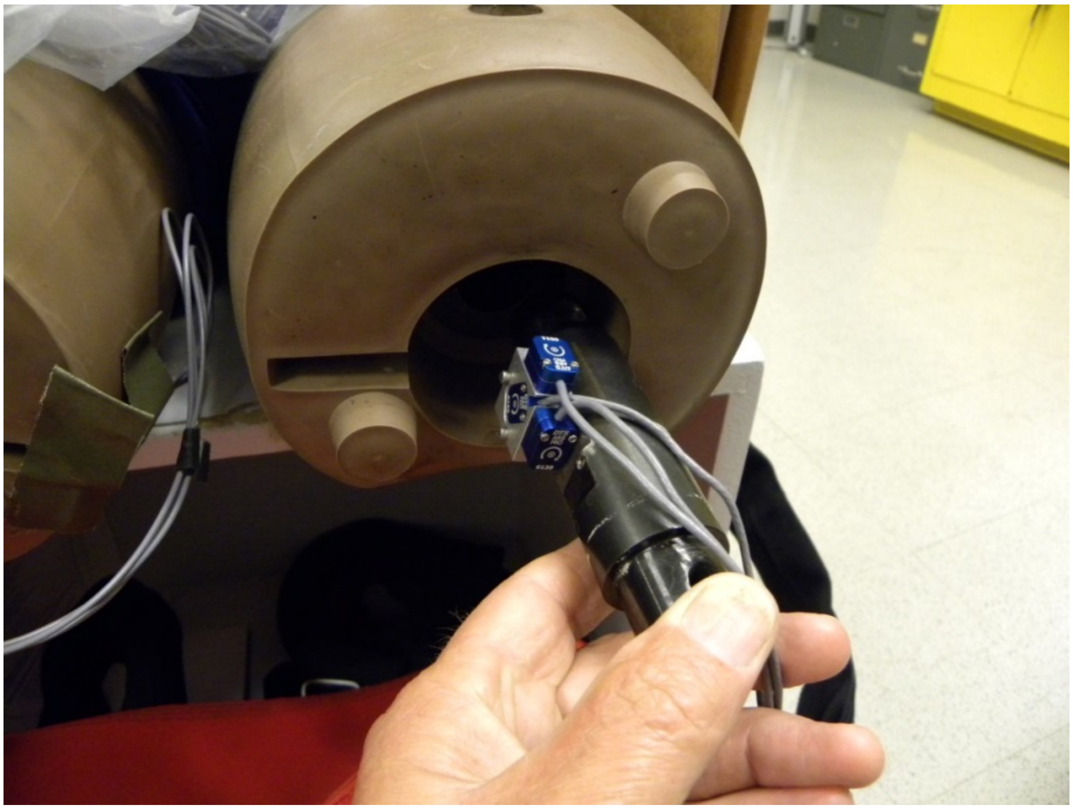

Figure 7. Tri-axial ARS Mounted to Femur Link

A piece of string was attached to the shoulder belt and then passed through a small block of dense foam fixed to the seat near the inertia reel (Figure 8). By measuring the amount of string pulled through the foam block, the maximum webbing payout during each test was estimated.

High-speed (1000 frames per second), high resolution (1024 x 768 pixels) color video was captured from the side and overhead directions by cameras aimed perpendicular to the sled travel. Rectilinear targets were placed on the ATD’s forehead, chin, and knees to facilitate motion analysis.

Figure 8. Shoulder Belt Showing String in Foam and Lower Webbing Transducer

RESULTS

Table 1 summarizes the data for the three tests and includes the pass-fail limits where applicable; values in red indicate that the limit was exceeded. The reported data provide an evaluation of the overall occupant kinematics and a thorough evaluation of the severity of the impact from the perspective of the occupant. Upper neck bending moment includes the maximum value in both the positive and negative directions. Head Injury Criteria (HIC) results were not included since the head impact was not considered representative of a typical aircraft installation. Peak lateral accelerations (Ay) are provided for the upper thoracic spine (approximately the T1 location), three rib locations, and the pelvis.

Table 1: Test Peak Values

Pulse	Limit	Research Pulse	"Duration" Pulse	"Slope" Pulse
Test Number		A16031	A16033	A16032
Peak G's		11.3	9.9	9.7
Average G's		7.76	4.73	4.93
Velocity (ft/s)		27.9	29.2	17.3
Shoulder Strap Load (lb)	1750	1109	1011	542
Max Shoulder Belt Payout (in)		0.8	0.55	0.55
Upper Rib Deflection (in)	1.73	0.00	0.00	0.02
Middle Rib Deflection (in)	1.73	0.05	0.03	0.07
Lower Rib Deflection (in)	1.73	0.38	0.47	0.31
Sum Abdominal Force (lb)	562	151	178	91
Pubic Symphysis Force (lb)	1350	347	267	228
Upper Neck Tension (lb)	405	*558*	*463*	233
Upper Neck Compression (lb)	405	1	1	1
Upper Neck Bending Mx (in-lb)	1018	485/-350	477/-255	394/-293
Upper Neck Shear Fxy (lb)	186	*201*	181	145
Left Leg Rotation (degrees) *	35	*59*	*61*	*54*
Right Leg Rotation (degrees) *	35	*62*	*61*	*53*
Upper Thoracic (T1) Ay (g)		33	31	18
Upper Rib Ay (g)		33	34	19
Middle Rib Ay (g)		29	30	16
Lower Rib Ay (g)		43	41	26
Pelvic Ay (g)		28	21	23
Center Belt Anchor Force (lb)		537	431	401
Trailing Belt Anchor Force (lb)		1057	960	599

* Result based on subsampled 1000 Hz data

In general, the research pulse and the duration pulse resulted in similar kinematics as would be expected due to the similarity in velocity change (27.9 ft/s and 29.2 ft/s, respectively). The slope pulse, which had only a 17.3 ft/s velocity change, generally produced lower values. For all three tests, the injury criteria were mostly low; however, the upper neck tension and shear were exceeded or nearly exceeded for both the research and duration pulses. Figure 9 shows the head acceleration and upper neck tension for the research pulse. The neck tension follows the head z-component acceleration throughout the test, peaking at approximately 125 ms (Figure 9). The head resultant acceleration deviates at the time of head contact, approximately 142 ms. In these tests, the neck tension is solely driven by the inertia and weight of the head. Rib deflections were very low as there was little contact between the ribs and the armrest (Figure 9).

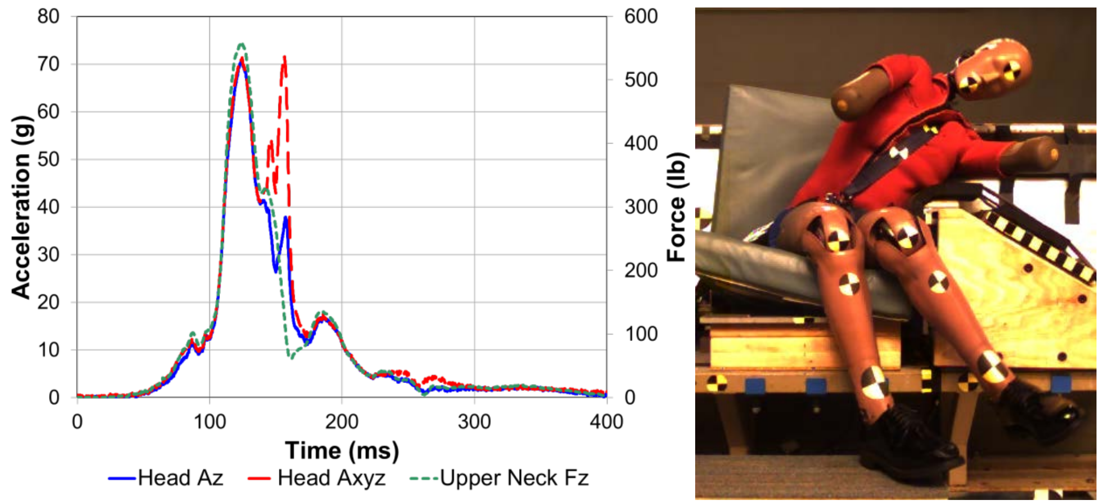

Figure 9. Neck Load, Head Accelerations, and Video Still at the Time of Peak Neck Tension (125 ms) for the Research Pulse Test (A16031)

Beyond the injury criteria, the lateral accelerations at T1, each rib, and the pelvis follow a similar trend where the research and duration pulses produce similar results and the slope pulse is lower. This also holds true for the lap belt anchor forces, although the research pulse produces slightly higher belt loads than the duration pulse. Figures 10 and 11 show the phasing of the T1 and pelvis lateral acceleration, respectively. While the phasing follows the rise time of the input pulses, the duration of the peaks are similar.

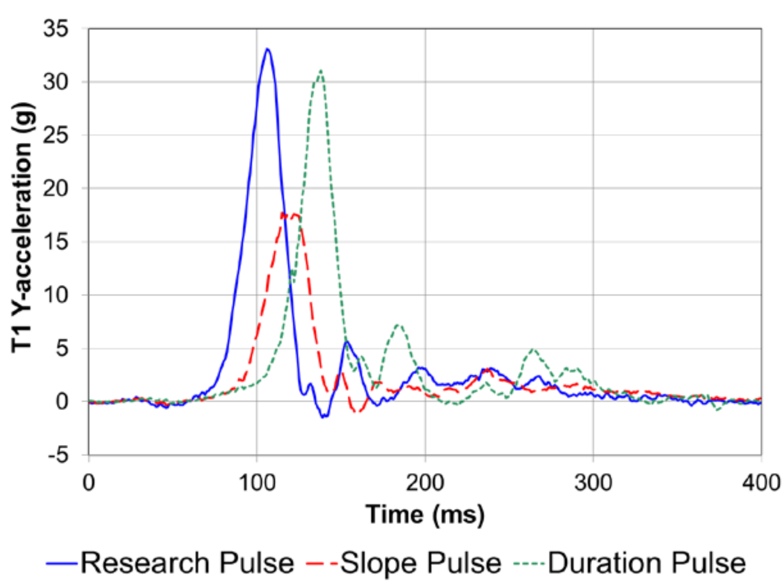

Figure 10. T1 Lateral Acceleration

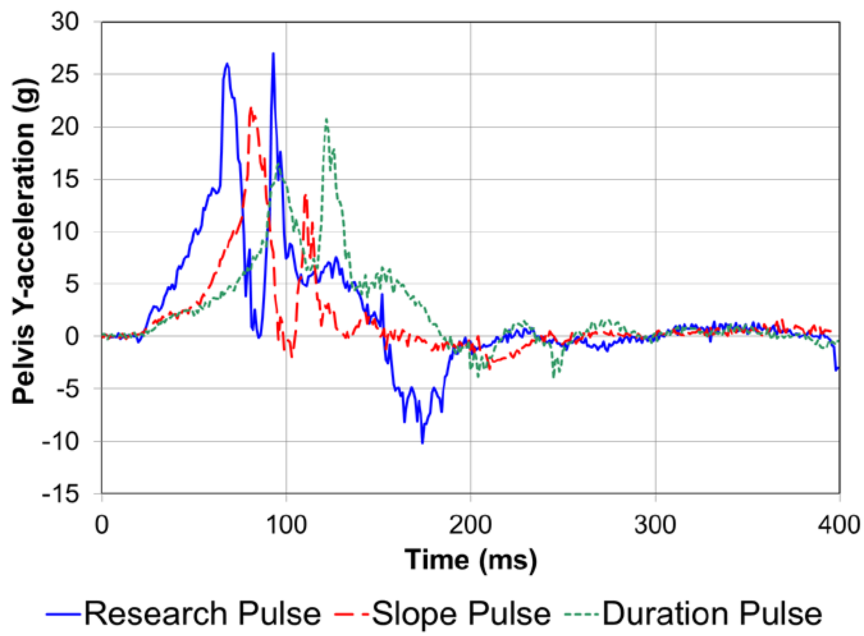

Figure 11. Pelvis Lateral Acceleration

Leg rotation was calculated using the angular rate sensors fixed to the femur. The rotational velocity was integrated to determine leg rotation using a simple trapezoid method (example input and output in Figure 12). No offset was applied as the femur was positioned in a neutral orientation at the onset of the test. This method assumes negligible pelvic rotation.

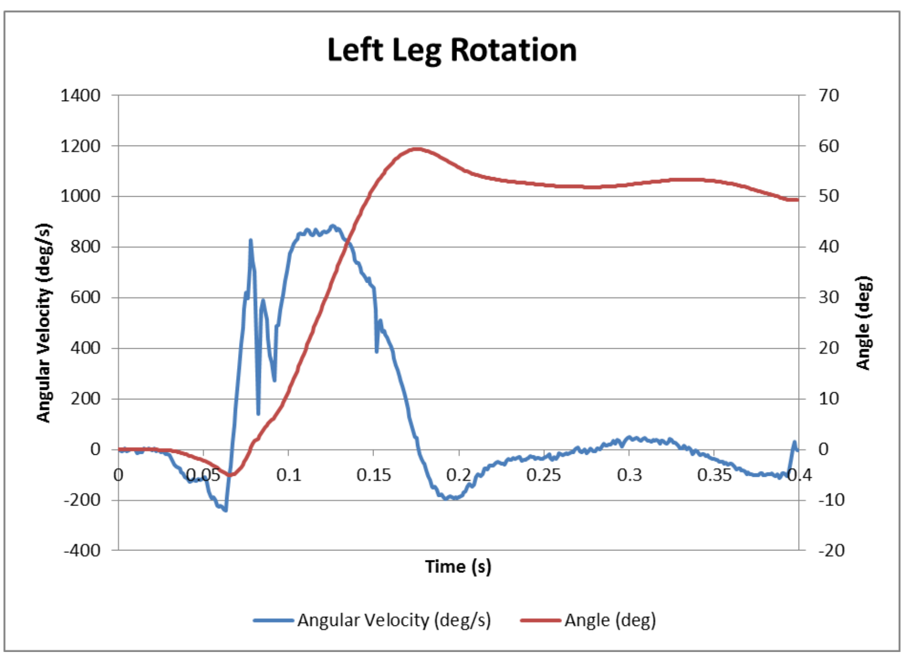

Figure 12. Left Leg Rotation for the Research Pulse Test (A16031)

DISCUSSION

Performance Measures

To ensure occupants are protected in crash severities at or below the specified certification test requirements, the injury criteria defined in the FAA side-facing seat policy should be evaluated for the 16g test and any threshold tests. As noted above, the upper neck tension force limit was exceeded and the upper neck shear force was nearly exceeded for both the research and duration pulses. This is partially expected since the PMHS was moderately injured in one of the two MCW tests at this pulse level. The results underscore that even with a relatively low velocity input, there is still a possibility that the restraint system will not provide adequate protection to the occupant. Results for the injury criteria are likely to be configuration specific as some seat and restraint configurations will amplify the loads on the occupant.

Leg Rotation

The static range of motion for the ES-2re is approximately 78° for both internal and external rotation. During dynamic testing, the leg rotation shows a limited ability to differentiate impact severity (Figure 13). This plot includes the peak leg rotation from a 16g (triangular pulse) test from the 2005 series (A05076). The 16g test had an impact velocity of 45 ft/s and the forward leg rotation, which was derived photometrically, peaked at 73° [3]. While highly linear, the unbounded trendline suggests that at zero velocity, the leg will rotate over 40°. Forcing the trendline through zero results in a very poor correlation (R^2 = -2.4). Overall, this agrees with the notion that the ES-2re does not provide a rigorous quantitative assessment of the risk of leg injury.

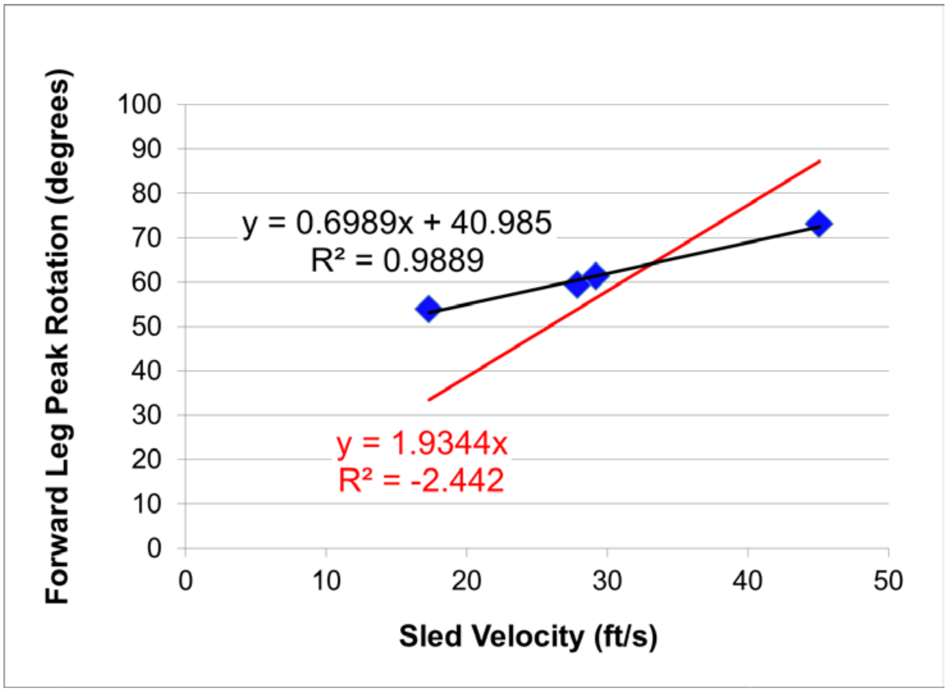

Figure 13. Peak Leg Rotation as a Function of Sled Velocity

Leg Rebound Response

The ATD femur torque is not expected to be proportional to leg injury risk, based on either the amount of rotation (Figure 13), or the torque produced (Figure 3). However, since the ES-2re legs have the same weight distribution and joint articulation range as an average adult male, the ATD femur rotation is useful for assessing the effectiveness of leg flail mitigation strategies. An effective mitigation design will absorb most of the impact energy, returning only a portion to the legs. The lack of biofidelity of the ES-2re hip rotation stiffness means low energy can still create high rotation during rebound. Therefore, the maximum femur rotation angle limit may not be applicable to the legs during their rebound as long as the method of mitigation does not return excessive energy to the legs. This applies to both the full 16g test and any threshold tests.

Trailing Leg Flail Limit Assessment

Current side-facing seat policy limits leg injury risk by ensuring that ATD leg flail is limited during seat qualification tests to an angle known to be non-injurious for the average person i.e. the normal range of hip motion [7]. The source of that limit cites the same angles for both internal and external hip rotation (Figure 14). In feedback from seat manufacturers, it has been noted that the ATD legs can cross in the 10° yaw test, and there is a belief that the normal range of human motion is actually greater for external rotation than for internal rotation. However, the "leg crossing movement" cited as the basis for this observation actually involves hip motion in multiple axes (flexion, abduction, and external rotation), rather than the single axis motion limited in the policy. During the loading phase of a lateral impact, it is unknown whether the hip joint of the trailing leg would exhibit these additional degrees of freedom. In this test series, the two legs moved symmetrically and no additional rotation was observed in the trailing leg. Before a change in the external rotation limit is considered, information is needed about the kinematics of the unrestrained human trailing leg during lateral impact, and the effect that multi-axis hip motion occurring during that type of impact would have on the magnitude of non-injurious rotation.

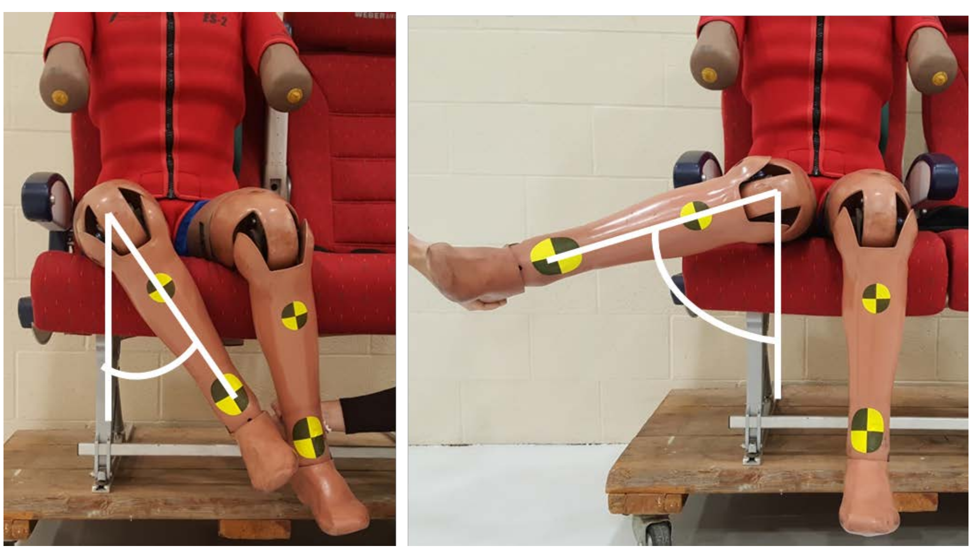

Figure 14. Hip Rotation: External (Left) and Internal (Right)

Submarining

In lieu of requiring the belt remain on the pelvis during rebound, limiting the belt tension measured whenever the belt is not on the pelvis to a sub-injurious level could be a means to provide the intended level of protection from abdominal injury. There is no regulation citing the magnitude of lap belt tension permitted during contact with the abdomen; however, data is available to provide a conservative load limit.

An abdominal injury risk assessment method is available for the ES-2re side facing dummy. This ATD has an abdominal injury criteria based on the sum of the force applied to three load cells mounted under the abdomen on the leading side of the ATD. While the ES-2re abdomen was intended to measure lateral contact forces with adjacent structures (e.g. an armrest), an abdominal force could also be produced by a strap bearing on the side of the abdomen in the area over the load cells. For instance, a 500 lb loop load applied laterally would produce a reaction force in the ES-2re abdomen that is in the same range as the 562 lb abdominal load limit defined in the side-facing seat policy. Since the lap belt could load areas of the abdomen that are not directly over the load cells, using the output of those cells to assess the risk of belt induced injury is not adequate.

Some studies of belt loading into the abdomen are available that produced data relevant to this loading scenario [16, 17, 18]. The tests in these studies applied dynamic loads onto the upper abdomen of Post Mortem Human Subjects (PMHS) with a loop of seat belt webbing centered on the front of the abdomen, wrapped horizontally around the abdomen, and attached to an actuator. In these tests, the applied loads that produced injury ranged from 920 lb to 2170 lb. The loads that produced no injuries were mostly between 625 lb and 1285 lb, although one no injury test was as high as 2260 lb. These values are a combination of the symmetrical tension produced at each end of the strap (a loop load). The latest study combined the PMHS test results from several studies with advanced human body model output to compare the ability of various combinations of test measurements to predict injuries observed [18]. This study concluded that belt tension was not the best parameter for predicting abdominal injury but it was related to injury risk. Combining the data from these three studies, a threshold analysis indicates that the lowest peak belt tension at which injuries occurred was 920 lb.

Considering the above information, a 250 lb lap belt tension limit (one half of a 500 lb loop load) would be in line with the 562 lb ES-2re contact force limit and be conservative with respect to lowest injury point (920 lb loop load) from the PMHS test data.

Three things are needed to evaluate the pelvic restraint performance using this tension criterion:

1) A clear indication of when the belt moves above the pelvis. Loose clothing can make it difficult to determine where the top of the pelvis is, and in turn make it hard to discern exactly when the belt moved above it. This can be improved by marking the top of the pelvis clearly and by positioning the cameras so that the position of the belt, relative to the top of the pelvis can be observed throughout the test (Figure 15).

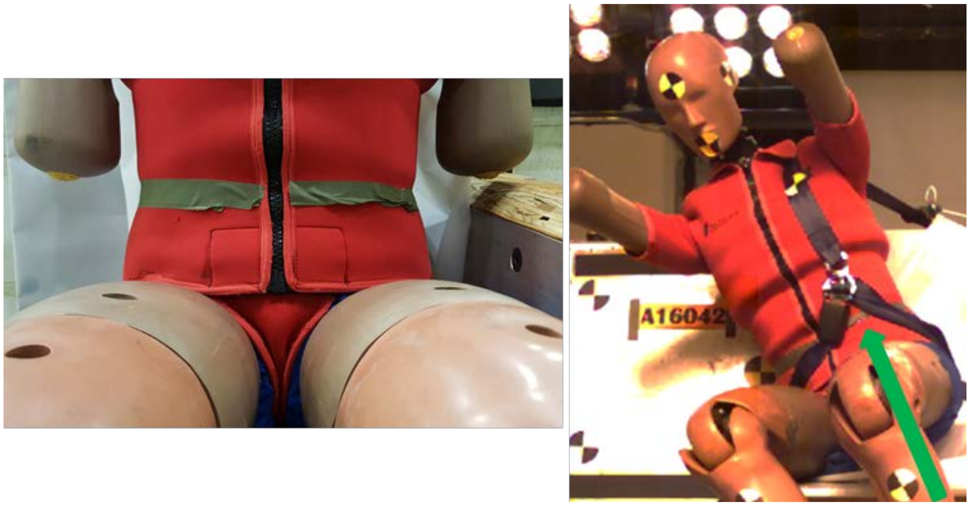

Figure 15. Top of Pelvis Marked: Pretest (Left), Belt Relative to the Top of the Pelvis (Right)

2) A measurement of the belt tension during the time when the belt moves above the pelvis. The webbing transducer should be placed to measure the total tension in the forward lap belt segment. If a split (combined body-centered and conventional) leading belt is used, the tension should be measured in the common section so that it reflects the contribution of each segment. Since this placement typically produces contact between the ATD and the transducer, it is important to use a webbing transducer that is not sensitive to contact.
3) Useful video and belt load data must be recorded until significant ATD rebound motion stops. Extra recording time is necessary because submarining usually occurs later in the test than other injury criteria maximums. To completely capture ATD rebound, the necessary time could exceed 500 ms.

Threshold Pulse Shape and Duration

The goal of an airbag threshold test is to demonstrate the occupant would be protected in the event of a crash where the severity was insufficient to cause deployment of the airbag. The timing of airbag deployment is proprietary but is known to be a function of acceleration and impact duration. As such, there is no simple method to determine the most appropriate threshold pulse shape and duration for compliance testing. One proposed method is to follow the rise time of the 16g pulse and terminate at a G-level at which the airbag would fire. This method suggests that the “standard” crash follows the rise time of the 16g pulse and that the lower severity is defined solely by the G peak. As seen in Table 1, impact velocity has a large effect of occupant response and rise time appears to have little effect.

Previous research has shown that aircraft velocity at impact will affect the G peak and duration of a crash [6]. At this time, it is an open question as to what should be the proper shape for the threshold pulse; more research is recommended. One approach, when sufficient data is available, would be for the FAA to define a standard shape and duration, while allowing the applicant to define the installation specific peak G.

LIMITATIONS

This test series was limited to one seat configuration. It is unknown whether the test results hold for other configurations, although a side-facing seat with a partial wall (such as the configuration tested) seems to be the most likely configuration where the legs are free to rotate. This test series was also limited to one test per sled pulse. The specific measurements likely have some inherent variability; although the test scatter in the original 2005 test series was low [see Table 8 in ref. 3].

CONCLUSIONS

Application of FAA Policy Statement PS-ANM-25-03-R1, Technical Criteria for Approving Side-Facing Seats, has revealed a need for additional guidance regarding risk of leg injury, protection of occupants during crashes that are not severe enough to deploy inflatable restraints, and risk of injury due to submarining during rebound. The Civil Aerospace Medical Institute reviewed existing literature and conducted a series of sled tests to provide recommendations for these issues. Previous research showed that leg injury in postmortem human subjects occurs as a result of inertial loading, and sled pulses with a change in velocity of 28.5 ft/s did not produce these leg injuries. Using an ES-2re ATD in a side-facing seat with an armrest, the ATD kinematics and measured responses were compared between the research sled pulse and two tests using potential airbag threshold pulses. The threshold pulses were isosceles triangles with a 10g peak, one with a 29 ft/s velocity change (90 ms rise time, 180 ms duration) and one with an 18 ft/s (56 ms rise time, 113 ms duration). The research pulse, a rectangular waveform with an 11.3g peak and a 28 ft/s velocity change, produced occupant responses that were more severe than either of the threshold pulses.

Based on the data documented in this report, the following observations may be useful for developing new guidance to address these certification issues:

- For airbag threshold tests, any input acceleration that produces energy below the 28.5 ft/s test case should not result in serious leg injury, and therefore the 35° leg rotation limit could be exempted for these tests.
- The maximum femur rotation angle limit is only applicable to the loading phase as long as the method of mitigation does not return excessive energy to the legs during rebound.
- Based on currently available information, the femur rotation limit should be applied to both the leading and trailing legs.
- Calculating leg rotation using angular rate sensor data in accordance with SAE AS 8049/1B should be considered for approval as an acceptable method to derive this parameter.
- Permitting the pelvic restraint to slide off the pelvis during the rebound phase of the impact should result in a low risk of injury if the tension in that strap is less than 250 lb.
- Defining a standard threshold pulse shape and duration for airbag tests requires additional research; however, the appropriate peak G specified is installation specific, and may vary for each application.

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APPENDIX

A Method for the Calculation of Leg Rotation Using Angular Rate Sensor Data

Angular rate sensors (ARS) provide rotation rate as a function of time. When mounted to a rigid body and exposed to planar motion, calculation of the rotation as a function of time is a straight forward computation. In short, once the rate data is integrated and any existing offset is corrected, the result is a time history of the degrees of rotation for that rigid body. As a means to show compliance with the leg rotation requirement in FAA policy ANM-25-03-R1, use of ARS data is a fast and effective method. This method assumes that the pelvis does not rotate a significant amount. For seat configurations where the pelvis has significant rotation, it may be possible to offset the femur rotation by the amount of pelvis rotation, obtained from ARS mounted in the pelvis, however this approach has not been validated.

Figure A-1: Single ARS Mounted to End of Femur Link [18]

It is recommended that the ARS be rigidly mounted to the femur along the femur z-axis, or inside a specifically designed femur sensor (Figure A-1). Leg axial rotation is calculated by integrating this angular velocity time history using the trapezoidal method represented by Equation (1). An illustration of this method's input and output are shown in Figure A-2. Per SAE J211/1, angular rate should be filtered at a channel filter class (CFC) 180 when integrating for rotational displacement. Due to the ES-2re initial position requirements, no initial angular offset of the rotational displacement should be necessary. Validation of the procedure has been independently reported by Humm and Hucaluk and proposed for inclusion in SAE AS 8049/1B [8, 19, 20].

$$\int_a^b f(t)dt \approx \frac{b-a}{2N}\sum_{i=1}^{N}[f(t_i)+f(t_{i+1})]$$

Equation (1)

where f(t) is the angular rate as a function of time and N is the number of intervals such that $\Delta t = \frac{b-a}{N}$.

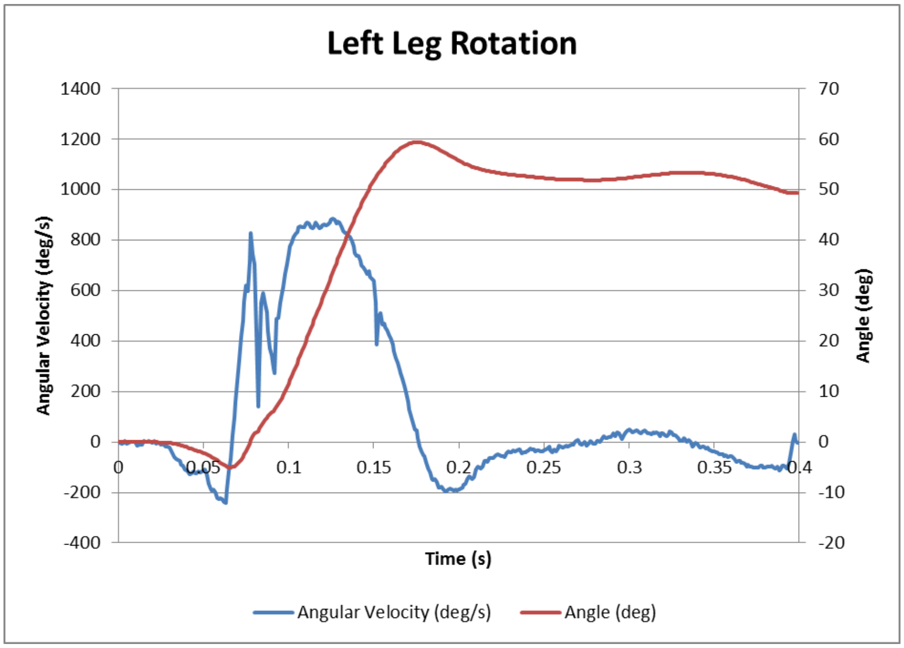

Figure A-2: Angular Velocity Input and Angle Output (A16031)