Driver Lower Extremity Response to Out of Position Knee Airbag Deployment

Xin Ye, Matthew B. Panzer, Greg Shaw, Jeff R. Crandall

Abstract The 5th percentile female was chosen for an investigation of knee loading resulting from interaction with a deploying knee airbag. In this study, a total of 11 static knee airbag deployment tests were performed with a 5th percentile female Hybrid-III dummy outfitted with either the original Hybrid-III lower extremities or the 5th percentile THOR-FLx. Baseline tests were performed with FMVSS 208 seating specifications, and a design of experiment for out-of-position conditions was developed with multiple factors including knee-to-instrument panel distance, knee-to- knee distance, and foot placement. The upper tibia index values ranged from 0.95 to 1.31, and 0.78 to 1.21 for baseline tests of Hybrid-III LX and THOR-FLx, respectively. Lower tibia index values varied from 0.30 to 0.46 (Hybrid-III) and from 0.51 to 0.79 (THOR-FLx). For baseline tests, highest injury risk of AIS 2+ leg shaft fractures occurred in upper right tibia of Hybrid-III LX (31.15%) and in upper left tibia of THOR-FLx (51.17%). Translating the dummy to the full-forward position with the tibia contacting the knee bolster resulted in an average TI increase of 10% and greater abduction of both legs during knee airbag deployment. With the right foot moved inboard from accelerator to brake pedal, the average TI increased 120% relative to baseline. Overall, the highest average TI was recorded with the left foot moved inboard creating an adducted initial position. The results also predicted higher injury risk of tibia shaft fractures than foot and ankle fractures. The elevated dummy lower extremity response recorded in this study suggests considerations to be made for out-of-position small female occupant response during knee airbag deployment.

Keywords Injury risk, knee airbag, lower extremity, out-of-position

I. INTRODUCTION

Currently, 45% of AIS 2+ injuries for occupants involved in frontal crashes occur in the lower extremities [1]. Although improvements in occupant safety have resulted in a reduction of head and chest injuries over the past 15 years, the rate of lower limb injuries over this time has remained virtually unchanged. This finding contracts with frontal crash tests data that has shown significantly decreased vehicle measures (e.g., toe pan intrusion), and responses measured in the dummy have steadily decreased during the same period.

Given the prevalence of lower limb injuries and the fact that current vehicle modifications (e.g., structural modifications to reduce intrusion) have not reduced incidence rates, consideration must be given to other available countermeasures that could mitigate lower limb injuries. In addition to controlling occupant kinematics through earlier engagement of the pelvis, knee airbag (KAB) has reportedly been designed and developed to prevent lower limb injuries. Jenkins et al. discussed the structural improvement of conventional knee bolster material from steel brackets to engineering plastics with the implementation of an inflatable knee bolster [2]. This change may also provide extra space for lower limb placement and ultimately for more energy absorption. Knee airbags deployment along the lower panel fascia can restrain the knees during early phases of the crash and can also help reduce the loading to upper tibia [3].

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Two recent publications have analyzed data from the Crash Injury Research and Engineering Network (CIREN) and National Automotive Sampling System Crashworthiness Data System (NASS-CDS) to evaluate real-world lower extremity injury risk in frontal crashes. Weaver et al. [4] compared 9 CIREN cases with knee airbag to 183 no-knee airbag cases of the same vehicle model, crash type, and severity using a similarity scoring algorithm. Results indicated a statistically significant reduction in femur fractures, but an increased incidence rate of proximal tibia/fibula and foot/ankle fractures (also statistically significant), for occupants in crashes with deployed knee airbags. While the study by Patel et al. [5] combined NASS-CDS and CIREN data to maximize case availability for a matched cohort study, there were still an insufficient number of cases to find statistical significance of the lower extremity injury risks, although a decreased risk of hip and thigh fracture, and an increased risk of tibia/fibula and foot fracture were identified.

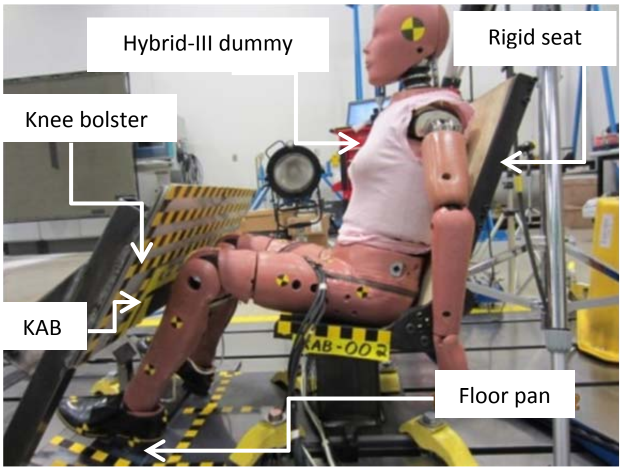
Beyond these two studies, relatively little has been published regarding the performance of knee airbags in real-world crashes, despite their increasing market penetration. Part of the difficulty results from the fact that there are a multitude of different airbag configurations (bottom-deployed or rear-deployed, high-mount or low-mount, KAB size, inflator output, etc.) that confound the assessment of KAB performance in retrospective field studies. Given the lack of understanding of real-world performance, questions arise regarding the knee airbag effectiveness in different frontal crash scenarios, the limitations of airbag coverage and overloading, the changes in injury patterns relative to knee bolsters, and the potential for lower limb injuries resulting from deployment of the knee airbag itself. This study aimed to investigate the biomechanical response of the lower extremities during knee airbag deployment in various out-of-position driving scenarios. Specifically, this study used dummy tests to assess the potential for out-of-position lower extremity injuries upon knee airbag deployment and to observe how knee airbag deployments could alter the occupant's positioning during a crash.

II. METHODS

Among standard adult dummies, the 5th percentile female occupants were chosen to represent the most vulnerable group for sustaining lower limb injuries, given a lower injury tolerance and a closer seating proximity to the instrument panel/ knee bolster. Therefore, the 5th percentile female was the target occupant for an investigation of knee loading resulting from interaction with a deploying knee airbag.

The current study consisted of 11 knee airbag static deployment tests, with a 5th percentile female Hybrid-III dummy seated in a simplified vehicle buck. The simplified test buck was designed to match the dimensions typical of a production small compact sedan profile. The buck structure consisted of occupant seat, instrument panel, knee bolster, toe pan structures, and pedals. The non-production knee airbag used in this test series was a rear-deploy type, mounted on the reinforced instrument panel of the simplified buck. The knee airbag assembly included the housing, cover, and inflator module (ARC hybrid gas inflator, 194kPa maximum tank pressure at 24.65ms, 28.3L tank volume and 0.9 mole). Vent holes in the airbags were initially blocked by stitching as unvented knee airbags represent a larger number of modules in the field. Details regarding the knee airbag are provided in Appendix 2.

All tests were performed in a static condition. The dummy was positioned in various out-of-position configurations representative of potential worst-case scenarios in frontal crashes, and in-position baseline tests with occupant positions comparable to specifications in the Federal Motor Vehicle Safety Standard (FMVSS) 208 (Figure1). Positioning of the seat also matched with FMVSS 208 test for a 5th percentile female dummy (i.e., forward most position in seat track, mid-height) [6]. The seat was then fixed and dummy was translated on the seat for various out-of-position postures. The seat was a simplified wooden rigid plate, with supporting structures made of steel and geometry (height, inclination angle) equivalent to the standardized test, but with less energy absorption and no anti-submarining structure than a production vehicle seat.



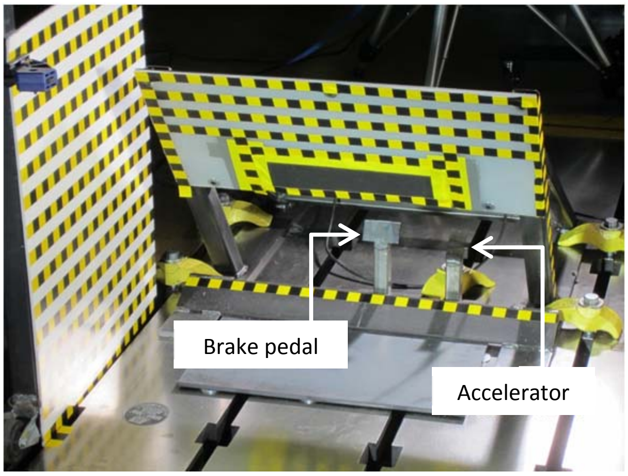


Figure 1. Schematic of test-setup with positioned dummy (Left); Overview of driver compartment (Right)

The Hybrid-III 5th female test matrix included two dummy lower extremities: the 5th percentile female Hybrid-III with the Hybrid-III Denton lower leg and the advanced THOR-FLx. THOR-FLx was retrofitted to the distal femur of the 5th percentile female Hybrid-III dummy as a more biofidelic testing device [7]. Components from the THOR-FLx are mostly scaled representations of the original 50th percentile male THOR-Lx counterparts. New design aspects related to the THOR-FLx included modifications to the tibia axial compliance, the elastomeric stops at two principal ankle-joint stops, the Achilles tendon, the anterior tibia shape, and the side knee covers attached to the knee clevis [8]. Given the identical input test conditions, this parametric study investigated the similarity of response between Hybrid-III Denton leg and THOR-FLx and analyzed any potential differences during KAB interaction.

Regarding dummy positioning, baseline tests generally matched the FMVSS 208 in-position tests for the 5th percentile Hybrid-III dummy. Dummy calibration and polarity testing were performed before positioning, while the posture measurements were taken using a 3D coordinate measurement machine (FARO Technologies, Lake Mary, FL, USA), as well as traditional measurement tools including calipers, tape measures and inclinometers. Markers were placed at multiple locations of both left and right extremities to capture the postures for scanning measurements of pre-test posture. The dummy femurs and tibias were painted and chalked to observe contact with the knee airbag. The dummy upper extremities were placed vertically in line with the torso to avoid interference with lower extremity movement.

Table 1 below shows the test matrix in this study. A total of 11 tests were conducted, with four test configurations for both Hybrid-III and THOR-FLx dummy legs, and repeated baseline tests. An additional test (THOR-ADD1) was repeated from an earlier test (THOR-ADD) as it was noticed in post-test analysis that the right hind-foot in test THOR-ADD was elevated above the floor pan rather than resting on it. A detailed summary of dummy positioning is listed in Appendix 1.

Table1. Knee airbag test matrix

Num	Test	Dummy leg	Knee to instrument panel (mm)	Knee to knee distance (mm)	Right foot placement	Left foot placement	Comments
01	H3-BAS1	Hybrid-III	Right: 85 Left: 82	252	accelerator	footrest	Baseline#1
02	H3-BAS2	Hybrid-III	Right: 85 Left: 82	252	accelerator	footrest	Baseline#2
03	H3-FWD	Hybrid-III	Tibia contacts knee bolster	252	accelerator	footrest	Dummy translated full-forward

04	H3-ADD1	Hybrid-III	Tibia contacts knee bolster	180	brake pedal	footrest	Dummy at full-forward
05	H3-ADD2	Hybrid-III	Tibia contacts knee bolster	158	brake pedal	footrest	Adducted, left foot inboard
06	THOR-BAS1	THOR-FLx	Right: 85 Left: 82	252	accelerator	footrest	Baseline#3
07	THOR-BAS2	THOR-FLx	Right: 85 Left: 82	252	accelerator	footrest	Baseline#4
08	THOR-FWD	THOR-FLx	Tibia contacts knee bolster	252	accelerator	footrest	Dummy translated full-forward
09	THOR-ADD	THOR-FLx	Tibia contacts knee bolster	180	brake pedal	footrest	Dummy at full-forward, right heel elevated
10	THOR-ADD2	THOR-FLx	Tibia contacts knee bolster	158	brake pedal	footrest	Adducted, left foot inboard
11	THOR-ADD1	THOR-FLx	Tibia contacts knee bolster	180	brake pedal	footrest	Dummy at full-forward

SAE Channel Frequency Class 600 Hz filter was applied to the force and moment data and SAE Channel Frequency Class 180 Hz filter was applied to displacements following the SAE J211 standard. Data were all reported in accordance with the SAE coordinate convention. Data recording started 20 ms prior to the knee airbag firing time and ended 150 ms after firing. Three high-speed cameras (Memrecam GX-3, NAC Image Technology, California, USA) documented the deployment process with a frame rate of 2000 frames per second for kinematics analysis.

For the calculation of tibia index (TI), a geometric adjustment of the tibia sagittal moment was performed for the upper and lower tibia load cell locations of the Denton leg. The adjustment compensated for the non-anatomical geometry of the Hybrid-III dummy lower extremity, which can result in an over-estimation of proximal tibia fracture [9]. The adjustment function was shown below, with the geometrical coefficients measured from the 5th percentile dummy [10].

$$My_{upper.adj} = My_{upper.meas} - (Fz_{upper})(0.01589) \qquad (1)$$

$$My_{lower.adj} = My_{lower.meas} + (Fz_{lower})(0.004665) \qquad (2)$$

The units for the compensation force and moments were force in N and moment in Nm. The resultant moment was calculated after the adjustment of moment for the Hybrid-III leg. Tibia index was calculated for the Hybrid-III leg, and the revised TI was calculated for the THOR-FLx dummy leg as indicated below [10].

$$M_r = \sqrt{M_x^2 + M_y^2} \qquad (3)$$

$$TI_{Hybrid-III} = \frac{F_z}{F_c} + \frac{M_r}{M_c} = \frac{F_z}{(-22900)} + \frac{M_r}{115} \qquad (4)$$

$$TI_{THOR-FLx} = \frac{F_z}{F_c} + \frac{M_r}{M_c} = \frac{F_z}{(-8600)} + \frac{M}{146} \qquad (5)$$

Where M_r is the resultant tibia moment, F_z is the tibia compression force, F_c and M_c are the critical threshold values for force and moment in tibia index. TI was calculated using compression force and resultant moment responses for the upper and lower, left and right tibia load cell locations.

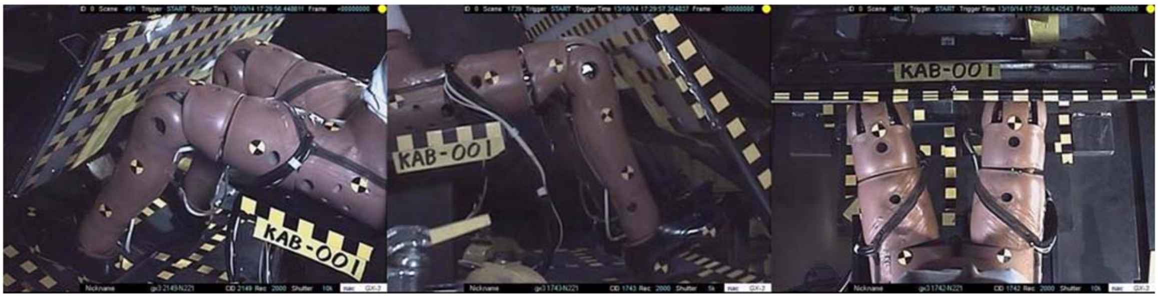
Multiple injury risk functions were used to estimate the injury risk of AIS 2+ lower extremity injuries, including tibia shaft fractures, knee-thigh-hip injuries, ankle fractures, and tibia plateau injuries. Scaling of the injury risk function was applied to account for the geometry and mass differences between the 50th percentile and the 5th percentile dummies [10].

Injury Assessment Reference Values (IARV) obtained from Insurance Institute for Highway Safety (IIHS) for the 5th percentile dummy were applied to the test data as a guideline for evaluating injury measures [11].

III. RESULTS

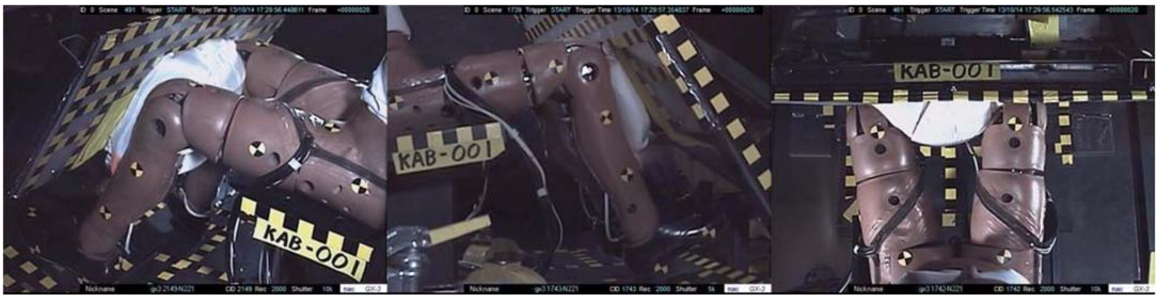
The deployment of the knee airbag was composed of several phases as indicated by the sequence of time-lapsed photos (Figure 2 and Figure 3). After triggering of the knee airbag, the cover of the airbag was breached and the airbag started unfolding. Initial contact of the airbag with the occupant started with the upper tibia region and migrated upwards to the knee region. The airbag unfolded on the medial side of each knee simultaneously and abducted both legs. The closed vent holes ruptured in three tests (H3-ADD1, H3-ADD2, and THOR-ADD2); while in the other tests the knee airbags remained intact. The final stage of knee airbag interaction with the occupant occurred with the knee airbag wrapped over both knees of the dummy.

1. Starting point of trigger (t=0ms)



2. Airbag unfolded and contacted upper tibia region (t=5ms)

3. Airbag deployed and contacted knee region (t=10ms)



4. Unfolding continuation (t=15ms)

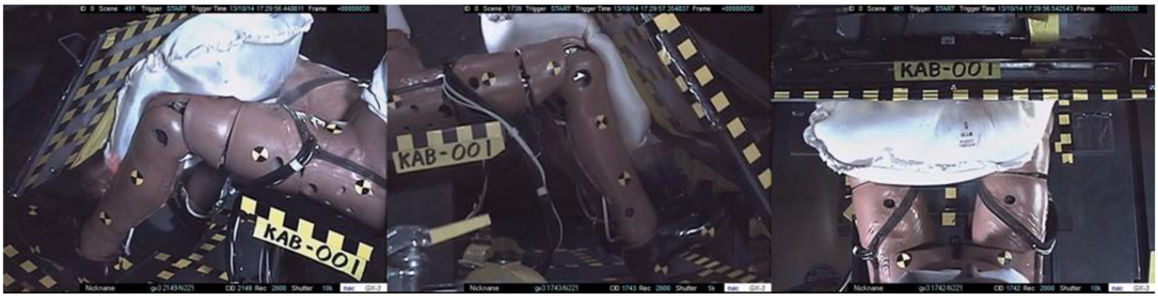
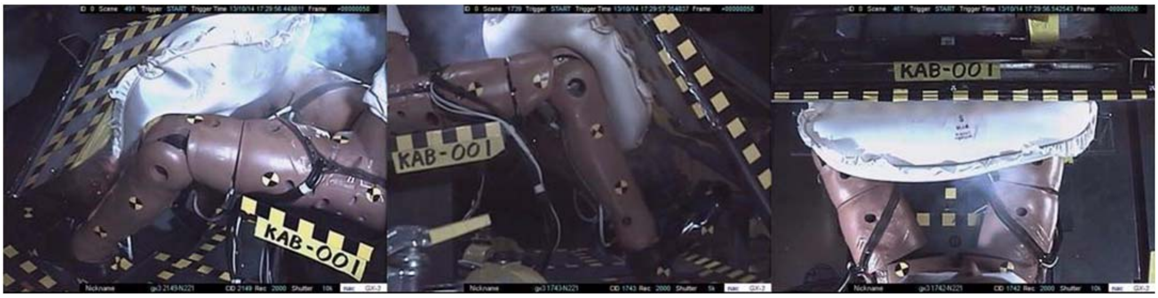


Figure 2. Typical response of the knee airbag during the deployment phase

5. Abduction of both legs due to airbag deployment (t=20ms)

6. Full contact with lower extremity (t=25ms)



7. Opening of vent holes (for some tests) (t=30ms)

8. Airbag wrapped over the knees at final stage (t=50ms)

Figure 3. Typical kinematic response of the dummy following knee airbag deployment

The lower left tibia compression force F_z from the THOR-FLx was consistently higher than those in the Hybrid-III, with an average difference of more than 75% in magnitude (Figure 4). Repeated baseline in-position tests with the Hybrid-III leg showed similar responses with peak left lower tibia compressive force at 1382 N and 1264 N. When translating the dummy full-forward and maintaining the knee-to-knee distance, maximum force decreased slightly to 900 N. With the dummy at the full-forward position and both thighs adducted, the highest compression loading of 2397 N (H3-ADD2) occurred in the lower left tibia for the Hybrid-III leg, an increase of 45% over the average of the two baseline tests. A similar trend was observed in THOR-FLx tests, with initial peak force from the two baseline tests reaching 1843 N and 1581 N. A second peak force of 2606 N was observed in test THOR-BAS1. Adduction of the knee at full-forward seating position generated a high compression force of 2928 N for THOR-FLx; while in test THOR-ADD1, peak force elevated to 3307 N. In addition, more oscillation occurred in both lower and upper left tibia from THOR-FLx tests than Hybrid-III. This is due to the structural difference where axial loading was generated by the Achilles tendon assembly in the THOR-FLx, and additional compression force was superimposed at the lower tibia from this loading path. Lower left tibia moments M_x and M_y from THOR-FLx showed comparable values to the Hybrid-III tests (Figure 5 and Figure 6).

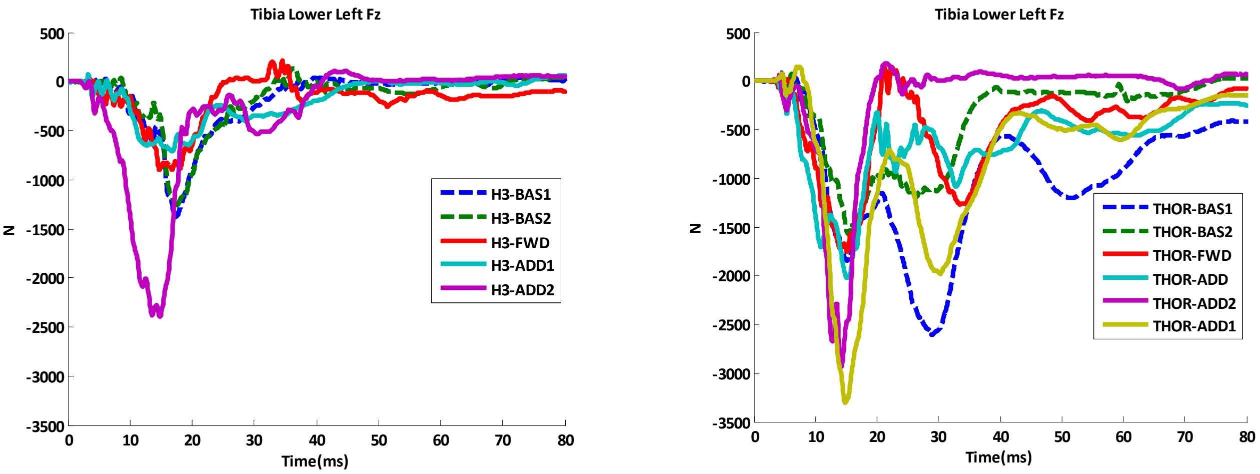


Figure 4. Tibia lower left force Fz in Hybrid-III (left) and THOR-FLx (right)

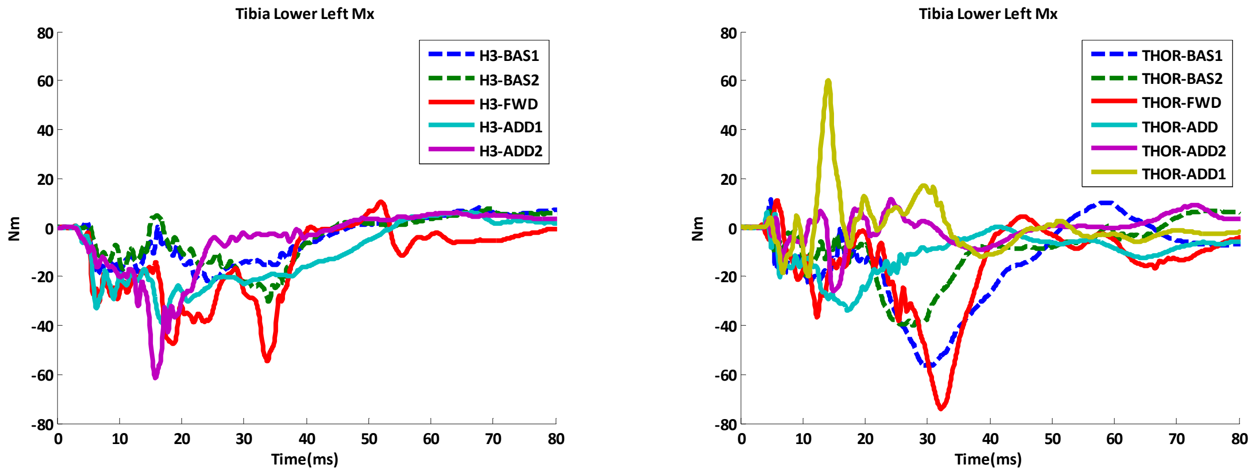


Figure 5. Tibia lower left moment Mx in Hybrid-III (left) and THOR-FLx (right)

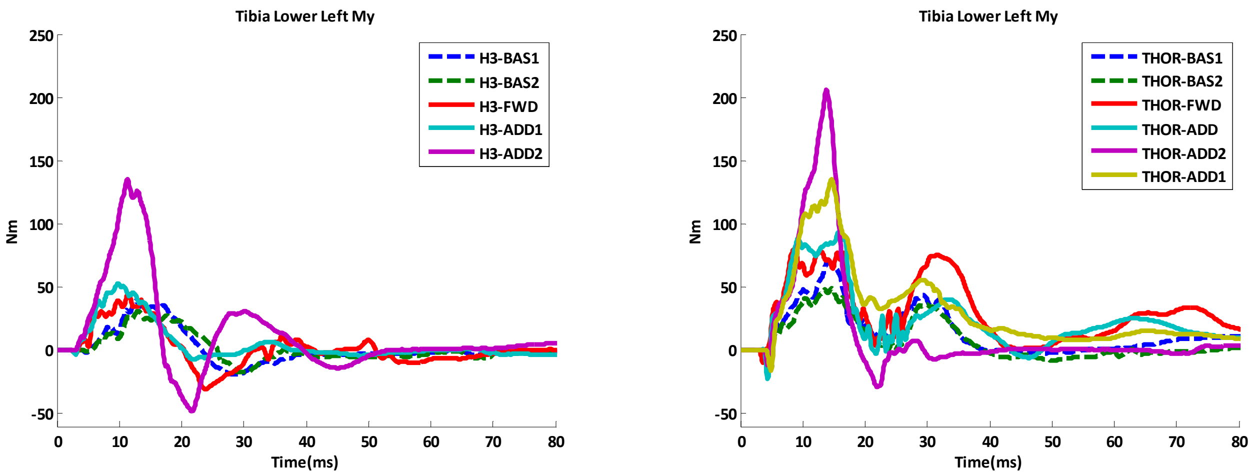


Figure 6. Tibia lower left moment My in Hybrid-III (left) and THOR-FLx (right)

Upper tibia index ranged from 0.95 to 1.31, and 0.78 to 1.21 for baseline tests of Hybrid-III LX and THOR-FLx, respectively. Lower tibia index varied from 0.3 to 0.46 (Hybrid-III) and from 0.51 to 0.79 (THOR-FLx) (Figure 7).

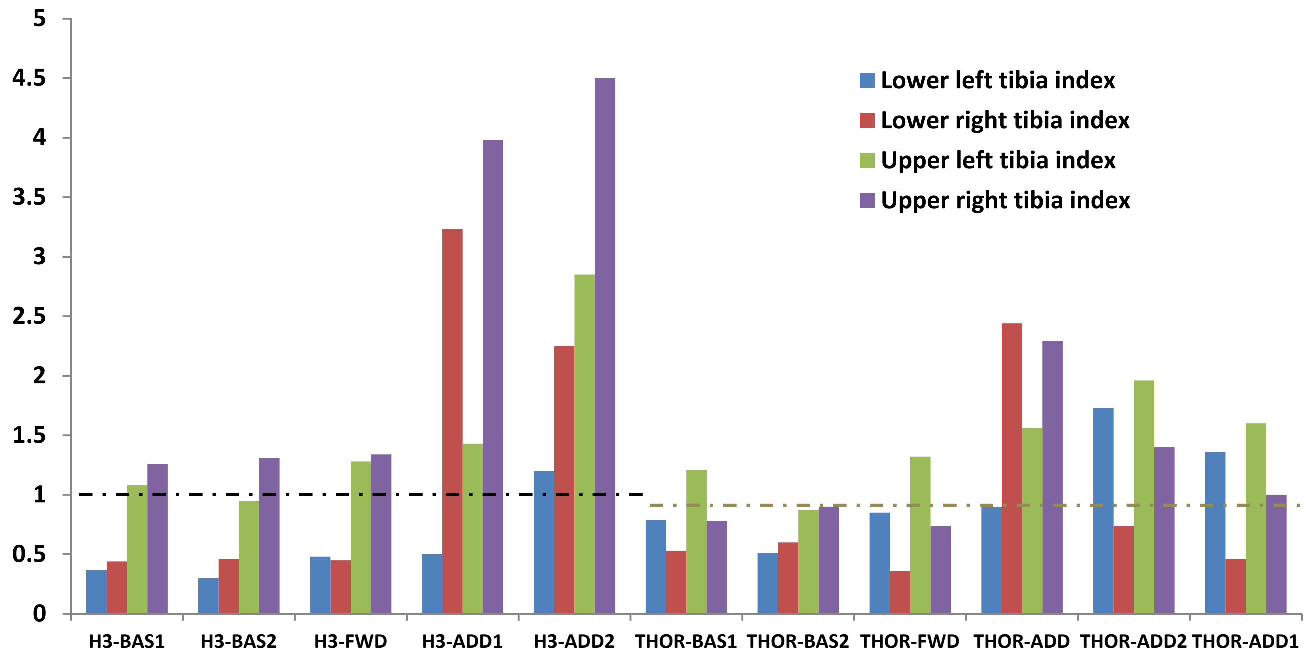


Figure 7. Summary of tibia index for all tests

As depicted in Figure 7, the average tibia index increased by 15% for the Hybrid-III and 6% for the THOR-FLx in the full-forward position compared to baseline. With the right foot moved inboard from the accelerator to the brake pedal, the average TI increased 196% (Hybrid-III) and 43% (THOR-FLx) relative to baseline tests. Finally, the highest average TI, 250% (Hybrid-III) and 88% (THOR-FLx) greater than baseline, was recorded with the left foot moved inboard creating an adducted initial position of the lower limbs. In general, the upper tibia sustained higher bending moments resulting in higher tibia index values, and the right TI was generally higher than the left. As noted in Figure 7, a threshold of 1.0 (black dotted line) was set as the tibia index for Hybrid-III, and a revised critical value of 0.91 was used(grey dotted line) as the proposed THOR-FLx injury limit [7]. For most out-of-position tests, right TI exceeded the threshold, with the maximum TI of 4.5 occurring in the upper right tibia from test H3-ADD2, mostly resulted from extreme high tibia upper right moment M_y (543 Nm).

The results from injury risk functions predicted higher injury risk of tibia shaft fractures than foot and ankle fractures (Figure 8-10). In addition, for the risk of AIS2+ knee-thigh-hip injuries based on left and right axial femur forces, predicted injury risk ranged from 0.35% to 0.52% across all the tests, but the difference between tests was not distinctive so the plot was not shown. The increased risk of tibia shaft resulted from the high value of moments upon knee airbag deployment, while relatively less loading was applied to the foot/ankle complex. For test THOR-ADD, due to the elevation of right hind-foot, extremely high compression force was applied to the right leg as the heel was driven downward and landed on floor pan, with lower right tibia axial compression force of 8404 N and upper right tibia force of 4723 N. This driving posture also resulted in large dorsiflexion and compression of the right foot, while the foot was initially placed on the brake pedal. With respect to injury risk of lower extremity, data recorded from Hybrid-III Denton leg was comparable with the retrofitted THOR-FLx. Rudd et al. also found that the lower limb responses between the 5^{th} percentile Hybrid-III and THOR-FLx leg were less distinct than the differences for the 50th percentile dummy legs, while only the ankle y-axis moment showed clear differences under dynamic sled test conditions [7].

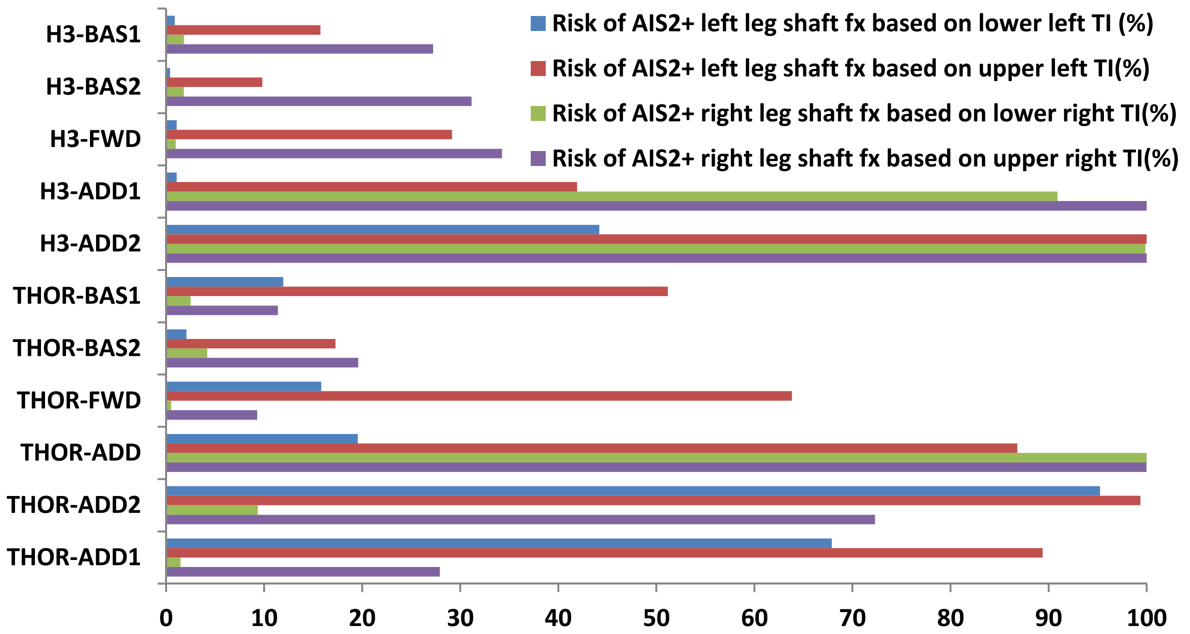


Figure 8. Risk of AIS2+ leg shaft fractures based on tibia index (%)

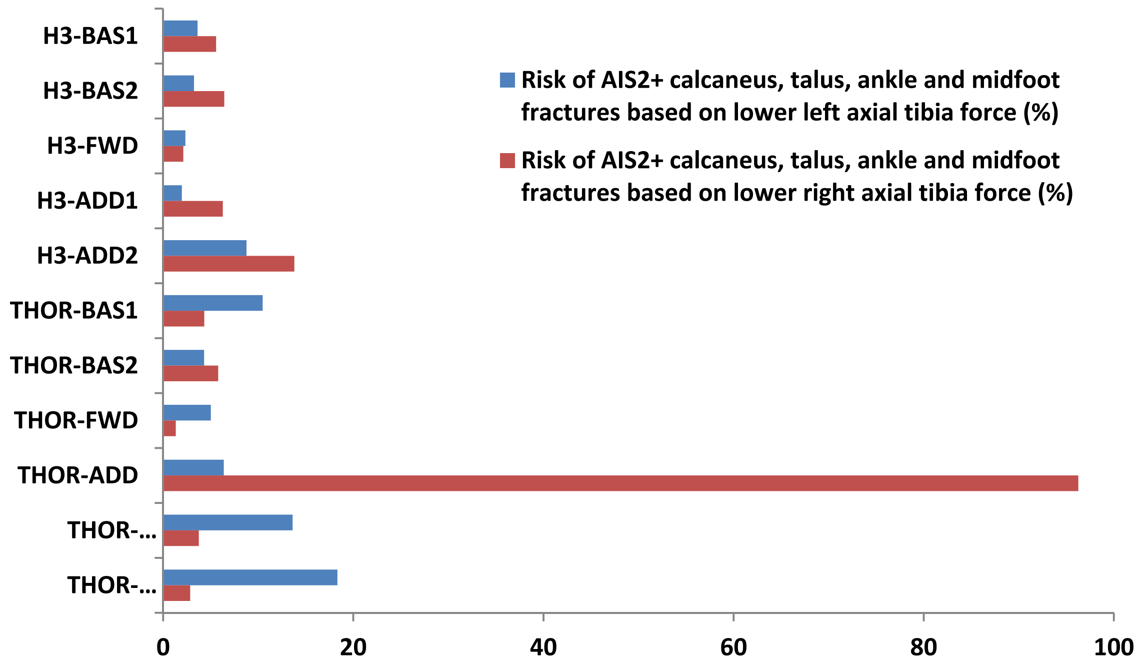


Figure 9. Risk of AIS2+ calcaneus, talus, ankle and mid-foot fractures based on axial tibia force (%)

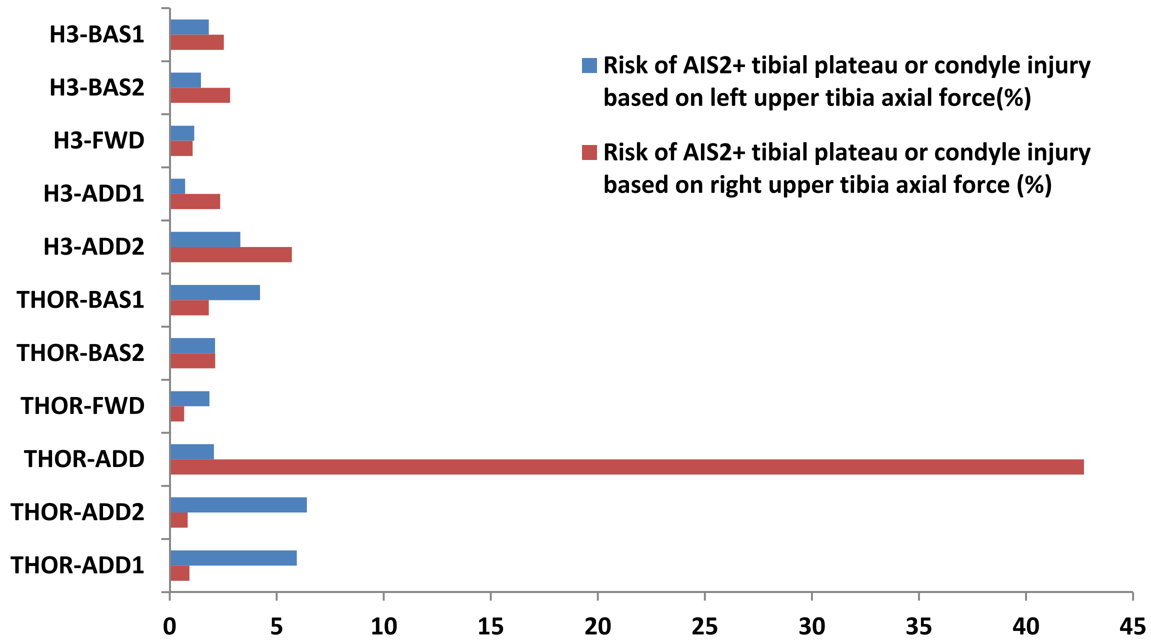


Figure 10. Risk of AIS2+ tibia plateau or condyle injury based on tibia axial force (%)

The IIHS rating system for the 5th percentile Hybrid-III was applied to the dummy lower limb response and tests data was categorized with reference to the rating boundary values (Table 2).

Table 2. Summary of tests data with IIHS rating system

Num.	01	02	03	04	05	06	07	08	09	10	11
Test	H3-BAS1	H3-BAS2	H3-FWD	H3-ADD1	H3-ADD2	THOR-BAS1	THOR-BAS2	THOR-FWD	THOR-ADD	THOR-ADD2	THOR-ADD1
Tibia Lower Left Fz	-1382	-1265	-900	-711	-2396	-2606	-1581	-1752	-2025	-2928	-3307
Tibia Lower Right Fz	-1870	-2036	-790	-2009	-2944	-1584	-1914	-277	-8404	-1423	-1117
Tibia Upper Left Fz	-1480	-1281	-1063	-644	-2012	-2237	-1610	-1492	-1590	-2625	-2552
Tibia Upper Right Fz	-1771	-1870	-998	-1709	-2516	-1479	-1617	-602	-4723	-783	-866
Left Femur Fz	-275	-210	-205	-192	-448	-336	-211	-366	-306	-532	-463
Right Femur Fz	-320	-334	-260	-745	-684	-367	-335	-234	-512	-391	-247
Resultant Left Foot Acceleration (x,z)	58	46	106	44	98	78	55	100	90	149	122
Resultant Right Foot Acceleration (x,z)	50	53	52	335	325	61	77	80	355	169	90

IV. DISCUSSION

Given the field data findings of increased risk of leg injuries in crashes involving a knee airbag, the tibia index was applied in this study of static knee airbag deployment as an injury criterion to represent lower limb injury risk. It is recognized, however, that TI can result in inaccurate injury prediction given the geometry and stiffness of Hybrid-III, since the TI values are affected by the geometry of the Hybrid-III dummy, which does not represent the geometry of the human leg in a biofidelic manner [12][13]. Due to the bent shape of the instrumented Hybrid-III leg, artifactual bending moments not present in the human leg are recorded at the upper and lower tibia load cells owing to the axial force being applied along a line of action behind the upper tibia load cell, but in front of the lower tibia load cell. The human tibia diaphysis generally bows anteriorly and medially, especially at the proximal tibia [13]. Therefore, a geometric adjustment developed by Zuby et al. for the tibia moments was applied in the study in an attempt to reduce this confounding factor [9]. Given the limited information on curvature of the tibia at the time of development, the THOR-FLx used a straight component for the leg, which, like the Hybrid-III, does not match the human geometry, although the variation between human and dummy anthropometry is much smaller for the THOR-FLx than the Hybrid-III. In addition to geometric issues, the compliance of the below-knee structures must be considered for characterization of axial loads. While geometric adjustment can partially compensate for the leg curvature, the stiff structure of the Hybrid-III frequently overestimates the loads relative to what a human leg would experience. For comparison, the THOR-FLx incorporates axial compliance of the lower leg using a deformable element inserted into the proximal tibia shaft. This element lowers the effective stiffness of the metal column that constitutes the tibia. As a result, the axial forces in THOR-FLx are more comparable to the human response whereas the Hybrid-III generally produces higher axial forces due to its stiff structure. In the deployed knee airbag environment, the Hybrid-III generally showed higher tibia index than THOR-FLx, especially in the upper right tibia region.

All tests involved static deployment of knee airbags in a simplified buck environment. The purpose of the study was to acquire a better assessment of driver lower limb kinematics and forces resulting solely from KAB deployment effects, and to exclude other contributing factors that may come to play in dynamic sled-tests, including the crash-pulse magnitude, vehicle intrusion levels and onset time, and occupant kinematics during the crash. Real-world crashes would superimpose crash loads and intrusion onto the forces observed with KAB deployment and the effects on injury in a dynamic environment cannot be assessed at this juncture. In addition, pre-impact braking and bracing could influence the occupant motions and forces within the occupant compartment. High incidence of pre-crash bracing has been indicated by skid marks and anticipated reaction time [14], and in more than two-thirds of occupants in frontal crashes who sustained lower extremity injuries, the occupants were noted to have braced their leg muscles during the impact [15]. While the driving posture from test H3-ADD2 and THOR-ADD2 attempted to reproduce the braking posture of small female drivers, actual muscle bracing would generate additional loading to the lower limbs. Levels of muscle activation could potentially affect load distribution and injury risks during a frontal crash, and braking could potentially elevate the foot placement and place the tibia position closer to the knee airbag.

Leg abduction as a result of deployment was observed in the tests, with an increased abduction angle occurring when the dummy was translated forward. Increased loading to the upper and lower tibia was observed when left leg was moved inboard and knees moved closer in lateral, creating an initial posture of adduction for both limbs which essentially “trapped” the deploying knee airbag. Video analysis supported the hypothesis that knee airbag could potentially alter the occupant positioning such that legs are repositioned towards stiffer outboard or inboard vehicle structures within the occupant compartment, which may cause higher loads during contact in a crash. Schroeder et al. [16] performed four out-of-position PMHS static deployment tests and one in-position PMHS sled test. High axial compression force in femur and lateral movement of legs was noticed due to abducting and rotational forces in static deployment tests, similar to the leg abduction observed from this study. Although no critical contact injuries occurred in the dynamic test with PMHS seated in normal position, the test sample size was too small to derive a conclusive judgment regarding the knee airbag performance on preventing lower extremity injuries.

In terms of the representativeness of the experiments, there are multiple contributing factors that may account for elevated dummy lower extremity responses in the experiments beyond that observed in production vehicles. Firstly, the mounting brackets and rigid boundary conditions of the instrument panel and floor pan may have prevented energy absorption by the supporting structures. This change from a potential OEM design could also be a factor to cause the airbag to seem more aggressive from an occupant loading point-of-view. Secondly, the use of a rigid flat seat could have influenced the interaction of the dummy and seat and, by extension, the loading of the upper and lower tibia. Perforation of the airbags occurred in three tests, which resulted in relatively less oscillation during the decaying phase of the data time histories, but the implication for peak loads and moments was negligible.

Results from this study indicate that knee airbag deployment alone may produce forces and moments that could result in lower limb trauma. Since this study was conducted with a single KAB design and inflator, in a controllable but simplified vehicle environment, the findings cannot be broadly generalized. Changes of knee airbag deployment characteristics and mounting positions could also potentially result in different responses in the lower limb. Improvements to knee airbag design have been proposed, including reduction of the gas-mass during the filling phase of the airbag by using a dual-staged gas inflator, structural improvement of the airbag mounting bracket, and redirection of the airbag gas flow [17]. Given the limitations in this static deployment test setup, further investigations may be necessary to assess the knee airbag performance for in-position and out-of-position occupants in dynamic events.

V. CONCLUSIONS

This study investigated the biomechanics of lower extremities subjected to direct loading by a deploying KAB. Results showed upper tibia index ranged from 0.95 to 1.31, and 0.78 to 1.21 for baseline tests of Hybrid-III and THOR-FLx, respectively. Lower tibia index varied from 0.3 to 0.46 (Hybrid-III) and from 0.51 to 0.79 (THOR-FLx). Translating the dummy to the full-forward position resulted in greater abduction of both legs during knee airbag deployment and an increase of tibia index. The highest average TI was recorded with the left foot moved inboard creating an adducted initial position. For baseline tests, highest injury risk of AIS 2+ leg shaft fractures occurred in upper right tibia of Hybrid-III LX (31.15%) and in upper left tibia of THOR-FLx (51.17%). The risk of AIS2+ calcaneus, talus, ankle and midfoot fractures ranged from 1.96% to 18.32% for left foot, and from 1.32% to 96.26% for right foot. The results predicted higher injury risk of tibia shaft fractures than foot and ankle fractures. Lastly, test data were categorized with reference to IIHS injury assessment reference values. The elevated dummy lower extremity response recorded in this study for out-of-position small female occupants suggests that occupant interaction during deployment needs to be a consideration during knee airbag design.

VI. ACKNOWLEDGEMENT

The authors would like to acknowledge NHTSA CIREN for funding this project (NHTSA cooperative agreement DTNH22-10-H-00293). Views and opinions expressed here are those of the authors and do not necessarily reflect those of the sponsors.

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VIII. APPENDIX

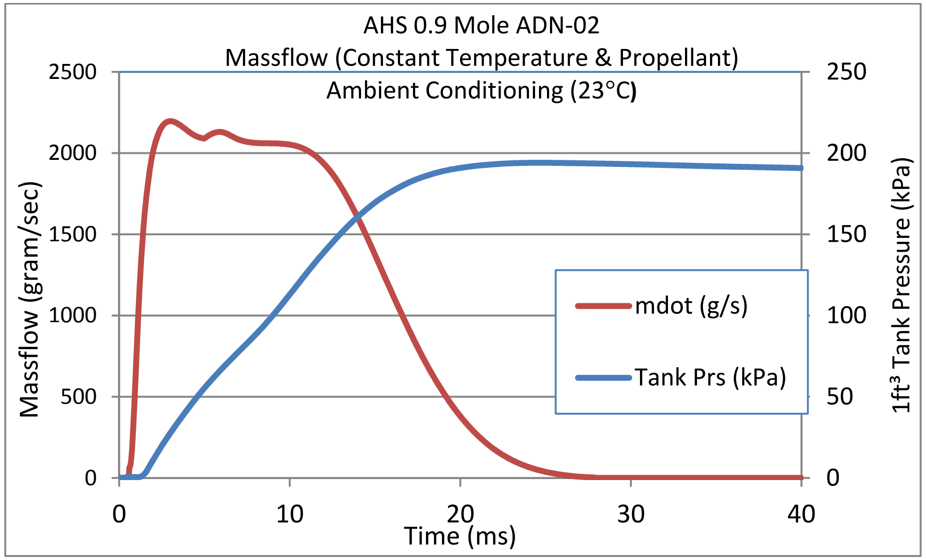
Appendix 1. Summary of dummy positioning for all tests

Measurement Description	Seatback angle (center line)	Seat angle (headrest)	Seat Height (mm)	Pelvic angle(Right)	Pelvic angle(Left)	Femur angle(Right)	Femur angle(Left)
FMVSS208 Reference	74°	85.7°	Mid-height	21.7°	21.7°		
Notes			seat bottom to ground in vertical direction			H-point to knee joint center	H-point to knee joint center
H3-BAS1	68.7°	85.5°	280	17.3°	17.1°	13.0 °	10.6°
H3-BAS2	68.7°	85.5°	280	17.6°	17.0°	12.1°	9.8°
H3-FWD	68.7°	85.5°	280	19.4°	19.0°	9.3°	8.7°
H3-ADD1	68.7°	85.5°	280	20.6°	19.9°	9.2°	9.0°
H3-ADD2	68.7°	85.5°	280	19.4°	19.2°	8.8°	7.5°
THOR-BAS1	68.5°	85.5°	280	16.1°	15.6°	12.0°	11.3°
THOR-BAS2	68.5°	85.5°	280	14.9°	14.3°	12.9°	9.6°
THOR-FWD	68.5°	85.5°	280	17.0°	16.4°	12.4°	8.5°
THOR-ADD	68.5°	85.5°	280	14.9°	14.1°	16.3°	4.5°
THOR-ADD2	68.5°	85.5°	280	21.2°	20.8°	11.8°	12.3°
THOR-ADD1	68.5°	85.5°	280	19.1°	18.3°	13.6°	12.3°
Measurement Description	Tibia angle (Right)	Tibia angle (Left)	Knee to Knee (mm)	Left knee to dash(mm)	Tibia to KAB module (mm)	Right knee to dash(mm)	
FMVSS 208 Reference	51.6°	51.6°	252	82		85	
Notes		Knee joint to ankle Y-rotation bolt joint center	Distance between knee centerline	Lateral knee joint center to closest IP	Anterior tibia surface to center of KAB module	Lateral knee joint center to closest IP	Anterior tibia surface to center of KAB module
H3-BAS1	70.3 °	60.1°	251	81	NA	66	NA
H3-BAS2	NA	NA	249	85	NA	67	NA
H3-FWD	NA	NA	252	67	2.7	68	7.3
H3-ADD1	NA	NA	180	73	1.9	63	12.5
H3-ADD2	NA	NA	158	77	0.5	65	18
THOR-BAS1	77.1°	58.9°	248	82	43.0	76	51
THOR-BAS2	67.6°	57.4°	250	82	47.0	73	54

THOR-FWD	50.3°	49.4°	249	72	8.0	70	11
THOR-ADD	59.0°	42.0°	180	99	25.0	65	32
THOR-ADD2	70.0°	67.2°	158	68	46.0	67	57
THOR-ADD1	72.1°	62.1°	180	71	29.0	65	55

*seat bottom to ground in vertical direction: 280 mm; seat front to IP in horizontal direction: 305 mm; seat width 432 mm; seat height top to ground: 782 mm (vertical); H-point to ground :365 mm (vertical) ; seat bottom inclined angle: 8.2°.

Appendix 2. Airbag mass flow rate and tank pressure during deployment



Appendix 3. Injury assessment reference values from IIHS

5th Female ATD	Rating Boundary Values			
	Good	Acceptable	Marginal	Poor
tibia index	<0.8	0.8-1.0	1.0-1.2	>1.2
tibia axial force (N)	<2600	2600-3900	3900-5100	>5100
foot acceleration (X,Z) (g)	<150	150-200	200-260	>260
femur force (N)	<5000	5000-6200	6200-7400	>7400