

CHALLENGES FOR OCCUPANT SAFETY IN HIGHLY AUTOMATED VEHICLES ACROSS VARIOUS ANTHROPOMETRIES.

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ABSTRACT

The introduction of automated driving systems (ADS) is likely to change the very nature of personal transportation. Without the need to drive, occupants will have more freedom to engage in other activities, which could result in major changes to vehicle interiors, controls, and seating configurations. Reclined posture seating may be an option that manufacturers consider in the relatively near term. The goal of this study is to evaluate how varying occupant anthropometry, distance to the knee bolster, and seatback angle affect occupant response.

A finite element model of a vehicle occupant compartment with the state-of-the-art seatback integrated restraint system was used, to evaluate three different simplified Global Human Body Model Consortium (GHBMC) occupant models (small female, midsize and large male) in frontal crashes. A full factorial sensitivity study was performed with four different levels of seatback recline (0, 10, 20, 30 deg) and four different distances to the instrument panel knee bolster resulting in total of 40 simulations.

Increasing the seatback recline angle caused the occupants' pelvis to submarine under the lap belt, which, in turn, resulted in poor pelvis-belt engagement and increased occupant excursion. Larger occupants tended to be able to withstand higher seatback recline angles without submarining than smaller occupants. Additionally, across all occupants, increased recline angle resulted in increased lumbar compression and shear force.

The new ADS environment is likely to pose substantial challenges to occupant restraints systems. Increased seatback angle increases the propensity of occupants to submarine, and results in increased lumbar spine load.

INTRODUCTION

The introduction of automated driving systems (ADS) is likely to influence almost every aspect of personal transportation. With Level 3 autonomy, the occupants will no longer be required to constantly interface with the vehicle controls [1-3]. Consequently, they may no longer be constrained to traditional seating postures. They will have more time and freedom to engage in other activities, which could result in major changes to vehicle interiors, controls, and seating configurations. While it will take time to develop the new automated technology, and revolutionize the layout of the occupant compartment, the greatest near-term changes will likely occur with drivers choosing to recline their seats and move them away from the knee bolster (KB) to rest during periods where autonomous modes are engaged. Thus, these seating choices may soon challenge the ability of current vehicle safety systems to adequately protect the occupants.

There are few studies focusing on occupant kinematics and restraint performance in reclined postures [4-7]. Those studies indicate that higher recline angles as well as increased distance to the KB may result in higher risk of submarining. Submarining occurs when the lap belt loads the abdominal area, after passing over the iliac crest of the pelvis to load the abdominal soft tissues without engaging, or after disengaging, the pelvis. This in turn results in series of adverse effects onto occupant-restraint engagement, occupant kinematics and occupant injury risk. These studies identified pelvis motion and lumbar spine loads as areas of particular interest. Additionally, some studies considered the differences between traditional b-pillar-mounted 3-point belt, and seat integrated restraint [4, 7]. While a seat-integrated D-ring resulted in earlier engagement of the torso, and less forward head motion, the b-pillar-mounted belt resulted in lower resultant force and flexion angle in the lumbar spine. However, none of these studies considered the effect of occupant anthropometry on occupant response.

The goal of this study was to evaluate the response for reclined occupants in frontal impacts across variations in occupant anthropometry, recline angle and the KB position. The specific goal of this study was to provide general overview of occupant, and restraint system responses across all varied conditions. This was accomplished using the family of Global Human Body Models Consortium (GHBMC) simplified human body models (HBM): mid-sized male, large male, and small female, subjected to 56 km/h frontal-impact simulations in a finite element model of a generalized vehicle interior.

METHODS

Overview

The simulation environment was developed based on the finite element (FE) model of the prototype vehicle provided by the OEM. Several changes were incorporated into the original model in order to make it suitable for the current study. First, the seatback integrated 3-point seatbelt system was developed. The seatbelt included lap belt pre-tensioner, shoulder retractor pre-tensioner and force limiter. Second, the seatback was reinforced with additional beam elements to provide appropriate structural support for the loads expected from the seatback integrated restraint system. Third, the KB was decoupled from the vehicle interior to facilitate rapid and parametric interior configuration adjustment. All simulations were performed with the occupant seated in the right front passenger seat, with generic passenger airbag, subjected to a USNCAP 56 km/h frontal crash pulse.

A full factorial design of experiments (DOE) was performed with respect to the parameters including, occupant anthropometry, seatback recline and KB position. Three different occupant anthropometries, small female (F05), midsize (M50) and large male (M95) were considered in this study. Seatback recline angle was defined as the angle between the headrest post and vehicle side sill. Four different recline angles were considered: 0, 10, 20 and 30 deg. recline (Figure 1). The distance between the occupant and KB was adjusted by moving the entire KB assembly relative to the vehicle frame (Figure 1). This was done in order to isolate the effect of the KB's position without altering any other restraint components such as belt anchorage position, or the distance to the frontal airbag. Four KB positions were considered, three positions representing a distance to a KB when the seat is placed at forward-track (fIP, +120mm), mid-track (sIP, 0mm) and back-track (bIP, -120mm) position, and one position when the KB is removed from the vehicle (nIP, -450mm). Since midsize and large male did not fit into the seat with the forward KB position, these conditions were removed from the simulation matrix. Consequently, the DOE resulted in total of 40 FE simulations (Table 1).

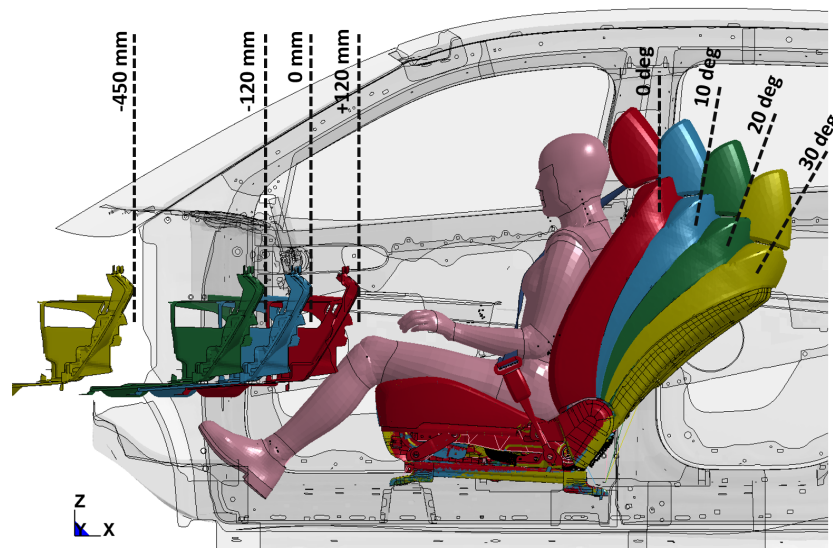


Figure 1. Simulation environment. Investigated seatback recline angles (0, 10, 20, 30 deg.) and knee bolster positions: fIP (+120 mm), sIP (0 mm), bIP (-120 mm), and nIP (-450 mm).

Table 1. Simulation matrix.

	Parameters			
Occupant anthropometry (version)	F05-OS (2.0)	M50-OS (1.8.4.1)	M95-OS (1.2)	
Seat recline angle (deg)	0.9	10.9	20.9	30.9
Knee bolster position (position)	Forward (fIP)*	Standard (sIP)	Backward (bIP)	No knee bolster (nIP)
	(+120 mm)	(baseline)	(-120 mm)	(-450 mm)
TOTAL	40 simulations*			

All of the simulation in this study were performed using LS-Dyna (R9.1.0) explicit finite element (FE) solver and the high performance computational cluster (Intel Xeon E5-2670v2, 2.5 GHz, 20 core). In order to eliminate decomposition performance variability, all jobs were run using two computational nodes.

Simulation setup

All occupant models were positioned in the vehicle seat following the methodology described in [7]. Additionally, care was taken to ensure that occupants' pelvis was positioned as close as possible to the seatback, thus avoiding unnecessary slouching that could lead to unfavorable belt placement and consequently submarining. The HBM and seat stress and strain data was carried through the positioning phase to the final simulations in order to achieve proper boundary conditions and contact initiation. The seat belts were fitted individually for each occupant size and each seat recline angle.

Additionally, throughout the setup process and during initial shakedown simulations several modeling issues/discrepancies were discovered in the utilized HBMs. First, M50 and M95 had several redundant single surface contact definitions, which impacted the overall stability of these models, and forced premature error termination. Second, it was discovered that male models had inverted polarities of the zero length discrete beam definitions in the lumbar spine, affecting the kinematic response as well as polarity of the obtained signal. Third, male models had a misaligned coordinate systems used for measuring forces in the occupant's femurs. Fourth, small female model carried additional attachment between pelvic flesh and pelvis which made it different from the male models. All discovered issues were addressed and the models were modified to unify the modeling approach.

Post-processing

A custom automated post-processing code was developed to analyze the results from all of the performed simulations. The occurrence of submarining was assessed through visual assessment of simulation results. The submarining was identified if the belt passed either of left, right or both iliac wings and moved above the anterior superior iliac spine (ASIS) into the abdomen.

RESULTS

A total of 40 simulations were performed in this study. Since some of the simulations did not proceed through a maximum of 150 ms, and terminated in error, the termination times were evaluated to identify trends with respect to simulation parameters (Table 2). The completion rate declined with the increase of the seatback angle. Forward and standard KB positions had the highest completion rate followed by the back and no KB condition. The M50 model had the highest percentage of normal terminations, followed by the M95 and F05 models.

Table 2. Termination times (out of 150 msec.) for all investigated cases.

HBM	IP Position	Recline Angle				Completion rate (IP)	Completion rate (HBM)
		0	10	20	30		
F05	fIP	150	150	82	90	50%	44%
	sIP	150	150	74	90	50%	
	bIP	150	150	110	78	50%	
	nIP	102	150	118	82	25%	
M50	fIP	N/A	N/A	N/A	N/A		67%
	sIP	150	150	150	84	75%	
	bIP	110	150	150	150	75%	
	nIP	150	150	70	74	50%	
M95	fIP	N/A	N/A	N/A	N/A		50%
	sIP	150	150	150	150	100%	
	bIP	150	88	88	96	25%	
	nIP	150	80	82	86	25%	
Completion rate (Rec.)		80%	80%	30%	20%		

For all occupants, increased occupant recline angle lead to increased posterior tilt of the pelvis. Additionally, with increased angle of recline, the lap belt moved vertically up and away from the ASIS (Figure 2).

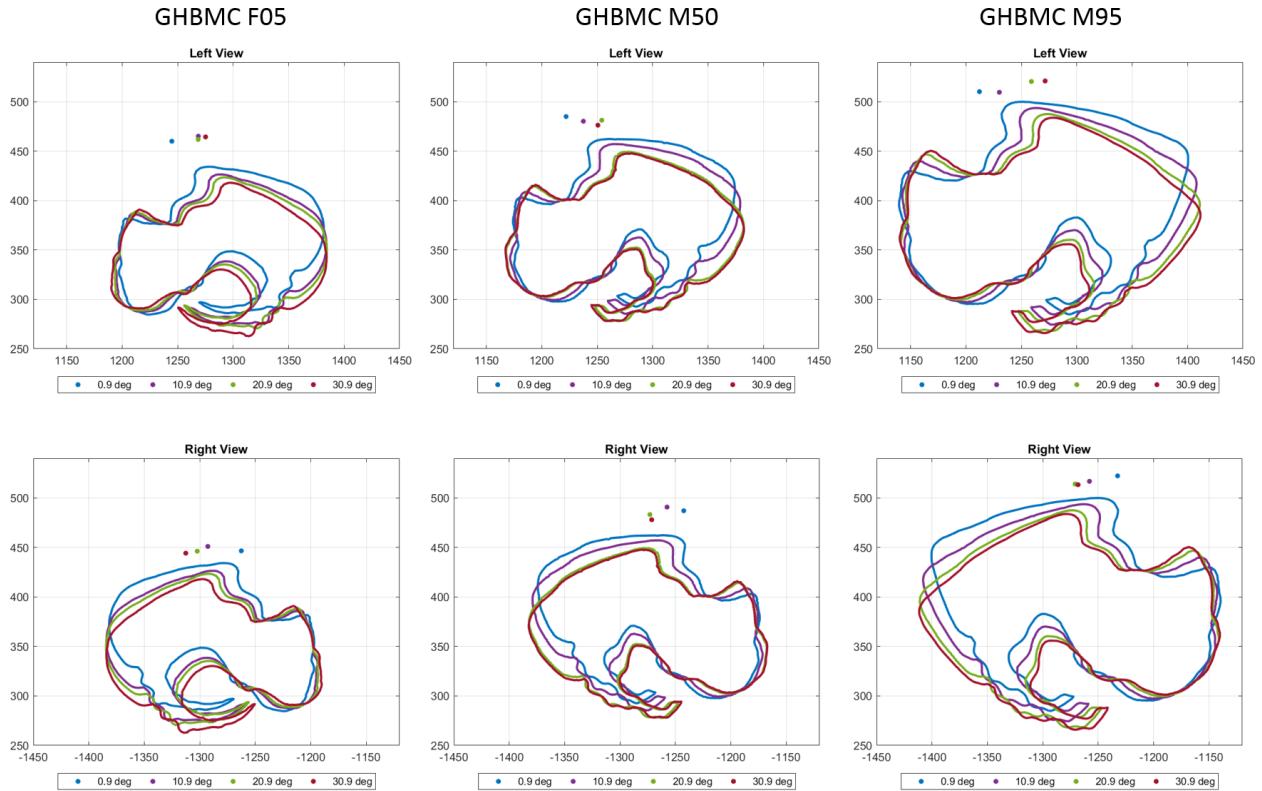
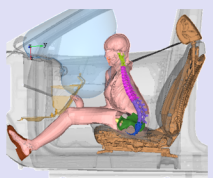
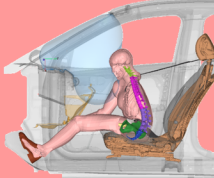
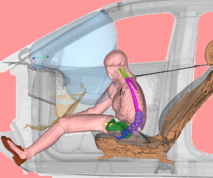
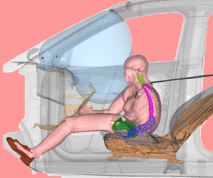


Figure 2. Lateral view of the pelvis with respect to the recline angle along with the top edge of the lap belt relative to the ASIS, shown for all three HBM models.

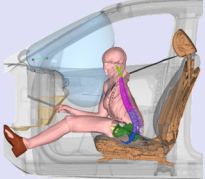
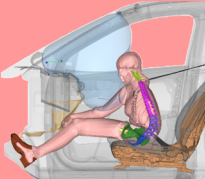
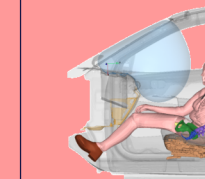
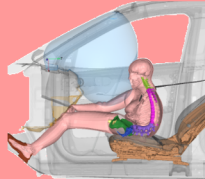
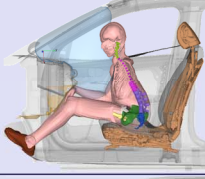
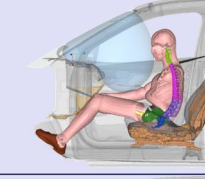
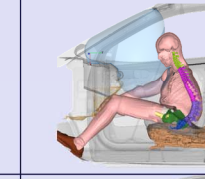

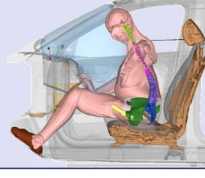
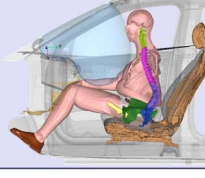
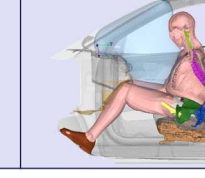
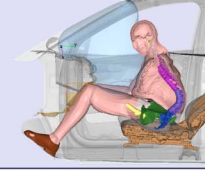
The occurrence of submarining was evaluated across all 40 of the simulations (Table 3, Table 4, Table 5, and Table 6). In general, submarining was observed more frequently at higher recline angles. The small female model submarined in the most cases, followed by the mid-size, which submarined in fewer cases, and then the large male, which submarined in the fewest cases. The KB distance also played a role in limiting the occurrence of submarining. In several cases where the submarining was observed in the back KB position it was effectively eliminated by moving the KB into the standard position (Table 4 and Table 5).

Table 3. Submarining outcome for the fIP knee bolster position. Cases highlighted with a red/pink background were cases where at least partial submarining occurred.

	0.9 deg	10.9 deg	20.9 deg	30.9 deg
F05				
M50	N/A	N/A	N/A	N/A
M95	N/A	N/A	N/A	N/A

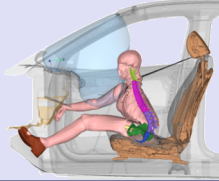
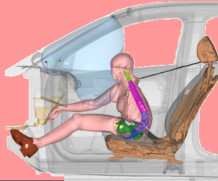
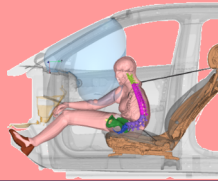
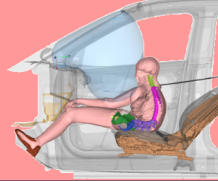
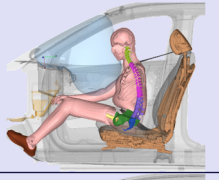
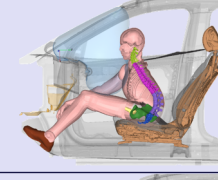

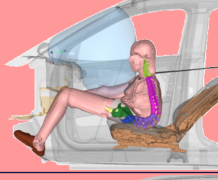
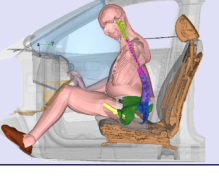
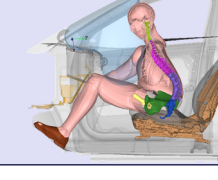
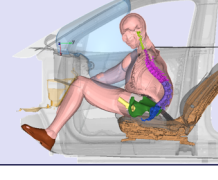
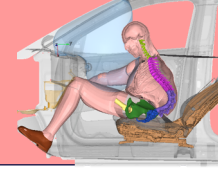
 No Submarining  Submarining

Table 4. Submarining outcome for the sIP knee bolster position. Cases highlighted with a red/pink background were cases where at least partial submarining occurred.

	0.9 deg	10.9 deg	20.9 deg	30.9 deg
F05				
M50				
M95				

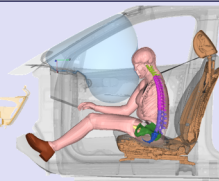
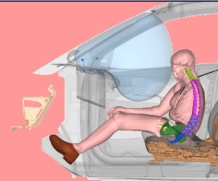
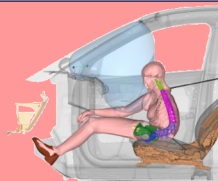
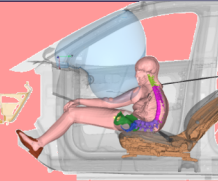
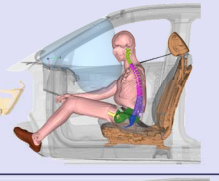
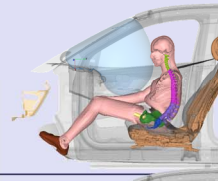

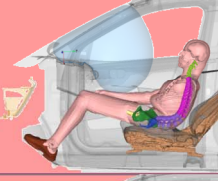
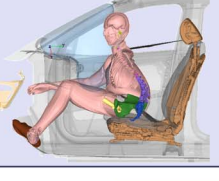

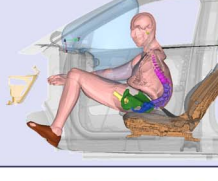

 No Submarining  Submarining

Table 5. Submarining outcome for the bIP knee bolster position. Cases highlighted with a red/pink background were cases where at least partial submarining occurred.

	0.9 deg	10.9 deg	20.9 deg	30.9 deg
F05				
M50				
M95				

No Submarining
 Submarining

Table 6. Submarining outcome for the nIP knee bolster position.

	0.9 deg	10.9 deg	20.9 deg	30.9 deg
F05				
M50				
M95				

No Submarining
 Submarining

In all cases, pelvis excursion increased with an increase of seatback recline angle and the increase of distance between the occupant and KB. In comparable cases with the KB present (fIP, sIP or bIP) larger occupant experienced smaller forward pelvis excursion (Figure 3).

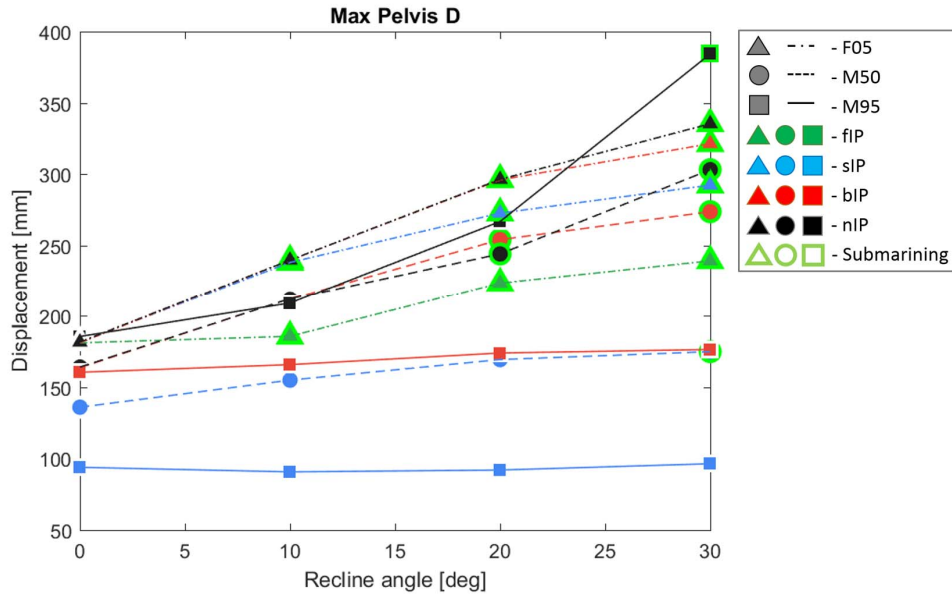


Figure 3. Maximum forward pelvis motion relative to the vehicle across all anthropometries, knee bolster positions, and recline angles.

As expected, the maximum lap belt force (measured at the anchor) increased with the increased size of the occupant. An increase in the lap belt force was observed with the increase distance between the occupant knees and KB. Interestingly the maximum lap belt force showed general decrease with the increased level of seatback recline (Figure 4).

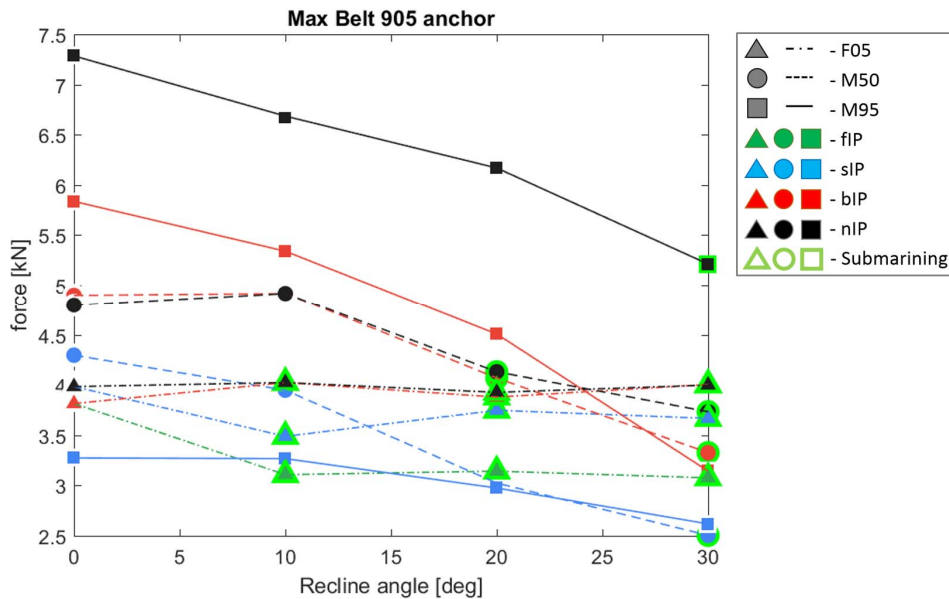


Figure 4. Maximum recorded lap belt force measured at the outboard anchor across all anthropometries, knee bolster positions, and recline angles.

The maximum femur compression force, used as a surrogate for knee to KB contact, showed an increase with the increase of the seatback recline angle. Only F05, siP, 20 deg. and 30 deg. recline cases showed the opposite trend, however upon in depth review it was discovered that these simulation terminated prematurely, before the maximum femur force was recorded (Table 2). Interestingly the maximum femur compression force didn't show consistent trend with the size of the simulated occupant (Figure 5).

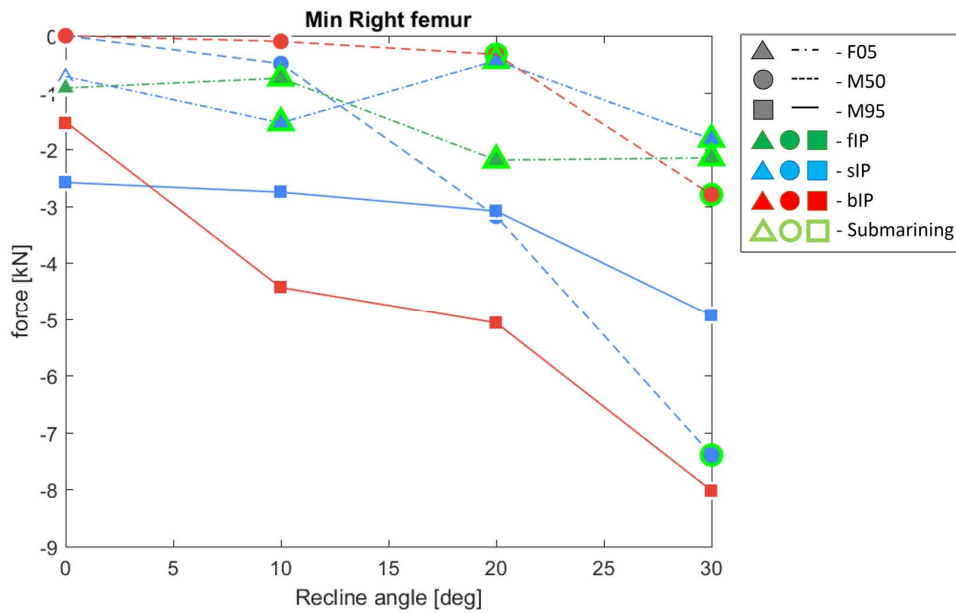


Figure 5. Maximum femur compression force across the cases where knee to knee bolster contact was present. No IP cases (nIP) for all anthropometries, and back IP (bIP) for F05 didn't have knee bolster contact and were removed for brevity.

The maximum lumbar spine forces were obtained by finding a maximum force across all vertebral levels in the lumbar spine. The maximum compression and anterior posterior (AP) shear force in lumbar spine increased with the increase of the recline angle (Figure 6 and Figure 7). Additionally, cases where submarining was observed, showed a substantial increase in a maximum lumbar spine shear force (Figure 7).

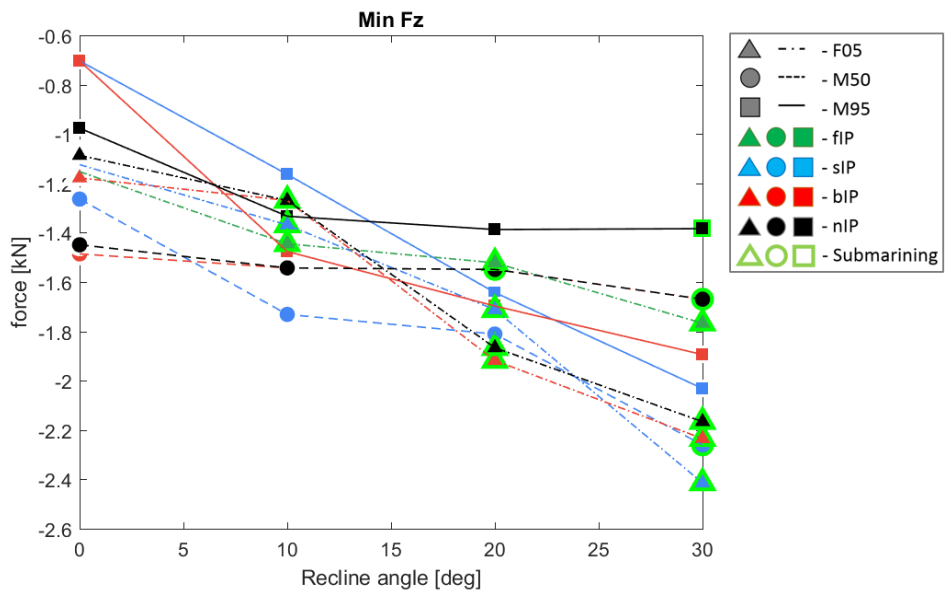


Figure 6. Maximum compression force in the lumbar spine measured for all lumbar vertebral levels (T12-S1), across all anthropometries, knee bolster positions, and recline angles.

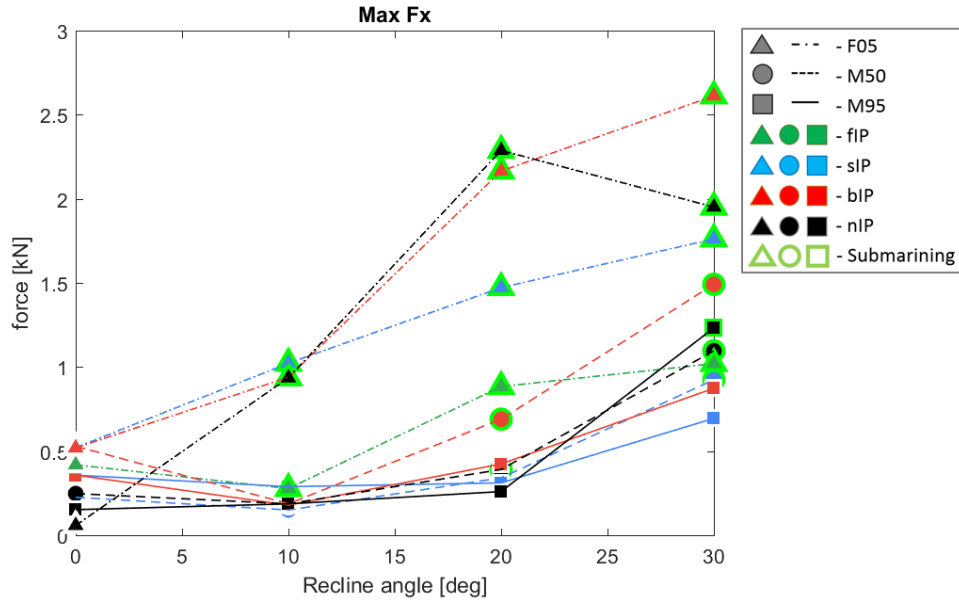


Figure 7. Maximum anterior-posterior shear force in the lumbar spine measured for all lumbar vertebral levels (T12-S1), across all anthropometries, knee bolster positions, and recline angles.

DISCUSSION

This study provides an overview of occupant responses in the environment relevant to the future of personal transportation. The initial results indicate that current state-of-the-art restraint systems will require additional research and development to offer an adequate level of occupant protection in the future ADS environment. Additionally, the results of this study show that current numerical tools need additional development, for evaluating occupant safety in nontraditional seating postures. Several modeling errors, which influenced either the stability or the actual response of the model were discovered. These modeling discrepancies have been addressed, and the modified models were used for this study.

The results show that these models perform best in the conditions that cover their development and validation regime, which is based on the current vehicle environment (upright occupant with KB). All models were also more stable in simulations with more upright occupants, and where traditional knee support was present. This is not surprising given that they were developed to be used in such environment [8]. However when used outside the development regime their stability decreases.

The occurrence of submarining was highly related to the setback recline angle and pelvis posterior rotation. All occupants were more likely to submarine with the increase of seatback recline, however each occupant had a different submarining threshold. The smallest occupants were most likely to submarine. When submarining was observed for larger occupants it was at higher seatback recline angles. All non-upright F05 simulations resulted in the model submarining under the lap belt, even in cases when the occupant was in contact with KB. This suggests that the occupant size, and consequently pelvis size and pelvis orientation may play a role in influencing occupant propensity to submarine (Figure 2). This also suggests that the current state-of-the-art restraint systems will be especially challenged by small occupants in recline configurations.

The KB was an effective measure controlling occupant's pelvis motion. The shorter the distance to the KB, the fewer submarining cases were identified. In cases where the occupant interacted with the KB (Figure 5), its pelvis forward motion was limited. Consequently, the pelvis forward excursion remained constant, or increased only slightly for the cases with increased seatback recline angle (Figure 3, F05:fiP, M50:siP, M95:siP, biP). The cases with limited or no KB engagement showed substantial increase in pelvis forward

excursion and increased submarining occurrence with increase of the seatback recline angle (Figure 3, Table 4 and Table 5). This suggests that the KB could be an effective countermeasure for controlling occupant kinematics, and reducing submarining likelihood for reclined occupants in the ADS environments.

The results indicate that reclined positions may lead to the increase in lumbar spine compressive loads (Figure 6). The increase of seatback recline angle aligns the occupant's lumbar spine with the direction of the acceleration pulse, resulting in increased lumbar compressive load from upper body inertia. Establishing lumbar spine biofidelity targets and injury tolerance should be at the center of future research. Especially, given limited development, biofidelity and validation data available for GHBMC's lumbar spine model, which is shared between simplified and detailed models [8, 9]. In author's understanding, the stiffness functions in the current model were calibrated to match a set of whole body PMHS sled tests [10, 11] without using data from component tests. Few studies attempted to address this issue by using available tests data. However, these studies used either data from unidirectional tests on functional spinal units without ligamentous structure [12], or whole spine experiments that had unrealistic boundary conditions and failed to apply and maintain follower load [13, 14].

The maximum lap belt force was dependent on occupant size and KB position (Figure 4). Naturally, larger occupants subject the belt system to higher restraint forces. Additionally, the contact with the KB creates an alternative load path through occupant femurs, further offloading the belt system (Figure 5). Interestingly, the lap belt forces obtained for both male HBMs showed a force reduction with an increase of initial recline angle. This was a consequence of the substantial belt transfer from the shoulder to the lap belt. The increase of seatback recline angle resulted in the increased flexion in the lumbar spine and reduction in seated height during torso forward motion (Table 6, M95:30:nip). The shortened distance between the occupant's shoulder and the buckle facilitated shoulder-lap belt transfer, and reduced the restraint of the pelvis allowing further forward excursion. This effect could be eliminated with the belt locking tongue, however an increase in lumbar spine forces (Figure 6) suggests that aggressive pelvic restraint may lead to increased lumbar spine injuries.

Lumbar spine AP shear force was a good predictor for submarining (Figure 7). In the model, when the belt slips off the ASIS it penetrates the abdomen and load is transferred directly to the lumbar spine. Out of all cases where submarining was observed, only two (F05:10:fIP, M50:20:nIP) did not show a substantial increase in the lumbar shear force. In both of these cases, the lap belt only slipped off one side of the pelvis, but remained hooked on the other (Figure 8), stopping the belt from engaging the lumbar spine. Interestingly, in all cases the buckle side, which was not pre-tensioned, was more prone to disengaging first. This indicates that pre-tensioning on both sides of the lap belt might be an effective countermeasure to ensure lap belt-pelvis engagement.

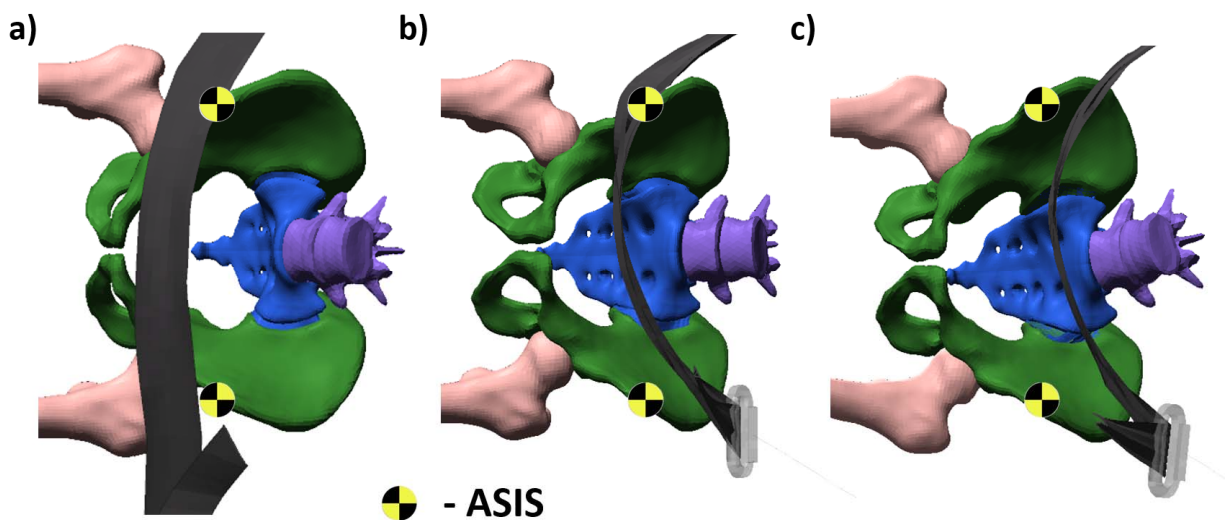


Figure 8. Comparison of different submarining mechanisms. Superior view, a) initial belt placement, b) unilateral submarining, c) bilateral submarining.

CONCLUSIONS

This study provides an overview of occupant responses in non-traditional vehicle environment relevant to the future automated vehicles. It focused on evaluating the occupant response with respect to anthropometry, recline angle and distance to the KB. The results lead to the following conclusions:

1. Current numerical tools need additional development, for evaluating occupant safety in nontraditional seating postures.
2. Reclined postures pose a challenge for the current state-of-the-art restraint systems.
3. Increased recline angles lead to more submarining cases.
4. Smaller occupants may be more prone to submarining.
5. The knee bolster could be an effective countermeasure for controlling occupant kinematics and preventing submarining.
6. Higher recline angle results in a high compression force in the lumbar spine
7. Submarining results in large shear force recorded in the lumbar spine.

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APPENDIX

Table A1: Data extracted from the simulations.

ID	Occupant	Recline Angle	IP location	Submarine (Yes = 1, No =0)	Max. Pelvis X Excursion [mm]	Max belt force (anchor) [kN]	Max femur comp. force [kN]	Max lumbar comp. force [kN]	Max lumbar AP shear force [kN]
1	M50	0	sIP	0	136	4.30	0.00	-1.26	0.23
2	M50	10	sIP	0	155	3.95	-0.49	-1.73	0.15
3	M50	20	sIP	0	169	3.02	-3.18	-1.81	0.34
4	M50	30	sIP	1	175	2.50	-7.40	-2.26	0.92
5	M50	0	bIP	0	164	4.90	0.00	-1.49	0.53
6	M50	10	bIP	0	212	4.92	-0.10	-1.54	0.19
7	M50	20	bIP	1	254	4.07	-0.33	-1.55	0.69
8	M50	30	bIP	1	274	3.33	-2.80	-1.67	1.49
9	M50	0	nIP	0	164	4.80	-	-1.45	0.25
10	M50	10	nIP	0	212	4.92	-	-1.54	0.19
11	M50	20	nIP	1	244	4.13	-	-1.55	0.39
12	M50	30	nIP	1	303	3.73	-	-1.67	1.10
13	M95	0	sIP	0	94	3.27	-2.58	-0.70	0.36
14	M95	10	sIP	0	91	3.27	-2.75	-1.16	0.29
15	M95	20	sIP	0	92	2.97	-3.09	-1.64	0.31
16	M95	30	sIP	0	96	2.62	-4.93	-2.03	0.69
17	M95	0	bIP	0	160	5.84	-1.51	-0.70	0.36
18	M95	10	bIP	0	166	5.34	-4.44	-1.48	0.18
19	M95	20	bIP	0	174	4.51	-5.07	-1.70	0.42
20	M95	30	bIP	0	176	3.14	-8.02	-1.89	0.87
21	M95	0	nIP	0	185	7.29	-	-0.98	0.15
22	M95	10	nIP	0	209	6.69	-	-1.33	0.19
23	M95	20	nIP	0	267	6.17	-	-1.39	0.26
24	M95	30	nIP	1	384	5.21	-	-1.38	1.23
25	F05	0	sIP	0	182	3.98	-0.72	-1.12	0.52
26	F05	10	sIP	1	238	3.49	-1.53	-1.37	1.02
27	F05	20	sIP	1	273	3.75	-0.44	-1.71	1.47
28	F05	30	sIP	1	292	3.67	-1.82	-2.41	1.76
29	F05	0	flP	0	181	3.81	-0.92	-1.15	0.42
30	F05	10	flP	1	186	3.11	-0.75	-1.45	0.28
31	F05	20	flP	1	223	3.14	-2.19	-1.52	0.88
32	F05	30	flP	1	239	3.08	-2.15	-1.77	1.02
33	F05	0	bIP	0	181	3.81	-	-1.18	0.52
34	F05	10	bIP	1	240	4.02	-	-1.27	0.94
35	F05	20	bIP	1	296	3.88	-	-1.92	2.17
36	F05	30	bIP	1	321	4.00	-	-2.23	2.61
37	F05	0	nIP	0	182	3.98	-	-1.09	0.06
38	F05	10	nIP	1	240	4.02	-	-1.27	0.94
39	F05	20	nIP	1	296	3.93	-	-1.87	2.29
40	F05	30	nIP	1	335	4.00	-	-2.17	1.95