

INVESTIGATING SLOUCHING IN FRONTAL IMPACTS USING AN HBM IN THE REAR SEAT

Katarina Bohman

Emil Fågelberg

Lotta Jakobsson

Volvo Cars

SAFER, Vehicle and Traffic Safety Centre at Chalmers

Gothenburg, Sweden

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ABSTRACT

Car occupants may choose a wide range of sitting postures, including rearward rotation and forward excursion of the pelvis, through slouching. The overall objective of the study was to contribute to the understanding of restraint interaction, as a function of pelvis orientation and lumbar spine posture. Specifically, the aim was to investigate kinematics of and loading to the occupant in frontal impacts by comparing slouched and upright sitting postures using state-of-the-art restraints.

A human body model (HBM) of a mid-sized male, the SAFER HBM, was restrained in a simulation model of the rear seat of a large passenger car and exposed to a full frontal 50 km/h impact. Three different sitting postures, with constant seat backrest angle were included; a nominal upright sitting posture and two slouched sitting postures, representing moderate and extreme slouching, respectively. The position of the seat in front of the occupant was varied to the mid-track position and the most forward-track position, respectively, to allow for different knee-interaction.

When the front seat was in a mid-track position, submarining did not occur in any of the slouched postures, while partial submarining occurred for the extreme slouched posture with the front seat in the most forward-track position in the model.

During the impact, both slouched postures of the HBM resulted in less torso pitch compared to the nominal posture. The shoulder belt moved up the sternum to a higher extent in the slouched postures, leading to less balanced kinematics with the pelvis moving forward and the upper torso held back by the shoulder belt, contributing to the less torso pitch. These changes in kinematics for the slouched postures resulted in higher lumbar spine compression and lower chest loading, relative to the nominal posture.

In summary, slouched sitting postures affect occupant kinematics and loadings in a frontal impact. By exploring variations in sitting posture in terms of slouching using a HBM, knowledge can be gained in understanding the mechanisms of submarining and lumbar spine loading. These findings are relevant for sitting postures in conventional cars today, in addition to a wider range of sitting postures as a result of future seat developments.

Keywords: sitting posture, slouching, HBM, rear seat, submarining, pelvis orientation

INTRODUCTION

In most standardized vehicle crashworthiness assessment tests, anthropomorphic test devices (ATDs) are positioned in upright sitting postures; centralized in the seat and with the back against the seat backrest. Only in a few exceptions a minor slouched sitting posture is allowed, for instance for the 10-year-old ATDs in frontal impact tests (FMVSS 213, EuroNCAP). Their slouched sitting posture is achieved by adding a spacer of 20 mm behind the pelvis.

However, changing posture is part of natural sitting behavior to feel comfortable over time (Helander and Zhang, 1997), whereby a range of sitting postures is expected to occur during a drive. A driving study on adult front seat passengers showed a wide range of sitting postures, for which a slouched posture was detected 3.9% of the time (Reed et al. 2020). For rear seat occupants, driving studies on older child occupants confirmed a wide range of sitting postures including slouched sitting posture (Jakobsson et al. 2011, Osvalder et al. 2013). A naturalistic driving study with rear seat adult passengers, showed that the passengers spend about 27% of the time leaning laterally inboard or outboard. However, slouching was not annotated in the study (Reed et al. 2022). In a laboratory

setting, Park et al. (2016) conducted a sitting posture study on rear seat adult passengers, deriving a statistical model to predict adult sitting postures.

Sitting postures at impact may influence injury risks in vehicle crashes. Occupant posture was identified as a major influencing factor on front seat occupant response on injury outcome in frontal impacts (Bose et al. 2010) as well as in side impacts (Hwang et al., 2016). Izumiyama et al. (2018) quantified initial pelvis orientation through x-ray of 75 individuals, and there after morphed an HBM into several initial pelvis orientations. A more rearward tilt of the pelvis prior the impact, resulted in increased pelvis excursion and rotation, when exposed to frontal impact. Beck et al. (2014) found an increased risk of submarining in frontal impacts, when positioning rear seated ATDs in slouched sitting postures. Uriot et al. (2015) conducted postmortem human subject (PMHS) tests in standard and slouched sitting postures with the pelvis 60 mm moved forward. All three PMHS tests in this slouched posture resulted in submarining while no submarining occurred in the standard posture. Furthermore, submarining has been addressed focusing on restraint geometries (Håland et al. 1991), influence of occupant size (Gepner et al. 2018) and reclined seats (Boyle et al. 2019, Mroz et al. 2020).

There is a need to further understand the details in lap belt interaction and the balance between risk for submarining and lumbar spine loading, especially in the rear seat. Addressing a natural everyday situation of slouching, the overall objective of the study was to contribute to the understanding of restraint interaction, when influenced by pelvis orientation and lumbar spine posture. Specifically, the aim of this study was to investigate kinematics and loading to the occupant in frontal impacts by comparing slouched upright sitting postures, using an HBM in a rear seat environment.

METHODS

Finite element (FE) simulations were run using MPP LS-DYNA (LSTC, Livermore, CA) R9.3.1 with the SAFER Human Body Model (HBM) v10, investigating the effect of different degree of slouched sitting postures in a simulated frontal impact. The SAFER HBM is a 50th percentile male HBM (stature 175 cm and weight of 77 kg), originally based on the THUMS v3, but as of v10 most parts have been updated or replaced. The SAFER HBM was validated for occupant kinematics in reclined postures (Mroz et al. 2020). Since then, a new pelvis model with 50th percentile male shape based on a data set of 57 CT scans and positioned to the average male pelvic angle of 45° (Izumiyama et al. 2018) has been implemented (Pipkorn et al. 2021), together with an updated improved hexahedral soft tissue mesh which is continuous from the torso to the extremities and the updated model was once more validated for reclined kinematics and compared with other HBMs (Gepner et al. 2022). The HBM was positioned in a nominal sitting posture and two slouched sitting postures, in a model of the rear seat of a large passenger car.

User range of slouched sitting posture

In a laboratory user study, 18 test participants were seated in the outboard rear seat of a large passenger car. The participants gave their consent to participate in the study and they were informed about their unconditional right to abort the test at any time. Their buttock to knee measures ranged from 556 mm to 597 mm, corresponding to 10 percentile females up to 30 percentile males (Hanson et al. 2009). The participants were asked to enter the car and buckle up, without further information. This initial sitting posture is referred to as their self-selected posture, and measurements were taken. Thereafter, they were asked to position their pelvis in contact with the seat backrest. This position is referred to as their reference posture. Their left and right ASIS (Anterior superior iliac spine) were identified through palpation and measured with a digital arm, for both sitting postures. The longitudinal difference between the two sitting postures is referred to as the distance of slouching of the pelvis. All participants except one, experienced some extent of slouching. The average slouching was 23 mm, and the 3rd quartile of the boxplot was 36 mm (see Appendix A for details).

Based on the results from the user study, three sitting postures were selected for the simulation series. A nominal sitting posture and a moderate slouched posture of 40 mm H-point forward translation to cover the 3rd quartile of the slouched postures in the user study. In addition, a slouch of 60 mm H-point forward translation was chosen, to cover an extreme slouched posture.

Sitting postures in simulation series

Figure 1 shows the three different sitting postures; nominal, 40 mm slouch and 60 mm slouch. Following rigid body translation and rotation using Primer pre-processor (v17.1, Oasys Ltd, Solihull, UK), the HBM was positioned by simulating a system of tension cables attached to the skeleton. At the end of the positioning simulation, the system was at rest. In the slouched postures, the cables attached to the pelvic bones were modified.

Any change in position of other body regions is thus a result of the pelvis positioning. The positioning simulations were run for 300 ms on 120 CPUs.

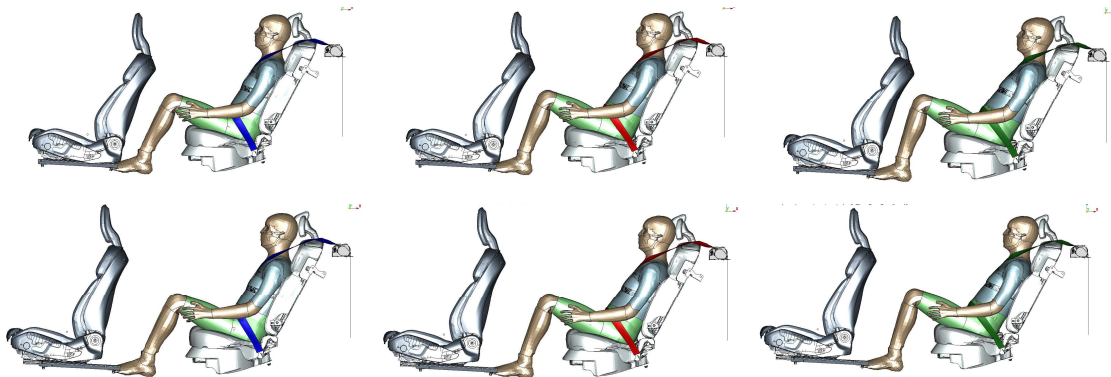


Figure 1 The SAFER HBM v10 positioned in three sitting postures in the rear seat; nominal (blue seat belt), 40 mm slouch (red seat belt) and 60 mm slouch (green seat belt). First row shows set-ups with the front seat in mid-track position, and second row with the front seat in most forward-track position.

In the resulting nominal sitting posture, the HBM was positioned with the H-point 10 mm in front of the SAE manikin position and rotated 5° rearward to match the angle of the seat back. The knees were 300 mm apart with the feet resting flat on the carpet with a knee flexion angle of approximately 90°. The resulting pelvic angle (Izumiyama et al. 2018, see Appendix B) after the positioning simulation was 52.5°.

For the 40 mm slouch posture, the resulting ASIS coordinates were 40 mm forward and 5 mm upward relative the nominal posture after the positioning simulation. The resulting pelvic angle was 56.0° and the knee to mid-track front seat distance was 96 mm. For the 60 mm slouch posture, the resulting ASIS coordinates were 60 mm forward and 10 mm upward relative the nominal posture after the positioning simulation. The resulting pelvic angle was 58.9° and the knee to mid-track front seat distance was 77 mm. See Appendix C for details on pelvis and spine posture.

Simulation series set-up

The HBM was positioned in the outboard left side of a large passenger vehicle interior FE model. The front seat fore-aft track position was varied to enable variation of leg and knee interaction. The two front seat positions used were mid-track position and the most forward-track position (Figure 1). For the HBM in the nominal posture, the distances from the knees to the back of the front seat were 127 mm and 296 mm, for the mid-track position and the most forward-track position, respectively.

A state-of-the-art load limited three-point seat belt model with a pyrotechnical shoulder belt pretensioner was used. The shoulder belt was routed using pre-processor Primer (v17.1, Oasys Ltd, Solihull, UK) without any friction, enabling the seat belt to follow the shortest path over the occupant chest from anchor to retractor outlet.

Six degree-of-freedom vehicle motions simulating a full-frontal rigid barrier impact at 50 km/h was applied to the sled model. All simulations were run for 110 ms using 120 CPUs.

Study design and analyses

The three sitting postures and the two front seat positions are combined in six configurations, see Appendix D for the simulation series matrix. Submarining was evaluated from the simulation animations and defined if the lap belt slipped completely over the ASIS. Left and right ASIS were analyzed separately to detect partial submarining. The moment at the medial-lateral axis in a cross-section through the ilium passing above the ASIS and below the ASIS, was analyzed to understand the lap belt interaction with the pelvis. The shoulder belt fit was evaluated using the measure of the vertical distance between jugular notch (top edge of sternum) and shoulder belt mid-line. Head acceleration, rib strain, lumbar spine compression, femur forces and pelvis acceleration were analyzed.

RESULTS

Kinematics and seat belt interaction

No submarining occurred in any of the six configurations. However, partial submarining, with lap belt slip-off of the ASIS on the outboard side, was detected in the 60 mm slouch posture with the front seat in most forward-track position. See Figure 2 and Appendix E for lap belt to pelvis interaction.

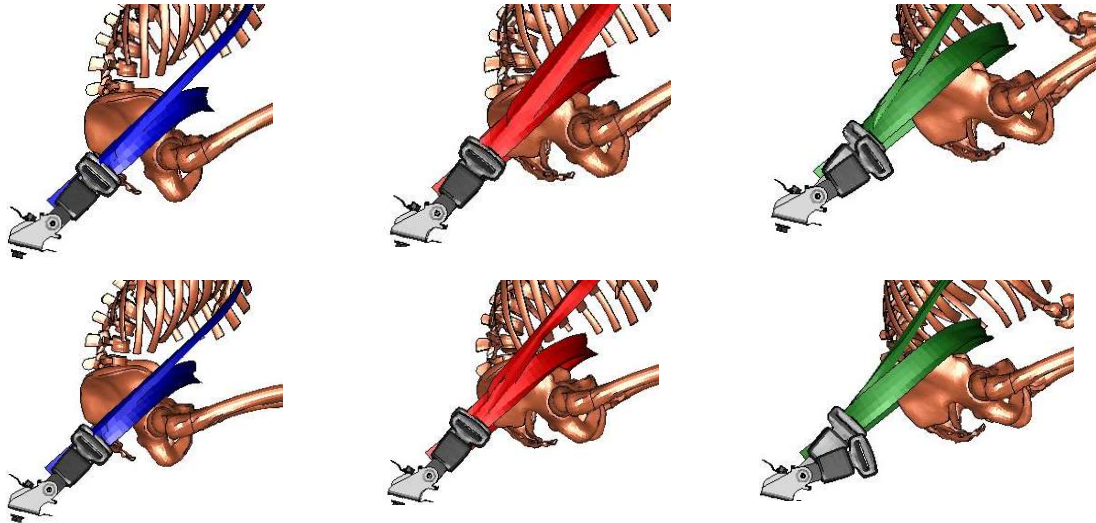


Figure 2 Close-up on inboard side view of the HBM at maximum forward excursion; nominal (blue seat belt), 40 mm slouch (red seat belt) and 60 mm slouch (green seat belt). First row shows simulations with the front seat in mid-track position, and the second row with the front seat in the most forward-track position.

Negative ASIS moment values (left and right side) in the nominal posture and 40 mm slouch, with either front seat position, indicated that the lap belt was engaging the pelvis below the center of the ASIS load cell. In the 60 mm slouch posture, positive ASIS moments suggest that the belt was partly or completely over the ASIS load cell, which indicated a potential risk of submarining (see Appendix F).

The displacement trajectories over time showed that kinematics varied with sitting posture (Figure 3). For the two slouched postures the pelvis was positioned further forward at start. The nominal posture showed a greater torso pitch with a greater head displacement compared to the other two sitting postures. The 60 mm slouch posture showed less torso pitch and shorter head displacement compared to the 40 mm slouch posture (Figure 3). The different front seat positions had limited influence on the trajectories.

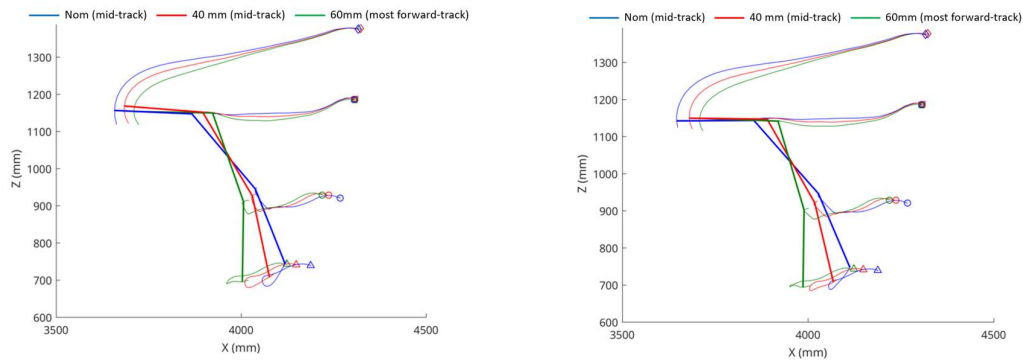


Figure 3 Visualization of trajectories and posture at peak forward displacement for head (diamond), T1 (square), T12 (circle), and pelvis (triangle) displacement, for the three different sitting postures (nominal : blue; 40 mm slouch: red; 60 mm slouch: green); when front seat in mid-track position (left) and front seat in the most forward-track position (right).

The top views of the T1 trajectory and the arms (Appendix G) showed that the nominal posture resulted in a more inboard torso rotation compared to the two slouched sitting postures, and it was not influenced by the front seat position.

With the front seat in mid-track position, the legs were restricted to stretch out to the extent possible in the configuration with front seat in most forward-track position (Appendix E).

The rearward rotation of the pelvic angle started earlier in the slouched sitting postures compared to the nominal posture (Appendix H). For the nominal and the 40 mm slouch postures, the pelvis rotation changed direction at about 80 ms, while no change of direction occurred in the 60 mm slouch posture.

The jugular notch/shoulder belt vertical distance showed that the shoulder belt has an initially higher position on sternum at time 0, and that it moved closer to the neck and up the sternum in the two slouched postures during the crash compared to the nominal posture (Appendix I and Figure 4). In both slouched postures, the spine got into a lateral s-shape during the event, being most pronounced for the 60 mm slouch posture (Figure 4).

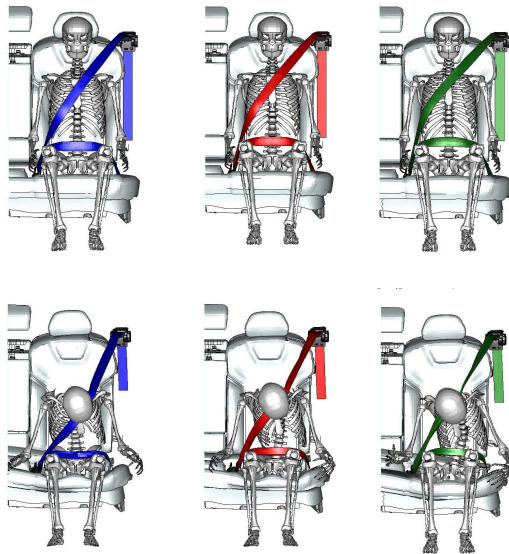


Figure 4 Shoulder belt position at start (first row) and at approximately time of maximum forward displacement (second row), for nominal (blue seat belt), 40 mm slouch (red seat belt) and 60 mm slouch (green seat belt) postures. Front seat in mid-track position.

Occupant response

The maximum responses are presented as normalized values relative to the nominal sitting posture with the front seat in mid-track position (Table 1). A small increase in head acceleration was seen in the slouched postures compared to nominal posture. A minor relative increase of neck tension was also seen.

The upper chest band deflection was 44-67% lower for the slouched postures relative the nominal posture with mid-track front seat position (Table 1). The lower chest band deflection was substantially less in the slouched postures, compared to the nominal; especially the 60 mm slouch posture with 99% lower deflection than the nominal. The rib strain pattern shows that the highest strain was obtained for upper left rib (L1), in all postures (Appendix J). Furthermore, a higher strain was seen to the left upper ribs (L2 to L4) and to the right mid ribs (R5 to R8) in the nominal posture, as compared to in the slouched postures.

Up to 38% relative difference between slouched and nominal postures is seen for lumbar spine compression forces (Table 1). Lumbar spine sagittal flexion moments follow the trend of the compression forces. Lateral bending moment in the lumbar spine changes sign from negative values (lumbar vertebrae L1, L2, L3) to positive moments (lumbar vertebrae L3, L4), for both slouched postures (Appendix K). Shoulder belt forces are at the same levels for all configurations, due to the seat belt load limiting function (Table 1). However, the shoulder belt forces started slightly earlier in the nominal posture with its more upright torso, compared to the slouched sitting postures.

When comparing the influence of the two front seat positions for the nominal sitting posture, the head and neck loadings were slightly lower, while lumbar spine forces are slightly higher in the most forward-track position

(Table 1). Overall, the simulations with most forward-track front seat showed similar trends to both kinematics and loadings as for the mid-track comparison, when comparing the nominal sitting posture with the slouched postures.

Table 1 The maximum responses of head, chest, lumbar spine, femur and seat belt, normalized relative the simulation with nominal sitting posture with front seat in mid-track position and most forward-track position.

	Mid-track position			Most forward-track position		
	Nominal	40 mm	60 mm	Nominal	40 mm	60 mm
		slouched	slouched		slouched	slouched
Max head acceleration	1	1.04	1.02	0.95	1.00	0.99
Max chest acceleration (T8)	1	1.19	1.08	0.94	1.02	0.91
Upper neck force (tension)	1	1.04	1.06	0.95	1.01	1.07
Chestband (upper)	1	0.56	0.33	1.11	0.73	0.40
Chest band (lower)	1	0.25	0.01	1.01	0.28	0.01
Lumbar spine force (compression)						
L1	1	1.22	1.38	1.03	1.20	1.37
L2	1	1.20	1.34	1.04	1.21	1.33
L3	1	1.16	1.26	1.04	1.16	1.22
L4	1	1.14	1.20	1.02	1.10	1.15
L5	1	1.13	1.17	1.01	1.08	1.11
Shoulder belt force	1	0.99	0.99	1.02	1.01	1.01
Lap belt force	1	0.93	0.97	1.04	0.97	0.99

DISCUSSIONS

This study investigated the effect of slouched posture on occupant kinematics and responses in frontal impact by HBM simulations in a rear seat environment with a state-of-the-art restraint. It illustrates the importance of balanced interaction with the lap and shoulder belt in a frontal impact and shows that this interaction can be influenced by the initial pelvis rotation and its longitudinal position on the seat. Balanced interaction with the lap and shoulder belt comprises of an early and tight coupling to the pelvic bones, enabling a controlled forward torso and head movement, including a desired torso pitch (Adomeit and Heger, 1975, Adomeit, 1977, Kent and Forman, 2015). The preferred balance of lap and shoulder belt interaction was affected by the initially more rearward tilted and further forward positioned pelvis in the slouched postures, also resulting in a more rearward reclined torso and a slightly higher lap belt position on the pelvis. In comparison to the nominal posture, this unbalance influenced the restraint of the pelvis and the torso pitch during the simulated crash, having impact on the movement of the shoulder belt and the loading of the spine.

During the impact, both slouched postures exhibited less torso pitch compared to the nominal posture. The pelvis was not restrained as efficiently as in the nominal posture simulation since the lap belt had a slightly higher initial position on the ASIS. Furthermore, the shoulder belt moved up the sternum to a higher extent in the slouched postures. In the extreme slouched posture, the mid-line of the shoulder belt even moved above the sternum. This shoulder belt interaction amplified the kinematics imbalance with the pelvis moving forward and the upper torso held back by the shoulder belt, reducing the torso pitch. This type of kinematics contributed to the higher lumbar spine compression forces in the slouched postures.

As the mid and upper part of the shoulder belt moved up the sternum and closer to the neck in the slouched postures, the lower part of the shoulder belt moved upwards as well. This is seen when comparing the rib strain pattern in Figures J1 and J2 (Appendix J). Although the shoulder belt interaction in the slouched postures was undesirable, the maximum rib strain was favorable relative to the nominal posture, while the neck tension was slightly higher. In addition, the shoulder belt interaction resulted in a prominent lateral s-shape of the spine in the slouched postures, which can be seen when studying the front view of the spine (Figure 4) at maximum forward displacement. The potential consequences of this lateral s-shape of the spine are reflected in the lumbar spine lateral bending moment, where the highest moments are negative for L1 to L2 and then gradually shift to positive values for L4 and L5 (see Appendix K). This change in lumbar spine lateral bending is not seen in the nominal posture, with the shoulder belt spread over the sternum embracing larger part of the ribcage.

No submarining of the whole pelvis occurred. However, partial submarining occurred in the extreme slouched posture of 60 mm forward translation and with the most forward-track front seat position, with the outboard lap belt slipping over the ASIS. Lack of contact with the front seat allowed some upward rotation of the leg, which contributed to the lap belt sliding off the pelvis. Exploring submarining risk in frontal impacts, Beck et al. (2014) found that a slouched sitting posture, achieved with 38 mm foam behind the pelvis, had the largest effect in a parameter study varying pretensioner, anti-submarining seat pan and upper anchorage points, in addition to a slouched posture. Furthermore, Forman et al. (2022) also found a slouched sitting posture being one of two most important parameters increasing the risk of submarining, when investigating various parameters influence on protection for a booster seated child HBM exposed to a frontal impact.

The modelled vehicle is spacious, offering 127 mm knee to front seat distance in the nominal posture with the front seat in mid-track position. In the nominal posture, there was no knee to front seat contact during the crash, but the feet and the lower part of the leg interacted with the front seat. In the slouched postures, larger areas of both legs were in contact with the front seat, but there was still no loading through the knee, meaning no femur compression forces. Especially for front seat occupants in conventional passenger cars, knees often serve as load paths in frontal impacts, and have shown to be efficient in reducing the risk of submarining in reclined seating position (Rawska et al., 2019). In some vehicle seat configurations, such as living room seating or limousine configuration with generous leg space, there are limited possibilities to use the knees as a load path to control the pelvis movement. The choice of the spacious rear seat environment in the present study, would likely better reflect such environments, and the study can contribute to the understanding of load paths and means to control the kinematics for submarining and lumbar spine forces.

Limited data is available regarding slouched sitting postures in vehicles. Reed et al. (2020) identified slouched posture in 3.9% of the time, for adult front seat passengers in a driving study. Identifying slouching is difficult, especially through camera detection only. In the study by Reed et al. (2020) it is not clear how much forward pelvis movement was needed to identify it as slouched posture. Due to lack of data for adult rear seat passengers, and the need to get more precise measurements, a limited laboratory user study was used as input in the present study. Eighteen individuals participated and the degree of slouch could be established by measuring ASIS location, comparing their initial self-selected posture to an upright reference sitting posture. The selected slouched postures for the simulations were based on representative slouching (40 mm), in addition to an extreme slouched posture (60 mm), which was not found among the self-selected postures in the user study. Being a limited user study in a stationary car, it probably does not cover all real-world slouched postures. A driving study would likely contribute to a wider range of slouched postures compared to this laboratory user study. The test persons covered 10 percentile females up to 30 percentile males. Additional studies, with wider range of test persons and evaluation of time influence, is needed to further understand the range of sitting postures in terms of slouched sitting posture.

Several of the findings in this study would not have been possible without the use of an advanced HBM. With its anatomically representative design, an HBM offers the possibilities to detect occupant detailed kinematics, such as the phenomenon of lateral s-shape of the spine due to unfavorable shoulder belt interaction. This would not be possible if using a crash test dummy, due to the lack of segmented spinal design. Also, the increased stiffness in the lumbar spine in certain crash test dummies, limits the sensitivity to parameters influencing submarining (Uriot et al., 2015). Although not validated for different pelvis rotations and the rearward reclined torso, it is believed that the HBM was able to capture the essence of the study. The HBM used in this study has a lumbar spine which was validated on a subsystem level (Östh et al., 2020), and the model's kinematics has previously been validated for reclined seating positions (Mroz et al., 2020). Since then, the pelvis model has been updated with a new pelvis which is more representative of a 50th percentile male occupant (Pipkorn et al., 2021). Gepner et al. (2022) showed that the kinematic response of SAFER HBM v10 compared relatively well with respect to PMHS tests in a reclined posture, and the SAFER HBM v10 was also found to correlate equally well as the GHBM v6.0 and THUMS v6.0, but all three models showed a more compliant lumbar flexion than the PMHS.

The study focuses on kinematics. Some occupant responses are included to quantify relative differences in load transfer through the body parts. Due to lack of validated injury criteria and risk functions for all body parts, and to focus on the relative comparison, the occupant responses are presented as normalized values relative to the nominal sitting posture with the front seat in mid-track position.

Today, there is a high research interest on reclined seating positions, since it is expected that customers will demand relaxed seating as new possibilities are made possible in autonomous vehicles (Jorlöv et al., 2017). In addition, consumer information test organizations are starting to investigate virtual testing possibilities, which allows a wider range of parameters, also including sitting posture. Some of the challenges emphasized in this study, especially regarding lumbar spine loads and pelvis rotation, are also seen in reclined seating positions. There is an increased risk of submarining in reclined seating positions, and when that is addressed, lumbar spine forces increase (Mroz et al., 2020, Boyle et al., 2019). Research programs are ongoing to establish validation data for reclined seating positions. This progress will likely benefit tools to be used to evaluate slouched sitting postures

as well, since there are many similarities in these loading conditions. However, as wider range of sitting postures are addressed in the development of vehicles, validation data is needed to cover those aspects.

This study was limited to slouching of the pelvis, by modifying the position and orientation of the pelvis. A slumped posture, with more kyphosis in thoracic spine, was not included in the study. The amount of slouching was based on observations of short occupants. Seat cushion length may be a possible parameter influencing slouched posture of shorter occupants to a higher extent than taller occupants, due to reduced ability to comfortably bend their legs around the seat cushion. It is possible that taller occupants, such as 50th percentile males, would be less prone to slouch. Further studies, with a larger range of test persons is needed to further understand the extent of slouched posture.

CONCLUSION

Slouched sitting postures affect occupant kinematics and loading in a frontal impact. The slouched postures resulted in less torso pitch, contributing to higher lumbar compression forces. By exploring variations in sitting posture in terms of slouching, within a reasonable user range, knowledge can be gained in understanding mechanisms of submarining and lumbar spine loading. These learnings are relevant for sitting postures in conventional cars today, in addition to a wider range of sitting postures, such as reclined seats, likely increasing as a result of future car interior developments.

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APPENDIX A. RESULTS FROM THE LABORATORY USER STUDY

The boxplot (Figure A1) shows the slouching of the 18 test participants, by calculating the difference in x-position of the left and right ASIS in their self-selected posture and their reference posture.

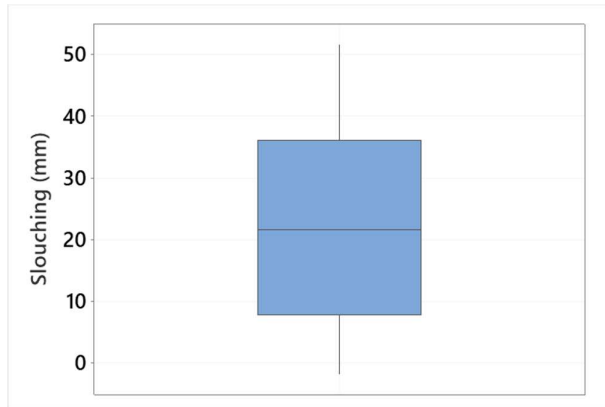


Figure A1 The boxplot shows the slouching of the 18 test participants.

APPENDIX B. THE PELVIC ANGLE (PA) MEASUREMENT

The pelvic angle (PA) was measured as the angle between pubic symphysis (mid) and ASIS in the mid-sagittal plane, similar as Izumiyama et al. (2018).

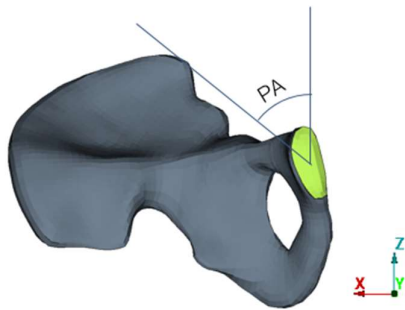


Figure B1 The pelvic angle.

APPENDIX C. PELVIS AND SPINE POSTURE

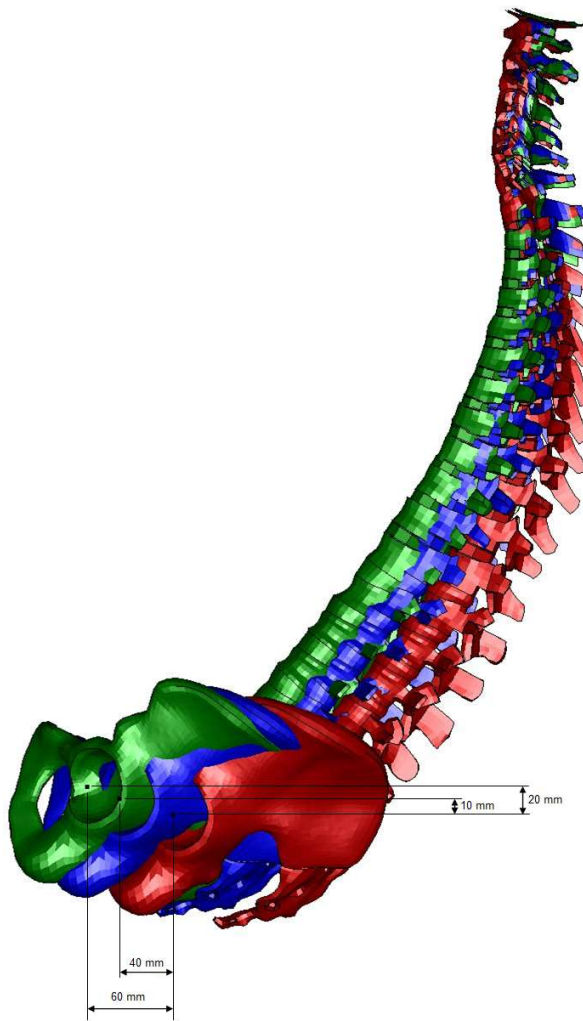


Figure C1 A side view of the three sitting postures (green-nominal, blue-40 mm slouch, red – 60 mm slouch), viewing pelvis orientation and spine curvature.

APPENDIX D. SIMULATION SERIES MATRIX

Table D1 The simulation series matrix.

Sim. No.	Sitting posture	Pelvic Angle	Front seat position
1	Nominal	52,5°	Mid-track
2	Nominal	52,5°	Most forward-track
3	40 mm slouch	56°	Mid-track
4	40 mm slouch	56°	Most forward-track
5	60 mm slouch	59°	Mid-track
6	60 mm slouch	59°	Most forward-track

APPENDIX E. SIDE VIEWS

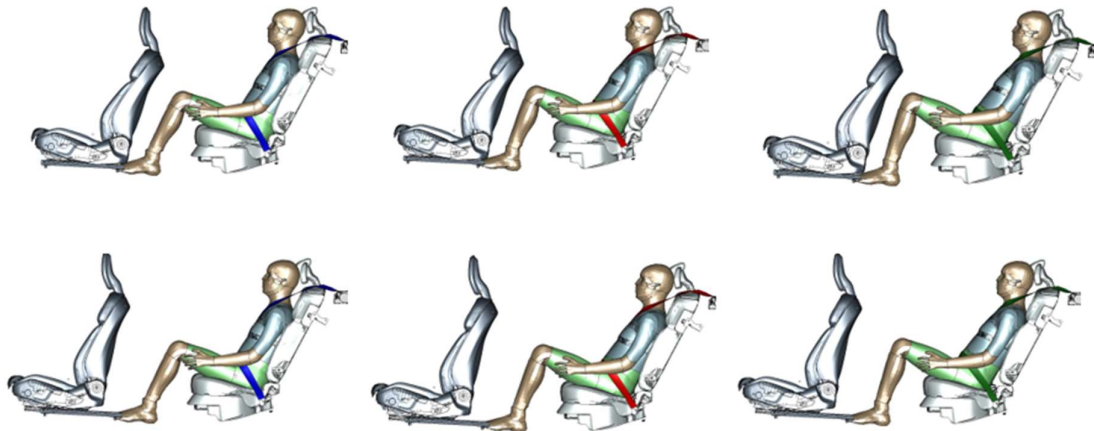


Figure E1 Outboard side view of the HBM at time 0; nominal (blue seat belt), 40 mm slouch (red seat belt) and 60 mm slouch (green seat belt). First row shows simulations with front seat in mid-track position, and second row shows front seat in most forward-track position.

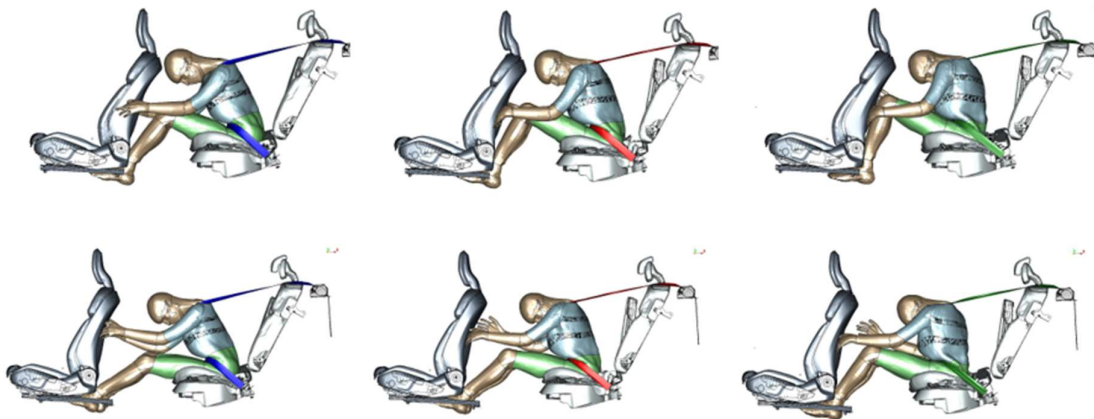


Figure E2 Outboard side view of the HBM at maximum excursion; nominal (blue seat belt), 40 mm slouch (red seat belt) and 60 mm slouch (green seat belt). First row shows simulations with front seat in mid-track position, and second row shows front seat in most forward-track position.

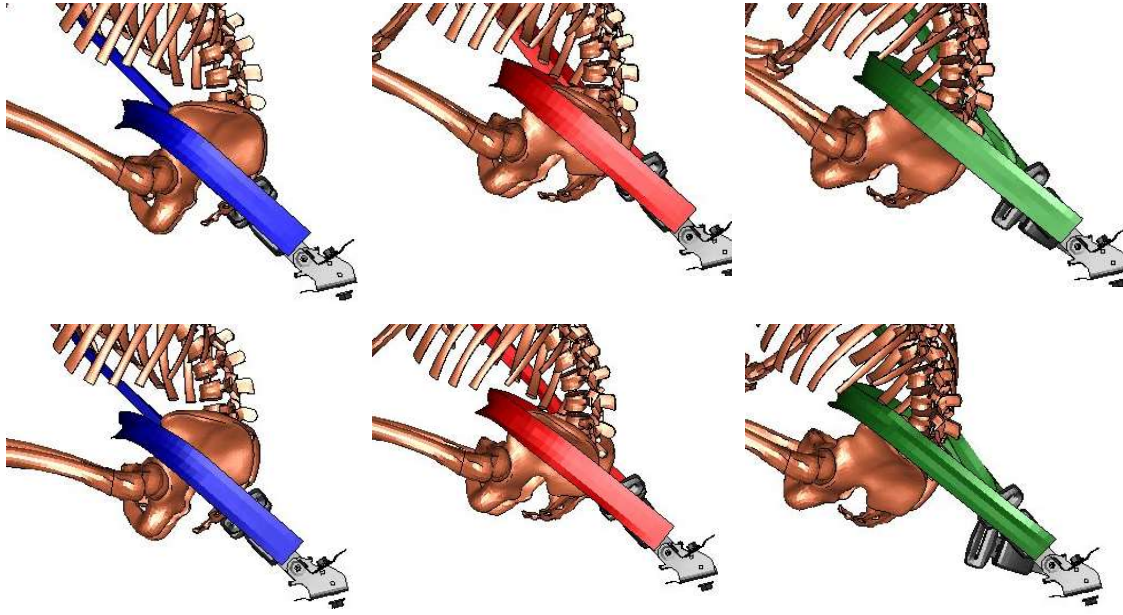
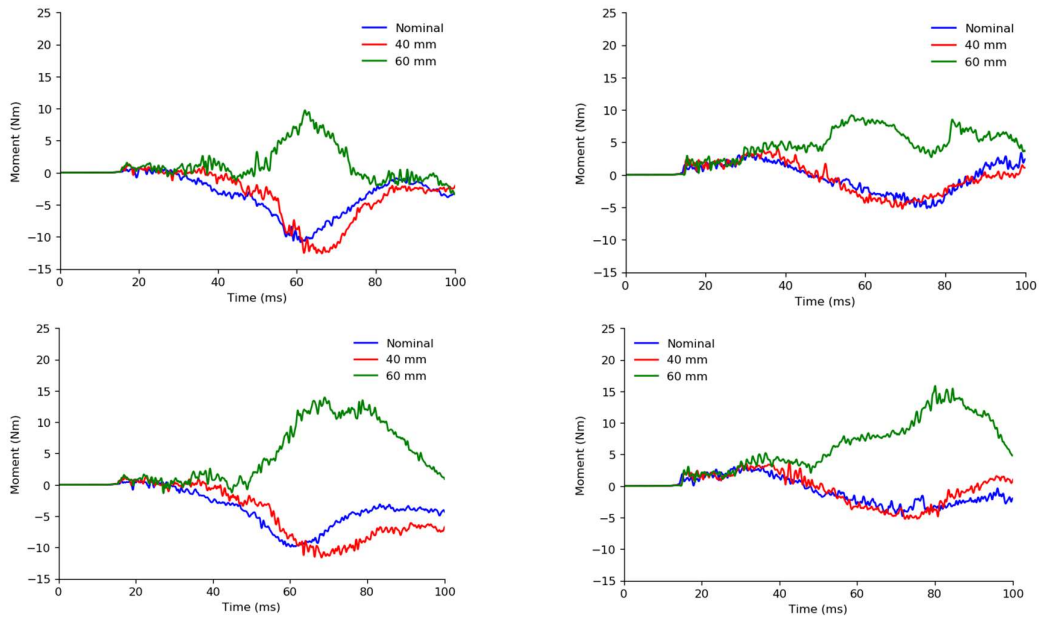


Figure E3 Close-up on outboard side view of the HBM at maximum forward excursion; nominal (blue belt), 40 mm slouch (red belt) and 60 mm slouch (green belt). First row shows simulations with front seat in mid-track position, and second row shows front seat in most forward-track position.

APPENDIX F. ASIS MOMENTS

The negative ASIS moment values indicate that the lap belt is engaging the pelvis below the center of the ASIS load cell.



Appendix F1 The moment of ASIS as function of time. First row shows left and right ASIS with front seat in mid-track position. Second row shows left and right ASIS with front seat in most forward-track position.

APPENDIX G. TOP VIEW T1 TRAJECTORIES

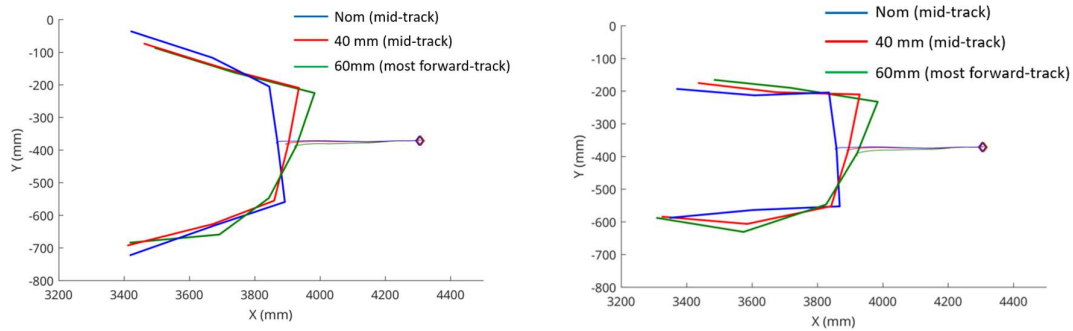


Figure G1 Top views showing the T1 trajectories and the arms connected to the T1 vertebra via nodes on the acromion processes at time of maximum excursion, for the three different sitting postures (nominal: blue; 40 mm slouch: red; 60 mm slouch: green), when front seat in mid-track position (left) and front seat in most forward-track position (right).

APPENDIX H. PELVIC ANGLE AS FUNCTION OF TIME

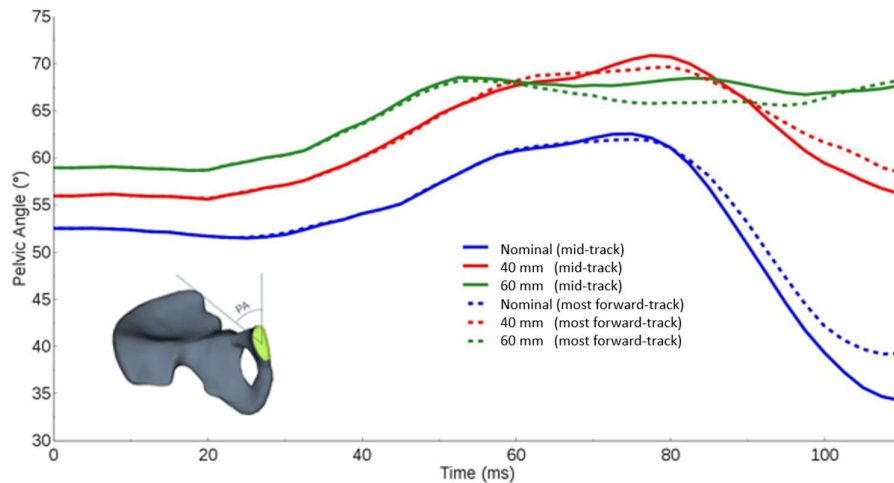


Figure H1 Pelvic angle as function of time, for the three sitting postures (Nominal, 40 mm slouch and 60mm slouch) and with the front seat in the two positions (mid-track, and most forward-track).

APPENDIX I. VERTICAL DISTANCE BETWEEN JUGULAR NOTCH AND SHOULDER BELT

Table I1 The vertical distance between the jugular notch and the shoulder belt mid-line. A negative value indicates that the mid-line of the shoulder belt is above the jugular notch.

Sitting posture	1st row	Distance at 0 ms	Distance at max forward excursion
		(mm)	(mm)
Nom	Mid-track	73	69
40 mm	Mid-track	62	18
60 mm	Mid-track	49	-14
Nom	Most forward-track	73	48
40 mm	Most forward-track	62	-3
60 mm	Most forward-track	49	-16

APPENDIX J. MAXIMUM RIB STRAIN

Figures J1 and J2 show the maximum strain for each rib. Please note that the time for maximum strain may differ between the ribs.

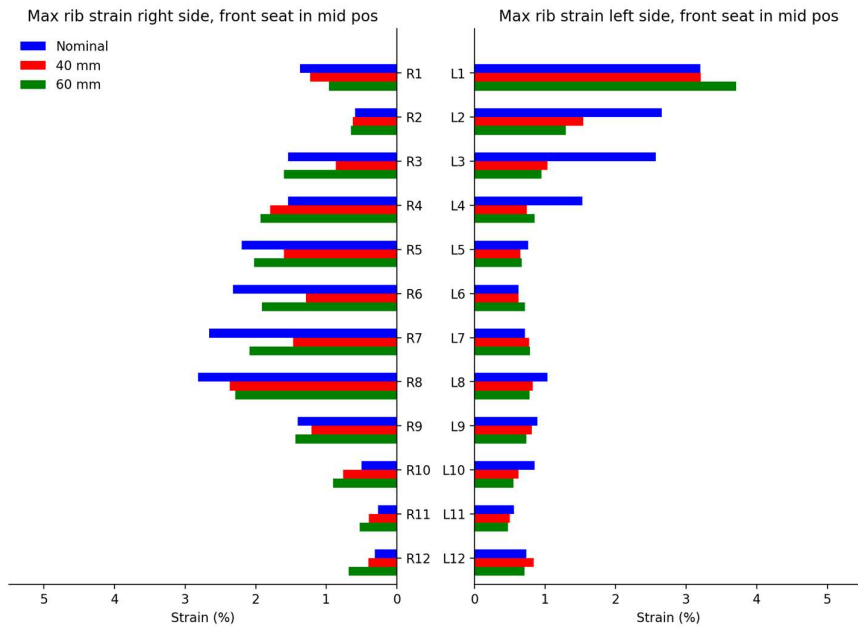


Figure J1 Rib strain (%) for each rib, on right and left side, for nominal (blue), 40 mm slouch (red) and 60 mm slouch (green) postures, with front seat in mid-track position.

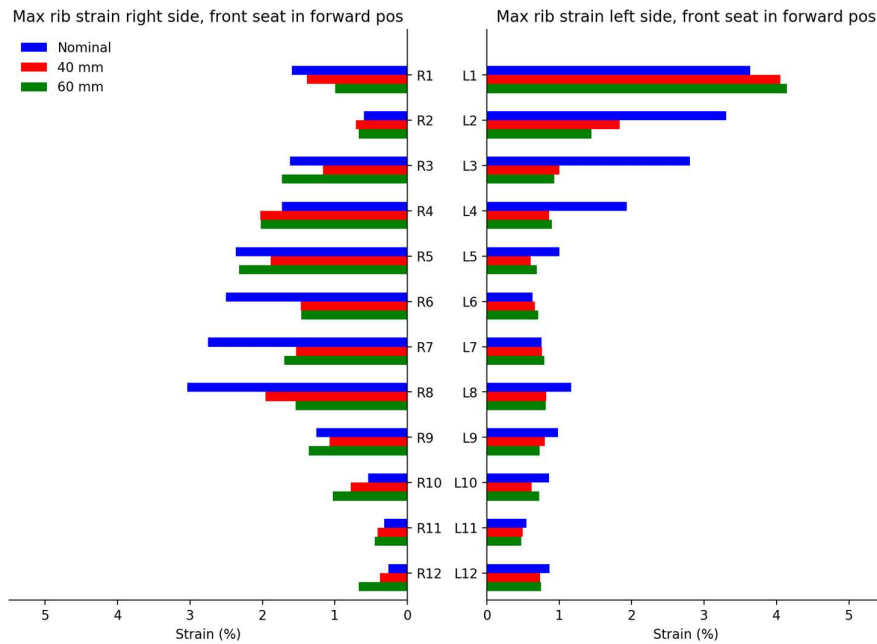


Figure J2 Rib strain (%) for each rib, on right and left side, for nominal (blue), 40 mm slouch (red) and 60 mm slouch (green) postures, with front seat in most forward-track position.

APPENDIX K. LUMBAR SPINE LATERAL BENDING MOMENT

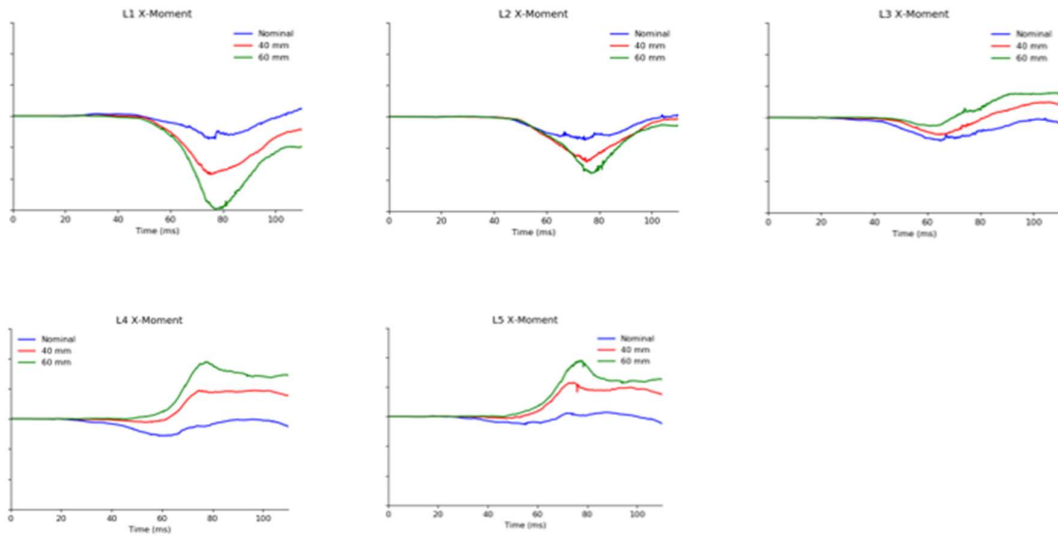


Figure K1 Lumbar spine lateral bending moment (x-moment) for L1, L2, L3, L4 and L5 vertebrae, for the simulations in nominal (blue), 40 mm slouch (red) and 60 mm slouch (green) postures, with front seat in mid position .