The Influence of a Seat Track Load Limiter on Lumbar Spine Compression Forces in Relaxed, Reclined, and Upright Seating Positions: A Sled Test Study using THOR-50M

Martin Östling, Christer Lundgren, Nils Lubbe, Andreas Huf, Philipp Wernicke and Bengt Pipkorn

Abstract Automated vehicles come with the expectation of new, comfortable seating positions, in particular with seats moved rearward to increase legroom, and with reclined seatbacks and tilted seat pans for relaxing and sleeping. However, in a frontal crash the increased seat back angle can induce more severe compression forces in the lumbar spine.

This research evaluates the influence of active and passive seat track load limiting on lumbar spine compression forces in frontal impacts for three seating positions using THOR-50M. The objective was to reduce the lumbar spine compression force for reclined occupants to a level similar to that of upright occupants, yet without increasing the levels of any variables measured in the European New Car Assessment Programme (Euro NCAP) assessments of adult occupant safety.

The lumbar compression forces sustained in the reclined seat back positions were reduced effectively by the active seat track load limiter from 6 kN to the 4 kN levels observed for upright occupants. All other injury measures except for chest compression measured as Rmax were likewise reduced. Despite the limitations of a simplified set-up and the use of THOR-50M outside its validation regime, the active seat track load limiter appears to be an implementable and efficient engineering solution to a pressing real-world issue.

Keywords Lumbar spine compression, new seating positions, seat track load limiter, sled testing, THOR-50M

I. INTRODUCTION

Automated Vehicles (AVs) are developing rapidly, bringing the promise of safer travel [1-3] along with the expectation of greater comfort by offering a wide range of new seating positions with seats able to be moved rearward, creating more room for the legs, to be reclined fully, or tilted to provide more relaxed conditions for sleep or relaxation [4-7]. Figs. 1 and 2 show two examples of how such interior concepts of the future may make use of automation. Although both vehicles are still conventionally operated by a human driver, the goal was to explore how future mobility may look in cars specially designed for automated driving. The Zero-gravity (ZeroG) lounger (Fig. 1) facilitates an optimal sleeping position that was derived from the posture a human body assumes under zero gravity [7].The Urban suite (Fig. 2) shows a rearward-moved, combined relax and work position.

Fig. 1. BMW X7 ZeroG Lounger features next-level seats, presented at CES 2020

Fig. 2. BMW I3 Urban suite features a combined relax and work position, presented at CES 2020.

However, AVs are still expected to be exposed to crashes, at least through impacts with manually driven

M. Östling (e-mail: martin.ostling@autoliv.com; tel: +46(0)322 62959) is a Senior Research Specialist, B. Pipkorn is Director of Simulation and Active Structures, C. Lundgren a CAE specialist and N. Lubbe Research Director, all at Autoliv Research, Vårgårda, Sweden. A. Huf is

vehicles [2][8]; therefore, it is important to understand how to assess the crashworthiness of an AV and the protection offered to its occupants. The assessment method should include both the crash configurations of the AV (AVs are likely to be involved in different types of crashes than those of manually driven vehicles [2]), and occupant interaction with the restraint system (including all occupants in any alternative planned seating or interior configurations) [8].

The Anthropometric Test Devices (ATDs) used in regulation and rating today are neither developed nor validated for any seating position other than upright postures. ATD prototypes designed for new seating positions lack validation and it is therefore proposed also to include virtual assessment using human body models (HBMs) to assess occupant protection [8-10]. However, although HBMs through their human like design potentially replicate human kinematics in a crash more accurately than ATDs and have the potentially to predict human injury risk at a detailed level by a physical representation of the injury mechanism, as with ATDs, HBMs have limitations and remain relevant only within their development and validation regime [11]. A third alternative to assess occupant protection is to use post-mortem human subjects (PMHSs) directly. However, performing tests with PMHSs is technically complicated and requires strict medical guidance [12-13]; these are thus only performed by dedicated test institutes. The few PMHS tests that are done should be put to their best use. Rather than designing and evaluating restraint systems, PMHS tests should be used to create validation data for ATDs and HBMs and to increase our understanding of fundamental impact biomechanics. In turn, this leads to more biofidelic ATDs and HBMs. Current research on occupant protection in new seating positions encompasses restraint system evaluation with ATDs and HBMs, despite their lack of thorough validation, along with PMHS testing to improve ATD and HBM validation [11][13-15].

A current state-of-the-art frontal restraint system, i.e. a 3-point seat belt with B-pillar mounted belt guide, driver airbag in the steering wheel and knee bolster in the instrument panel, has limited protection functionality in the new proposed seating positions in which seats are located away from the steering wheel and instrument panel or with a reclined seat back [16-17]. In particular, a reclined occupant posture may increase the risk of *submarining*, which is where the lap belt translates over the anterior superior iliac spines (ASIS) to load the abdomen directly [12][18] and can result in injuries to the lumbar spine and hollow organs of the lower digestive system [18-20]. If submarining is avoided and the lower body properly restrained, it is expected that the lumbar spine compression forces will increase due to body kinematics: when the upper body pitches forward while the lower body is restricted from translating forward by the lap belt and seat pan, a compression force and flexion moment are built up in the lumbar spine [21-22]. Having both the seat back reclined and the seat pan tilted (Fig. 1) to form a relaxed position optimal for sleeping [7] is judged as being the most critical position with three clearly defined challenges: first, the reclined posture with a rearward-rotated pelvis increases the risk of submarining; secondly, the reclined upper body and absence of a knee bolster to support the lower body increases spinal and pelvic forces; and thirdly, the absence of head restraining airbags may increase the risk of high head accelerations and neck extensions [14].

Submarining in reclined seating positions can be avoided. In mechanical sled tests with the Test Device for Human Occupant Restraint 50th percentile male (THOR-50M) in a reclined position with the seat back at 48° to the vertical, the ATD submarined when a single retractor pretensioner in the shoulder belt was used and likewise when a lap belt pretensioner at the end braked was added in the belt system [15]. However, a restraint system that integrated double lap belt pretensioners (adding a buckle pretensioner) resulted in no submarining, but in increased spine compression forces. To support the validation of THOR-50M in this application and increase confidence in these results, frontal sled tests with a PMHS in a reclined seating position using a generic environment and same belt system as in [15], i.e. double lap belt pretensioner, were undertaken [13][23]. It was found that the belt system with double lap belt pretensioner used in the reclined THOR-50M testing was effective in preventing submarining also with the PMHS in a reclined posture. Submarining was only found in one out of five tests and limited to one side only (buckle side). However, when there was no submarining, forces to the lumbar and pelvis were substantial. Three out of the five tests had lumbar spine (L1) fractures and two out of the five tests had fractures to the iliac wing.

Nonetheless, the transfer of forces to the lumbar spine and pelvis in reclined seating positions can be influenced. In a parallel study to [13], a HBM was correlated to the reclined PMHS tests, demonstrating its

an Expert of Passive Safety at BMW Research and Innovation Center Munich, Germany and P. Wernicke is a Vehicle Safety Engineer at the BMW Group Munich, Germany.

usefulness for the evaluation with a total correlation and analysis (CORA) rating of 0.81. The HBM was then used to investigate the influence of a number of countermeasures to reduce forces to the lumbar spine and pelvis [24]. It was found that a seat track load limiter was the most effective countermeasure in this regard. An evaluation of seat track load limiting with ATDs in the relaxed position (reclined seat back and tilted seat pan) was conducted for a relaxed position with the seat back at 60° and seat pan at 40° [14]. It was found that introducing an energy management system into the seat track in the longitudinal direction not only reduced the forces acting on lumbar spine and pelvis, but reduced all ATD measurements to levels comparable to those seen for upright seated postures in current state-of-the-art vehicles.

Many different studies have been conducted for the reclined seating position; these have been either purely virtual using HBMs [24-26], or mechanical using ATD [14-15] or PMHS tests [13]. To date, the authors are not aware of any study that evaluates both the reclined (seat back tilted) and relaxed (seat back and seat pan tilted) seating positions, compares these to an upright seated occupant, and proposes a single countermeasure to reduce the overall effect of the crash on the occupant in all three positions. It is the objective of this study, therefore, to investigate the influence of seat track load limiting devices on the lumbar spine compression force in frontal impacts for three different seating positions using THOR-50M as a human surrogate. The target is to reduce the lumbar spine compression force for reclined and relaxed seated occupants to a level similar to that experienced by an upright seated occupant, yet without increasing the levels of any variables measured in Euro NCAP assessments of adult occupant safety [27]. THOR-50M was selected as it is the most advanced ATD for frontal sled testing and has been shown to be somewhat suitable for seated reclined positions [28]. Both active and passive seat track load limiting devices were evaluated, presented below.

II. METHODS

Frontal 50 km/h sled tests were performed using THOR-50M in three different seated positions in an adjustable generic seat rig and the influence of an active and passive seat track load limiter function was evaluated.

Test Environment

Sled. The tests were performed in a hydraulic-type sled catapult manufactured by Mannesmann Rexroth with maximum acceleration of 50 g. A 30 g peak (ΔV = 50 km/h) acceleration pulse was used, which has previously been used in several sled and simulation investigations assessing both upright and reclined occupants [13][24][29-30].

Generic seat rig. The THOR-50M was seated on a recently developed generic seat rig with many built-in functionalities for high adjustability. The seat back, with a built-in belt guide, can be individually adjusted to any seat back angle; the seat (sitting area) can be tilted to any angle having the same pivot point as the seat back and a lower leg support can be added when the seat is tilted (see Figs. 3 and 4). For these tests the semi-rigid seat [30] was used as sitting area (using an adapter plate any production seat may be used). The semi rigid seat was used in its front passenger geometry configuration as described in [30] but with slightly modified spring stiffnesses. The seat pan was supported by two springs with spring stiffness 128 N/mm and one centre spring with 379 N/mm spring stiffness. The anti-submarining ramp was supported with one spring with 132 N/mm spring stiffness at each side. Further, the generic seat rig incorporates attachments for the buckle and the lap belt retractor which both follow the generic seat rig when it is tilted (Figs. 3 and 4).

Seat track load limiter and release function. The generic seat rig was built upon a rail, making it possible for the whole generic seat rig, including all belt attachments, to move under a controlled force-displacement characteristic. The total mass that has to be controlled is 124 kg, which includes the weight of all moving parts of the generic seat rig, with an additional weight of 10 kg when the lower leg support is used. The load limiting functionality comes from two steel sheet metal elements which deform during displacement with a progressive characteristics. The starting force level can be adjusted using different widths of the steel elements and the progressivity can be adjusted as a built-in functionality of the rig. Additionally, the generic seat rig can either be fixed to the sled, be free to move when the seat track load limiter starting force is overcome (referred to as *passive seat track load limiter*), or released from the sled fixation by activation of a pyrotechnical unit, which releases the generic seat rig from the sled 1 ms after activation (referred to as *active seat track load limiter*). The active seat track load limiter was hypothesised to make the load limiting more effective than the passive seat track load limiter in reducing lumbar spine compression force as it makes it is possible to use a lower load limiting force for the same stroking distance (the allowable forward displacement of the generic seat rig). For all tests, the maximum stroking distance was set to 250 mm.

Lower extremity support. As the generic seat rig is designed to move forward, a foot support fixed to the sled cannot be used. However, for the relaxed tests a lower leg support was used to mimic a more comfortable seating position (Fig. 4).

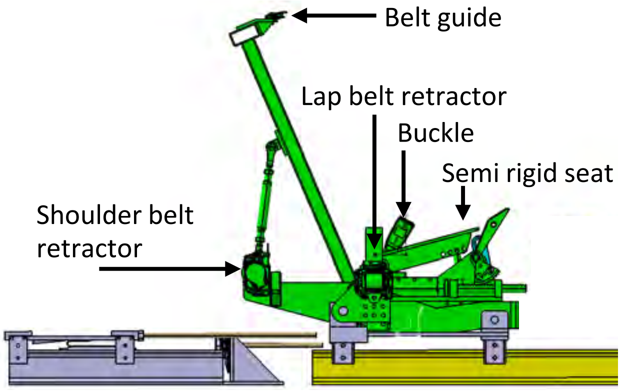

Fig. 3. Generic seat rig without lower leg support, lap belt retractor side.

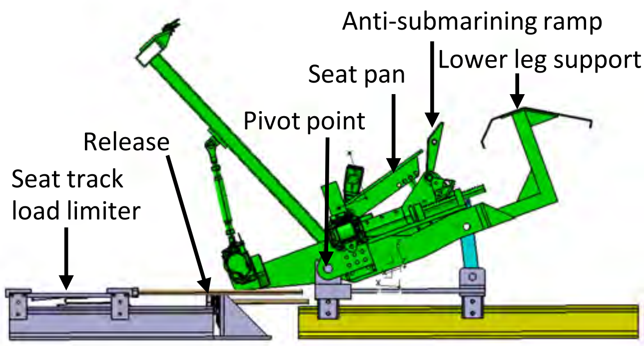

Fig. 4. Generic seat rig with tilted seat pan, reclined seat back and lower leg support, lap belt retractor side.

Restraint system. The THOR-50M was restrained by a seat belt concept developed to reduce the risk of submarining of THOR-50M in reclined seating positions [15] and later also used in reclined PMHS tests [13]. It consists of a 3-point belt with the belt guide in the seat back. The shoulder belt retractor with pretensioner and a 4 kN load limiter is mounted below the seat back, the lap belt is equipped with a retractor with pretensioner at the end bracket and a buckle pretensioner both attached to the generic seat rig. Additionally, the seat belt tongue is equipped with a crash locking tongue (CLT). When the belt is loaded by the occupant in a frontal crash, the CLT mitigates webbing transfer from shoulder belt to the lap belt, thereby providing a higher force in the lap belt portion compared to the shoulder belt portion which is load limited at 4 kN by the retractor. A low force in the shoulder belt reduces the risk of rib fractures [31]. The buckle pretensioner is activated at 3 ms and pulls the webbing in by 50 mm (affecting both the lap belt and the shoulder belt), and is followed by the simultaneous activation at 10 ms of the lap belt retractor pretensioner (pulling in 100-120 mm) and the shoulder belt retractor pretensioner (pulling in 25-50 mm). The total weight of the seat belt concept is 3 kg including shoulder and lap belt retractor and the buckle pretensioner.

High-speed cameras. Six on-board high-speed cameras recorded the tests at 1000 Hz. The cameras provided images of the left and right side overview and left and right side detailed view of the pelvis and its interaction with the seat and lap belt. A frontal view provided information about shoulder belt interactions with the chest and a rear mounted camera provided information about the shoulder belt retractor and the pyrotechnical release of the generic seat rig when used.

Instrumentation. Accelerometer sensors were mounted to the sled and the generic seat rig to measure the acceleration in the direction of the motion, accelerometer signals were filtered with CFC 60. A string potentiometer was installed on the generic seat rig and attached to the seat pan 210 mm from its rotation axis measured in the seat pan plane, to measure seat pan displacement when loaded. Due to this simple arrangement, the measurement cannot be directly compared when the seat is rotated. A second string potentiometer installed on the sled was attached to the generic seat rig to measure the stroke of the generic seat rig relative to the sled when the seat track load limiter was used. A third string potentiometer installed on the generic seat rig was attached to the rear part of the pelvis of the THOR-50M measuring displacement relative to the generic seat rig. Additionally, the shoulder belt retractor included a webbing payout sensor to measure webbing pull in and payout, and two uniaxial webbing load cells on the seat belt webbing measure belt forces. One load cell was located at the upper shoulder belt between the THOR-50M shoulder and the belt guide (B3), and the other at the lap belt between the THOR-50M right hip and the lap belt retractor (B6). The webbing load cells signal were filtered with CFC 600. Further, two load cells were mounted between the generic seat rig and the seat track load limiter units to measure the transferred forces. These load cells signals were filtered with CFC 180. All sensors used are listed with manufacturer and model name in Table AVII.

Human Surrogate and Seat Positions

THOR-50M. THOR-50M was used in all tests. The ATD was equipped with the instrumentation specified in the Euro NCAP test protocol [32], including three axis accelerometers in the head, spine (at T1,T4, T12) and pelvis; Infra-Red Telescoping Rods for the Assessment of Chest Compression (IR-TRACCs) for the chest (4) and abdomen (2); six axis load cells for the upper neck and at lower spine at T12 (referred to as lumbar spine); two axis load cells for the anterior superior iliac spine (ASIS); and chest and pelvis angular rate sensors. All signals from the ATD were filtered according to SAE J211. The sensors used are listed with manufacturer and model name in Table AVIII.

Positioning procedure. Three different seat positions were evaluated: relaxed, with a seat back angle of 60° and a seat pan angle of 35° including a lower leg support (also called ZeroG in [14]); reclined, with a seat back angle of 45°, a seat pan angle of 15° and feet on the floor; and upright, with a seat back angle of 23°, a seat pan angle of 15° and feet on the floor (see Figs. 5-7). THOR-50M, with the spine box set to the *slouched* position [32-33], was placed keeping the H-point in relation to the seat pan plane constant in all tests (H-point coordinates in Appendix). THOR-50M tilt sensors of the pelvis, chest, and head were used to keep the test position consistent between each test. The target tilt sensor angles are found in Table I; for the upright position, a pelvis angle of 33° ± 2.5° and head angle of -2.5 ° ± 1.0° [32-33] were used. Additional measurements of the THOR-50M position and generic seat rig can be found in Appendix.

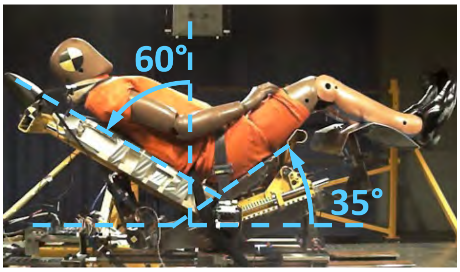

Fig. 5. THOR-50M relaxed position.

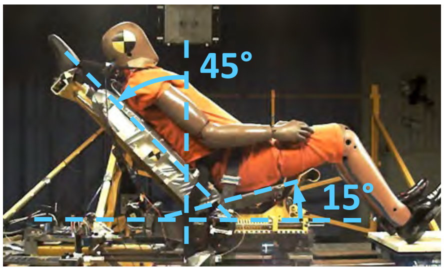

Fig. 6. THOR-50M reclined position.

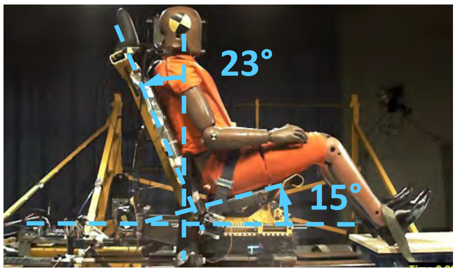

Fig. 7. THOR-50M upright position.

Test Matrix

In total, 18 sled tests were performed. Three different seating positions were evaluated, each tested with the generic seat rig either fixed to the sled, having a passive seat track load limiter, or having an active seat track load limiter releasing at 30 ms with a lower starting force compared to the passive one (see Table I). Each of the nine tests was repeated to capture potential variations.

TABLE I

TEST MATRIX OF THREE SEATING POSITIONS, THREE VERSIONS OF SEAT TRACK STIFFNESS (FIXED TO SLED, PASSIVE AND ACTIVE SEAT TRACK LOAD LIMITER (STLL)) AND TARGET POSITION MEASUREMENTS. (NOT SHOWN: TESTS WERE REPEATED)

Seating position	Seat back angle	Seat pan angle	STLL start force	Release of generic seat rig	Pelvis angle	Chest angle	Head angle	Lower leg angle
Relaxed	60°	35°	Fixed	Fixed	62°	60°	45°	30°
Relaxed	60°	35°	24 kN	0 ms	62°	60°	45°	30°
Relaxed	60°	35°	20 kN	30 ms	62°	60°	45°	30°
Reclined	45°	15°	Fixed	Fixed	48°	45°	26°	55°
Reclined	45°	15°	24 kN	0 ms	48°	45°	26°	55°
Reclined	45°	15°	20 kN	30 ms	48°	45°	26°	55°
Upright	23°	15°	Fixed	Fixed	33°	23°	-2.5°	55°
Upright	23°	15°	24 kN	0 ms	33°	23°	-2.5°	55°
Upright	23°	15°	20 kN	30 ms	33°	23°	-2.5°	55°

Analysis

Moving away from the traditional frontal restraint system (3-point seat belt with B-pillar mounted belt guide, driver airbag and knee bolster) and reclining the seat back primarily influences the risk of submarining and of increased spine and pelvis forces, while the absence of head restraining airbags may increase the risk of high head accelerations and neck extensions. These three areas were analysed in four steps.

First, error-free test execution was ensured in terms of the restraint function (reviewing belt forces in shoulder belt (B3) and outer lap belt (B6) and webbing pay-out of the shoulder retractor) and the test set-up (reviewing maximum values of seat track load limiting features such as force level, generic seat rig stroke distance, seat pan deflection, pelvis displacement and pelvis rotation around the ATD's y-axis, calculated by integrating the output form pelvis angular rate sensor). Both consistency within the repeated tests and between the different test set-ups was reviewed. Secondly, the interaction of the lap belt with the pelvis (submarining or no submarining) was evaluated by a combination of film analysis, lap belt force data, iliac wing forces and abdomen IR-TRACCs measurements. Thirdly, analyses were made of seat track load limiting force vs. stroke distance curves, generic seat rig acceleration characteristics compared to the sled acceleration pulse, and lumbar spine compression forces at T12, over time. Fourthly, the measurements from THOR-50M were compared to the higher and lower performance limits of criteria used in the Euro NCAP mobile progressive deformable barrier frontal impact assessment for the driver side (the only rating where THOR-50M is currently used) [27][32]. As no foot support or knee bolster was used, compression forces in acetabulum, femur and tibia were not relevant. The criteria used and their higher and lower performance limits can be found in Table AIX.

III. RESULTS

Test results from each of the three test positions are presented in three formats. First, Tables II - IV present the maximum values of belt characteristics (forces and webbing payout), test rig measurements (seat pan deflection, and for tests with seat track load limiting also generic seat rig stroke and maximum force), and ATD kinematics (pelvis displacement and rotation angle, where a positive angle represents a rearward rotation). Secondly, curve comparisons are presented for seat track load limiting force vs. stroke distance (Fig. 8) and influence on the generic seat rig acceleration compared to the sled acceleration pulse (Fig. 9). Lumbar spine compression forces over tome are presented for all three seating positions in Figs. 10, 12 and 14. Thirdly, Figs. 11, 13 and 15 present column diagrams of the ATD measurements in comparison to Euro NCAP higher and lower performance limits.

Upright

The overall results for restraint function and test dynamics are given in Table II. There were only small variations in the repeated tests. THOR-50M did not submarine in any of the six tests in the upright position, evaluated by continuous B6 forces, iliac wing forces and abdomen IR-TRACCs. In the tests with seat track load limiters, belt forces and webbing payout were reduced, and in particular the outer lap belt force (B6) was reduced substantially. The shoulder belt force (B3) depends on the load limiter torsion bar (normally referred to as load limiter), friction in the belt guide and the amount of belt payout. More payout results in a somewhat progressive force because of the smaller retractor diameter and deformation stiffens of the torsion bar. This explains the variation seen in the shoulder belts forces. In addition, pelvis displacement were also reduced while the rotation angle was not affected.

TABLE II

UPRIGHT TESTS, RESTRAINT INTERACTION, GENERIC SEAT RIG MEASUREMENTS AND ATD KINEMATICS FOR THREE VERSIONS OF SEAT TRACK STIFFNESS (FIXED TO SLED, PASSIVE AND ACTIVE SEAT TRACK LOAD LIMITER (STLL))

Test type	B3 [kN]	B6 [kN]	Webbing payout [mm]	STLL max force [kN]	Generic seat rig stroke [mm]	Seat pan deflection [mm]	Pelvis displacement [mm]	Change in pelvis rotation angle [°]
Fixed to sled #1	4.7	9.1	357	N/A	N/A	42	186	4
Fixed to sled #2	4.6	8.8	347	N/A	N/A	42	193	3
Passive STLL #1	4.1	6.0	266	31	199	36	151	5
Passive STLL #2	4.1	6.0	253	30	203	34	150	4
Active STLL #1	3.9	5.6	250	25	193	33	133	4
Active STLL #2	3.9	5.4	241	26	214	31	129	5

The maximum force measured for the seat track load limiter was lower in the active than the passive tests. The passive seat track load limiter force started at 24 kN, increasing to approximately 30 kN, while the active seat track load limiter started at 20 kN, increasing to approximately 25 kN, with both having a similar stroke distance of around 200 mm (Fig. 8). The initial higher force peaks in Fig 8 (light blue curves) occurs before activation of the seat track load limiter. The load limiters, both passive and active, had a substantial influence on the acceleration that the generic seat rig experienced (Fig. 9). By initially fixing the generic seat rig to the sled (active) rather than not fixing it (passive), the seat was exposed to the sled acceleration pulse until released, with higher initial accelerations. As the kinetic energy between active and passive seat track load limiter tests did not differ, and the total stroke was intended to be similar, the initial higher acceleration was followed by a lower acceleration as lower load limiting forces were subsequently applied. In all tests, first a positive peak of approximately 1 kN was seen in the lumbar spine load cell of the ATD relating to the pretensioning of the seat-belt which was then followed by a compression force when the ATD starts to load the lap belt and the seat pan. Maximum lumbar spine compression occurs at maximum pelvis displacement where the lap belt force (B6) also reaches its maximum. As shown in Fig. 10, seat track load limiting, both passive and active, was found to substantially reduce lumbar spine compression from approximately 4 kN (the negative peak at 65 ms) to approximately 1.5 kN.

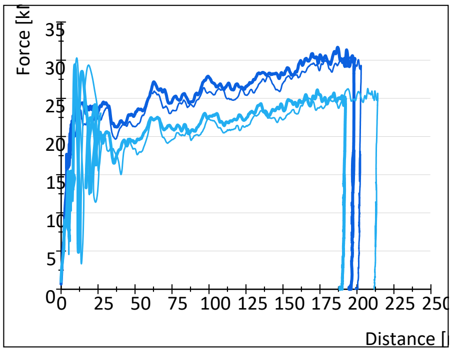

Fig. 8. Seat track load limiter force characteristics. Dark blue: passive; light blue: active. Thin and bold lines represent data from the two repeated tests.

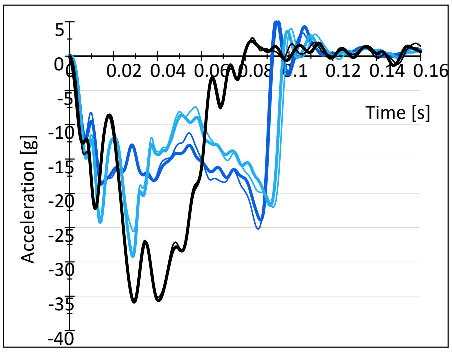

Fig. 9. Generic seat rig accelerations. Black: tests with the seat fixed to sled (no seat track load limiter); dark blue: passive; light blue: active. Thin and bold lines represent data from the two repeated tests.

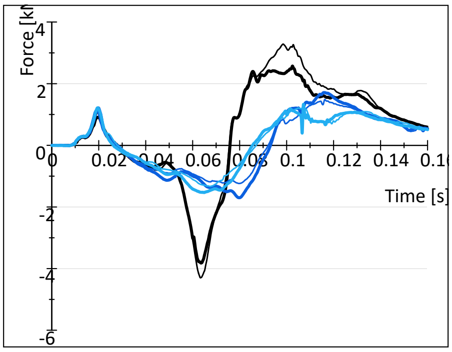

Fig. 10. Lumbar spine forces. Black: tests with the seat fixed to sled (no seat track load limiter); dark blue: passive; light blue: active. Thin and bold lines represent data from the two repeated tests.

In evaluating the test results to Euro NCAP performance levels for THOR-50M (Fig. 11), it can be seen that all values are well below the lower performance limits, and that all values except chest compression are below the higher performance limits. The seat track load limiter reduces all values, with the largest drop in head injury criterion maximum value of 15 ms (HIC15) and neck tensions forces and a relatively small reduction in chest and abdomen max compression.

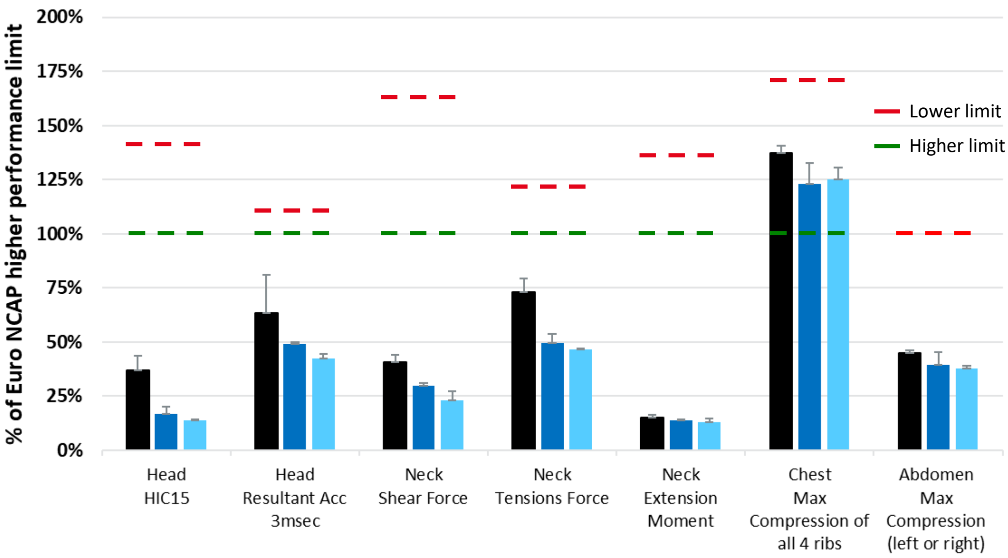

Fig. 11. Test results for upright tests assessed according to Euro NCAP higher performance limit, represented by a green dotted line (lower performance limit represented by red dotted line). Black represents tests with the seat fixed to the sled, dark blue represents passive seat track load limiter tests and light blue represents active seat track load limiter tests. Error bars represent the variation in the two repeated tests.

Reclined

For the reclined tests, the repeated tests also showed good consistency and again THOR-50M did not submarine in any of the tests. Belt forces as well as webbing payout reduced in the tests where seat track load limiting was used (Table III). A larger pelvis displacement and rearward pelvis rotation occurred in the reclined position compared to the upright position. In this test configuration, the generic seat rig stroke had a somewhat larger spread compared to the upright tests (219 mm and 242 mm for the active load limiter; 203 mm and 226 mm for the passive load limiter) (Table III).

TABLE III

RECLINED TESTS RESTRAINT INTERACTION, GENERIC SEAT RIG MEASUREMENTS AND ATD KINEMATICS FOR THREE VERSIONS OF SEAT TRACK STIFFNESS (FIXED TO SLED, PASSIVE AND ACTIVE SEAT TRACK LOAD LIMITER (STLL))

Test type	B3 [kN]	B6 [kN]	Webbing payout [mm]	STLL max force [kN]	Generic seat rig stroke [mm]	Seat pan deflection [mm]	Pelvis displacement [mm]	Change in pelvis rotation angle [°]
Fixed to sled #1	4.3	10.1	300	N/A	N/A	42	229	16
Fixed to sled #2	4.3	9.9	308	N/A	N/A	42	236	20
Passive STLL #1	3.9	6.8	182	31	203	40	164	15
Passive STLL #2	3.8	6.7	173	30	226	39	153	12
Active STLL #1	3.8	6.0	142	27	242	36	150	12
Active STLL #2	3.9	6.5	158	25	219	37	144	11

The curve analysis again parallels the findings from the upright position. However, the reclined tests fixed to the sled produced substantially higher lumbar spine compression forces at maximum pelvis displacement, 6 kN compared to the 4 kN of the upright position (Fig. 12). The influence of the seat track load limiter on lumbar spine compression is clearly noticeable: it was reduced from 6 kN to 3.1 kN and 3.4 kN (repeated tests with the active seat track load limiter) or 3.6 kN and 3.9 kN (repeated tests with the passive seat track load limiter).

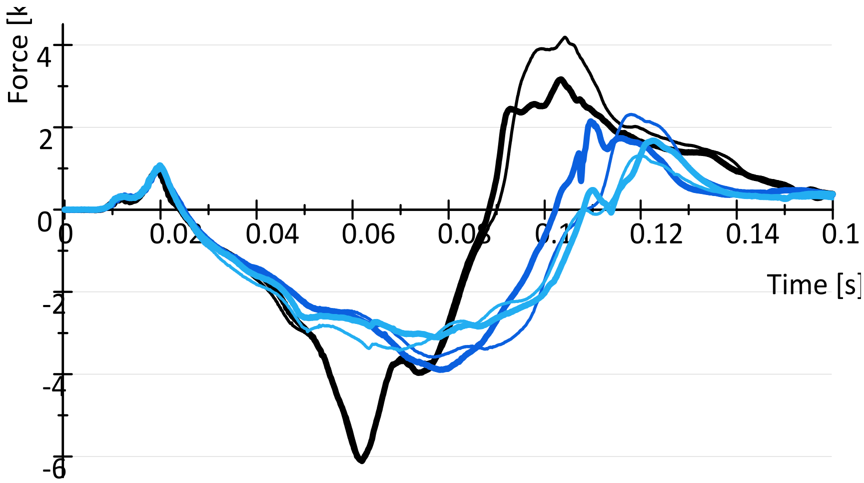

Fig. 12. Lumbar spine forces for the reclined seating position. Black: tests with the seat fixed to sled (no seat track load limiter); dark blue: passive; light blue: active. Thin and bold lines represent data from the two repeated tests.

All ATD measurements increased compared to the upright tests, except for abdomen compression. As can be seen in Fig. 13, measurements are below the Euro NCAP higher performance limit, except for chest compression which here exceeds the lower performance limit. However, in the tests with the seat fixed to the sled, neck shear and tension exceeded 90% of the higher limit, highlighting the neck as an area of interest as well as the chest. Again, the seat track load limiter reduced all values substantially, except for chest and abdomen compression, with the largest reduction to HIC15 and neck tensions forces.

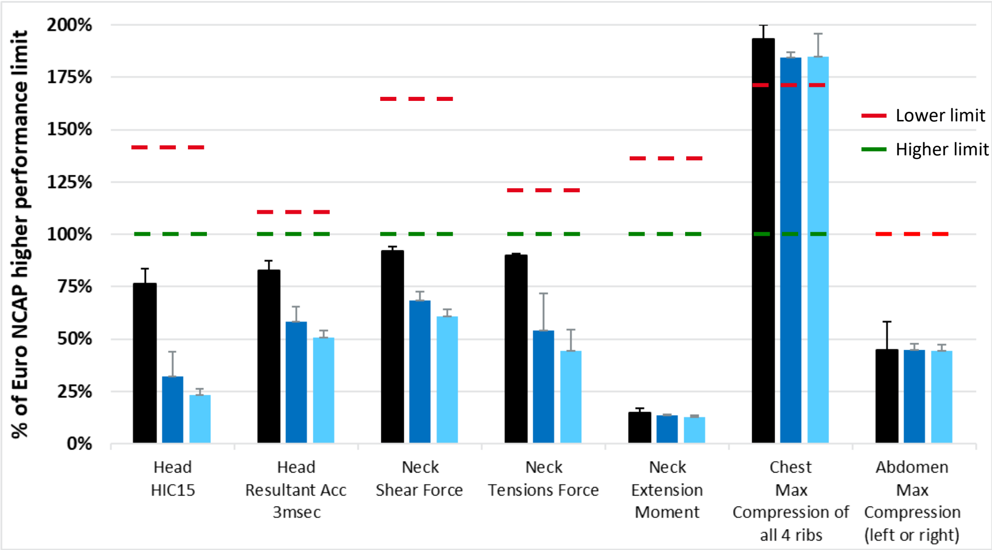

Fig. 13. Test results for reclined tests assessed according to Euro NCAP higher performance limit represented by the green dotted line (lower performance limit represented by the red dotted line). Black represents tests with the seat fixed to the sled, dark blue represents passive seat track load limiter tests and light blue represents active seat track load limiter tests. Error bars represent the variation in the two repeated tests.

Relaxed

The relaxed tests also show good consistency and again, THOR-50M did not submarine in any of the tests. In Table IV, as with the tests reported above, it can be seen that belt loads and webbing payout reduced when seat track load limiting was used. Additionally, it can be noted that webbing payout and thereby shoulder belt forces (B3) were substantially lower for the relaxed tests compared to the upright and the reclined tests. Larger pelvis displacement and rearward pelvis rotation is seen in the relaxed position compared to the reclined position. Note that the seat pan deflection measurement is not direct comparable to the measurement reported in upright and reclined position because of the tilted position of the seat. A slightly longer stroke of the generic seat rig was observed, most likely due to the increased moving mass when the lower leg support was added.

TABLE IV
RELAXED TESTS RESTRAINT INTERACTION, GENERIC SEAT RIG MEASUREMENTS AND ATD KINEMATICS FOR THREE VERSIONS OF SEAT TRACK STIFFNESS (FIXED TO SLED, PASSIVE AND ACTIVE SEAT TRACK LOAD LIMITER (STLL))

Test type	B3	B6	Webbing payout	STLL max force	Generic seat rig stroke	Seat pan deflection	Pelvis displacement	Change in pelvis rotation angle
	[kN]	[kN]	[mm]	[kN]	[mm]	[mm]	[mm]	[°]
Fixed to sled #1	3.8	9.7	131	N/A	N/A	33	241	26
Fixed to sled #2	3.9	9.5	118	N/A	N/A	34	250	27
Passive LL #1	3.5	6.3	64	33	241	30	181	22
Passive LL #2	3.5	6.5	55	34	247	30	192	23
Active LL #1	3.4	5.7	72	28	239	28	158	19
Active LL #2	3.4	5.6	71	29	244	29	160	21

Curve analyses conform to the findings in the upright and reclined tests in terms of the influence of the generic seat rig acceleration and seat track load limiter forces. However, with the seat pan at a 35° angle instead of 15°, the lumbar spine force develops in a different way, especially in tests with the seat fixed to the sled (see Fig. 14). The compression force first rises to a peak of 6 kN at approximate 45 ms, when the seat pan reaches its maximum deflection. It then drops slightly to increase again in a second peak of 6 kN at maximum pelvis displacement and maximum lap belt force. While both seat track load limiters reduce the maximum peak force, the active load limiter is substantially more successful in reducing this compression force, to 3.7 kN and 3.9 kN maximum peak force (repeated tests) compared to 4.6 kN and 5.0 kN (repeated tests) for the passive load limiter.

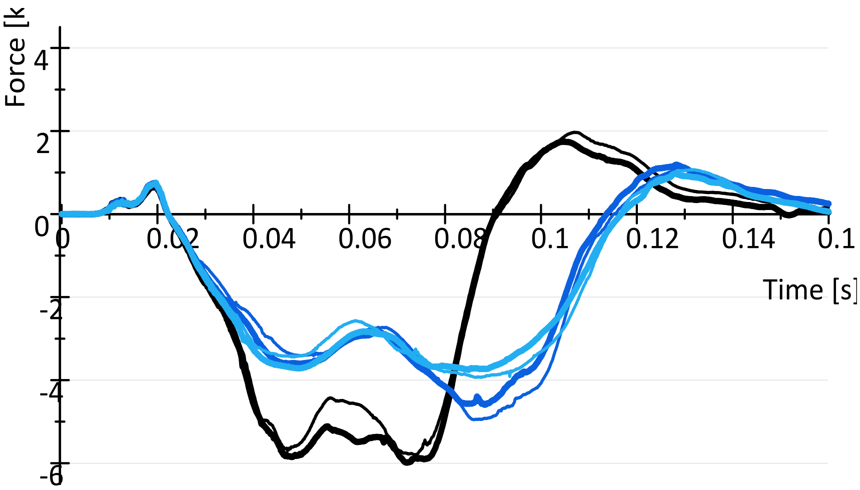

Fig. 14. Lumbar spine forces for the relaxed seating position. Black: tests with the seat fixed to sled (no seat track load limiter); dark blue: passive; light blue: active. Thin and bold lines represent data from the two repeated tests.

ATD measurement in relaxed tests were similar to those of the reclined tests except for the neck shear force, which now also exceeds the higher performance limit for the fixed to sled rig (see Fig. 15). Again, the seat track load limiter reduces all values except chest and abdomen compression which it increases; neck shear forces are reduced to below the higher performance limit.

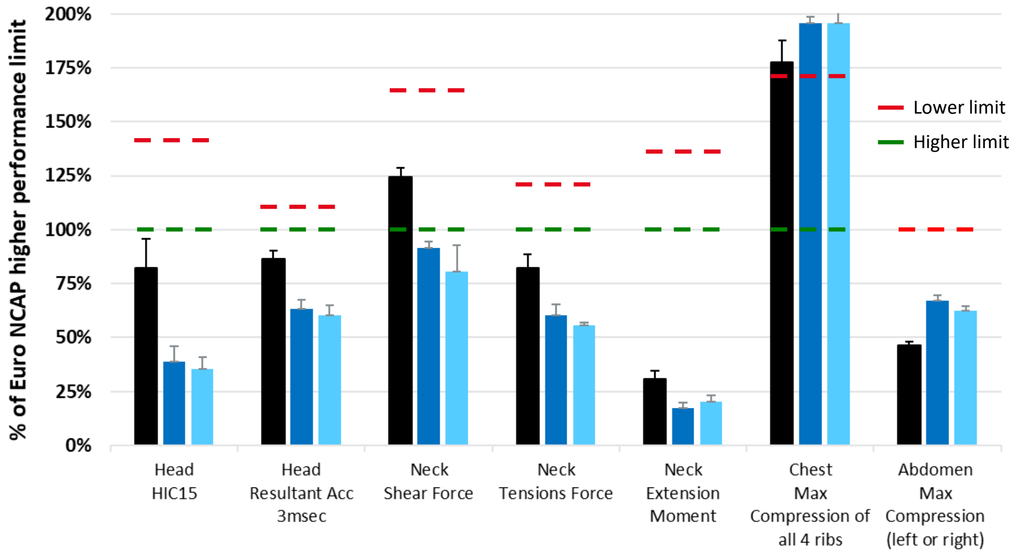

Fig. 15. Test results for relaxed tests assessed according to Euro NCAP higher performance limit represented by the green dotted line (lower performance limit represented by the red dotted line). Black represents tests with the seat fixed to the sled, dark blue represents passive seat track load limiter tests and light blue represents active seat track load limiter tests. Error bars represent the variation in the two repeated tests.

IV. Discussion

Three configurations of seat track, seat fixed to sled, passive seat track load limiter, and active seat track load limiter, were evaluated using THOR-50M for three different seating positions, upright, reclined and relaxed. The seat track load limiter was found to successfully decrease acceleration and force measures in the ATD. In particular, the active seat track load limiter reduced the lumbar spine force to levels similar to those of an upright occupant. In addition, ATD measurements from the tests with the active seat track load limiter in all three positions indicate that no supplementary restraints are needed to meet Euro NCAP higher performance criteria, with the exception of chest compression measured as Rmax, which was not reduced.

However, the study has two important limitations. The generic seat rig was proven useful in that it was easily adjusted in between tests and repeatable and cost-efficient tests were easily performed. However, it represents a rough simplification of a production seat in terms of seat back and seat pan stiffness. Furthermore, its weight is approximately double that of a production seat with an integrated belt. Therefore, the results of this study are not generalisable to all seats and crash configurations, but should rather be seen as one successful application, demonstrating the potential of a seat track load limiter in reducing ATD measurements.

In addition, using THOR-50M in any position other than upright lies outside its validated regime. Nonetheless, measured accelerations and forces appear meaningful in relative comparisons even if a kinematic validation is preferred. However, chest compression, measured as the maximum of the resultant value from the four IR-TRACCs (Rmax), might not be meaningful. Rmax increased for the reclined occupant despite lower shoulder belt peak forces. However, dividing the IR-TRACCs measured resultant into its components, longitudinal displacement in x-direction and angular change information in y and z directions [34], indicates that the longitudinal displacement (compression) decreased in the reclined and the relaxed tests compared to the upright (see Fig. 16). Instead of a longitudinal displacement, an angular change in z-direction dominated. In the upright tests, the IR-TRACCs were initially in a horizontal position and affected by the shoulder belt in its longitudinal direction. In the reclined and relaxed tests, the initial position of the IR-TRACCs deviates from the horizontal (see Fig. 17). In the tests, the IR-TRACCS position changed over time but its initial position is likely to affect how the IR-TRACCs react to the force from the shoulder belt. Rmax in THOR-50M was validated as correlating to risk of rib fractures in the upright position [35]; however, whether Rmax is useful or not as an indicator for risk of rib fractures in the reclined and relaxed positions is unknown. Beside Rmax, Xmax (based on longitudinal deflection only) has been proposed in previous research as a better indicator for rib fracture [36]. One indication from these tests is that Xmax would give a different risk of rib fracture in the reclined and relaxed positions, in fact rather than increasing the risk of rib fracture, the seat track load limiter decreasing the risk in the relaxed position.

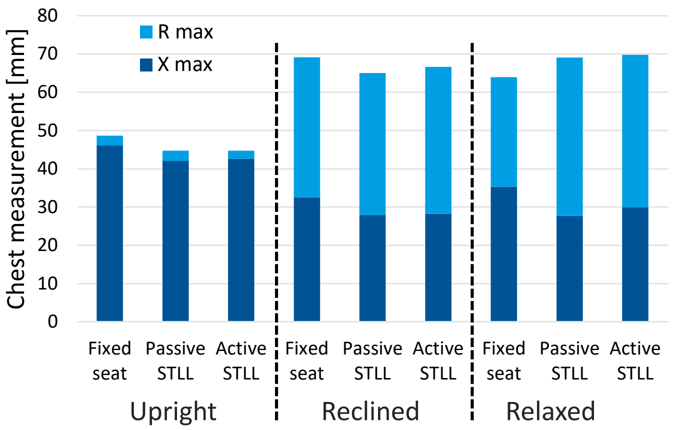

Fig. 16. THOR-50M chest compression as Xmax (max longitudinal displacement of all four IRTRACCs) (average value of two tests, dark blue) and Rmax (max resultant value of all four IRTRACCs) (average value of two tests, as the sum of the dark blue and the light blue bars).

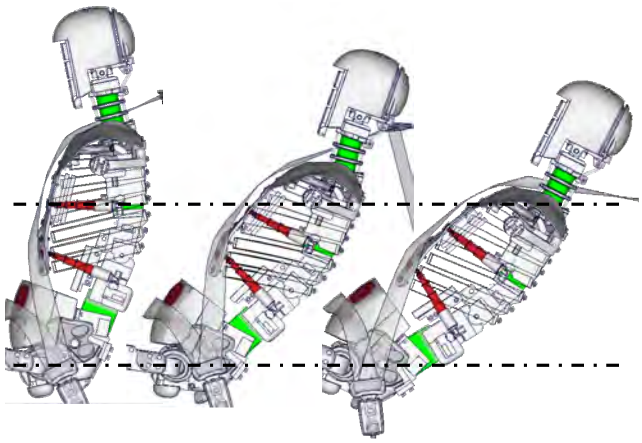

Fig. 17. THOR-50M in the upright, reclined and relaxed positions. IR-TRACCs highlighted in red.

With this conflicting evidence of the influence of reclining on rib fracture risk in THOR-50M, we revert to previously reported PMHS tests. These tests do not provide clear evidence that reclined positions substantially influence rib fracture risk. In five reclined PMHS tests under similar test conditions, the number of fractured ribs sustained varies [13]. Two PMHSs sustained zero and one rib fracture each, while two other PMHSs sustained multiple rib fractures (18 and 22), and the fifth PMHS fell in between with six rib fractures. Results are similar to further PMHS tests in the upright position, where tests with a 4.5 kN force limit with an airbag in a 48 km/h sled test yielded 0 to 15 rib fractures for 10 PMHSs [37].

While we cannot draw a conclusion regarding the merits of Rmax and Xmax for THOR-50M in reclined positions, we do not necessarily suggest further research or modifications of THOR-50M. We believe HBMs with human-like design and use of rib strain as indicator of risk of rib fracture [38], are likely to be more biofidelic than chest deflection to evaluate a potential increase or decrease in risk of rib fractures in reclined and relaxed positions. Evaluation and validation of HBMs with reclined PMHS tests appears to be of most importance.

Despite the limitations described above, it is still the belief of the authors that the test results presented here are meaningful, especially when comparing measured accelerations and forces, and that conclusions can be drawn about the seat track load limiter, discussed further below.

Seat track load limiter. The seat track load limiter was effective in reducing accelerations acting on the generic seat rig compared to the sled acceleration. The reduced acceleration level had the effect that all ATD acceleration and force-based criteria for all three positions were significantly reduced. In particular, lumbar spine compression was markedly reduced, confirming previous work using an HBM [24]. Notably, the target of reducing the lumbar spine compression force in reclined and relaxed seating positions to that of the upright position was met. However, whether 4 kN measured by THOR-50M would reliably avoid spinal fracture is still an open question. A lumbar spine compression criterion is needed for ATDs as well as for HBMs. A previous study suggests 4.5 kN to indicate a 50% risk of a vertebra fracture [39] but further work is needed to investigate the biofidelity of the THOR-50M response and whether or not the value is directly applicable.

In addition to lumbar spine compression, pelvic forces in reclined and relaxed positions are also of importance. In previously reported reclined PMHS tests, two out of the five PMHSs sustained pelvic fractures [13][40]. In the current tests, pelvic forces, indicated by lap belt forces, were at similar levels of around 9-10 kN in all three test positions in the tests without a seat track load limiter. However, when the seat track load limiter was used, lap belt forces were reduced to approximately 6 kN. This is close to the 5 kN that has been recommended as a threshold to avoid pelvic fractures [29-30]. However, as with the lumbar spine, no criterion exists for either ATDs or HBMs to evaluate and predict this type of injury.

As noted, the seat track load limiter was not effective in reducing chest compression measured as Rmax, despite the reduced accelerations acting on the generic seat rig. However, the seat track load limiter resulted in less webbing payout. This indicates that more room for forward displacement is available, which in turn opens up the possibility of using less shoulder belt force (B3), which is known to reduce the risk of rib fractures [41]. This can for example be done by switching the seat belt load limiter to a lower level when the seat track load limiter is used [42]. However, changing B3 force levels affects occupant kinematics and most likely injury measurements such as lumbar spine compression force and head acceleration. More thorough investigations with the target of reducing chest compression below Euro NCAP performance levels, while avoiding head-to-femur contact, are needed to conclude with certainty that chest compression can be substantially reduced using this relatively straightforward modification.

Active or passive seat track load limiter. Seat track load limiters, both active and passive, demonstrate promising injury reductions. Using an active load limiter was hypothesised to make the load limiting more effective as it allows less force to be used for the same stroking distance. This was supported by our findings: the lower force contributed to the target being met of reducing the lumbar spine compression force for reclined and relaxed occupants to a level similar to that of upright occupants. Adding an activation feature to the seat track load limiter makes the function more complex, but also increases its functionality as it can be switched on or off depending on, for example, the seat position or type of crash.

Vehicle integration. To be able to implement seat track load limiting, the vehicle must have a seat integrated belt system, room for the stroke distance and an activation strategy. Additionally, to increase functionality, the seat position, the occupant weight, and the crash severity should be considered in the activation strategy. A potential area of use for a seat track load limiter might be new types of vehicles, seen as concept cars today, designed with living room seating where the occupants have more space in the interior but at the cost of shorter frontal deformation zones [43].

Alternatives. The seat track load limiter has been shown to be effective in reducing lumbar spine compression forces but should be considered alongside alternative solutions. Past studies have, for example, proposed to actively re-position an occupant into a safer position before the impact [44]. Repositioning a reclined seat back up to an upright position has also been investigated [45]. However, here submarining was not avoided as the upper body was pushed upwards but the pelvis did not fully rotate to the upright position. The study also revealed that repositioning could be achieved by the occupant's own torso inertia during pre-crash braking as well as by moving the seat back. However, this study was done with the belt guide in the B-pillar. With the belt guide in the seat this might not be possible. Additionally, the re-positioning protection strategy relies on accurate pre-crash sensing and high mechanical power to move the seat back to an upright position, neither of which are needed by the seat track load limiter.

V. Conclusions

The seat track load limiter was shown to be effective in supporting the belt system in protecting occupants. It reduced the lumbar spine compression in reclined and relaxed positions without negatively affecting other injury measures except chest compression measured as Rmax. Actually, ATD measurements in this study indicate that no supplementary restraints would be needed if there is no risk of impacting any vehicle interior structure.

VI. Acknowledgements

The authors want to thank Benny Tholin, Per-Erik Johansson, Sonny Muhoray and Mikael Lindberg all at Autoliv Safety Center in Sweden for executing the sled tests and for their patience when changes were made at the last minute. We also thank Dr Helen East for her help with language revisions. The project was partly financed by FFI (Strategic Vehicle Research and Innovation), VINNOVA, the Swedish Transport Administration, the Swedish Energy Agency, and industrial partners. The project is associated to SAFER, the Vehicle and Traffic Safety Centre at Chalmers.

VII. References

[1] Lubbe N, Jeppsson H, Ranjbar A, Fredriksson J, Bärgman J and Östling M. Predicted road traffic fatalities in Germany: The potential and limitations of vehicle safety technologies from passive safety to highly automated driving. Proceedings of IRCOBI conference, 2018, Athens, Greece.

[2] Östling M, Lubbe N and Jeppsson H. Predicted crash configurations for Autonomous Driving vehicles in mixed German traffic for the evaluation of occupant restraint system. VDI-Conference “Vehicle Safety” 27th and 28th November 2019, Berlin, Germany.

[3] Wang L, Fahrenkrog F, Vogt T, Jung O, and Kates R. Prospective safety assessment of highly automated driving functions using stochastic traffic simulation. The 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2017, Detroit, Michigan USA.

[4] Filatov A, Scanlon JM, Bruno A, Danthurthi SSK and Fisher J. Effects of innovation in automated vehicles on occupant compartment designs, evaluation, and safety: A review of public marketing, literature, and standards. SAE Technical Paper 2019-01-1223, 2019, doi:10.4271/2019-01-1223.

[5] Östling M and Larsson A. Occupant Activities and Sitting Positions in Automated Vehicles in China and Sweden. Proceedings of Conference for the Enhancement of Safety Vehicles (ESV), 2019, Eindhoven, Netherlands.

[6] Koppel S, Octavio J, Bohman K, Logan D, Raphael W, Jimenez Q and Lopez-Valdes F. Seating configuration and position preferences in fully automated vehicles. Traffic injury prevention 2019. https://doi.org/10.1080/15389588.2019.1625336

[7] Stanglmeier MJ, Paternoster FK, Paternoster S, Bichler RJ, Wagner P-O and Schwirtz A. Automated driving: A biomechanical approach for sleeping positions, Applied Ergonomics 86, 2020: 103103

[8] The U.S. Department of Transportation's: Automated driving systems 2.0 a vision for safety, September 2017. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf, accessed 1st of April 2021.

[9] Eggers A, Mayer C and Peldschus S. Validation procedure for simulation models in a virtual testing and evaluation process of highly automated vehicles. VDI-Tagung Fahrzeugsicherheit, 2019.

[10] EU project OSCCAR https://www.osccarproject.eu/

[11] Gepner B, Draper D, Mroz K, Richardson R, Ostling M, Pipkorn B, Forman JL, and Kerrigan JR. (2019) Comparison of Human Body Models in Frontal Crashes with Reclined Seatback. In Proceedings of IRCOBI conference, 2019, Florence, Italy.

[12] Luet C, Trosseille X, Drazetic P, Potier P and Vallancien G. Kinematics and dynamics of the pelvis in the process of submarining using PMHS sled tests. Stapp Car Crash Journal, 2012, Vol. 56: pp. 411-442.

[13] Richardson R, Donlon JP, Jayathirtha M, Forman J, Shaw G, Gepner B, Kerrigan J, Ostling M, Mroz K and Pipkorn B. Kinematic and Injury Response of Reclined PMHS in Frontal Impacts. Stapp Car Crash Journal, Vol. 64, November 2020.

[14] Sengottu Velavan S and Huf A. Development of occupant restraint systems for future seating positions in fully or semi autonomous vehicles. Proceedings of FISITA World Automotive Congress, 2018, Chennai, India.

[15] Östling M, Sunnevång C, Svensson C and Kock HO. Potential future seating positions and the impact on injury risks in a Learning Intelligent Vehicle (LIV). VDI-Tagung Fahrzeugsicherheit, 2017, Berlin, Germany.
[16] Lin H, Gepner B, Wu T and Forman J. Effect of Seatback Recline on Occupant Model Response in Frontal Crashes. In Proceedings of IRCOBI conference, 2018, Athens, Greece.
[17] Forman J, Lin H, Gepner B, Wu T and Panzer M. Occupant safety in automated vehicles – effect of seatback recline on occupant restraint. JSAE, Paper Number 20185234, 2018.
[18] Leung YC, Hureau J, Patel A, Guillon F, Got C, Lestrelin D and Tarriere C. Submarining Injuries of 3 Pt Belted Occupants in Frontal Collisions -Description, Mechanism and Protection. Stapp Car Crash Conference Proc. 1982; Paper 821158.
[19] Lamielle S, Cuny S, Foret-Bruno JY, Petit P, Vezin, P, Verriest, J P and Guillemot, H. Abdominal injury patterns in real frontal crashes: influence of crash conditions, occupant seat and restraint systems, Annu Proc Assoc Adv Automot Med, 50, 2006, p103-118.
[20] Poplin GS, Timothy L, McMurry TL, Forman JL, Hartka T, Park G, Shaw G, Jangho Shin J, Kim HJ, and Crandall J. Nature and etiology of hollow-organ abdominal injuries in frontal Crashes. Accident Analysis and Prevention 78, 51–57, 2015.
[21] Kyle J, Boyle KJ, Reed MP, Zaseck LW and Hu J. A Human Modelling Study on Occupant Kinematics in Highly Reclined Seats during Frontal Crashes. In Proceedings of IRCOBI conference, 2019, Florence, Italy.
[22] Richardson R, Jayathirtha M, Chastain K, Donlon JP, Forman J, Gepner B, Östling M, Mroz K, Pipkorn B and Kerrigan J. Thoracolumbar Spine Kinematics and Injuries in Frontal Impacts with Reclined Occupants. Traffic Injury Prevention 2020. https://doi.org/10.1080/15389588.2020.1837365.
[23] Richardson R. et. al Test methodology for evaluating the reclined seating environment with human surrogates. The 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV) 2019, Eindhoven, Netherlands.
[24] Mroz K, Ostling M, Richardson R, Kerrigan J, Forman J, Gepner B, Lubbe N and Pipkorn B. Effect of Seat and Seat Belt characteristics on the Lumbar Spine and Pelvis Loading of the SAFER Human Body Model in reclined Postures. Proceedings of the IRCOBI Conference, 2020, Munich, Germany.
[25] Ji P, Huang Y, and Zhou Q. Mechanisms of using knee bolster to control kinematical motion of occupant in reclined posture for lowering injury risk. International journal of crashworthiness, 22(4), 415-424, 2017.
[26] Rawska K, Gepner B, Kulkarni S, Chastain K, Zhu J, Richardson R, Perez-Rapela D, Forman J and Kerrigan JR. Submarining sensitivity across varied anthropometry in an autonomous driving system environment. Traffic Injury Prevention, 2019, S123-S127, DOI: 10.1080/15389588.2019.1655734.
[27] EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) ASSESSMENT PROTOCOL – ADULT OCCUPANT PROTECTION Version 9.1.2 June 2020. https://cdn.euroncap.com/media/58227/euro-ncap-assessment-protocol-aop-v912.pdf, accesses 24th of May 2021.
[28] Prasad A. NHTSA ATD Seating in Highly Reclined Seats. SAE Government Industry Meeting April 04, 2019 https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/atd_seating_in_highly_reclined_seats.pdf accessed 1st of April 2021.
[29] Uriot J, Potier P, Baudrit P, Trosseille X, Richard O and Douard R. Comparison of HII, HIII and THOR dummy responses with respect to PMHS sled tests. In Proceedings of IRCOBI Conference 2015, Lyon, France.
[30] Uriot J, Potier P, Baudrit P, Trosseille X, Petit P, Richard O, Compigne S, Masuda M and Douard, R. Reference PMHS Sled Tests to Assess Submarining. Stapp Car Crash Journal. Vol 59, 2015.
[31] Eickhoff B, Zellmer H and Forster E. The mechanism of belt induced chest deflection: analysis and possibilities for reduction. The 20th International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV) 2017, Lyon, France.
[32] EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) MPDB FRONTAL IMPACT TESTING PROTOCOL Implementation 1st January 2020 Version 1.1.1 October 2019. https://cdn.euroncap.com/media/55858/euro-ncap-mpdb-testing-protocol-v111.pdf accessed 1st of April 2021.
[33] Louden AE. Revised THOR 50th percentile male dummy seating procedure (Report No. DOT HS 812 746). Washington, DC: National Highway Traffic Safety Administration, 2019.
[34] KIR-TRACC Deformation measuring for THOR-50M. https://www.kistler.com/files/document/003-436e.pdf accesses 19th of February 2021

[35] Poplin GS et al. Development of thoracic injury risk functions for the THOR ATD. Accident Analysis and Prevention, 2017. 106 (2017) 122–130 http://dx.doi.org/10.1016/j.aap.2017.05.007
[36] Davidsson J. et al. Development of injury risk functions for use with the THORAX Demonstrator; an updated THOR. Proceedings of the IRCOBI Conference, 2014, Berlin, Germany.
[37] Kent RW, Crandall JR, Bolton J, Prasad P, Nusholtz G and Mertz H. The influence of superficial soft tissues and restraint condition on thoracic skeletal injury prediction (No. 2001-22-0008). SAE Technical Paper 2001.
[38] Forman JL, et al. Predicting rib fracture risk with whole-body finite element models: development and preliminary evaluation of a probabilistic analytical framework. Proceedings of the 56th annual AAAM Scientific Conference, Seattle, Washington, 2012.
[39] Stemper BD et al. Biomechanical Tolerance of Whole Lumbar Spines in Straightened Posture Subjected to Axial Acceleration. Journal of Orthopaedic Research, 36(6), 2017.
[40] Richardson R, Jayathirtha M, Donlon JP, Forman JL, Gepner B, Ostling M, Mroz K, Pipkorn B and Kerrigan JR. Pelvis Kinematics and Injuries of Reclined Occupants in Frontal Impacts. Proceedings of the IRCOBI Conference, 2020, Munich, Germany.
[41] Mroz K, Pipkorn B, Sunnevång C, Eggers A and Bråse D. Evaluation of Adaptive Belt Restraint Systems for the Protection of Elderly Occupants in Frontal Impacts. In Proceedings of IRCOBI conference, 2018, Athens, Greece.
[42] Clute G. Adaptive load limitation presentation and system validation of the adaptive load limiter. Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles, 2001, Amsterdam, The Netherlands.
[43] Linkenbach S, Rink K and Peters B. Integrated Safety for Automated Driving. 14th International Symposium on Sophisticated Car Safety Systems - airbag 2018, Mannheim, Germany.
[44] Jin X, Hou H, Shen M, Wu H and Yang KH. Occupant Kinematics and Biomechanics with Rotatable Seat in Autonomous Vehicle Collision: A Preliminary Concept and Strategy. Proceedings of the IRCOBI Conference, 2018, Athens, Greece.
[45] Östh J, Bohman K and Jakobsson L. Evaluation of Kinematics and Restraint Interaction when Repositioning a Driver from a Reclined to Upright Position Prior to Frontal Impact using Active Human Body Model Simulations. Proceedings of the IRCOBI Conference, 2020, Munich, Germany.

VIII. APPENDIX

TABLE AI
TEST RIG DIMENSIONS UPRIGHT SEAT POSITION

	X [mm]	Y [mm]	Z [mm]
Generic seat rig pivot point	0	0	0
Seat pan pivot point	-113	-130	126
Anti-submarining ramp pivot point	-373	-87	150
Shoulder belt retractor bolt	194	-52	62
Belt guide bolt	206	-6	826
Lap belt retractor bolt	-87	-3	35
Buckle bolt	-92	-508	34
Centre of webbing at tongue (buckle)	-133	-445	287
Floor plane			-44
Seat pan angle		15°	
Anti-submarining ramp angle		30°	
Seat back angle		23°	

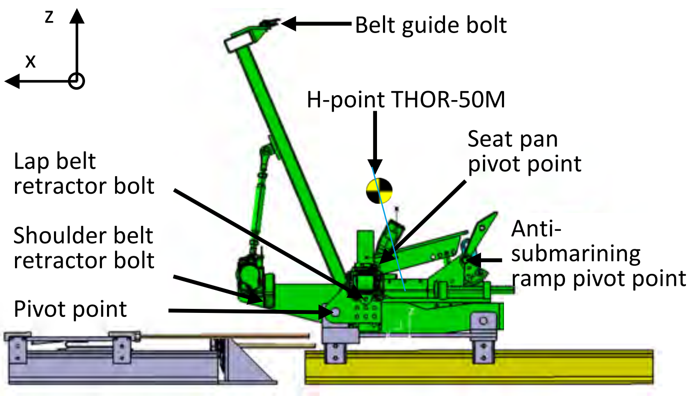

Fig. A1. Generic seat rig without lower leg support, lap belt retractor side, upright seating position.

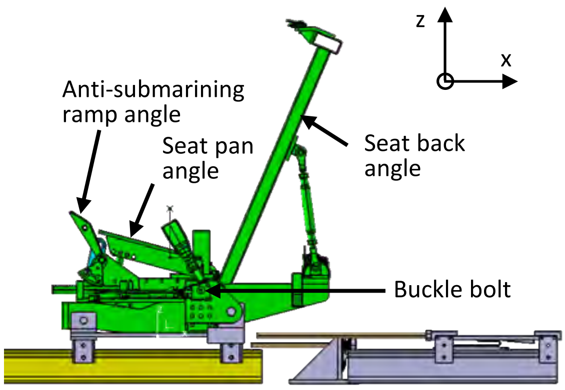

Fig. A2. Generic seat rig without lower leg support, buckle side, upright seating position.

TABLE AII
THOR-50M IN UPRIGHT SEATING POSITION

	Fixed to sled #1	Fixed to sled #2	Passive STLL #1	Passive STLL #2	Active STLL #1	Active STLL #2
H-point (x)	-190 mm	-188 mm	-188 mm	-187 mm	-187 mm	-187 mm
H-point (z)	305 mm	303 mm	302 mm	302 mm	302 mm	301 mm
Head angle	-1°	-2°	-2°	-2°	-3°	-2°
Neck angle	1°	0°	0°	0°	0°	0°
Chest angle	22°	22°	23°	22°	22°	22°
Lumbar angle	33°	32°	33°	32°	33°	32°
Pelvis angle	34°	34°	34°	34°	34°	34°
Femur angle	15°	15°	15°	16°	16°	16°
Lower leg angle	55°	56°	56°	55°	55°	56°
Foot to foot	230 mm	230 mm	230 mm	230 mm	230 mm	230 mm
Knee to knee	230 mm	230 mm	230 mm	230 mm	230 mm	230 mm
Belt to chin in sagittal plane	120 mm	120 mm	120 mm	120 mm	120 mm	120 mm

TABLE AIII
TEST RIG DIMENSIONS RECLINED SEATING POSITION

	X [mm]	Y [mm]	Z [mm]
Generic seat rig pivot point	0	0	0
Seat pan pivot point	-113	-130	126
Anti-submarining ramp pivot point	-373	-87	150
Shoulder belt retractor bolt	194	-52	62
Belt guide bolt	490	-25	694
Lap belt retractor bolt	-87	-3	35
Buckle bolt	-92	-508	34
Centre of webbing at tongue (buckle)	-120	-445	299
Floor plane			-44
Seat pan angle		15°	
Anti-submarining ramp angle		30°	
Seat back angle		45°	

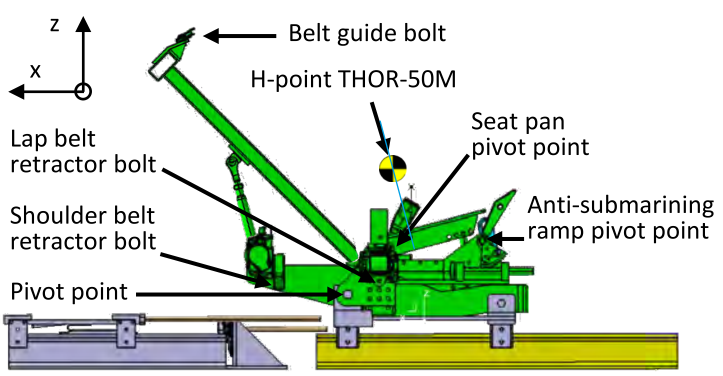

Fig. A3. Generic seat rig without lower leg support, lap belt retractor side, reclined seating position.

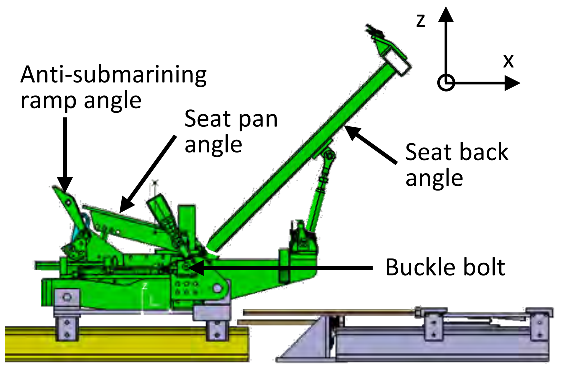

Fig. A4. Generic seat rig without lower leg support, buckle side, reclined seating position.

TABLE AIV
THOR-50M IN RECLINED SEATING POSITION

	Fixed to sled #1	Fixed to sled #2	Passive STLL #1	Passive STLL #2	Active STLL #1	Active STLL #2
H-point (x)	-173 mm	-173 mm	-173 mm	-174 mm	-172 mm	-173 mm
H-point (z)	302 mm	302 mm	304 mm	303 mm	303 mm	303 mm
Head angle	27°	28°	28°	28°	28°	28°
Neck angle	27°	28°	28°	57°	28°	28°
Chest angle	46°	47°	47°	47°	47°	47°
Lumbar angle	57°	58°	57°	58°	58°	58°
Pelvis angle	49°	48°	48°	49°	48°	48°
Femur angle	16°	16°	15°	16°	16°	16°
Lower leg angle	56°	56°	54°	56°	55°	55°
Foot to foot	230 mm	230 mm	230 mm	230 mm	230 mm	230 mm
Knee to knee	230 mm	230 mm	230 mm	230 mm	230 mm	230 mm
Belt to chin in sagittal plane	120 mm	120 mm	120 mm	120 mm	120 mm	120 mm

TABLE AV
TEST RIG DIMENSIONS RELAXED SEATING POSITION

	X [mm]	Y [mm]	Z [mm]
Generic seat rig pivot point	0	0	0
Seat pan pivot point	-63	-131	158
Anti-submarining ramp pivot point	-300	-90	269
Shoulder belt retractor bolt	204	-52	-7
Belt guide bolt	653	-23	547
Lap belt retractor bolt	-69	-4	64
Buckle bolt	-71	-513	65
Centre of webbing at tongue (buckle)	-29	-443	326
Seat pan angle		35°	
Anti-submarining ramp		50°	
Seat back angle		60°	
Lower leg support angle		15°	

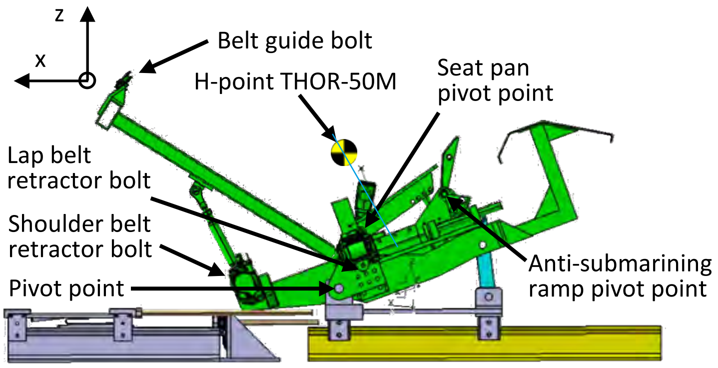

Fig. A5. Generic seat rig with lower leg support, lap belt retractor side, relaxed seating position.

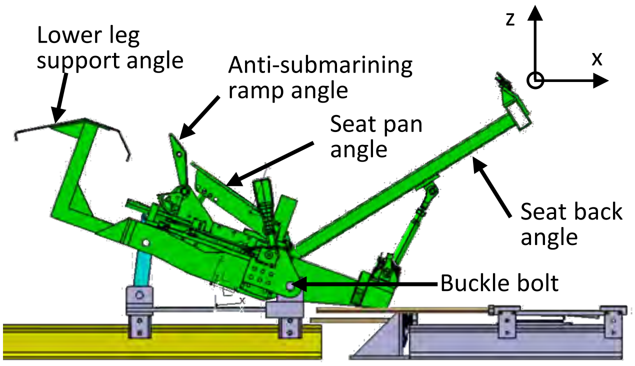

Fig. A6. Generic seat rig with lower leg support, buckle side, relaxed seating position.

TABLE AVI
THOR-50M IN RELAXED SEATING POSITION

	Fixed to sled #1	Fixed to sled #2	Passive STLL #1	Passive STLL #2	Active STLL #1	Active STLL #2
H-point (x)	-69 mm	-69 mm	-69 mm	-70 mm	-69 mm	-69 mm
H-point (z)	350 mm	349 mm	349 mm	348 mm	348 mm	347 mm
Head angle	46°	46°	46°	47°	46°	46°
Neck angle	46°	45°	44°	44°	45°	44°
Chest angle	63°	63°	62°	61°	62°	63°
Lumbar angle	74°	75°	73°	72°	73°	75°
Pelvis angle	63°	63°	62°	62°	62°	63°
Femur angle	38°	39°	37°	35°	37°	38°
Lower leg angle	30°	30°	26°	24°	27°	27°
Foot to foot	225 mm	225 mm	225 mm	225 mm	225 mm	225 mm
Knee to knee	225 mm	225 mm	225 mm	225 mm	225 mm	225 mm
Belt to chin in sagittal plane	120 mm	120 mm	120 mm	120 mm	120 mm	120 mm

TABLE AVII
SENSORS USED IN THE GENERIC SEAT RIG

Sensor type	Manufacturer	Model
Webbing load cells	Messring	DK11-35-23
String potentiometers	Space Age	160-1615-C8U9
Webbing payout sensor	IES	IES-2098
Load cells	Load Indicator	M16-30

TABLE AVIII
SENSORS USED IN THOR-50M

Sensor type	Manufacturer	Model
Accelerometers (head, spine and pelvis)	Endevco	7264C-2000
Angular rate head, chest and pelvis	Diversified Technical Systems, Inc	ARS PRO-18K DTS
Upper neck load cell	Humanetics	10380 JI4
Lumbar spine load cell (T12)	Humanetics	10415 JS1I4
IR-TRACCS (Chest and abdomen)	Humanetics	9945
ASIS load cells	Humanetics	10387 JS1I4

TABLE AIX
THOR-50M CRITERIA, HIGHER AND LOWER LIMIT VALUES USED IN EURO NCAP ASSESSMENT PROTOCOL [32]

Body region	Criteria	Higher limit	Lower limit
Head	Head HIC15	500	700
Head	Head Resultant Acc 3msec exceedance [g]	72	80
Neck	Shear Force [kN]	1.9	3.1
Neck	Tension Force [kN]	2.7	3.3
Neck	Extension moment [Nm]	42	57
Chest	Max Compression of all 4 ribs [mm]	35	60
Abdomen	Max Compression (left or right) [mm]	N/A	88