Passenger Kinematics in Reclined Sitting Position in Braking and Steering Manoeuvres

Kirschbichler S., Klein C., Breitfuss D., Steidl T., Pucher J., Aleksandra Krajnc, Lucas Iacono

Abstract This study investigates the kinematics of vehicle occupants on the passenger seat in reclined and upright seated positions. Thirty-nine volunteers (12 female and 27 male) were tested in 30 kph and 50 kph braking and steering manoeuvres. Eleven manoeuvres were conducted with each volunteer in aware and unaware states. A sedan modified with a belt integrated seat was used. The kinematics was recorded with a video-based system and (additionally) with acceleration / angular velocity sensors. Interaction with the seat was measured with pressure mats and the muscle activity was recorded in the upper body and in the lower body muscles. This publication focuses on the occupant kinematics and its processing with linear mathematical model. Kinematics and respective corridors are predicted for certain age, gender, and anthropometric data.

Keywords Braking and steering manoeuvre, occupant kinematics, reclined sitting position, volunteer study.

I. INTRODUCTION

Prior to a crash event, a pre-crash activity like braking or steering is conducted by the drivers in up to 50% of the cases [1]. The resulting occupant kinematics during the pre-crash phase influences the occupant kinematics during the in-crash phase [2] and moreover the injury risk [3-5]. Therefore, it is necessary to determine the pre-crash kinematics of occupants in braking and steering manoeuvres.

Several studies which have published the occupant kinematics in pre-crash manoeuvres can be found in literature [6-10]. In all mentioned studies, adult females and males were tested. Reference [6]-[9] conducted the tests in an upright seated position, [10] additionally tested in a reclined seated position. The determined data consider occupant kinematics and vehicle dynamics [7][10], and additionally muscle activity in [6][8][9]. Manually driven cars were used in [6][10], whereas [7-9] used steering robots or automated vehicle functions for a better repeatability.

To analyse the gained occupant kinematic data, the average excursion together with corridors (based on the quantiles) can be directly calculated from the data of the volunteer study as done in [6][8][9]. Alternatively, a principal component analysis together with a linear regression model was applied to the data in [7][10]. This method allows prediction of the occupant kinematics based on their anthropometric characteristics and gender.

With the upcoming possibilities for new seated postures due to automated driving, reclined seated postures are gaining focus in vehicle safety assessments. To enable reclined sitting without a huge belt slack, i.e. seat integrated belts might be used. Hence, this must be considered in pre-crash simulations, which requires data of the volunteers in such an environment.

FE Human Body Models (HBMs) are capable of simulating the pre-crash phase with active muscles [11]. To enhance this possibility also to reclined positions, the determination of muscle activity is also necessary in this posture.

The objective of the investigation was, to determine occupant kinematics, relevant vehicle data, contact forces to the seat and muscle activity in pre-crash scenarios with female and male volunteers in upright and reclined seated positions on the co-driver side. This publication focuses on the comparison of the occupant kinematics by using mathematical prediction models for their kinematics. An automated vehicle was used to achieve high accuracy in manoeuvre repeatability. Moreover, a seat with a seat integrated belt was mounted to the vehicle to minimise the belt slack in reclined seated postures.

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II. METHODS

Experimental Setup

A Ford Mondeo (year of production: 2017) was selected as the test vehicle for this study. To enable the recording and tracking of GPS trajectories, an extended drive-by-wire kit was obtained. By leveraging this technology in conjunction with a developed fault injection method it is possible to generate highly dynamic driving manoeuvres that can be reproduced with a high degree of accuracy [12]. Manoeuvres are initialized at specific GPS coordinates and are further conducted autonomous to a certain point (steering) or to the stand still (braking). In the steering manoeuvres, the driver takes over prior to the maximum excursion of the vehicle. The driver is not the occupant to be investigated in this study. To ensure optimal interaction with the seat belt system while in a strongly reclined seated position, a seat with an integrated belt system from the front right passenger seat of a Ford B-Max (year of production: 2014) was mounted. The study was conducted at a multilane test track without any signs or markings on the ground which would indicate the type or the initialization of the manoeuvre. (Fig. 1).

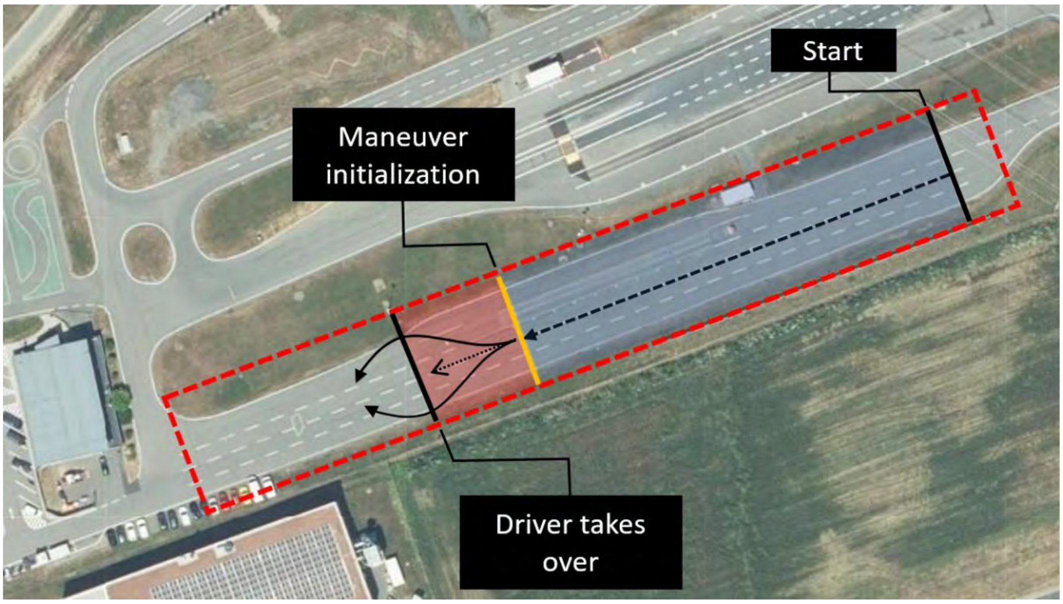

Fig. 1. Test site with schematic sequence.

Subjects

Thirty-nine volunteers, consisting of 12 women and 27 men participated in the study and are included in the evaluation. Before the volunteers entered the test vehicle, they were measured according to Table I. Their average age, weight, and height, as well as their standard deviation are shown.

TABLE I
VOLUNTEER AVERAGE (STANDARD DEVIATION) AGE AND PHYSIQUE.

	Females	*Males*
No.	12	27
Age [years]	35.5 (7.5)	36.2 (8.9)
Height [cm]	166.9 (4.4)	178.2 (6.4)
Weight [kg]	63.7 (6.2)	80.1 (10.2)

Additional anthropometry measures were recorded for the knee height, trochanter height, shoulder height, length of the collarbone, and distance from the body centre to the collarbone were measured (see Appendix A). Prior to the experiment execution, volunteers were asked to perform several overreaching isometric exercises using objects available on the test track to measure maximum voluntary contraction (MVC) of the four upper-body and six lower-body muscles of each individual participant. Muscle activity of each participant was defined as muscle contraction relative to the individual MVC (i.e. % MVC).

Next, the volunteers were seated in the front passenger seat of the vehicle. The feet were positioned on the ramped part of the footwell with the heel touching the lower edge (Fig. 2). The x-position of the seat was adjusted to get contact between the femur and the seat. The head should touch the head restraint and volunteers were asked to look forward with a comfortable head angle, to avoid any unnatural tensions in the neck. The belt was pulled out completely after the volunteers were seated in the vehicle to guarantee similar and reproducible boundary conditions for every participant.

Fig. 2. Positioned volunteer in reclined seat.

The documented anatomical landmarks include the longitudinal position of the seat in relation to the seat rail, the positions of the heel, knee, and trochanter in relation to interior markers, and the position of the seat belt in relation to the collarbone (body centre). The angles measured include the opening angle of the shoulder belt to the lap belt at the D-anchor, the angle of the upper leg in relation to horizontal, the opening angle of the upper- to lower leg, the Frankfurt plan angle of the head in relation to horizontal, and the knee distance with the centre of the kneecap as a reference point. The measurements described are shown in Appendix B. Recording of all measured data is initiated at the same time by an external trigger (button).

Manoeuvres

The study conducted several manoeuvres, including left and right turns and braking. The manoeuvres were performed at a speed of 50 kph and 30 kph (braking only), with a backrest angle of either 48 ° or 24 °, and the volunteers were either in an unaware or in an aware state. For the unaware state, the volunteers were not specifically distracted, but were not informed which manoeuvre will be conducted. Therefore, the unaware manoeuvres were the first ones for every volunteer and each of the manoeuvre types (braking, steering left, steering right) is conducted uniquely in the unaware state. During the preparation of the volunteers for the test, it was considered that volunteers don't recognise any of the conducted manoeuvres or any section of the test track. Overall, eleven different manoeuvres were performed with each volunteer (Table 2). The manoeuvres were conducted in this order for every volunteer.

TABLE II

PERFORMED MANOEUVRES WITH SPEED, BACKREST ANGLE AND STATUS.

#	*Event*	*Speed*	*Backrest angle*	*State*
1	Left turn	50 kph	48 °	unaware
2	Right turn	50 kph	48 °	unaware
3	Braking	50 kph	48 °	unaware
4	Left turn	50 kph	48 °	aware
5	Right turn	50 kph	48 °	aware
6	Braking	50 kph	48 °	aware
7	Braking	30 kph	48 °	aware
8	Braking	30 kph	24 °	aware
9	Left turn	50 kph	24 °	aware
10	Right turn	50 kph	24 °	aware
11	Braking	50 kph	24 °	aware

Instrument Data

The study utilised various measurement technologies to collect data during the test. The data of the vehicle was obtained by reading the CAN-BUS signals, including longitudinal, lateral, and vertical accelerations, as well as the steering angle, brake power, and vehicle speed.

To determine the kinematics of the occupants, two systems were utilised. A Microsoft® Kinect Azure camera, which uses advanced depth-sensing technology, captured 3D motion data of the occupants, allowing for accurate measurement of body position and movement. The inertial sensors (TEA® Captiv Motion), on the other hand, provided data on the angular and linear acceleration of the body segments to which they were attached, enabling calculation of joint angles and velocity and serves as assistance to the higher weighted Kinect measurement. The weight distribution of the volunteer on the seat was recorded using pressure mats (XSensor®), which were placed on the seat cushion and backrest.

Additionally, the muscle activity in the lower and upper body was being measured using a wearable fitness technology, i.e. athletic compression shorts/leggings and shirt with integrated surface electromyography (EMG) electrodes (Athos®, Redwood City, CA, USA). The following muscles were covered: hamstrings (biceps femoris), outer quadriceps (vastus lateralis), inner quadriceps (vastus medialis), and glutes (gluteus maximus), pecs (pectoralis major), triceps, biceps, shoulders (deltoid), upper back (trapezius), and lower back (latissimus dorsi). The data of the muscle measurement will be analysed in a future publication.

Method for statistical analysis of volunteer kinematics (kinematic prediction model)

For each manoeuvre a mathematical model (Fig. 3) has been computed, which allows the prediction of head and thoracic excursion angles for a selected age, gender and anthropometry. The model has been trained and tested by using the occupant kinematic data from the study. The used method follows the steps presented in [10].

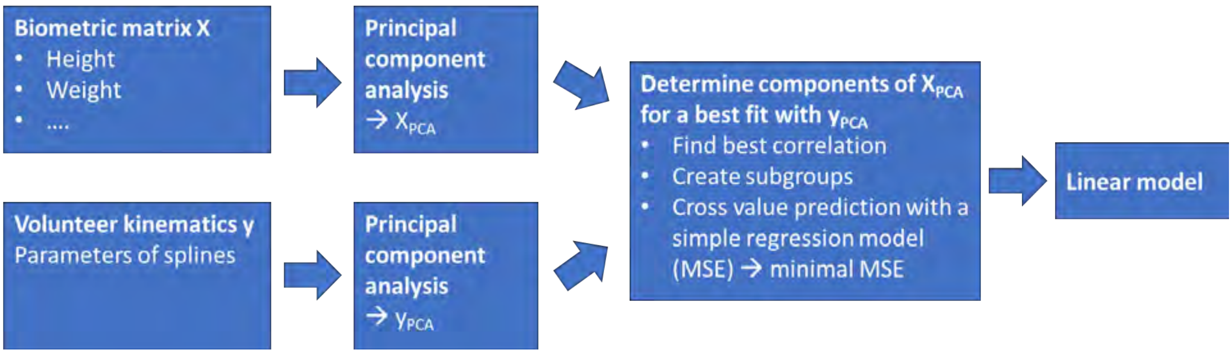

Fig. 3. Definition of a linear model to predict occupant kinematics.

At first, a biometric matrix X is defined: Anatomical distances as well as age and gender from all volunteers define the biometric matrix X. Moreover, products and quadratic combinations of the biometric matrix are added. Next, the principal component matrix (X_{PCA}) of X is calculated.

Secondly, occupant response with parameters are depicted: The occupant responses for head and thorax (angle over time) are approximated with cubic splines. For every manoeuvre and every volunteer, the parameters which characterize the spline define the occupant response vector y. Next, a principal component analysis is done (y_{PCA}).

Thirdly, the linear model is defined. Therefore, the correlations (Pearson correlation) between X_{PCA} and the current y_{PCA} vector are calculated. Next, it is determined, how many and which *components* of X_{PCA} are necessary for the linear model. This is done in three steps: Sort X_{PCA} by best correlation to get X_{sort} . Create subgroups (X_{sub}) of X_{sort} . Do a cross value prediction using X_{sub} and y_{PCA} and get the mean squared error (MSE) using a simple regression model. With that, the linear model (regression function) is then created by X_{Sub} that fits y_{PCA} best (minimised MSE)

Fourthly, the occupant kinematics is predicted: The biometric input data is used to calculate the parameters of the splines (head and thorax angle)

At last, the corridors (quantiles) are determined, by running a Monte Carlo Simulation with a set of 1000 randomized principal component matrices (X_{PCA}). The range is determined by the mean error of the regression function. Based on that, quantiles (5%, 25%, 50%, 75%, 95%) were computed.

III. RESULTS

The kinematic prediction model was used to determine the kinematics for male and female occupants Besides the gender and the age it requires certain anthropometric distances Therefore, the anthropometry of a Total Human Model for Safety version 3 (THUMS v3) (male) and VIVA (female) were used. Both were predicted for an age of 35 years. The age was chosen since this is the average age of the participating volunteers. The 50th percentile and the 25th and 75th percentile angles for head and torso were calculated and are shown in the diagrams in this paragraph. The upright seated position refers to a seat back angle of 24° and the reclined seated position to 48°. The thorax and head angles in this paragraph refer to the initial position of the respective body region. Fig. 4 shows the predicted kinematics (head angles, y-axis) in a 50 kph braking manoeuvre for THUMSv3 anthropometry and VIVA anthropometry, and the underlying kinematics of all volunteers. Note that the corridors provided in the figures demonstrate the prediction quality of the underlying model, which is (amongst other parameters) dependent on the numbers of volunteers. Therefore, the underlying volunteer kinematics are also documented for the demonstrated results either in this chapter or in the Appendix.

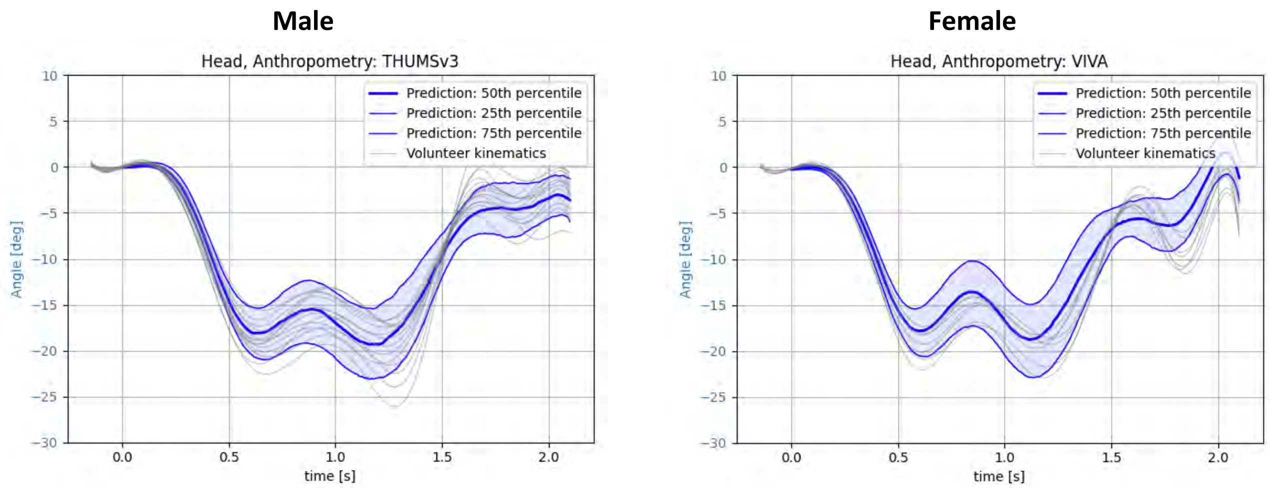

Fig. 4. Volunteer kinematics and predicted response corridors for males and females in a 30 kph braking manoeuvre in upright sitting position.

Fig. 5 shows the recorded vehicle accelerations for all conducted braking and steering manoeuvres. Due to the used equipment in the test vehicle a good repeatability of the accelerations for the first peak was achieved.

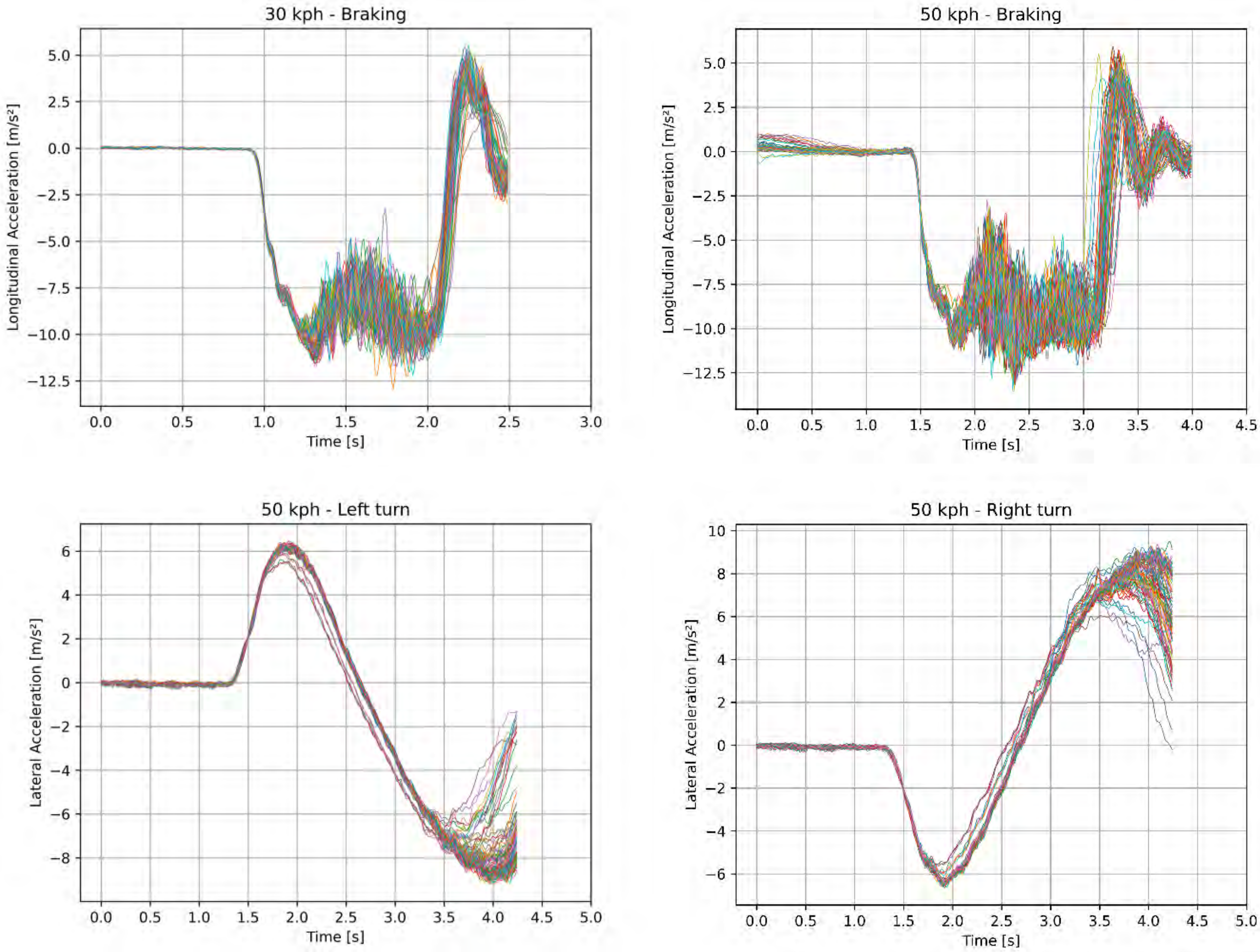

Fig. 5. Recorded vehicle accelerations for braking and steering manoeuvres.

Muscle activity

The activity of 10 muscle (groups) was recorded for 20 of the volunteers. Exemplarily, the activity of the upper back (deltoid) and the lower back (latissimus dorsi) muscles – expressed as % MVC – is shown in Fig. 6 for one participant in a 50 kph braking manoeuvre. A detailed analysis of the muscle activity will be given in a future publication.

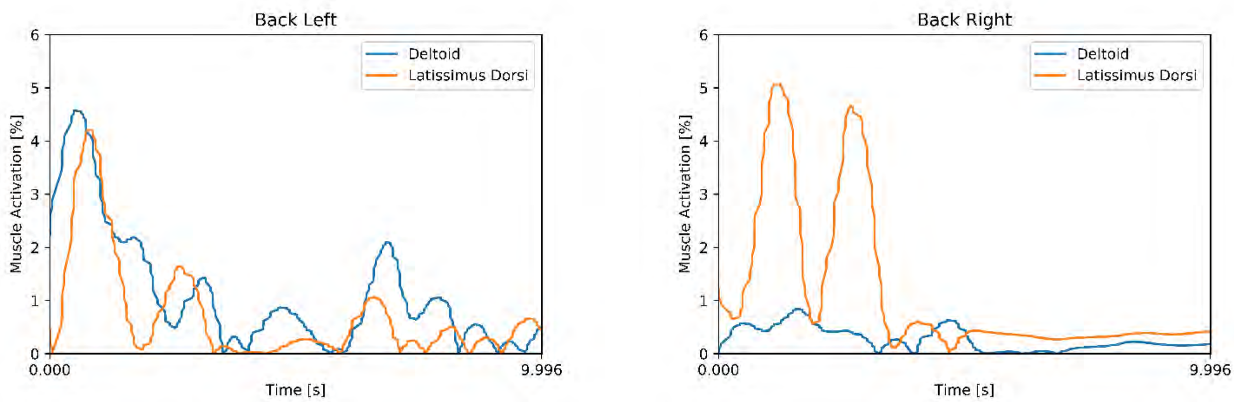

Fig. 6. Normalized muscle activity in the upper and lower back (left and right) of a volunteer in a 50 kph braking manoeuvres.

Predicted occupant kinematics: 30 kph Braking, upright vs. reclined

Fig. 7 shows the predicted head kinematics for males and females in a 30 kph braking manoeuvre for reclined and upright sitting positions. Further, the entire set of volunteer kinematics and the predicted corridors are shown.

For the male (THUMSv3) anthropometry setting, the relative head excursion is roughly the same for reclined and upright seated positions. For female (VIVA) anthropometry higher excursions are predicted in reclined seated position. A comparison of the original volunteer kinematics in Fig. 7 indicates, that the difference between male and females are rather low. The gradient of the first excursion is similar for all diagrams in Fig. 7. Furthermore, the time at which the forward motion is initialized is similar in all shown cases.

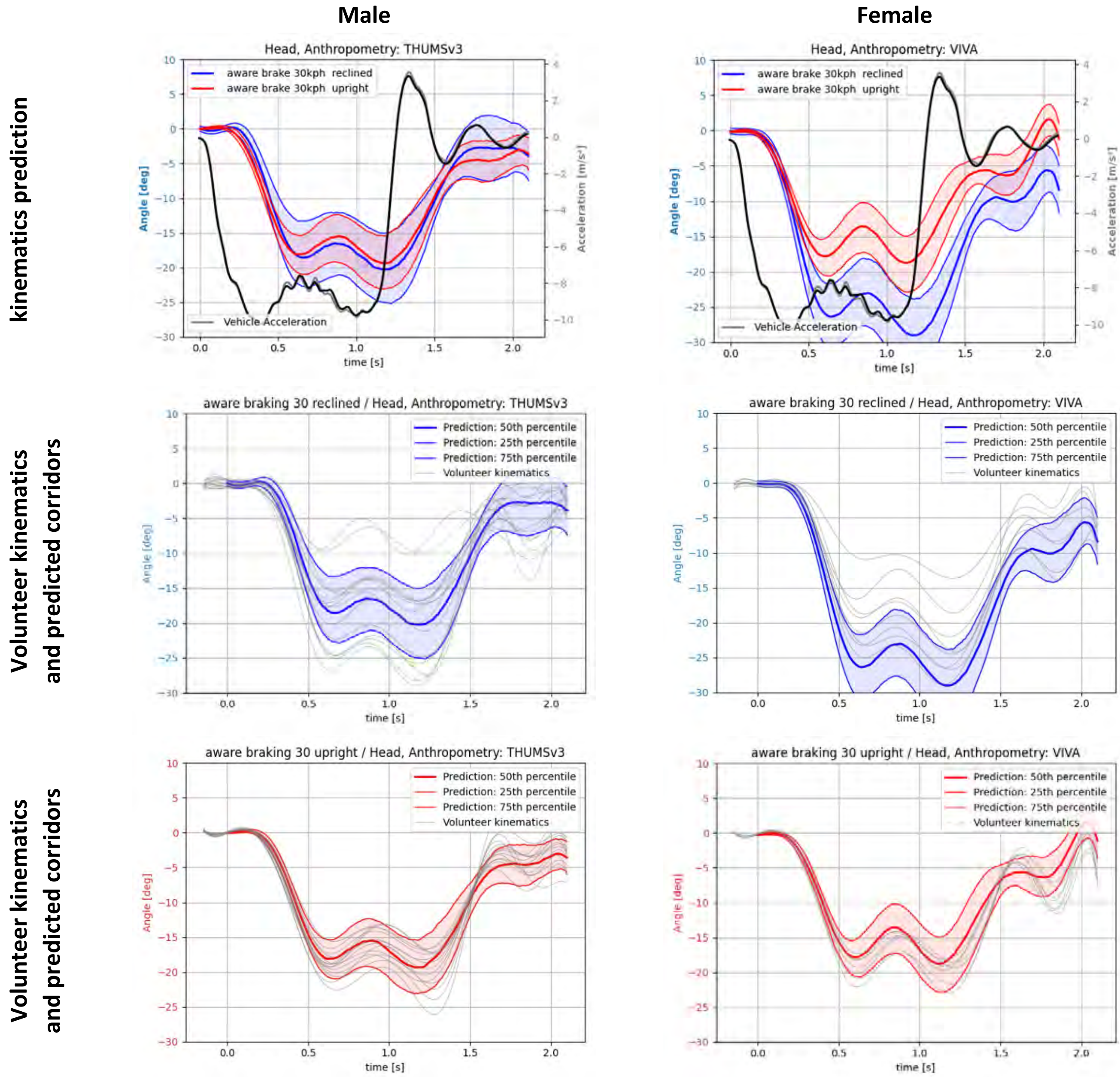

Fig. 7. Response corridors for the head (50th percentile +/- 25%) in 30 kph braking manoeuvres, reclined and upright seated positions and for male and female anthropometry.

As the torso kinematics (Fig. 8) is mostly controlled by the belt characteristics, the thorax excursion is lower than the head excursion. That is also reported in [13]. Note, that the used seat has a seat integrated belt which avoids huge belt slacks in case of reclined seated positions. The original volunteer data for the thorax excursion is documented in Appendix C.

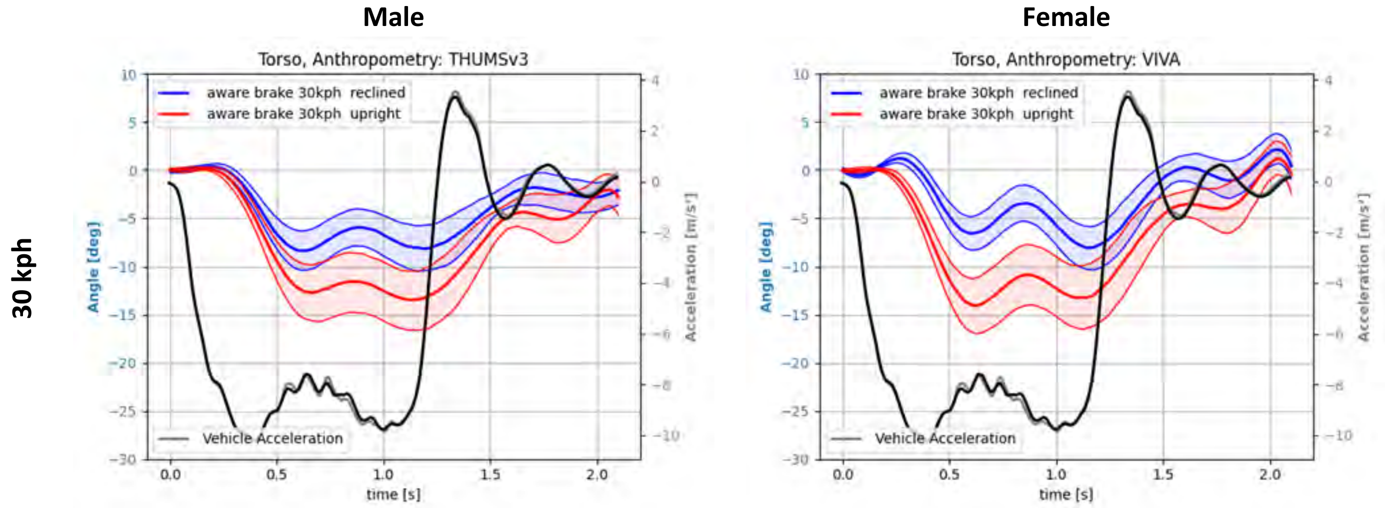

Fig. 8. Response corridors for the thorax (50th percentile +/- 25%) in 30 kph and 50 kph braking manoeuvres, reclined and upright seated positions and for male and female anthropometry.

Predicted occupant kinematics: Braking, 50 kph, reclined, male, aware vs. unaware

Fig. 9 shows a comparison for an aware and an unaware state in a 50 kph braking manoeuvre in a reclined sitting position for male occupants. The original volunteer kinematics data is reported in Appendix D. Female data are not compared since the prediction model shows a low quality for this case.

The forward excursion of the head is approximately 5° higher in the unaware state compared to the aware state as predicted by the mathematical model. Both curves are still in the +/-25% range of each other. A visual comparison of the underlying volunteer data (Appendix D) indicates that the difference between aware and unaware state is rather low. The thorax kinematics is similar for the aware and the unaware state since it is mainly influenced by the shoulder belt.

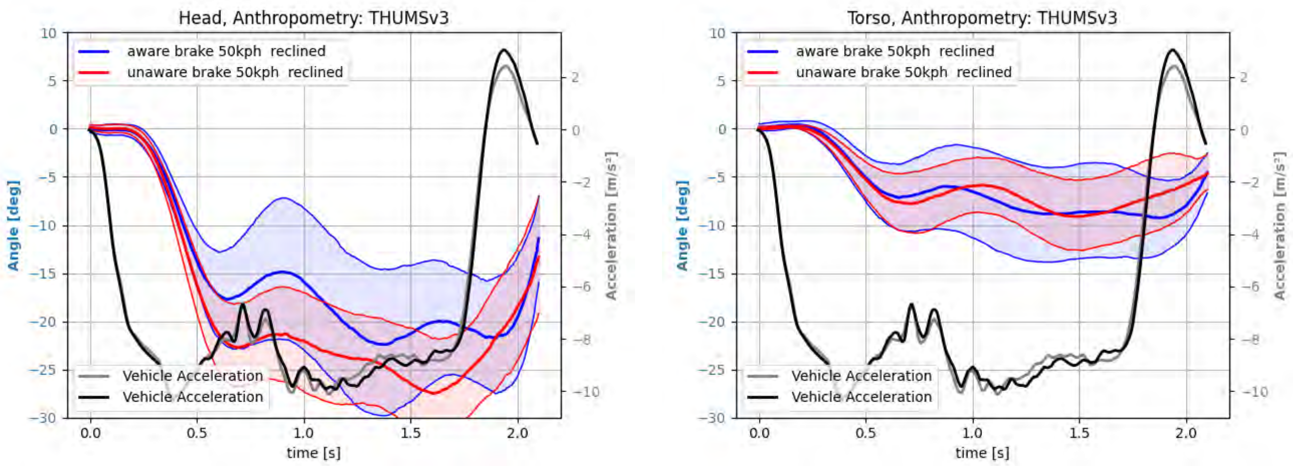

Fig. 9: Predicted response corridors for males in a 50kph braking maneuver in a reclined sitting position

Predicted occupant kinematics: Reclined sitting position, Steering left vs right

Generally, the head excursions (Fig. 10) in the conducted steering manoeuvres were rather low compared to the braking manoeuvres. A slight difference in the head kinematics can be observed between left and right steering. Volunteers tended to have a lower excursion in left turns, where they moved towards the B-Pillar. They seemed to avoid a possible contact with the B-Pillar, as also reported in [6][13] for upright seated positions. Further, the differences between male and female volunteers were low compared to braking manoeuvres. That is also reported for upright seated positions by [14].

The volunteer data together with the predicted corridors can be found in the Appendix E.

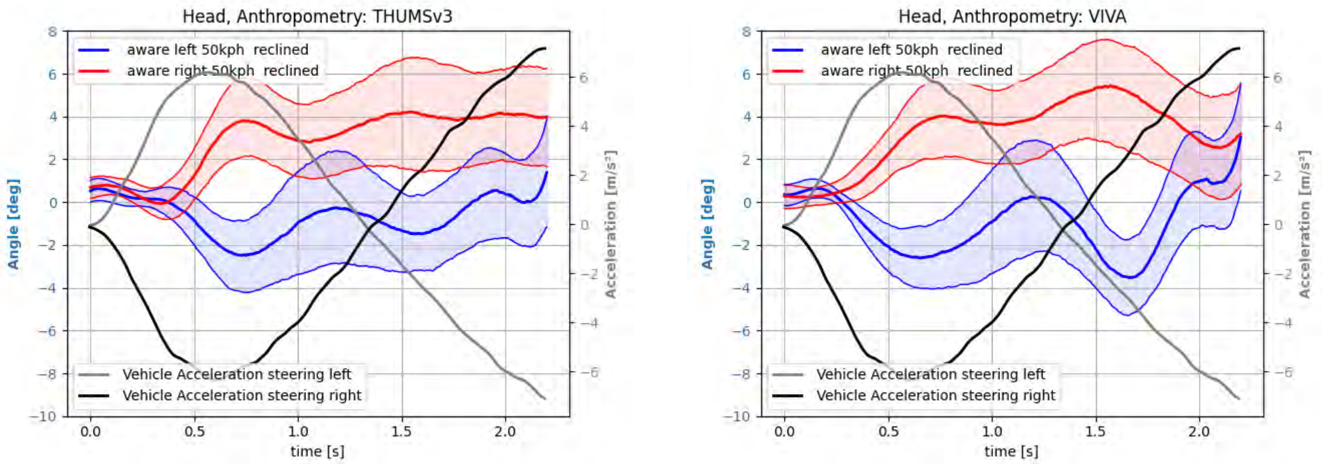

Fig. 10. Response corridors for left and right steering manoeuvres in reclined sitting position for head.

Thoracic kinematics (Fig. 10) is low for the male volunteers (< 1°) in reclined seated positions. For the female volunteers, the excursion in steering manoeuvres to the left shows slightly higher excursion of ~ 3°. The corridors for the thorax kinematics are wide compared to the predicted 50% curve. Therefore, the +/- 25% corridors include 0 ° excursion axis most of the time.

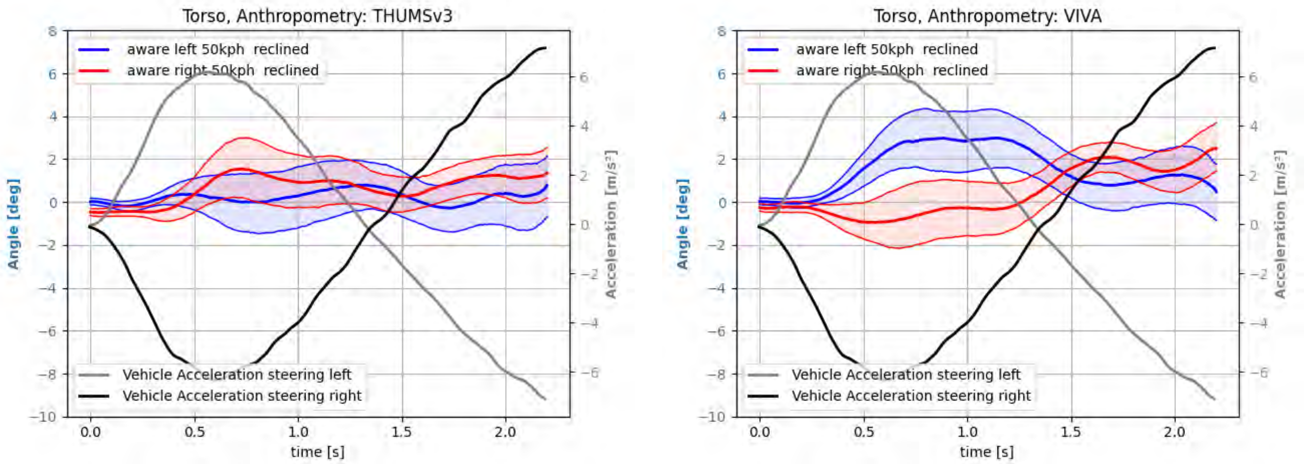

Fig. 11. Response corridors for left and right steering manoeuvres in the reclined seated position for torso.

IV. Discussion

For this study, 39 volunteers (12 female and 27 male) were tested, to determine the kinematic, muscle activity and environment interaction in braking and steering manoeuvres. This publication focuses on the occupant kinematics in reclined sitting position and the differences to an upright sitting position. Tests were done in aware and unaware states with 30 kph and 50 kph. The vehicle was equipped with a seat with an integrated belt to avoid unrealistic belt slacks in case of reclined seated positions. An automated vehicle was used, which allowed the repetition of the manoeuvres with high accuracy and guaranteed the same boundary conditions for every tested occupant. Muscle activity was measured with surface electromyography electrodes but was not further analysed in this publication.

The kinematics of the occupants was measured with a camera system and an inertial sensor system. It was observed that the camera system delivered more trustable results inside the vehicle. The inertial measurement system was used to have backup data, but they were not further analysed. The camera system was tested beforehand to ensure that it is mostly independent from light and weather conditions as it is reported in [9].

The chronological order of the conducted manoeuvres was the same for all volunteers, which should be adapted for upcoming studies to avoid nervousness in the earlier manoeuvres and learning effects in the later manoeuvres. Further, for testing the unaware status manoeuvres, the volunteers were not informed about the next manoeuvres, although they were not distracted specifically. To reach a natural state of awareness a specific distraction might be useful as e.g., in [15].

The set of volunteers had an average age of 35 years (male) and 36 years (female) with a standard deviation of 8.9 years (male) and 7.5 years (female), which resulted in a dataset for a rather young population.

To indicate the beginning of the measurement, a manual trigger signal was used for all included measurement systems. Hence, a few seconds of measured data are recorded before the braking of steering is indicated. For the data analysis, all the measured data are trimmed based on a certain acceleration level.

A mathematical model was built to analyse the kinematics and to predict expected excursions for certain anthropometries and gender. The quality of the predicted occupant kinematics was compared to the kinematics of all volunteers in the study. That was done by comparing the predicted corridors to the entire bunch of occupant kinematics. Manoeuvres with a low prediction quality were not further compared. The prediction quality was lower for the female datasets which might be caused by a smaller number of female volunteers. The kinematics was predicted for the anthropometry of a THUMS v3 HBM and a VIVA HBM. The anthropometric parameters which are required by the mathematical model are shown in Fig. 12. The parameter values of the HBMs (red) are mostly on the upper or lower bound of the anthropometries of the volunteers (grey) in this study. This issue can be solved by either using average parameter values for the kinematics prediction or (for future studies) aiming for a better-balanced group of volunteers in terms of anthropometric boundaries. The parametric boundaries for which the model predicts robust results in all manoeuvres need to be further investigated.

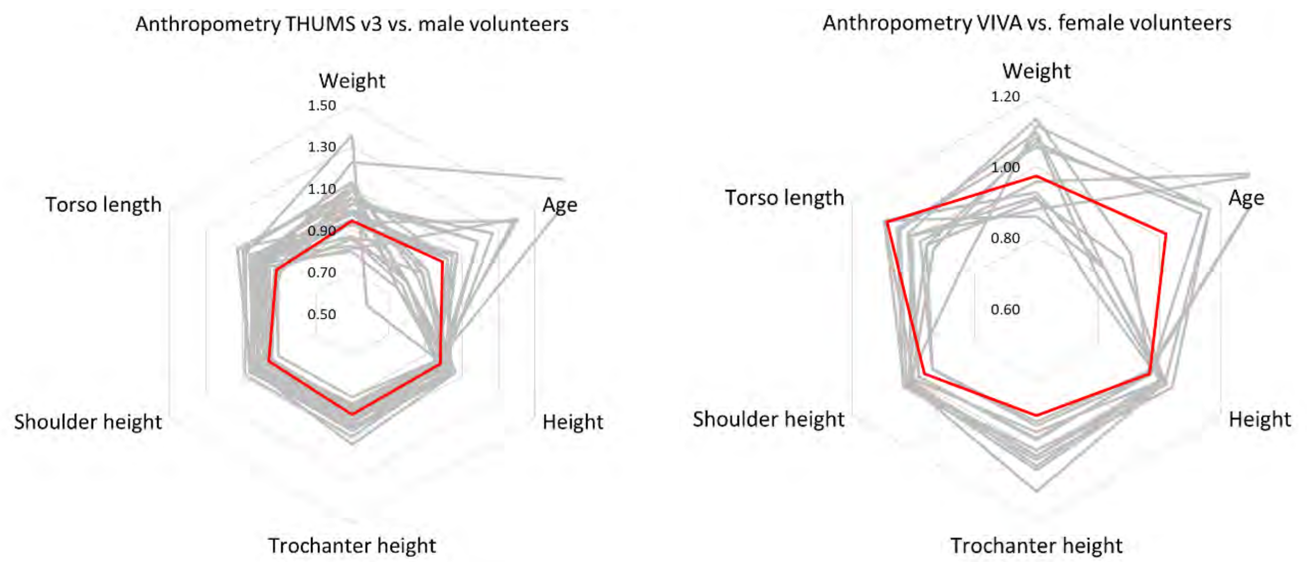

Fig. 12. Comparison of volunteer anthropometry and HBM anthropometry.

The kinematic comparison shows variability in the occupant kinematics, as this is also reported by [6] and [9]. The results of the kinematic comparison show, that in braking manoeuvres, the torso kinematics is dependent on the belt characteristics and is therefore rather low compared to the head kinematics. The maximum forward excursion of the head is similar for upright and reclined sitting position. Note, that the angle is measured related to the initial sitting position.

The comparison between aware and unaware state for males in a 30 kph braking manoeuvre in reclined sitting position showed, that the influence of the unaware state is higher according to the prediction model as it is according to the underlying volunteer data. Female data are not compared for this manoeuvre, as the quality of the kinematic prediction was low.

Differences in head kinematics between left and right steering (reclined seated position) can be observed both for males and females. There is a tendency that in left turns (occupant motion towards the B-Pillar) the excursion is lower than in right turns. The excursions for males and females in steering manoeuvres are similar. The torso kinematics in braking manoeuvres is rather low compared to the excursion for head.

V. CONCLUSIONS

To enhance occupant protection strategies in reclined sitting positions, the knowledge about occupant kinematics in pre-crash manoeuvres is required. In this study, the head and torso kinematics of 27 male and 12 female volunteers in reclined and upright sitting positions was quantified for braking and steering manoeuvres. To get more reliable results in future studies, the volunteers should be better balanced in terms of gender, age and anthropometric boundaries. The focus of the data analysis was on the effect of reclined sitting positions.

The data were used to develop mathematical models which predict the head and thorax kinematics based on anthropometric parameters. For some of the conducted manoeuvres the developed mathematical models do not show a sufficient prediction quality. Therefore, these manoeuvres were excluded from comparisons for this publication. For the demonstrated manoeuvres, the underlying kinematics of all volunteers and the predicted corridors are documented in the Appendix C-E. The robustness of the mathematical modelling approach should be improved for future studies. The predicted occupant responses were compared for 30 kph and 50 kph braking manoeuvre, 50 kph braking in reclined sitting position comparing aware and unaware state as well as steering in reclined sitting position comparing left and right steering.

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VIII. Appendix A

A. Anthropometric documentation

Fig. A1. Determination of height of knee, trochanter, shoulder with respect to the floor level. Collarbone is measured to the mid-sagittal plane.

B. Documentation of the sitting position in the vehicle

Fig. A2. Longitudinal position of the seat and position of the heel relative to the seat rail.

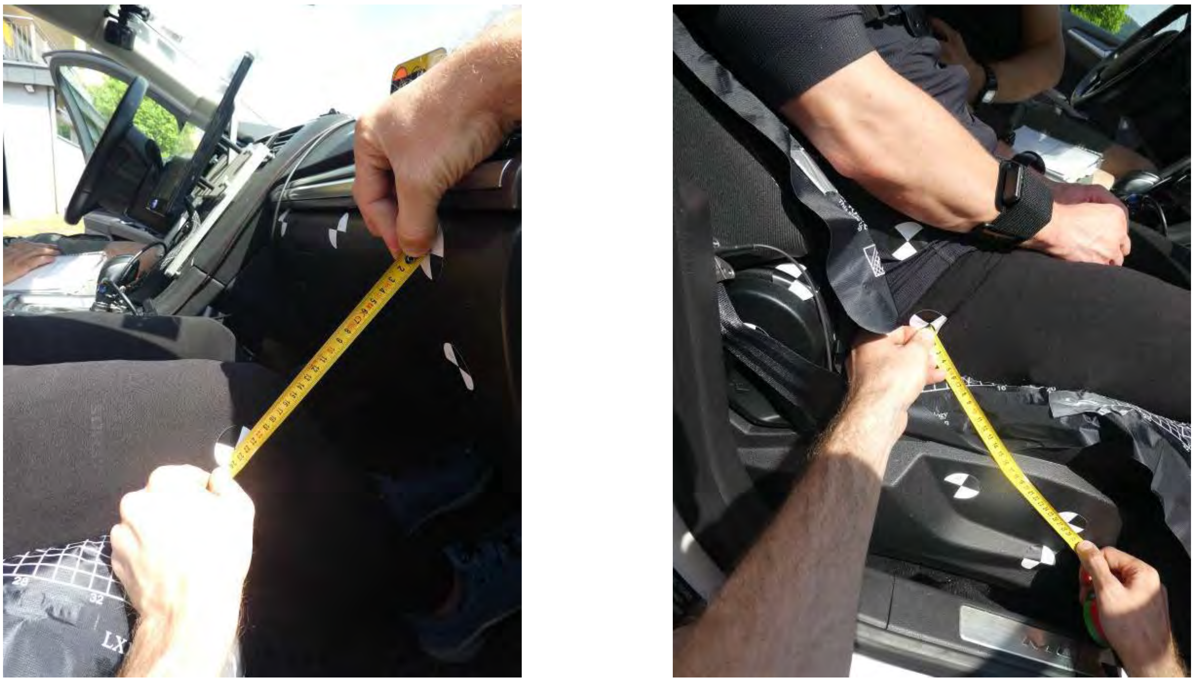


Fig. A3 Position of knee and trochanter relative to vehicle interior markers.

Fig. A4. Position of the seat belt in relation to the collar bone (body centre).

Fig. A5. Angle of the lap belt relative to the horizontal plane and angle of the upper leg relative to the horizontal plane.

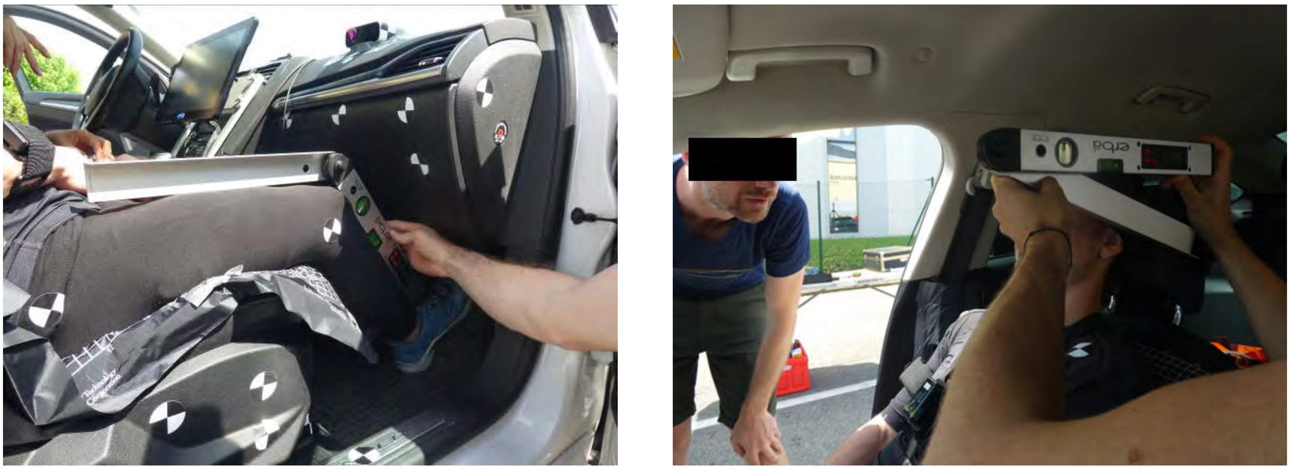
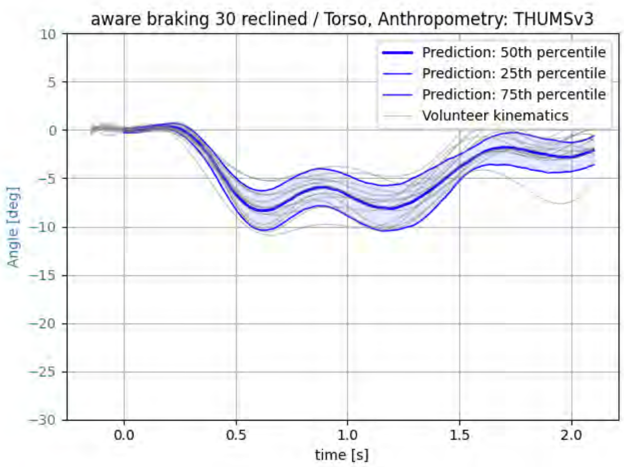


Fig. A6. Angle between upper / lower leg and angle of the Frankfurt plane.

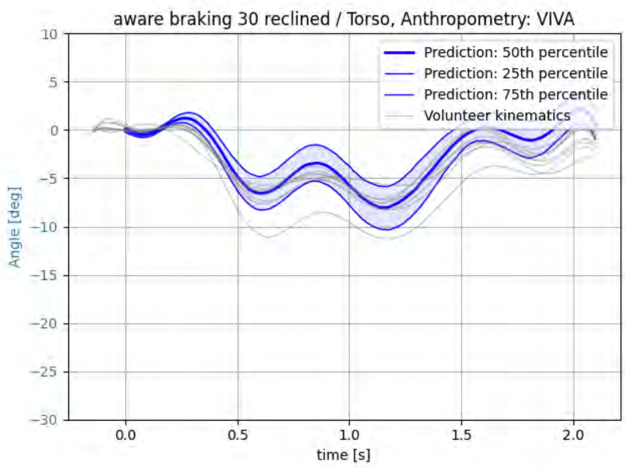
Fig. A7. Distance of the knees.

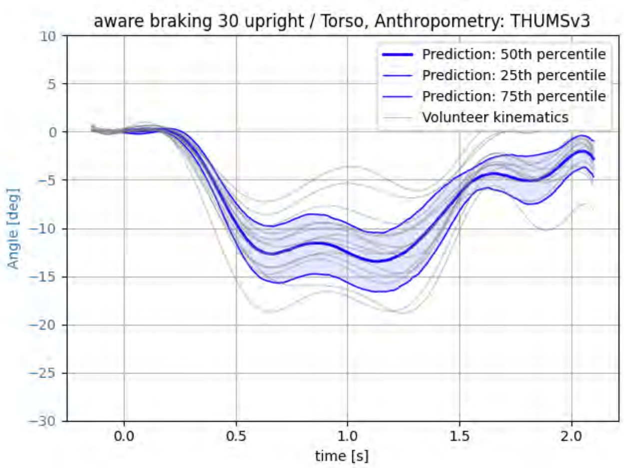
C. Volunteer kinematics and predicted corridors: Braking, 30 kph, reclined sitting position, aware, Torso angle

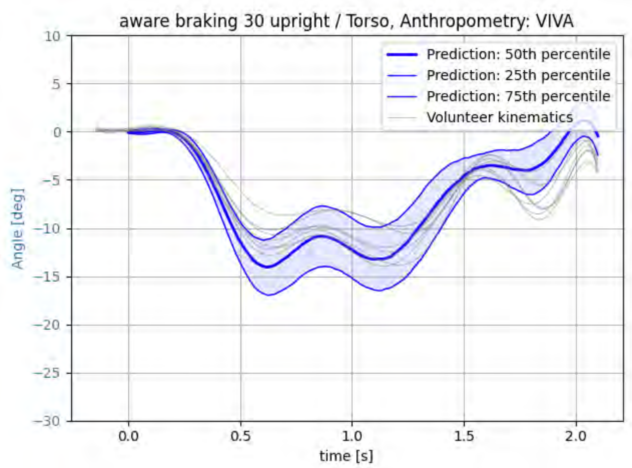
Male



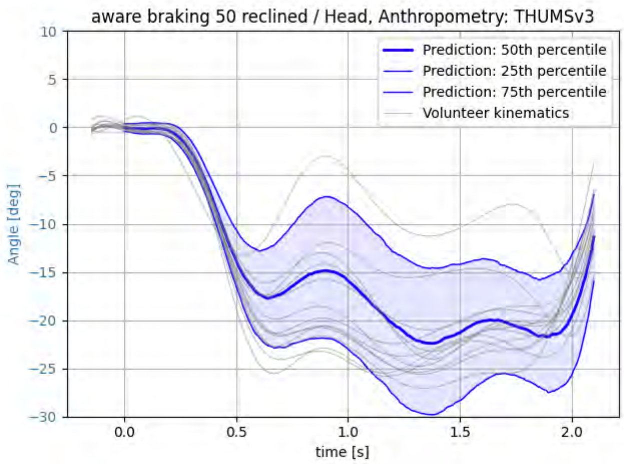
Female

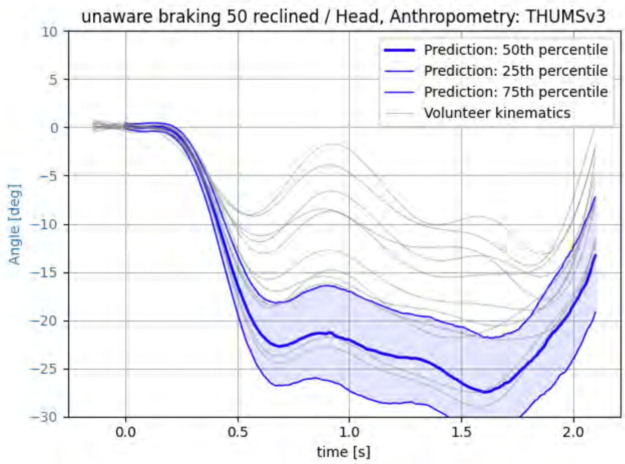


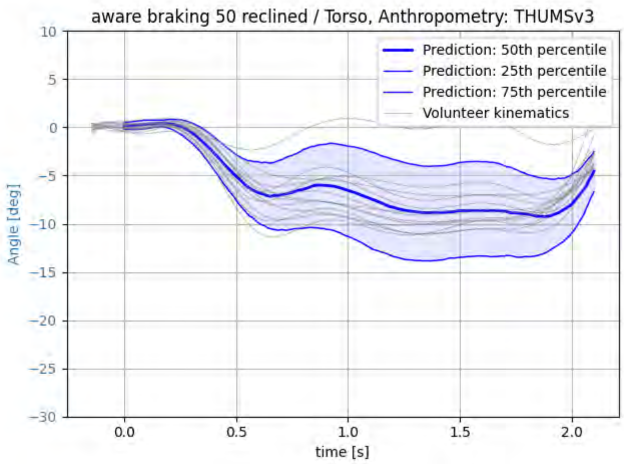


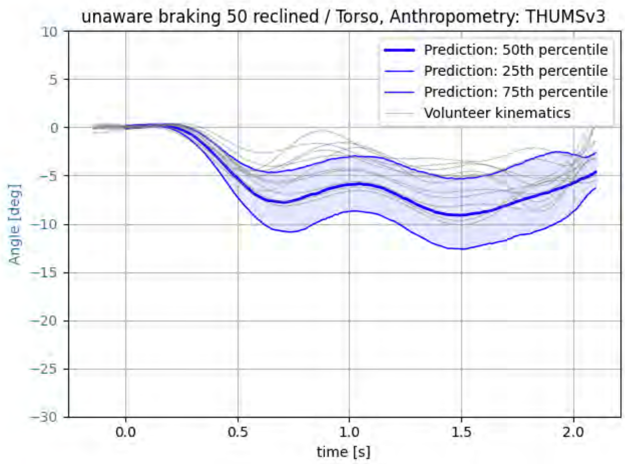


D. Volunteer kinematics and predicted corridors: Braking, 50 kph, reclined sitting position, male, aware vs. unaware



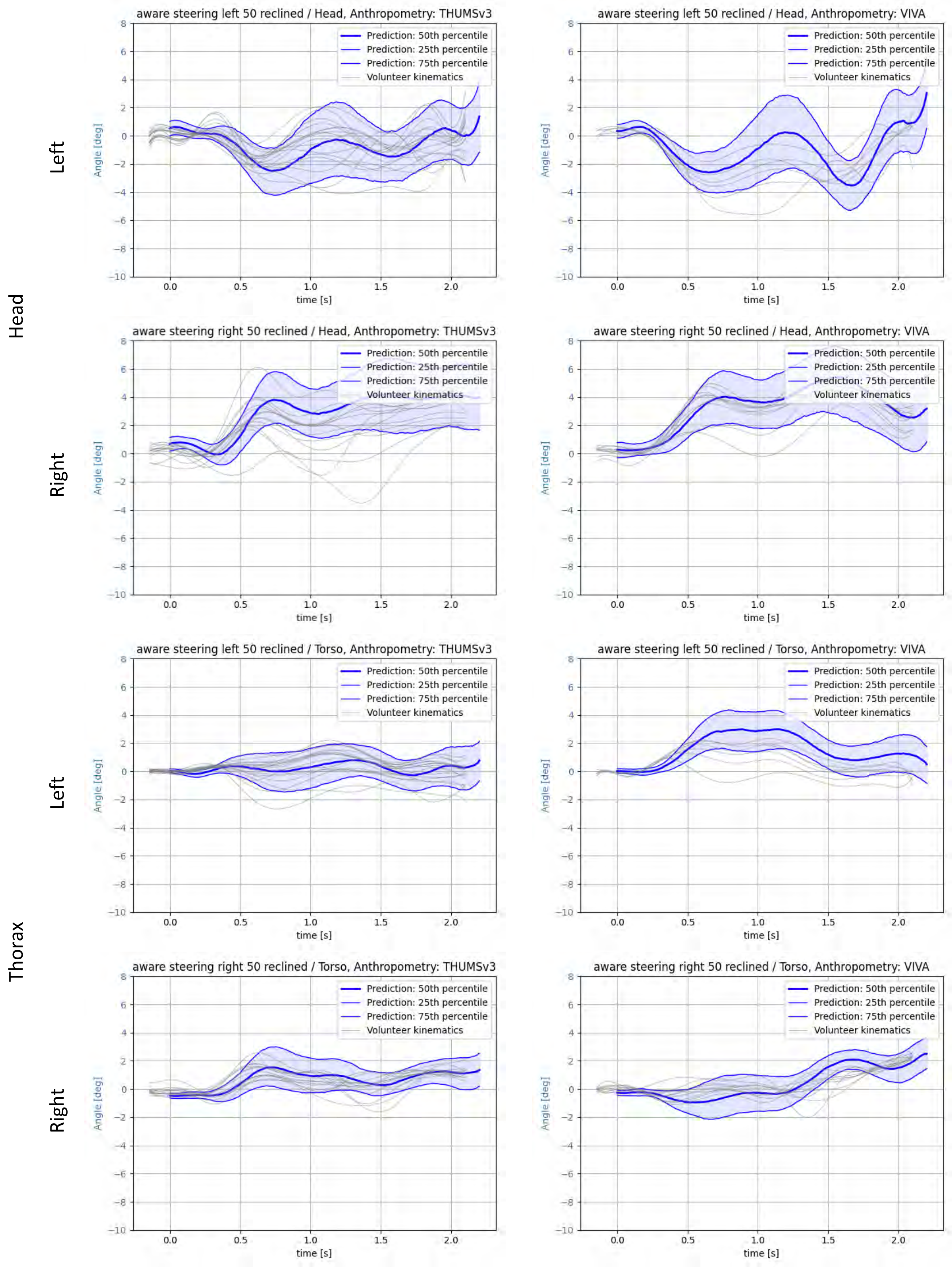






E. **Volunteer kinematics and predicted corridors:** ***Steering, 50 kph, aware, reclined sitting position***

Male Female


Head
Left
aware steering left 50 reclined / Head, Anthropometry: THUMSv3
aware steering left 50 reclined / Head, Anthropometry: VIVA
Right
aware steering right 50 reclined / Head, Anthropometry: THUMSv3
aware steering right 50 reclined / Head, Anthropometry: VIVA
Thorax
Left
aware steering left 50 reclined / Torso, Anthropometry: THUMSv3
aware steering left 50 reclined / Torso, Anthropometry: VIVA
Right
aware steering right 50 reclined / Torso, Anthropometry: THUMSv3
aware steering right 50 reclined / Torso, Anthropometry: VIVA
Prediction: 50th percentile
Prediction: 25th percentile
Prediction: 75th percentile
Volunteer kinematics
Angle [deg]
time [s]