Passenger Kinematics Variance in Different Vehicle Manoeuvres – Biomechanical Response Corridors Based on Principal Component Analysis

Emma Larsson, Ghazaleh Ghaffari, Johan Iraeus, Johan Davidsson

Abstract This study explores the influence of occupant characteristics and belt type on occupant kinematics in evasive manoeuvres and provides models for construction of response corridors. Data originated from evasive manoeuvres with male and female volunteers.

Principal component analysis and linear mixed models were used on selected data to create predictive models for kinematics and belt time histories, using belt configuration, sex, age, stature, and BMI as co-variates. Monte Carlo simulations of resulting models were used to generate upper and lower response corridor limits around the predicted responses.

For translational and rotational displacements of the head and the torso, the first three principal components together captured 91%-99% of the variance in the responses. Belt configuration, sex, age, stature, BMI, and their interaction effects were found statistically significant ($p < 0.05$) in the linear mixed model analysis in lane changes, braking and U-turns at 40 km/h but not in U-turns at 30 km/h or when aware of turn. Response corridors for average sex, stature and BMI, were provided.

In conclusion, the models and data provided can be used for validation of human body models with a range of anthropometries and in different manoeuvres and belt configurations potentially occurring in pre-crash manoeuvres.

Keywords Evasive manoeuvres, linear mixed model, occupant kinematics, principal component analysis, volunteer response corridors

I. INTRODUCTION

Evasive manoeuvres prior to a crash have been shown to alter the injury risk in a subsequent crash, either by changed posture or sitting position [1-3], or by changed state of muscle forces [4,5]. Since the events prior to a crash can affect the injury risk, there is a desire to understand the occupant response to the evasive manoeuvres, to accurately predict the occupant state when transitioning to a crash. Head and torso kinematics have been studied for evasive manoeuvres, such as braking or lane change, in several volunteer studies previously [6-18]. In these studies, large variability between the occupants have been found.

Traditionally, the average male has been used as norm in vehicle safety evaluation [19], but in recent years, efforts have been made to include larger portions of the population in vehicle safety evaluations, for instance by using morphable human body models (HBMs) [20-23]. These HBMs have so far mainly been evaluated in crash scenarios. To allow for use of these models in simulations of evasive manoeuvres as well, the HMBs are to be evaluated also in these manoeuvres. Hence, there is a need to understand if and how the time-history response to these manoeuvres varies with occupant characteristics, such as age, sex, stature and body mass index (BMI), and make data available for evaluations of HBMs with anthropometry representative of the population at risk in these manoeuvres.

There are only a few studies that have investigated the effect of occupant characteristics to occupant kinematics in evasive vehicle manoeuvres. One study [6] found that in braking manoeuvres, female occupants exhibited larger average forward excursion than males, taller occupants had larger average forward excursion than shorter occupants and passengers had larger average forward excursion than drivers, although no statistical analysis was performed to show significance of these differences. In that study, seat belt locking was also found influential in occupant kinematics. Another study [24], using analysis of variance (ANOVA), found that sex affected the maximum excursions in braking, but not in lane change. When omitting sex as a predictor, but keeping both sexes in the data set, stature was instead found to be a significant predictor for maximum excursion in braking.

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Also in that study, a significant difference in response was found between occupants restrained with a lap belt only and a three-point seat belt. In a large study [25], passenger BMI and age was found as significant predictors of maximum head forward excursions in harsh braking, and in lane change, stature was significantly related to lateral head excursion. All tests were performed with the same belt system and thus no effect from belt system was studied. Although these studies have all investigated occupant characteristics and response to vehicle manoeuvres, none of them have studied the time histories of occupant kinematics, only maximum or average excursion. To study the relationship between occupant characteristics and kinematics time histories, principal component analysis (PCA) together with linear regression was used to relate passenger seated height to head, spine and pelvis sagittal plane kinematics in low-speed and low-acceleration (<4g) frontal impacts [26]. In the study, it was found that occupants with larger seated heights had flatter trajectories and smaller excursions. Although this study performed an analysis of influence of occupant characteristics on kinematic time histories, the acceleration levels are higher than those in typical evasive manoeuvres, and it was limited to longitudinal acceleration of the volunteers.

The objective of this study was to investigate predictors for vehicle passenger kinematics, such as belt configuration, sex, age, stature and BMI, for different types of vehicle manoeuvres. Another objective of the study was to create and report kinematic corridors for selected combinations of predictors, to be made available for validation of active HBMs.

II. METHODS

To investigate predictors for passenger vehicle front row passenger kinematics and create associated corridors, several steps were carried out. Volunteer data was collected for a range of manoeuvres and resulting kinematics, belt forces and position were analysed. For each subject the kinematics and belt force data were processed, going from individual marker signals to head and torso kinematics. Next, a principal component analysis (PCA) was performed on the kinematic and belt force time-history curves to reduce the data. This data reduction allowed for a linear mixed model regression on the principal component (PC) scores, with sex, stature and BMI as co-variates. Finally, the regression models were used to create kinematics signals and corridors based on occupant characteristics and belt configuration. Each of the analysis steps is described more in detail below.

All data analysis was performed in MATLAB R2020b (The Mathworks Inc., Natick, MA, US).

Experimental Setup

The experimental setup has previously been described in detail in [16]. The study protocol was reviewed and approved by the Ethical Review Board at the University of Gothenburg, Sweden (Application 602-15). All tests were performed with a Volvo V60 (model year 2016) with leather upholstery seats, equipped with summer tyres (Continental Sport Contact 3 235/45/R17 inflated to 250 kPa). Volunteers were instructed to keep their feet on the provided foot support, keep their hands in their lap, look forward and relax. Between each test, the volunteers were instructed to pull out the entire belt length from the belt spool, and then release the belt and adjust it to a snug fit. All tests, except a manual U-turn, were performed without any prior announcement of the oncoming manoeuvre. For the manual U-turn, the volunteers were made aware of the manoeuvre approximately 15 s prior to manoeuvre initiation. During the tests, initial velocity and vehicle acceleration, seat belt force, seat belt position, foot-well force, and seat pan pressure distribution were recorded. Occupant movement was recorded using three video cameras, and kinematics was calculated by video marker tracking. Included in the analysis were tests where a full data set was available for the test, the volunteer was sitting still and looking forward prior to manoeuvre initiation and kinematics was available for the majority of test duration (maximum 20 frames missing). For full inclusion/exclusion criteria, see TABLE B. II in Appendix B.

Subjects

Twenty-one volunteers, consisting of nine males and 12 females, with age, stature and BMI averages, standard deviation (SD), and ranges according to TABLE I, were tested and included in the analysis. At the time of the test, all volunteers were healthy, without any known history of neck pain or other medical conditions that could present an increased risk for injury during the test series.

TABLE I
VOLUNTEER AGE AND ANTHROPOMETRIC MEASUREMENTS

	Female			Male		
	Minimum	Average (SD)	Maximum	Minimum	Average (SD)	Maximum
Age [years]	19	37.7 (13.1)	65	23	34.6 (15.5)	71
Stature [cm]	160	168.1 (5.8)	180	174	183.0 (6.1)	192
BMI [kg/m^2]	18	23.7 (5.5)	36	18	21.6 (1.7)	23

Instrument Data

The vehicle kinematics and seat belt forces and position, measured near the belt spool, were mainly processed as described in [16]. Marker movement, used to calculate kinematics, was recorded using three DS-CAM 600 cameras (DEWESoft d.o.o., Slovenia) connected to a SIRIUS SBOX computer via a CAM-BOX3 (DEWESoft d.o.o., Slovenia) using wide-angle lenses at 50 f/s with a resolution of 1280×1080. The cameras recorded front (focal length 6 mm), side (focal length 6 mm) and rear oblique (focal length 4.5 mm) views of the volunteer. Marker tracking was done with TEMA Automotive (Image Systems, Linköping, Sweden). Before maker tracking lens calibrations, a uniform coordinate system in all three camera views was defined. Initial vehicle velocity was previously reported as target velocity, while in this study it was collected from the CAN-bus. The vehicle acceleration data were smoothed using a 3rd-order Butterworth low-pass filter with 20 Hz cut-off frequency, and then compensated for vehicle angular accelerations to estimate mid-vehicle acceleration at approximately the occupant H-point height and fore-aft location. Belt forces and position were measured at 10 kHz, using two low load belt force sensors and an optical belt movement sensor, respectively. These were later down sampled to 1 kHz using time series resample in MATLAB.

Manoeuvres

The volunteers were exposed to a total of six different types of manoeuvres while seated in the passenger seat: lane change (L), lane change with braking (LB), braking (B), three different U turns with turning radius of approximately 13 m, (at 40 km/h (U) and at 30 km/h (U30) with robot steering, and at 40km/h with manual steering, where the volunteer was aware of the planned manoeuvre, (MU)). Lane change, lane change with braking and robot steered U-turn at 40km/h was performed with two seat belt configurations (standard (SB) and pre-pretensioned (PT) (activated at approximately 200 ms prior to vehicle manoeuvre, with a target force of 170 N [16])), braking with three seat belt configurations (SB, PT, and standard with belt slack (SBS)), and the remaining two manoeuvres with SB only. This resulted in 11 different test configurations, e.g., LSB for lane change and standard belt, with initial velocity and peak accelerations in TABLE A. I in Appendix A, and lateral and longitudinal accelerations in Fig. 1. Each combination of manoeuvre and belt configuration was repeated at least three times per volunteer, resulting in a minimum of 33 tests per volunteer while seated in the passenger seat, and a minimum of 63 tests per manoeuvre. The manoeuvres were randomized within two blocks. One block contained U-turns and the other one contained lane changes, braking and lane changes with braking. All manoeuvres, except MU, were performed with a driving robot to ensure high repeatability. The driving robot consisted of two servos [16]; one connected to the steering shaft, and one via a leveller to the brake pedal. The servos were connected to a control/power unit that was triggered by the main measurement system.

In addition to the tests in the passenger seat, presented in this study, volunteers were exposed to seven test conditions in the driver seat, also repeated a minimum of three times per volunteer, resulting in a minimum of 21 tests in the driver seat. Half of the volunteers were tested in the passenger seat first, and the other half were tested in the driver seat first.

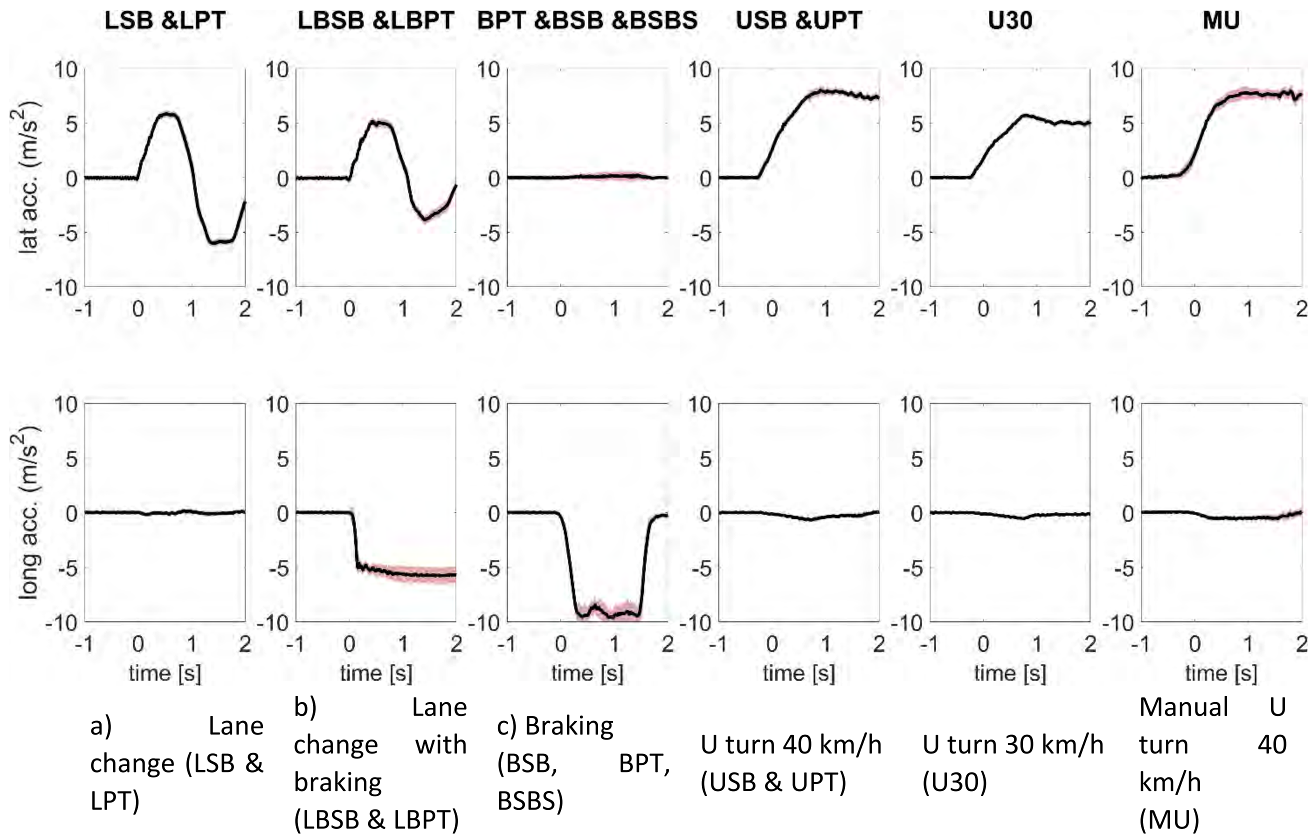


Fig. 1. Average lateral and longitudinal vehicle acceleration pulses [m/s^2] for the six different manoeuvres. Average acceleration in black and ±1 SD in red.

Kinematic Processing

The video tracked kinematic signals were processed as described in [16,17], with some small modifications. The tracking followed the procedure below.

1. Data availability was checked.
2. The signals of all available tests were synchronised using acceleration signals. t_0 was determined as first time of 55% of peak acceleration minus a time shift that is reported below. Peak lateral acceleration was used for lane change and U-turn manoeuvres, and longitudinal peak acceleration for braking manoeuvres. The time shift was 400ms for U-turn manoeuvres and 300ms for the other manoeuvres.
3. Quality control, tests were removed if markers were obscured or badly tracked, Appendix B, TABLE B II. Signals were repaired if markers were obscured for a short duration of the test.
4. For the head, translational kinematics from the left side of the head was used as baseline, because it was visible from all three camera views. Left side marker kinematics was transformed from that marker to the head centre of gravity (CoG) using a head rotation matrix and distance from that marker to head CoG [16]. The rotation matrix was calculated using Horns method [27,28]. For the rotation matrix calculation, 3-5 markers were used depending on relative distance between markers to omit badly tracked markers from the analysis, further reported in TABLE B. II in Appendix B. T1 translations were estimated as the average translations of the posterior and the anterior torso markers.
5. Head and torso rotations were calculated using projected angles [17]. In some of the tests, some markers were obscured, a priority on which markers were used for the projected angles was implemented, see TABLE B. II in Appendix B. for further details.
6. Kinematics were zeroed out at 300ms before t0 (TABLE B. II in Appendix B), to ensure that reference position was prior to belt pre-pretensioner activation.
7. Median filters were applied to the signals to remove artificial noise, for details see Appendix B, TABLE B. II.
8. A second quality control was carried out where tests were removed if there was head misalignment prior to manoeuvre, or head or torso movement prior to manoeuvre or if tests were considered as outliers, see Appendix B, TABLE B. II for details.

All kinematics are presented in a vehicle coordinate system according to SAE J211, with positive x in forward direction, positive y in right-hand-side direction and positive z downwards.

Principal Component Analysis (PCA)

To allow for a regression analysis of the time series data obtained in the volunteer test, a PCA with mean centring was performed on the kinematic and belt signals to transform these from high-dimensional data sets to low-dimensional data sets while preserving the most important variability [29-32]. The first step was the PC transformation, whereby a set of n observations with p measurements (variables) are transformed from an n×p matrix to a set of min(n-1,K) vectors (**PC**s, or principal component loadings) with length K, where all vectors are uncorrelated and describe variations from the mean. The vectors are sorted in a way that the vector where the data varies the most is first, and the vector with lowest variation is last, i.e., the first vectors contain most of the important variation within the data, while the last vectors contain more subject-specific variations or random noise. With the PC vectors (Φ) and the average defined as ($\bar{\boldsymbol{X}}$), the original data ($\boldsymbol{X}_i$) can be recreated exactly by multiplying each PC vector with the corresponding PC score (s), according to Eq. 1.

$$\boldsymbol{X_i} = \sum_{j=1}^{p} s_j \Phi_j + \bar{\boldsymbol{X}} \tag{1}$$

However, since the first components contain the most important information, the most important features of the data can usually be represented fairly accurately with a subset of the first principal components, see Fig. 2. This is the data reduction part of PCA. In Fig. 2, head forward displacement for one test is recreated using a different number of PC vectors and corresponding scores. The predicted kinematic time series is converging to the true response (the black curve), and for five PCs the results are very close.

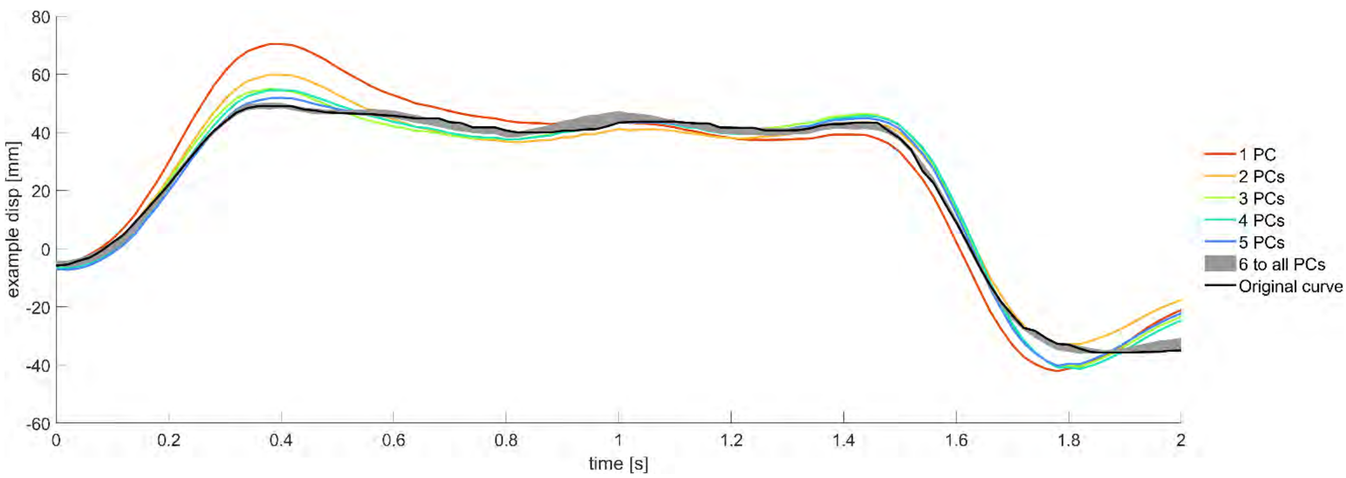


Fig. 2. Example of recreation of an original signal (black), using head forward displacement from one test in a braking manoeuvre as example. PC scores and vectors are created using all braking tests with standard and pre-tensioned belt. Showing average of all tests ($\bar{\boldsymbol{X}}$) plus one to all PCs. $\bar{\boldsymbol{X}}$+1 PC (red) to $\bar{\boldsymbol{X}}$+5 PCs (blue) are plotted individually, area between maximum and minimum of six to all PCs plotted using filled area (grey).

In this study, each observation vector ($\boldsymbol{X}_i$) contained the translational or rotational kinematics in x, y, or z for head or torso respectively and diagonal and lap belt forces and belt position, resulting in 15 observational vectors for each test. The observation vectors and scores were normalised, so each vector has a maximum absolute value of 1, thus describing only the shape, and the score contains the magnitude and unit, for example mm for head or torso displacement.

Linear Mixed Model (LMM)

To analyse the effect of volunteer characteristics on kinematics and belt characteristics, linear mixed models (LMM) were used, as tests were repeated for each volunteer [32-34]. The LMM includes both fixed (per subject) and random effects, meaning that both variability between subjects, and the variability for the specific subjects can be estimated. The subject-specific effect describes how the response of that subject systematically deviates from the average response [33].

The design of the LMM is described in Eq. 3 from [34], where indices k represents the subject, and i describes the test number (for the k^{th} subject) while h indicates the predictor. $\boldsymbol{y_{ik}}$ is the i^{th} response of the k^{th} subject. $\boldsymbol{\beta_0}$ is the intercept, $\boldsymbol{\beta_h}$ is the regression coefficient for the h^{th} predictor and $\boldsymbol{x_{hik}}$ is the i^{th} value of the k^{th} subject for the h^{th} predictor. $\boldsymbol{\alpha_k}$ is the subject-specific effect, assumed to come from a normal distribution of subject-specific effects with mean of 0 and variance of $\boldsymbol{\sigma_\alpha^2}$ (between-subject variance), Eq 3. $\boldsymbol{\varepsilon_{ik}}$ is the residual associated with i^{th} response for k^{th} subject, also assumed to come from another normal distribution of residuals with mean of 0 and variance of $\boldsymbol{\sigma_\varepsilon^2}$ (within-subject variance), according to Eq 4.

$$\boldsymbol{y_{ik} = \beta_0 + \sum_h \beta_h x_{hik} + \alpha_k + \varepsilon_{ik}} \tag{2}$$

$$\boldsymbol{\alpha_k \sim Gaussian(0, \sigma_\alpha^2)} \tag{3}$$
$$\boldsymbol{\varepsilon_{ik} \sim Gaussian(0, \sigma_\varepsilon^2)} \tag{4}$$

All first-order interaction effects were included in the analysis. All models were fitted using the restricted maximum likelihood method (REML) [35]. To determine the best subset of predictors, both backwards and forwards stepwise subset selection were used. The backwards subset selection was started with all possible models and reduced stepwise until no predictors remained. The forward subset selection was started with no predictors and increased stepwise until the maximum allowed number of predictors were included. Intercepts were always included regardless of significance level. In the subset selection, calculated R^2 of resulting model with/without each predictor was used to guide the selection of which predictor to add or remove. Ordinary R^2 was selected over adjusted R^2 because all models in the selection step had the same number of observations and predictors. For all models created using the stepwise subset selection (both backwards and forwards), with significant effects ($p<0.05$, calculated using Satterthwaite approximations [35]) for all predictors, the best model was selected using the Akaike Information Criterion (AIC). For models with significant interactions, main effects were included regardless of significance level [36]. Maximum allowed number of predictors in one model was set to one tenth of number of tests using downward rounding, e.g., 67 tests allowed for a maximum of six predictors.

In the occupant kinematic analysis, for each statistical model and manoeuvre, if available, two belt configurations were included in the analysis and belt configuration was used as a co-variate. For braking, where the manoeuvre was performed with a third belt configuration, i.e., belt slack, the belt slack condition was analysed together with the standard belt. This was done to analyse if and where there was a significant effect from belt type. Regression co-variates were age, belt, BMI, sex, and stature, except for in U30SB and MUSB where only age, BMI, sex, and stature, were used, since only one belt configuration was used for these manoeuvres. Belt force and belt position was treated separately from the occupant kinematics, and the analysis was done with the belt configurations in separate analyses because the forces and positions formed distinct groups depending on belt configuration. For belt forces and position, age, BMI, sex, and stature were used as co-variates, except for UPT, where only age, BMI and stature, were used. The reason was that there were not enough tests with enough volunteers for that configuration to fit the models with all predictors and interactions.

For both kinematics and belt forces, the predictors were treated as fixed effects. The subject-specific effect was treated as a random effect. Responses were PC scores for PC1-PC3 for head translations, head rotations, torso translations, torso rotations and belt forces. Since many models were created from the same set of tests, the Holm-Bonferroni sequential procedure ($\alpha=0.05$) [37] on p-value from F-test on fixed-effects, calculated using Satterthwaite approximations [35], was used to determine if a model was significant.

Response Corridors

To create the response corridors, Monte Carlo simulations were used to generate 10000 new samples, using the SD from the PC scores [38]. For the scores where LMMs were significant, the random variance was used for the residual and individual-specific effect. For the scores with no LMM, the SD of that PC score was used instead. The corridors were then estimated from the 16^{th} and 84^{th} percentiles for each time step, selected to approximately correspond to ±1 SD. When present, kinematics or forces from predictive models were used as centre of corridor. If no predictive models were available, the average from the tests was used. The corridors were visualised using the average test subject, i.e., average sex (43% male), average age (36.3 years), average stature (174.5 cm) and average BMI (22.8 kg/m^2).

III. RESULTS

Principal Component Analysis (PCA)

Using the first three principal components, 91%-99% of the variance in both translational and rotational kinematics could be explained, TABLE C. I in Appendix C. Similarly, three components explained 85%-100% of the variance in belt characteristics, see TABLE C. II in Appendix C.

Linear Mixed Model (LMM)

For occupant kinematics, belt pre-tensioning, age, sex, stature, BMI and belt slack, were all significantly related ($p<0.05$) in at least one of the LMM's created. The co-variate most often significantly associated to the occupant kinematics was belt pre-tensioning, significant in 48 out of 144 possible models, followed by sex (6 out of 252 possible models), BMI (3 out of 252 possible models), age (2 out of 252 possible models), stature (1 out of 252 possible models) and finally belt slack (1 out of 36 possible models). The most commonly significant interaction was belt*BMI (9 out of 144 possible models) followed by belt*stature and belt*sex (8 each out of 144 possible models). Belt slack*sex and sex*stature were found significant once each, with 36 and 252 models possible, respectively. No other interactions were found significant in the analysis of the head and torso kinematics. No LMM with the mentioned co-variates could predict occupant kinematics in U-turn at 30 km/h or for manual U-turn.

For belt forces, the only significant model that was found was for PC2 in the BSB manoeuvre, TABLE F. II, Appendix F. All other belt force and position models were non-significant.

In lane change, predictive models were found for head translation and torso rotations and translations, TABLE II. For head lateral translation, PC1 (Fig. D. 1), the largest effect was seen from the belt. For the average person from this study (43% male, 174.5 cm tall, BMI of 22.8 kg/m^2), the belt effect was 55 mm, accounting for main effect and interaction effects. For a female with average stature (from this study), the belt effect was 26 mm, and for a male the belt effect was 93 mm in this type of manoeuvre. Sex was less influential compared to the belt. The sex effect was 18 mm when a pre-tensioned belt was used and 49 mm when a standard belt was used. The stature was less influential than sex when combined with a pre-tensioned belt. A change in stature of 25 cm (difference between 5th and 95th percentile male [39]) gave a difference in lateral translation of 8 mm for pre-tensioned belt. Stature was more influential than sex when combined with standard belt. A change of 25 cm in stature combined with a standard belt gave 62 mm change in lateral head displacement.

Similar trends were seen for torso lateral translations. Just as for the head translation, the largest effect was seen from the belt. For the average person from this study, the belt effect was 40 mm, accounting for main effect and interaction effects. For a female with average stature (from this study), the belt effect was 27 mm, and for a male the belt effect was 57 mm. The stature was less influential compared to the belt, but more influential than sex. A change in stature of 25 cm gave a difference in lateral translation of 10 mm for pre-tensioned belt and 37 mm for a standard belt. Sex effect was least influential for torso lateral translation. For a pre-tensioned belt, the effect was 3 mm while for a standard belt it was 28 mm.

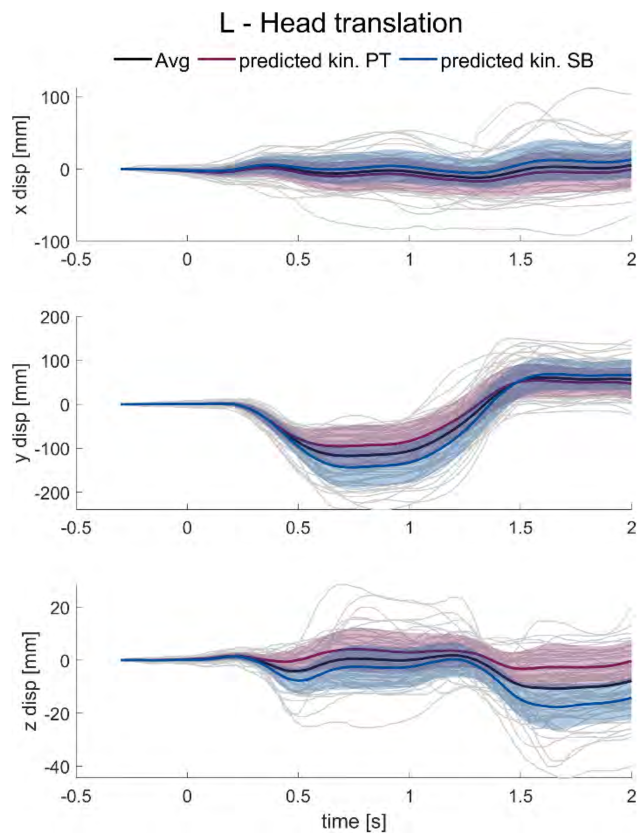
For head forward translation PC1 (Fig. D. 1), only the belt was influential, at 17 mm. For torso forward translation, predictive models were found for all three PCs. For PC1, the difference for the average volunteer (from this study), the belt effect was 10 mm. For BMI, the effect was similar in size. A difference in BMI of 7 kg/m^2 (approximately the range of normal BMI [40]) gave an effect of 10 mm when combined with belt pre-pretension. In standard belt conditions, the effect from BMI was only 2 mm.

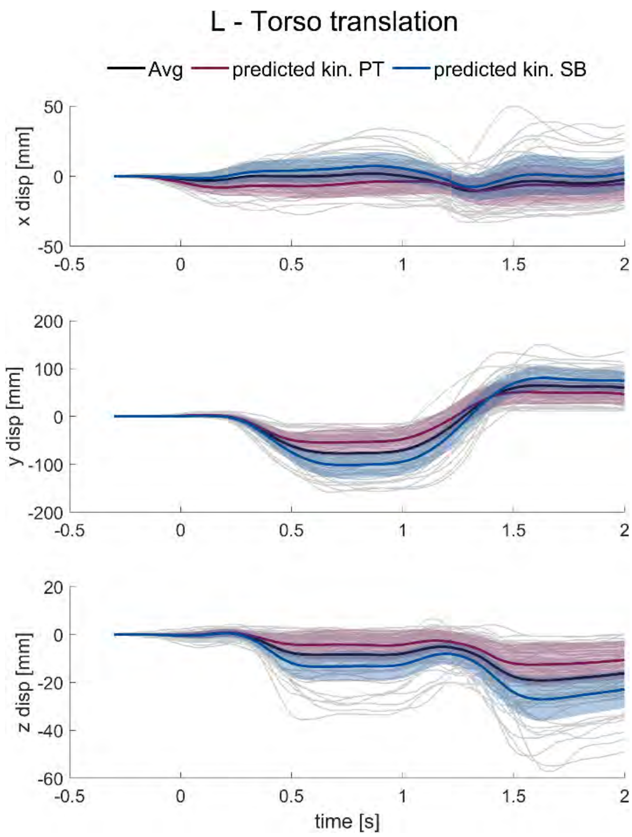
TABLE II
LINEAR MIXED MODELS FOR KINEMATICS IN LANE CHANGE

Comp	dir	PC	p-val	Intercept [mm]	Sex (F=0) [mm]	Stature (cm) [mm/cm]	BMI (kg/m^2) [mm/(kg/m^2)]	Belt (PT=0) [mm]	Sex*Stature [mm/cm]	Sex*Belt [mm]	Stature*Belt [mm/cm]	BMI*Belt [mm/(kg/m^2)]	Residual [mm]	Individual specific effect [mm]
Head transl.	x	1	<0.001	-7.1				16.6 ***					17.1	21.0
	y	1	<0.001	66.1	17.6	-0.3		-515 *		-66.6 *	2.8 *		30.6	32.4
	z	1	<0.001	20.0			-0.5	5.6				-0.9 **	4.5	6.0
Torso transl.	x	1	<0.001	27.0			-1.4 *	-14.9				1.1 *	8.6	10.1
		2	<0.001	-3.6				5.1 ***					3.2	4.4
		3	<0.001	-4.3	80.9 *	0		-3.3 ***	-0.5 *				3.4	1.8
	y	1	<0.001	96.8	2.5	-0.4		-358.3 *		-30.6 *	1.9 *		18.4	19.4
	z	1	<0.001	25.6			-0.8	5.5				-0.9 ***	4.1	7.6
Torso rot.	x	1	<0.001	2.0				-4.4 ***					2.2	2.0
		2	<0.01	1.1				-1.9 **					2.1	2.2
		3	<0.001	-2.7			0.1 **	1.3				-0.1 **	0.5	0.6
	z	1	<0.001	-2.6				5***					2.0	2.3

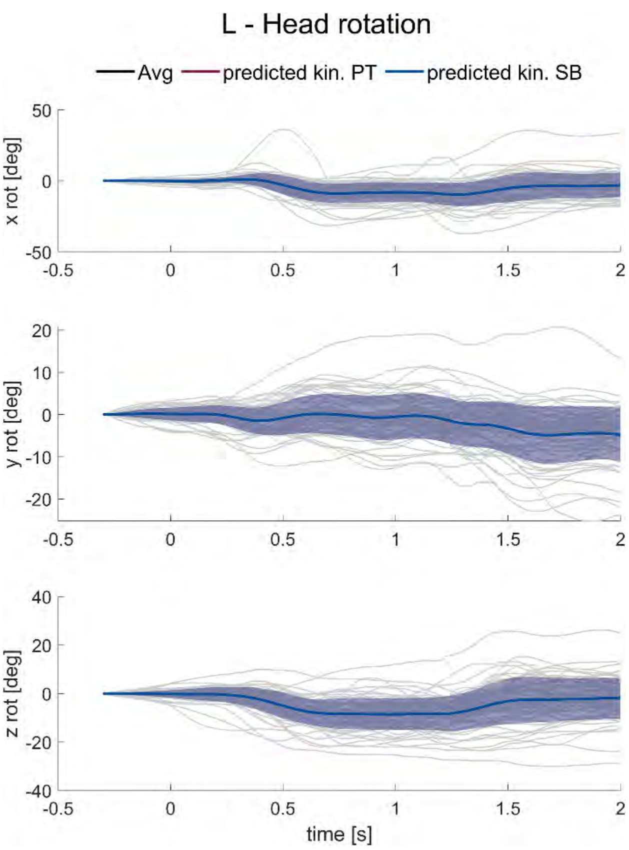
*** P-VAL<0.001
** P-VAL<0.01
* P-VAL<0.05

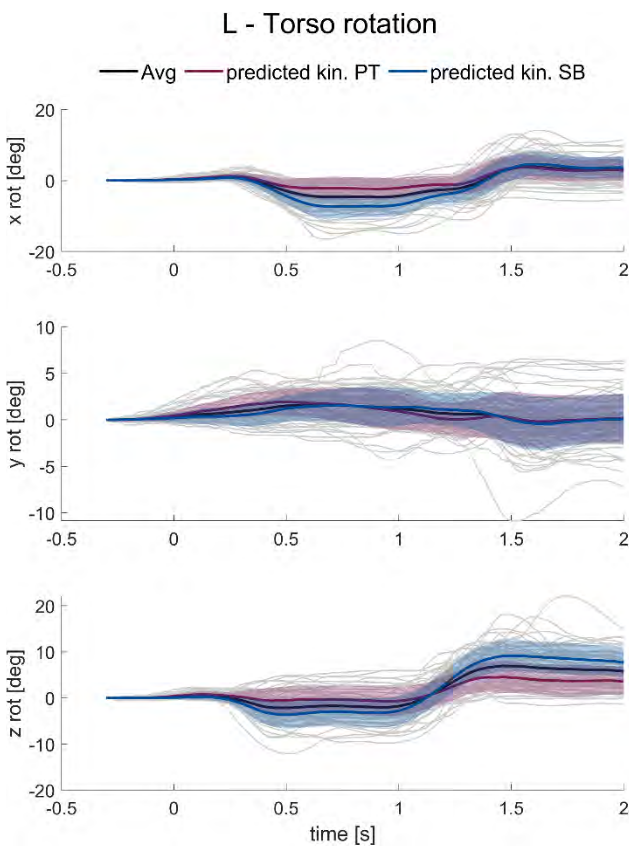
The occupants displaced less laterally in the second turn compared to the first turn, Fig. 3. Some occupants moved their head and torso rearwards during the lane change, others moved forward, with the average fairly close to no forward or rearward movement. Head translations were larger than torso translations, lateral translations larger than vertical or longitudinal translations. On average, occupants would move their torso slightly upwards during the last 1 s of the manoeuvre. The corridors for lane change indicate an increase in variation between roughly 0 and 0.5 s, and after that the variation is relatively stable.





a) Head translation *b) Torso translation*



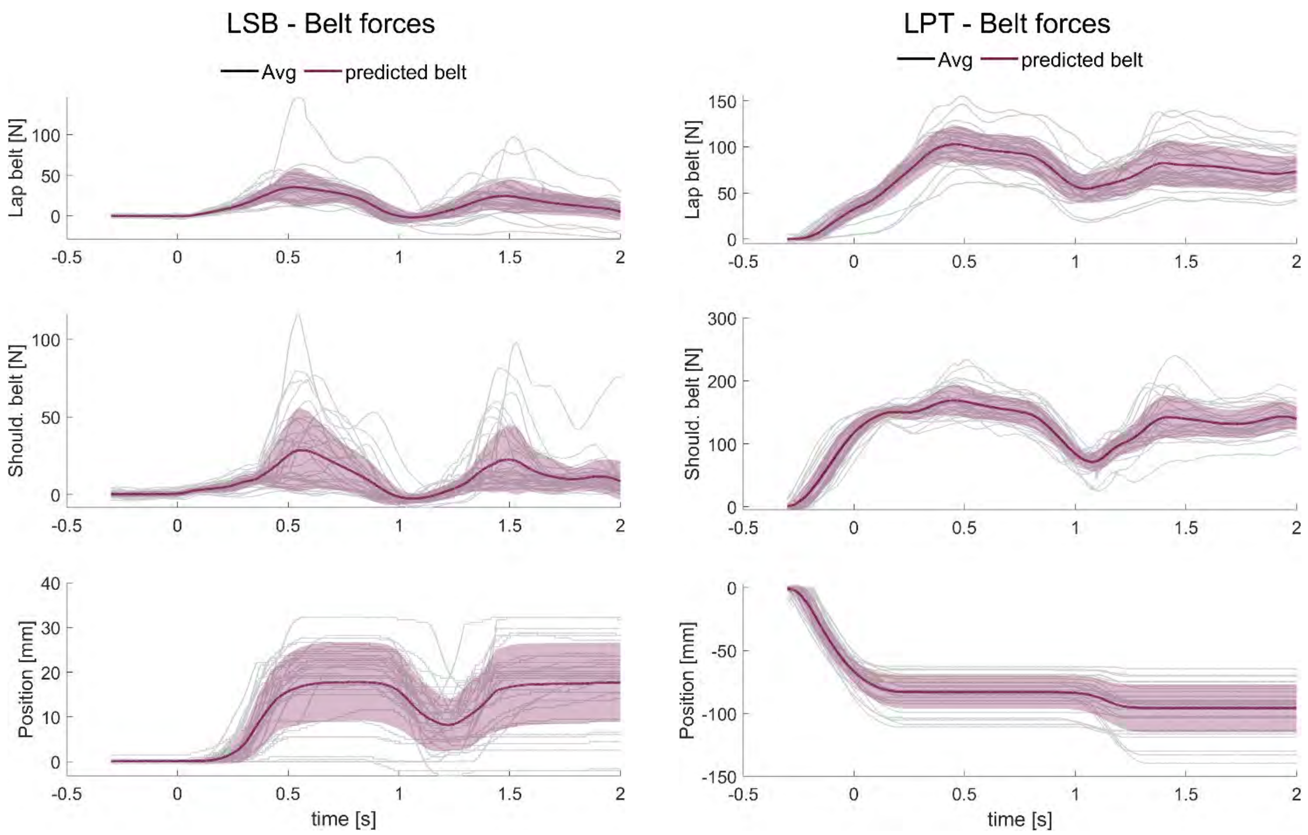


c) Head rotation *d) Torso rotation*

Fig. 3. Predicted kinematics (red/blue line) and corridors (filled red/blue) in a lane change manoeuvre, for a 43% male passenger, 174.5 cm tall, 36.3 years old, with a BMI of 22.8 kg/m^2, in a vehicle equipped with a pre-

tensioned belt (red) and standard belt (blue). Grey curves are individual kinematics from both manoeuvres with standard and pre-tensioned belt, males and females, and the black curve are the average of these kinematics.

No significant effects from age, BMI, sex or stature were found for the belt forces in LSB or LPT. For LSB, the averaged lap belt force was maximum 35 N, for LPT the maximum was 103 N, Fig. 4. For the shoulder belt, in LSB the maximum was 29N, and for LPT it was 169 N.



a) LSB *b) LPT*

Fig. 4. Predicted belt forces and positions (red line) and corridors (filled red) in a lane change manoeuvre with standard (a) and pre-tensioned (b) belt for a 43% male passenger, 174.5 cm tall, 36.3 years old, with a BMI of 22.8 kg/m^2. Grey curves are individual forces and positions, males and females, and the black curve are the average of these forces and positions.

IV. DISCUSSION

In this study, effects of seat belt and occupant characteristics on occupant kinematic time history in seven different vehicle manoeuvres was investigated using PCA and LLM. Time histories for belt force and belt position were also investigated for each manoeuvre and belt configuration. The results indicate that the most influential parameter for occupant kinematics is the belt configuration, here either a standard belt or a pre-pretensioned belt system. Between the occupant characteristics there is not as clear which of the predictors is the most important, as sex, stature and BMI, all were significant predictors for PC scores, either as main effect or together with the belt. Sex and BMI were determined significant more often than stature. In our volunteer setup, sex and stature were correlated (p-value <0.001) among the volunteers, so it is possible that some of the effects from stature is covered by the sex predictor instead.

The statistical models presented in this study, together with the PC vectors, average kinematics, and presented corridors can be used to create kinematic corridors for an occupant of selected sex, age and body size. To create a signal, for instance head lateral displacement for a 20-year-old male, 175 cm tall and a BMI of 22 kg/m^2, in a lane change manoeuvre in a vehicle with standard belt, the occupant and belt characteristics are multiplied by the corresponding regression coefficients in TABLE II, head y translations, PC1, according to Eq (2),e.g., effect from belt (SB=1) and stature (175 cm) interaction coefficient becomes $1 \times 175 \times 2.8 = 490$ mm. Using the specified characteristics, the PC score for the occupant and belt combination becomes -60.4 mm. This score is then multiplied to the PC vector (PC1, head y) in Fig. D. 1 in Appendix D. The resulting vector is the deviation from the average kinematics for the specified occupant and belt and is subsequently added to the average kinematics in Fig. 3, according to Eq (1). For the specified occupant and belt, this gives a larger displacement compared to the average, with the largest difference seen between approximately 0.5 s and 1 s. If there are several models available for the same time history, e.g., torso x translation, TABLE II, this process is repeated for all LMMs available. Lastly, the response corridor from Fig. 3 is added around this subject and belt specific kinematic time history.

The results from this study both agree and disagree with the findings from previous studies where occupant characteristics have been related to resulting kinematics in vehicle manoeuvres. Study [7] studied sagittal plane kinematics in 1.1 *g* steady-state braking, for two belt configurations, and used one-way ANOVA to investigate any correlation between occupant characteristics and kinematics. In a study with 0.5 *g* braking [6], differences between average forward excursions were investigated by comparing results from groups of passengers of different characteristics, although no statistical tests were performed to give significance of these comparisons. Study [25] used linear regression to relate occupant maximum and average forward excursion to occupant characteristics in 1 *g* braking. In the same study, linear regression was used to relate occupant characteristics to maximum and average lateral excursion in sharp turning. Study [24] also studied both braking and turning, and used ANOVA to investigate any correlation between occupant characteristics and kinematics. In that study, two belt configurations were used.

Belt was most commonly identified as a predictor of kinematics in this study. A similar relationship between kinematics and belt system used was noted in all other studies where belt characteristics was included as a parameter [6,7,24].

Sex was in this study found to be a significant predictor of occupant kinematics in lane change, lane change with braking, braking and U-turn at 40 km/h. In braking, sex was a significant predictor of head vertical translation in interaction with belt, and torso lateral (main effect and interaction with belt) and vertical translation (in interaction with belt). Sex was not a significant predictor of head longitudinal translation in braking. For head kinematics, this agrees with the findings in [7] where they found no significant difference between the sexes for sagittal plane head kinematics. For the torso kinematics, in our study sex was a significant predictor, while in their study, no significant difference between torso kinematics of males and females was found. However, noteworthy is that in their description of their results, a difference in vertical and forward torso movement between males and females was mentioned, but only for one of the two belt systems used (standard belt), which is the same effect as found for head and torso vertical translations in our study. This difference between sexes was not found to be significant in their study, but no interaction effects were included in their analysis. In [6], a difference between males and females was identified in average forward excursion during braking, disagreeing with the findings from this study. In [24], a significant effect of sex on maximum forward displacement of head and torso in braking was found. For the torso kinematics, this agrees with the findings from this study, while for the head it does not. In [25], sex was not found to be a significant predictor of forward excursions in braking.

In this study, sex was a significant predictor of head lateral translation in interaction with belt, and torso longitudinal (main effect and interaction with belt) and lateral translation (in interaction with stature). This disagrees with the findings in both [24] and [25], where no effects from sex on lateral translation was found, although no interaction with belt was studied in [24].

Stature was in this study found to be a significant predictor of occupant kinematics in lane change, lane change with braking, and U-turn at 40 km/h, in other manoeuvres such as braking. This agrees with study [25], where stature was not found significantly related to kinematics in braking. However [6] and [24] did find a difference in forward kinematics in braking for occupants of different statures, although again in study [6], no statistical test for significance was performed, and in [24], the effect was significant only when sex was omitted from the statistical analysis. It is possible that stature could replace sex as a predictor of head and torso lateral kinematics, and torso vertical kinematics in this study, but this was not tested. In [7], occupant stature was not included in the statistical analysis. In this study stature was however a significant predictor of belt position (pull-out of belt) in braking, for the standard belt with slack.

In lane change, stature was found to be a significant predictor of head and torso lateral kinematics, in interaction with the belt, and for torso longitudinal kinematics in interaction with sex in this study. This agrees with the findings in [25], where stature also was found a significant predictor of head kinematics in lane change. In [24], no such effect was found.

BMI was in this study found predictors of occupant kinematics in lane change, lane change with braking and U-turn at 40 km/h. In braking, BMI was a significant predictor of head vertical translations, in interaction with belt, and of torso longitudinal and vertical translations, and torso rotations around the y-axis (lateral), all in interaction with belt.

BMI was only included in the analysis carried out in one other analysis, [25]. In their study, BMI was a significant predictor of head forward excursion in braking, disagreeing with the findings from our study. In lane change in this study, just as for braking, BMI was a significant predictor of head vertical translations, in interaction with belt, and of torso longitudinal and vertical translations, and torso rotations around the y-axis (lateral), all in interaction with the belt. This disagrees with [25], where no relationship between BMI and kinematics was found for lane change.

In this study, age was found a significant predictor of torso lateral kinematics and y-axis rotations in U-turn at 40 km/h, while no relationship between age and kinematics was found for any of the other manoeuvres. Age was only included in one other study, [25]. In their study, age was found to be a significant predictor of forward excursions in braking, disagreeing with the results from this study.

In [25], an effect from erect sitting height was also found on lateral kinematics in lane change, but in the analysis carried out in this study, sitting height was not included.

Common for all studies, where analysed, is the strong effect from the belt systems, while for occupant characteristics the trend is less clear. In other studies, sex and stature has most commonly been found significant, however BMI and age have also been identified, both in this study and in previous studies by others on volunteer responses in evasive manoeuvres. These discrepancies could indicate that either there is a large variation among people that cannot be explained by physical characteristics, or there is some parameter that is influential but not included in any of the analyses. In this study, the individual-specific effect was similar in size as the residual, which indicates that there is similar variation within an individual and between individuals. The similar size could indicate that the remaining variation stems from something other than physical characteristics, as the subjects in this study were tested on the same day and would thus not have changed physical characteristics between trials. For instance, fatigue could have influenced the volunteers in this study, as many tests were performed within a short time frame. There could also have been habituation effects, however that was not investigated in the current study.

The corridors were constructed from Monte Carlo simulations of individual-specific effect and residual effect of fitted LMMs, or SD of PC scores for PCs without significant LMMs. From the generated data, the 16th and 84th percentile in each time step was used for the outer perimeter of the corridor. This resulted in narrower corridors, compared to what has been presented for the same data set previously [16,17]. In the previous studies, the kinematics and forces were constructed using average and SD of each time step, males and females separately, and belt configurations separately. The narrower corridors in the current study is in line with [38], where the authors showed that corridors created using Monte Carlo simulations resulted in narrower corridors with a shape more similar to that of the original data, compared to when creating the corridors using commonly used methods.

In this study, the Holm-Bonferroni sequential procedure [37] was used to remove any non-significant models in relation to the number of models created from the same tests, and reduces the risk of accepting a model where the effects are not true effects. However, this was done on the p-value of the whole model, and not on predictor level. For models where one predictor has a low enough p-value for the whole model to be significant according to the Holm-Bonferroni sequential procedure, the other predictors, with possibly larger p-values, would be determined significant at the unadjusted level. In our case where the belt was found very influential, that means that when including both belt configurations, the other predictors could be included at the original α-level ($p<0.05$).

Adopting principal component analysis and linear mixed modelling in the analysis of time series data of volunteers in evasive manoeuvres gave narrower corridors for kinematics and belt forces and position compared to when corridors were created using average and SD per time step. In this study, occupant kinematics were significantly associated to occupant characteristics in all manoeuvres except for U-turn at 30 km/h and manual U-turn, although significant associations were most frequent between kinematics and belt pre-tensioning.

The presented data, including time series of head and torso kinematics and belt forces and positions, together with the predictive models, can be used for validation of Human Body Models of an occupant of a specific sex, stature, age and BMI, in evasive manoeuvres. Such data has not yet been made available and can be used in the progress towards inclusion of a more diverse population in safety assessment of future restraints.

V. CONCLUSIONS

In this study, passenger kinematics and belt forces were quantified, and regression models were provided to show the influence of belt system and occupant characteristics on these metrics. The results indicate that the most influential parameter for passenger kinematics was belt pre-tensioning, followed by stature and BMI. Belt forces did not show any dependence on occupant characteristics. The regression models provided, together with principal component and corridors can be used to predict passenger kinematics and belt forces for occupants of different sex, stature, age and BMI. The kinematic and belt force corridors can be used in validation of HBMs, allowing for inclusion of larger portions of the population in human body model validations in evasive manoeuvres with both longitudinal and lateral acceleration components.

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A. APPENDIX

A. Acceleration levels

For the longitudinal and lateral peak vehicle accelerations both average peak of the magnitude of the acceleration, and peak value of averaged acceleration signal were calculated, TABLE A. I. The average direction was calculated with mean of sign of peak acceleration, i.e., a direction of 1 equals all peak accelerations were to the right/forward while -1 equals all peak accelerations were to the left/rearward. For lane change with and without braking, the manoeuvre was divided into two phases, and these were treated separately in the acceleration calculations. The first phase was accelerations to the right (approximately 0-1 s after t0, Fig. 1) and the second phase the acceleration to the left (approximately 1-2s after t0, Fig. 1), with the transition defined as when the lateral acceleration changes direction.

TABLE A. I

INITIAL VELOCITY AND PEAK ACCELERATIONS FOR THE SIX DIFFERENT MANOEUVRES.

Manoeuvre				Initial velocity [km/h]	Peak lateral acceleration [m/s^2]			Peak longitudinal acceleration [m/s^2]		
Vehicle manoeuvre	Belt				Average peak		Peak of average acc.	Average peak		Peak of average acc.
	SB	PT	SBS		direction	magnitude		direction	magnitude	
Lane change (LSB, LPT), phase 1	X	X		71.4	1	6.3	5.9	-0.1	0.6	0.2
Lane change (LSB, LPT), phase 2				70.8	-1	6.5	-6.0	-0.3	0.5	-0.1
Lane change with braking (LBSB, LBPT), phase 1	X	X		71.5	1	5.7	5.2	-1	6.2	-5.6

Lane change with braking (LBSB, LBPT), phase 2				51.8	-1	4.2	-3.9	-1	6.2	-5.8
Braking (BSB, BPT, BSBS)	X	X	X	71.5	0.4	1.1	0.2	-1	10.6	-9.5
U-turn 40km/h (USB, UPT)	X	X		37.2	1	8.5	8.0	0.7	1.2	0.7
U-turn 30km/h (U30)	X			28.0	1	6.0	5.7	0.5	0.8	-0.6
Manual U-turn 40km/h (MU)	X			37.2	1	8.8	8.1	0.1	1.1	0.8

B. Kinematics processing

TABLE B. I

MARKER NUMBERING

Number	**Location**
P1	Top of head
P2	Right side of head
P3	Front of head
P4	Left side of head
P5	Back of head
P6	C7/T1
P7	Right shoulder
P8	Sternum
P9	Left shoulder

TABLE B. II

DATA PROCESSING STEPS

	Measure	*criteria*	*Comment*
Inclusion of tests, step 1	*Recording system status*	*All systems flagged OK*	
	Data availability	*Full kinematics data set, vehicle acceleration, and belt responses available for the test*	*Majority of missing data was kinematic signals*
Inclusion of tests, step 2	*P6, P8 and P9 tracked for majority of data frames*	*> 160 frames available*	*180 possible frames*
	A majority of head markers (P1-P5) available for a majority of data frames	*> 160 frames available for > 3 markers*	*180 possible frames, 5 possible markers*
Signal repair	*Missing data repaired*	*> 160 frames available*	*If missing data at beginning*

			or end of manoeuvre, the missing data was replaced with "NaN" and subsequently removed from any calculations. If data was available before and after missing frames, a cubic spline interpolation was used to repair the signal.
Quality control. Head marker relative translation	*Markers included in head rotation matrix calculation if translation relative other markers small enough*	*<10mm relative translation, relative to ≥ 2 other markers*	*P1-P5 possible If no markers met this criterion, the three markers with smallest relative translations (relative all other markers) were used*
Filtering	*2 consecutive median filter applied to kinematic signals*	*3 frame window, then 5 frame window*	*To remove spikes from signals*
Inclusion of tests, step 3	*Head rotation before reference position*	*<10°*	
	Head translation before reference position	*<25 mm*	
	Torso rotation before reference position	*<10°*	
	Torso translation before reference position	*<25 mm*	
	Head and torso translations and rotations relatively similar to the other tests	*<3SD*	*Implemented to remove any tests with extreme kinematics. SD calculated before any tests were removed due to movement before reference position.*

TABLE B. III

PROJECTED ANGLES CALCULATION, MARKER PRIORITY. FOR PLACEMENT OF MARKERS, SEE TABLE B. I.

Rotation	Default	Second alternative	Third alternative
Head x rotation	P2-P4	P3-P4	P1-P3
Head y rotation	P3-P5	P4-P3	P4-P5
Head z rotation	P3-P5	P2-P4	P3-P1
Torso x rotation	P6-P9	-	-
Torso y rotation	P8-P6	-	-
Torso z rotation	P8-P6	-	-

C. PCA

TABLE C. I

PART OF VARIANCE EXPLAINED BY THE FIRST 3 PRINCIPAL COMPONENTS FOR THE SEVEN DIFFERENT MANOEUVRE/BELT COMBINATIONS EVALUATED, CUMULATIVE SUM.

Manoeuvre	No. tests	Body part	direction	Translations (%)			Rotations (%)		
				PC1	PC2	PC3	PC1	PC2	PC3
Lane change (LSB, LPT)	63	Head	x	72,6	90,3	94,1	52,0	82,0	91,2
			y	62,0	88,5	96,4	73,7	88,1	93,3
			z	61,8	91,4	94,2	70,8	86,6	93,1

		Torso	x	72,5	89,1	93,3	49,6	82,7	93,7
			y	69,3	88,6	97,1	62,7	83,8	91,5
			z	86,4	94,0	96,7	57,6	85,5	93,5
Lane change with braking (LBSB, LSPT)	67	Head	x	84,7	94,7	97,0	57,3	82,4	95,0
			y	60,9	89,5	95,7	83,7	91,0	95,5
			z	86,0	94,3	96,5	72,1	85,9	94,3
		Torso	x	86,5	96,8	98,0	65,8	90,8	95,2
			y	69,9	91,5	96,9	79,3	92,9	96,4
			z	89,4	96,2	97,4	50,2	84,4	95,0
Braking (BSB, BPT)	41	Head	x	87,1	94,8	97,2	84,1	92,8	95,9
			y	84,8	92,1	95,2	84,3	93,7	96,8
			z	86,0	93,0	95,4	82,1	89,5	95,4
		Torso	x	90,9	95,7	97,7	90,3	94,4	96,9
			y	84,8	92,3	95,3	75,4	89,3	94,0
			z	87,7	93,4	96,0	77,6	86,5	92,0
Braking (BSB, BSBS)	39	Head	x	87,4	94,2	97,2	87,9	94,2	96,5
			y	74,5	85,4	91,4	79,5	93,4	96,6
			z	87,8	93,1	96,5	81,1	89,1	95,2
		Torso	x	89,7	94,5	96,9	88,3	93,8	96,3
			y	76,3	88,1	92,8	76,3	90,2	94,7
			z	85,4	90,5	94,5	69,4	84,0	91,7
U-turn 40km/h (USB, UPT)	43	Head	x	86,8	94,9	97,4	78,9	95,4	98,3
			y	89,8	97,6	98,9	89,6	95,1	97,2
			z	89,6	95,6	97,9	84,8	95,4	97,7
		Torso	x	91,3	97,7	98,9	93,6	98,3	99,0
			y	94,7	98,6	99,4	89,3	96,4	98,0
			z	96,3	98,3	99,1	94,8	98,0	98,7
U-turn 30km/h (U30)	23	Head	x	83,5	96,5	98,1	87,7	95,4	97,5
			y	89,8	96,7	98,1	88,1	95,9	98,2
			z	74,9	89,7	94,7	90,8	95,4	98,7
		Torso	x	90,1	97,2	98,9	92,8	97,4	99,0
			y	91,3	96,6	98,0	85,7	93,9	97,7
			z	92,1	95,3	97,8	80,3	92,4	96,2
Manual U-turn 40km/h (MU)	28	Head	x	83,8	95,6	98,0	90,3	95,6	98,7
			y	92,8	97,0	99,3	87,5	97,0	98,6
			z	83,7	93,0	97,0	86,3	94,6	98,8
		Torso	x	91,3	98,1	99,2	95,0	98,2	99,3
			y	93,3	97,7	99,4	90,7	97,1	98,6
			z	93,1	97,3	98,9	89,2	95,1	97,9

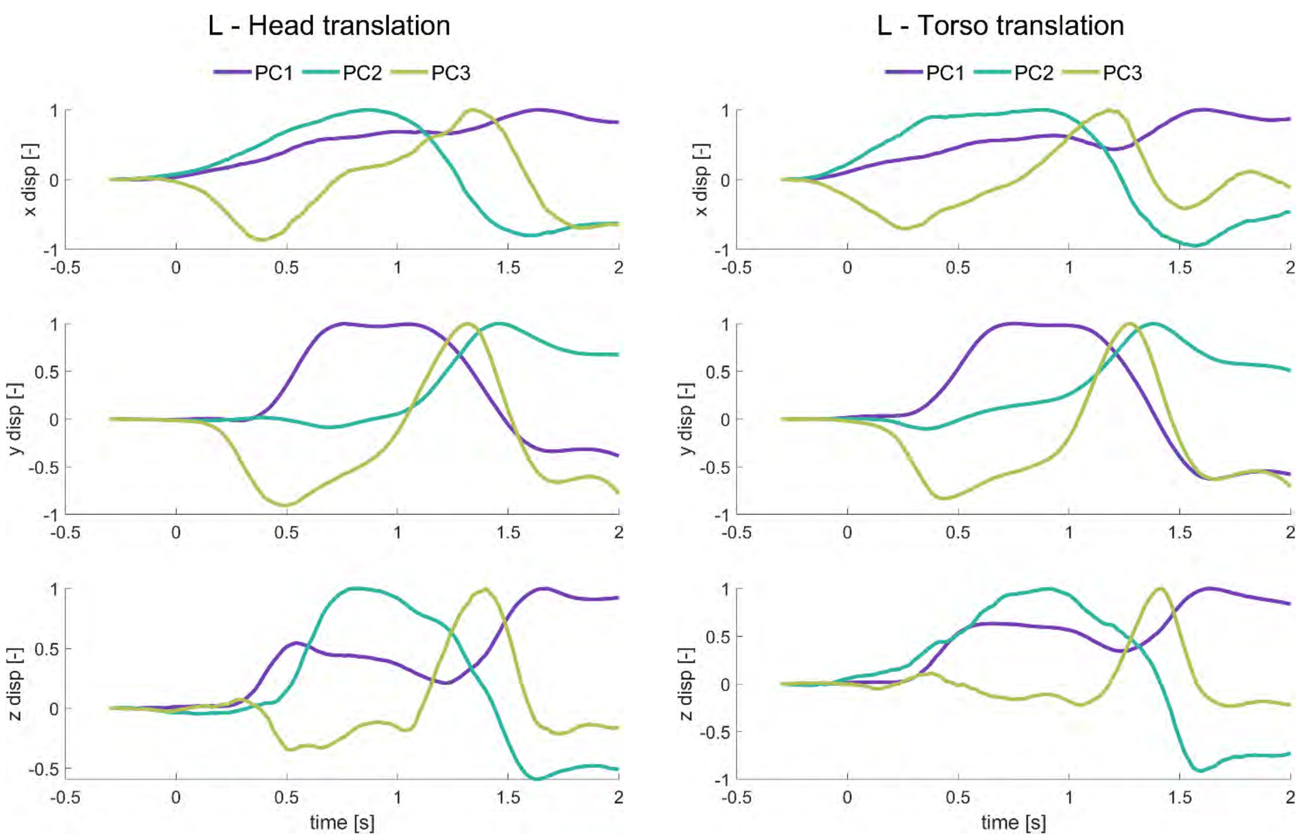
TABLE C. II

PART OF VARIANCE FOR BELT FORCE AND POSITION EXPLAINED BY THE FIRST 3 PRINCIPAL COMPONENTS FOR THE 11 DIFFERENT MANOEUVRE AND BELT COMBINATIONS EVALUATED, CUMULATIVE SUM.

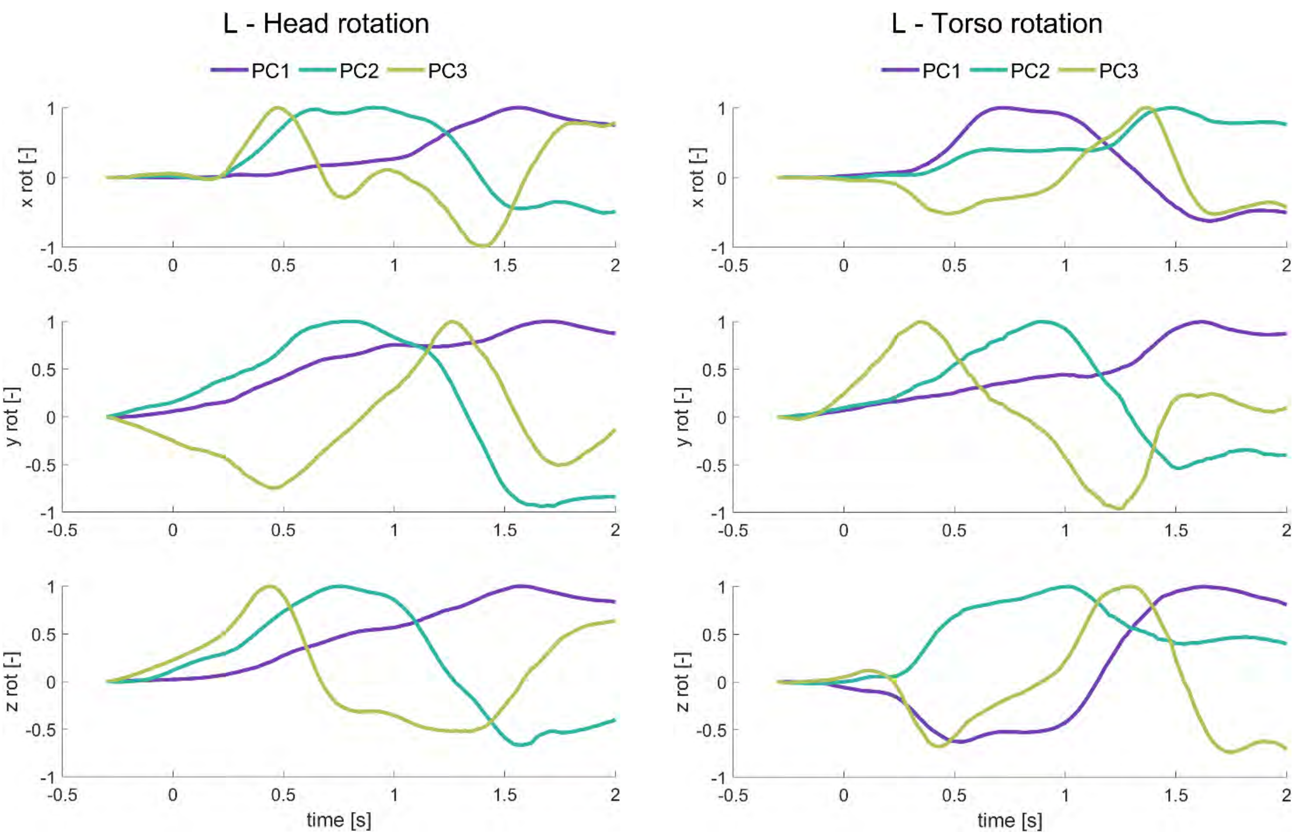
Manoeuvre	No. tests	Part	PC1	PC2	PC3
LSB	34	Lap belt	49,0	83,7	90,4
		Shoulder belt	57,5	79,8	89,5
		Position	72,1	92,4	95,0
LPT	30	Lap belt	76,4	88,8	94,3
		Shoulder belt	52,9	69,5	84,6
		Position	83,7	95,1	99,7
LBSB	35	Lap belt	51,8	76,8	84,8
		Shoulder belt	67,7	86,9	91,1
		Position	82,9	92,1	98,0

LBPT	32	Lap belt	83,2	88,8	94,0
		Shoulder belt	49,0	74,3	86,0
		Position	92,7	97,5	99,8
BPT	21	Lap belt	71,7	84,8	91,3
		Shoulder belt	75,3	83,6	90,3
		Position	91,1	97,3	99,3
BSB	20	Lap belt	79,4	88,0	92,0
		Shoulder belt	80,1	90,0	94,5
		Position	68,0	94,3	97,3
BSlack	19	Lap belt	80,7	89,4	92,1
		Shoulder belt	90,5	94,7	96,5
		Position	73,2	94,6	96,9
U40SB	24	Lap belt	85,0	93,6	96,7
		Shoulder belt	87,6	96,1	97,6
		Position	85,2	96,7	99,1
U40PT	19	Lap belt	88,0	95,3	98,5
		Shoulder belt	76,7	90,5	95,5
		Position	94,2	99,9	100,0
U30	22	Lap belt	86,5	92,2	95,2
		Shoulder belt	85,7	90,8	95,3
		Position	95,0	98,5	99,4
MU	28	Lap belt	90,1	95,0	97,8
		Shoulder belt	79,1	92,5	97,3
		Position	91,5	98,2	99,3

D. Lane change (L)

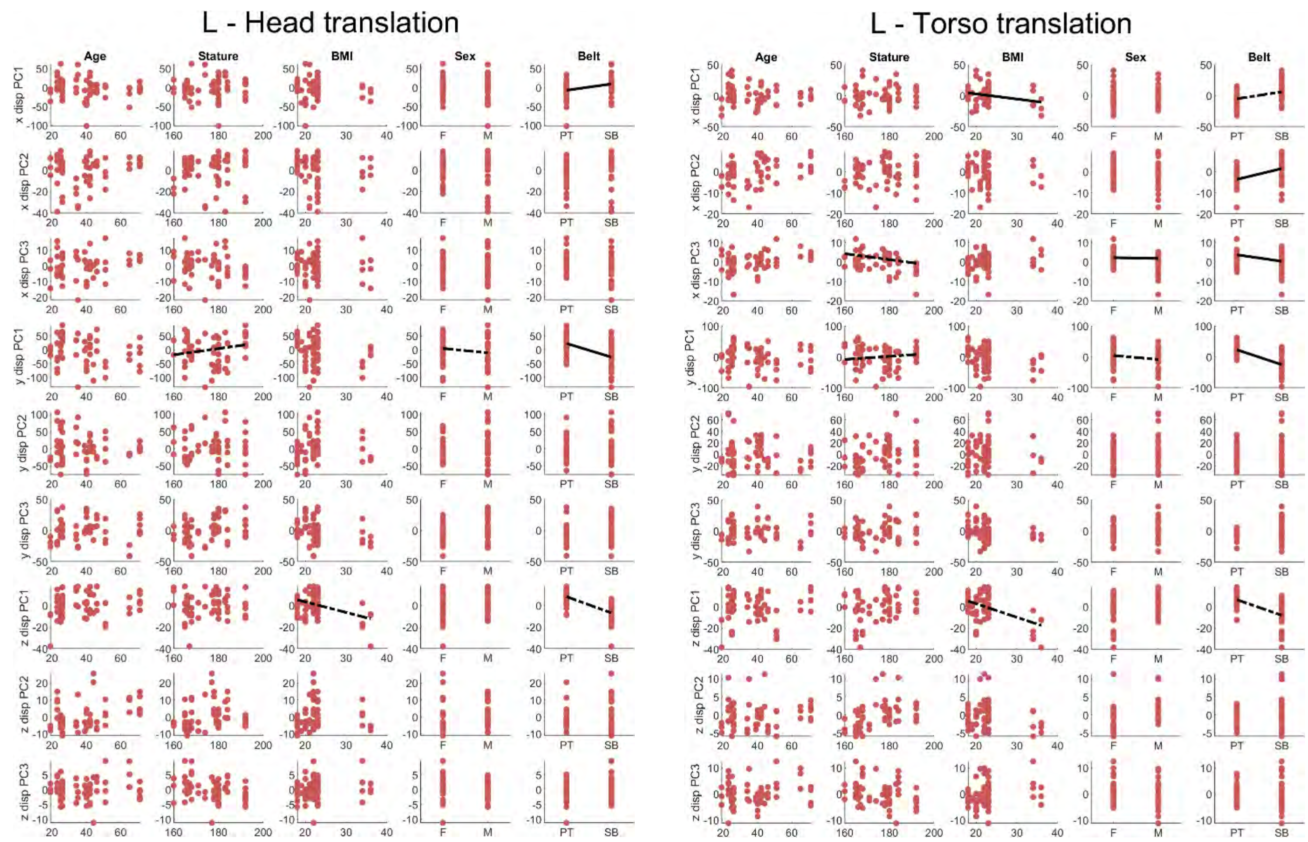


a) Head translation *b) Torso translation*

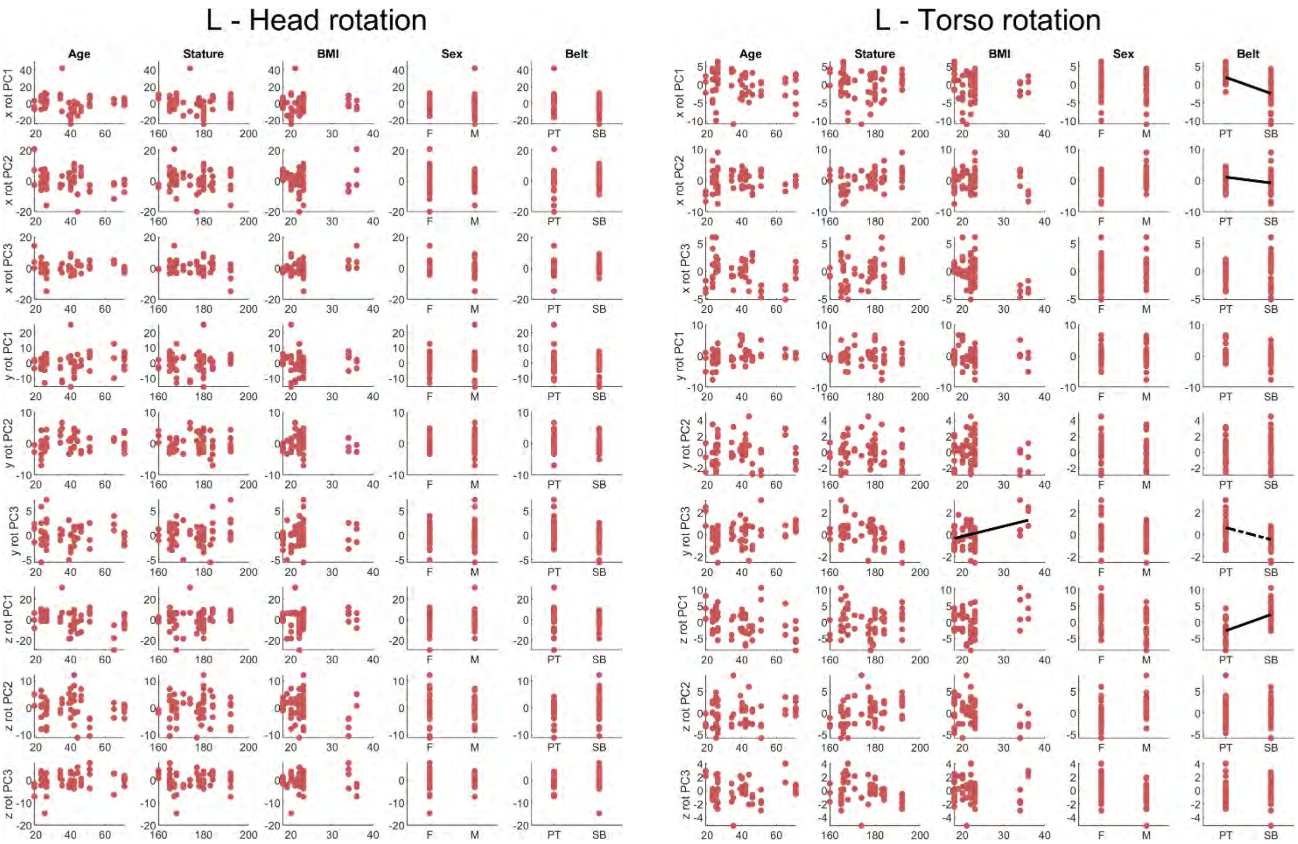


c) Head rotation *d) Torso rotation*

Fig. D. 1. First three principal component vectors for kinematics in lane change.



a) Head translation *b) Torso translation*



c) Head rotation *d) Torso rotation*

Fig. D. 2. Scatter plots of first three principal component scores for kinematics, and predictors in a lane change manoeuvre. For PCs with a predictive model, the line is created with the single predictor changed from the extremes. The baseline used for the other predictors is a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, vehicle equipped with a 50% standard belt. A solid line indicates a significant main effect, a dash-dotted line indicates a non-significant main effect.

E. Lane change with braking (LB)

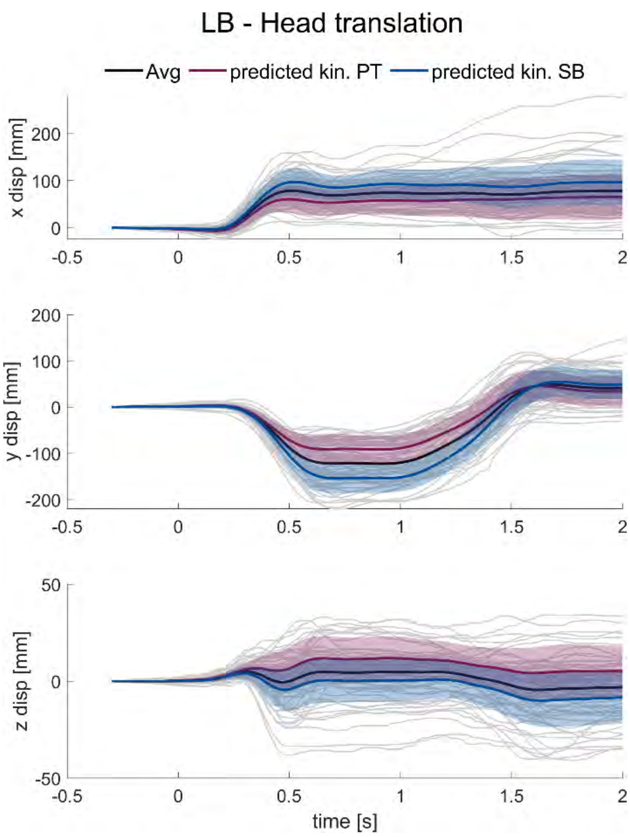
TABLE E. I

LINEAR MIXED MODEL FOR LANE CHANGE WITH BRAKING

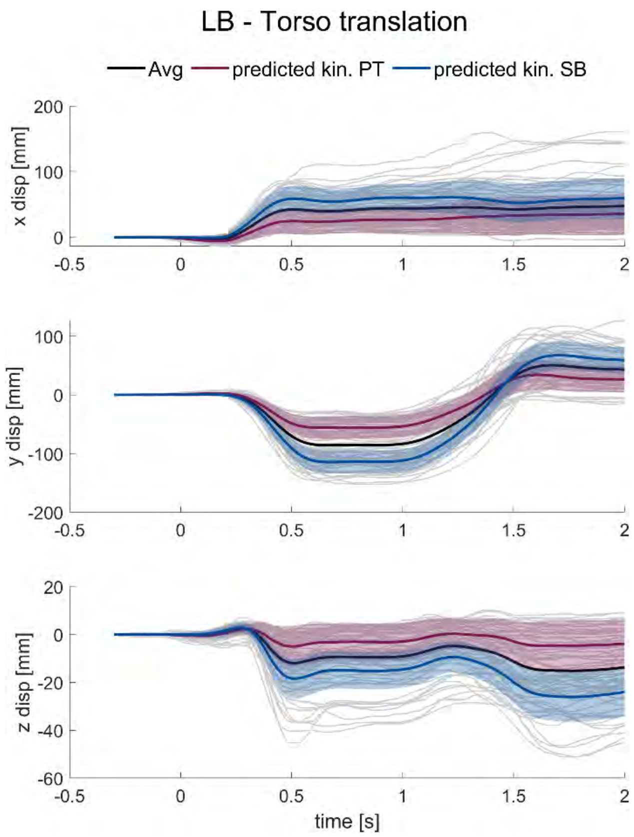
Comp	dir	PC	p-val	Intercept [mm]	Sex (F=0) [mm]	Stature (cm) [mm/cm]	BMI (kg/m^2) [mm/(kg/m^2)]	Belt (PT=0) [mm]	Sex*Belt [mm]	Stature*Belt [mm/cm]	BMI*Belt [mm/(kg/m^2)]	Residual [mm]	Individual specific effect [mm]
Head transl.	x	1	<0.001	-17.6				40.2***				23.0	42.6
		2	<0.001	-11.4				20.8***				15.2	11.9

	y	1	<0.001	-40.6	0.2	0.4		-430.5***	-41.5**	2.2**		17.6	23.8
	z	1	<0.001	-85.7		0.5		-81.9**		0.4**		5.0	11.6
Head rot.	x	1	<0.01	-9.8	5.4		0.5	17.3	-7.5*		-0.9*	6.3	7.7
Torso transl.	x	1	<0.001	47.7	11.7	-0.4		263***		-1.3**		15.1	26.3
		2	<0.001	-9.1				17***				9.0	6.4
	y	1	<0.001	-22.5	-6.4	0.3		-248.7**	-18.7*	1.1*		10.1	15.0
	z	1	<0.001	9.6				-18.9***				3.5	9.1
		2	<0.001	2.5	-3.4*			-2.6***				2.7	2.6
Torso rot.	x	1	<0.001	3.1				-5.9***				2.1	2.8
		2	<0.001	-1.8	3.1**			1.5***				1.6	1.9
	y	1	<0.001	1.1				-2.8***				2.2	3.5
		2	<0.001	0.8				-1.4***				1.5	1.5
	z	2	<0.001	1.7				-3.6***				1.7	2.0

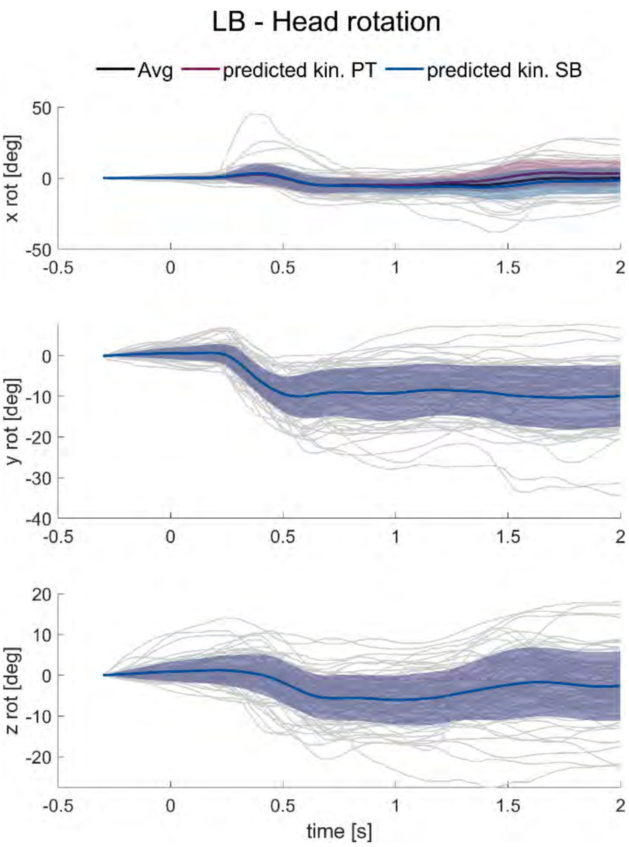
*** p-val<0.001
** p-val<0.01
* p-val<0.05



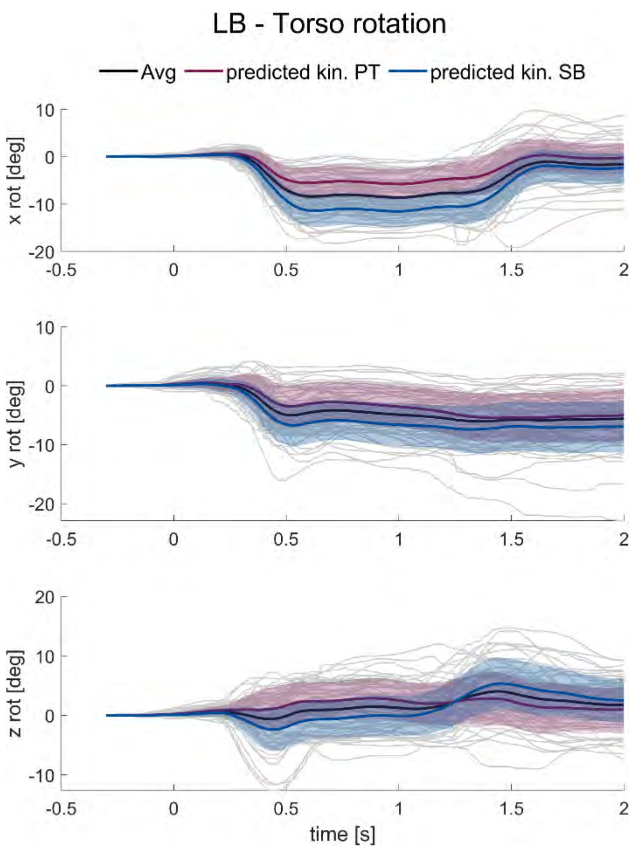
a) Head translation



b) Torso translation

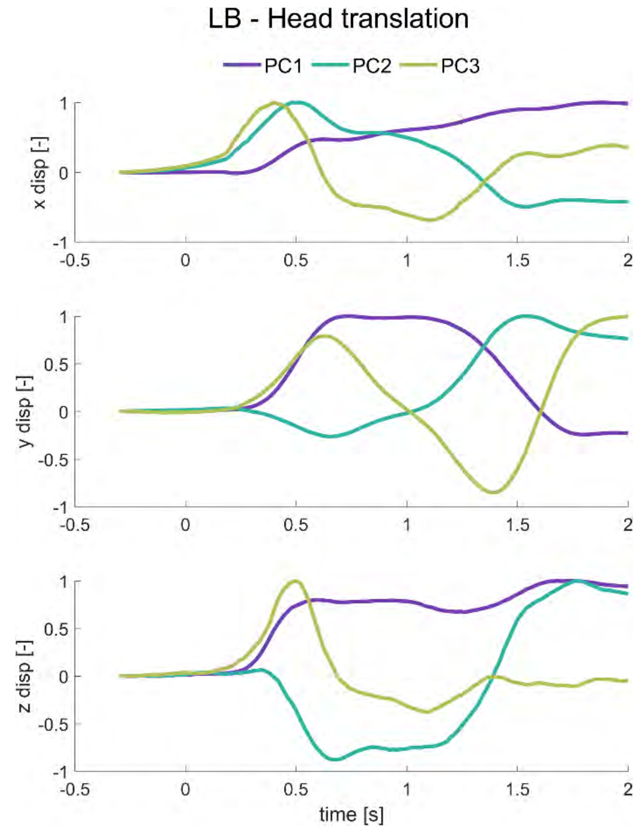


c) Head rotation

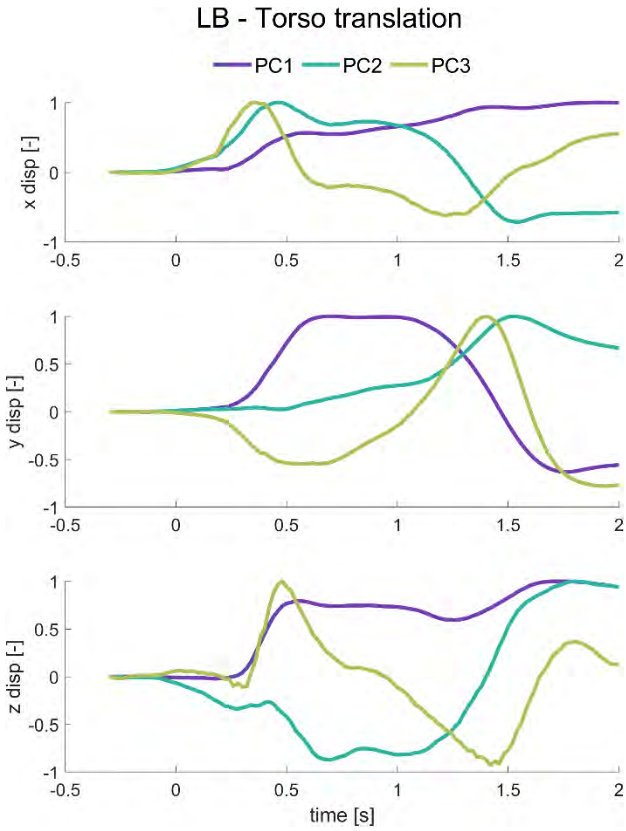


d) Torso rotation

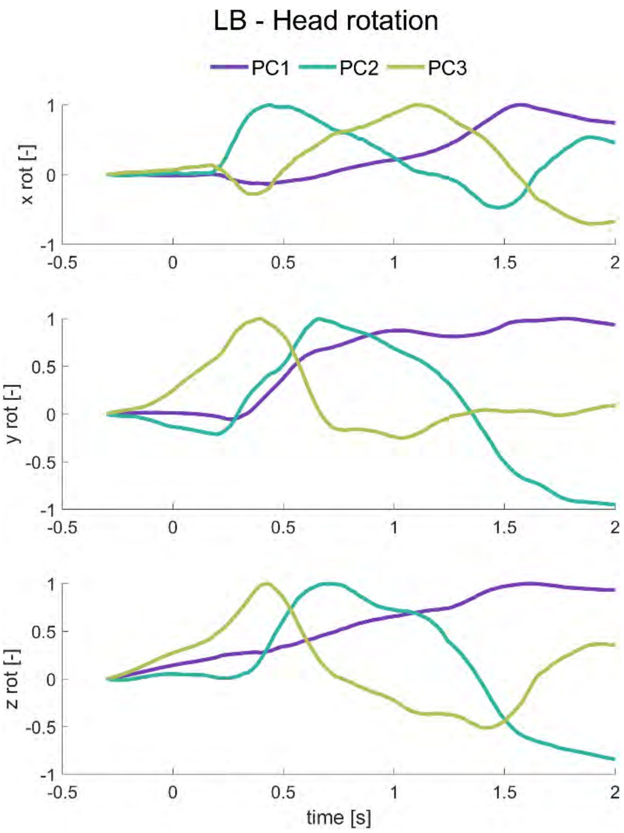
Fig. E. 1. Predicted kinematics (red/blue line) and corridors (filled red/blue) in a lane change with braking manoeuvre, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, in a vehicle equipped with a pre-tensioned belt (red) and standard belt (blue). Grey curves are individual kinematics from both manoeuvres with standard and pre-tensioned belt, males and females, and the black curve are the average of these kinematics.

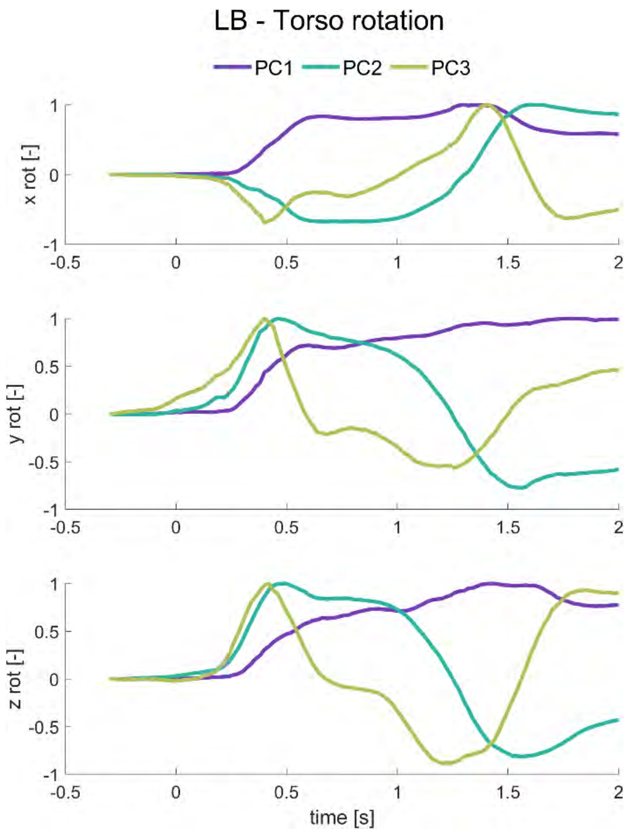


a) Head translation



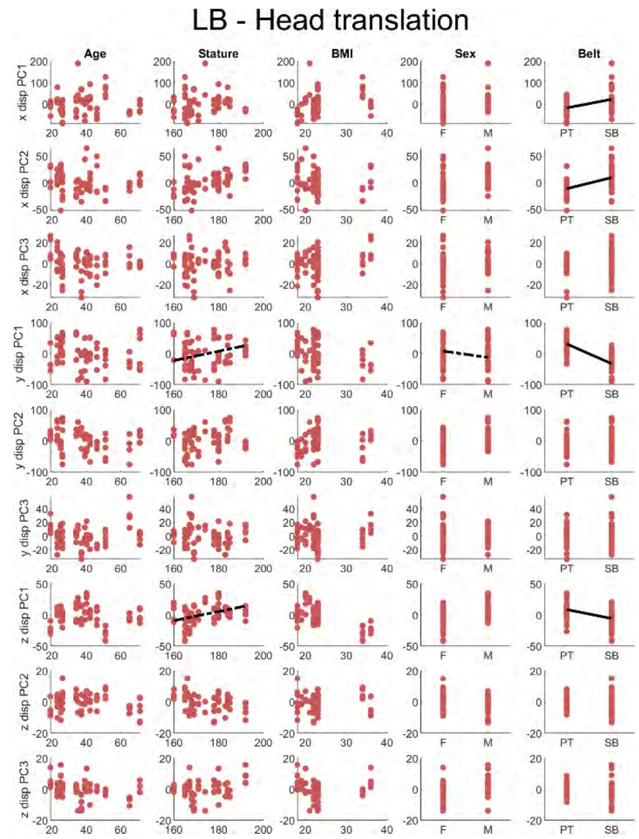
b) Torso translation

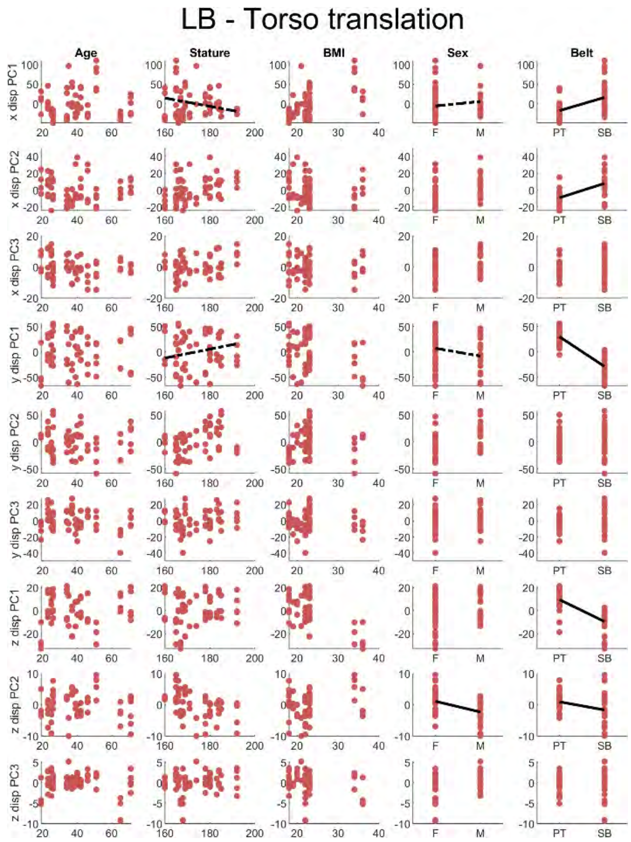




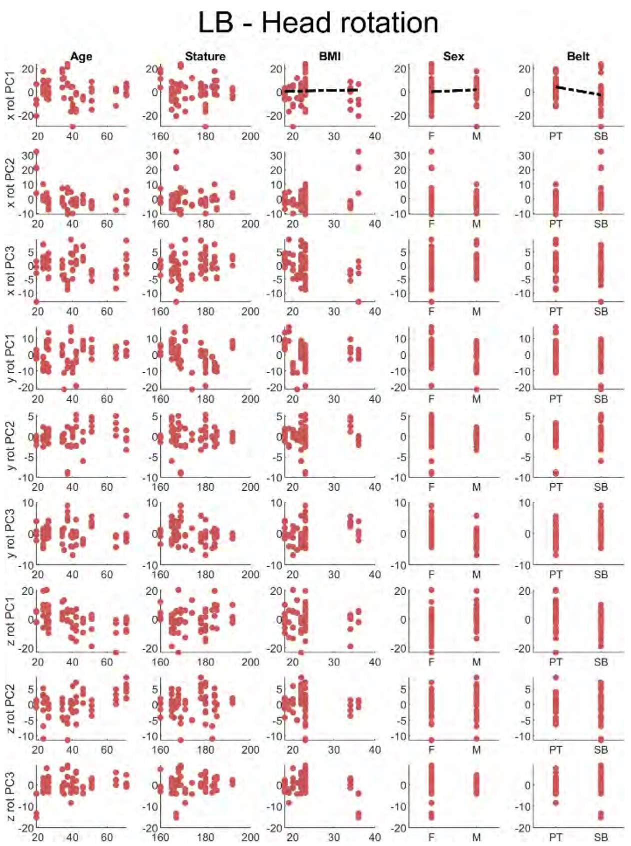
c) Head rotation *d) Torso rotation*

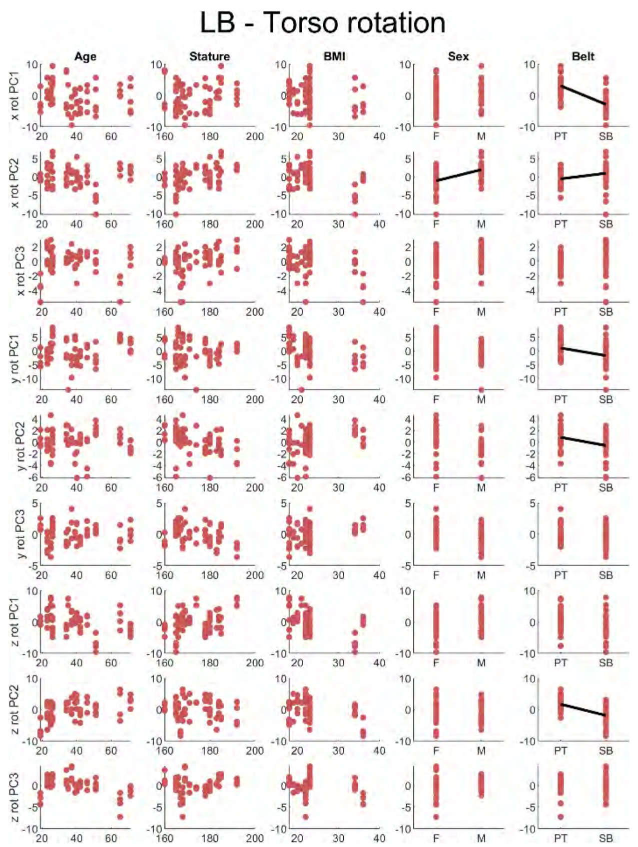
Fig. E. 2. First three principal component vectors for kinematics in lane change with braking.





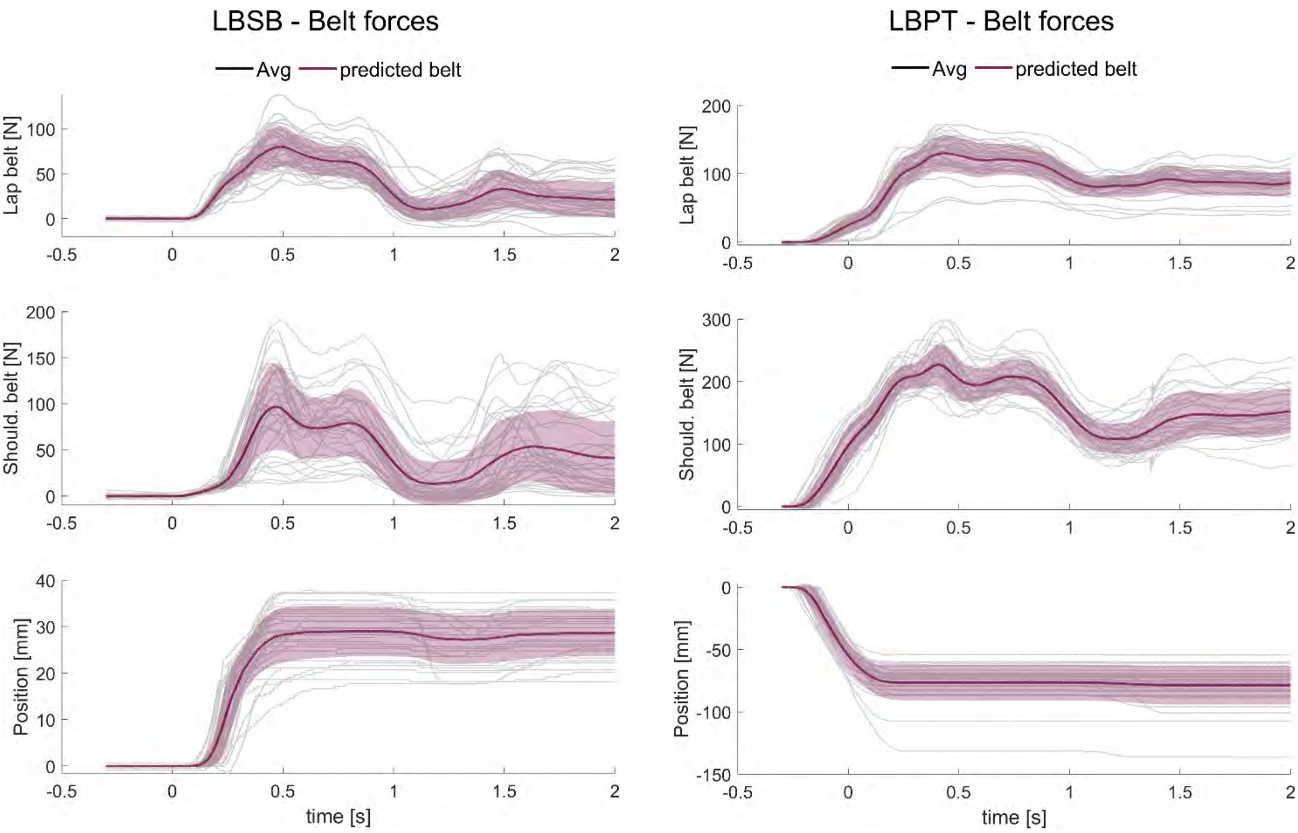
a) Head translation *b) Torso translation*





c) Head rotation *d) Torso rotation*

Fig. E. 3. Scatter plots of first three principal component scores for kinematics, and predictors in a lane change with braking manoeuvre. For PCs with a predictive model, the line is created with the single predictor changed from the extremes. The baseline used for the other predictors is a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, vehicle equipped with a 50% standard belt. A solid line indicates a significant main effect, a dash-dotted line indicates a non-significant main effect.



a) LBSB *b) LBPT*

Fig. E. 4. Predicted belt forces and positions (red line) and corridors (filled red) in a lane change with braking manoeuvre with standard (a) and pre-tensioned (b) belt, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. Grey curves are individual belt forces and positions, males and females, and the black curve are the average of these forces and positions.

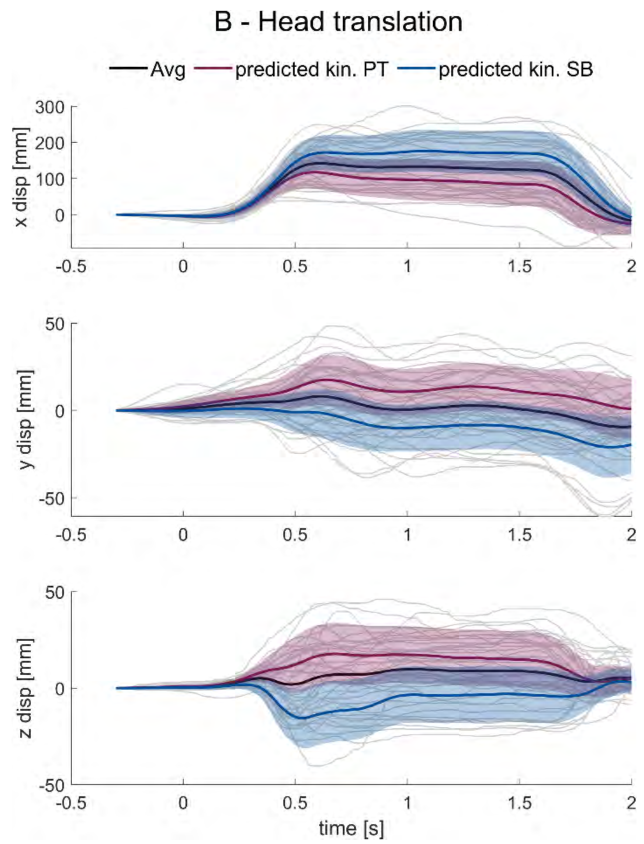
F. Braking, standard and pre-tensioned belt (BPT)

TABLE F. I

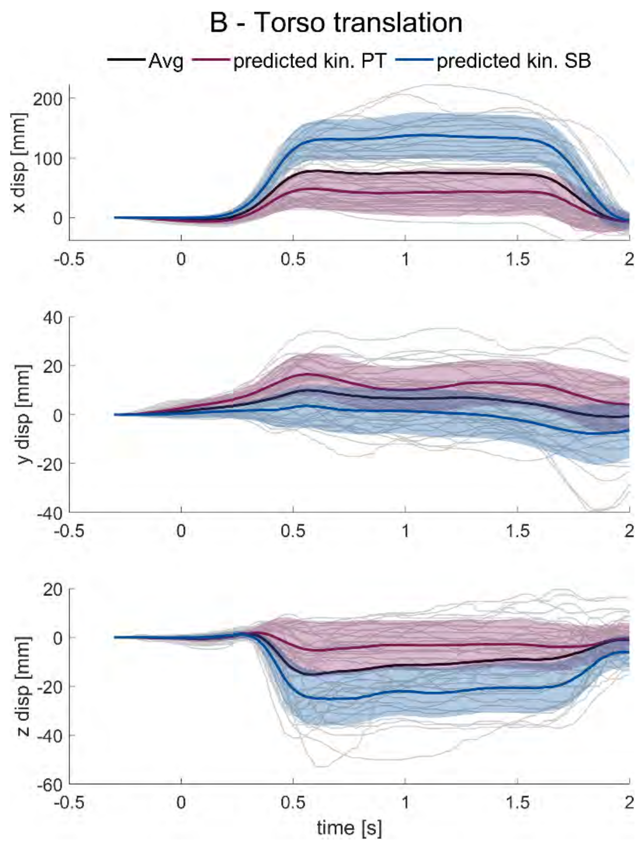
LINEAR MIXED MODELS FOR KINEMATICS IN BRAKING (STANDARD AND PRE-TENSIONED BELT)

Comp	dir	PC	p-val	Intercept [mm]	Sex (F=0) [mm]	BMI (kg/m^2) [mm/(kg/m^2)]	Belt (PT=0) [mm]	Sex*Belt [mm]	BMI*Belt [mm/(kg/m^2)]	Residual [mm]	Individual specific effect [mm]
Head transl.	x	1	<0.001	-40.3			86.6***			41.0	45.8
	y	1	<0.001	12.3			-24.9***			13.0	7.4
		1	<0.01	-7.0		0.7	82		-4.7*	12.1	9.2
		2	<0.001	3.9			-8.6***			5.0	5.6
	z	3	<0.001	-0.5	-1.7		-5.9*	13.1***		4.3	3.6
Head rot.	y	2	<0.01	-1.4			3.8**			3.2	3.7
Torso transl.		1	<0.001	-137.8		4.6	-127.3		9.8*	23.3	31.2
	x	2	<0.001	8.5			-16.5***			12.6	13.0
		1	<0.001	7.0			-14.6***			8.7	5.2
	y	3	<0.001	-3.4	2.4**		3.5***			2.4	0.0
		1	<0.001	8.1			-20.1***			5.9	8.6
		2	<0.001	-10.7		0.6	-50.4***		2.1**	3.2	4.8
	z	3	<0.01	-2.6	1.4		-3.1	8.9**		3.8	3.5
Torso rot.	x	1	<0.001	2.5			-5.2***			1.9	2.4
		1	<0.001	12.7		-0.5	21.9		-1.3*	3.3	2.1
	y	3	<0.01	1.2			-2.4**			2.0	1.0

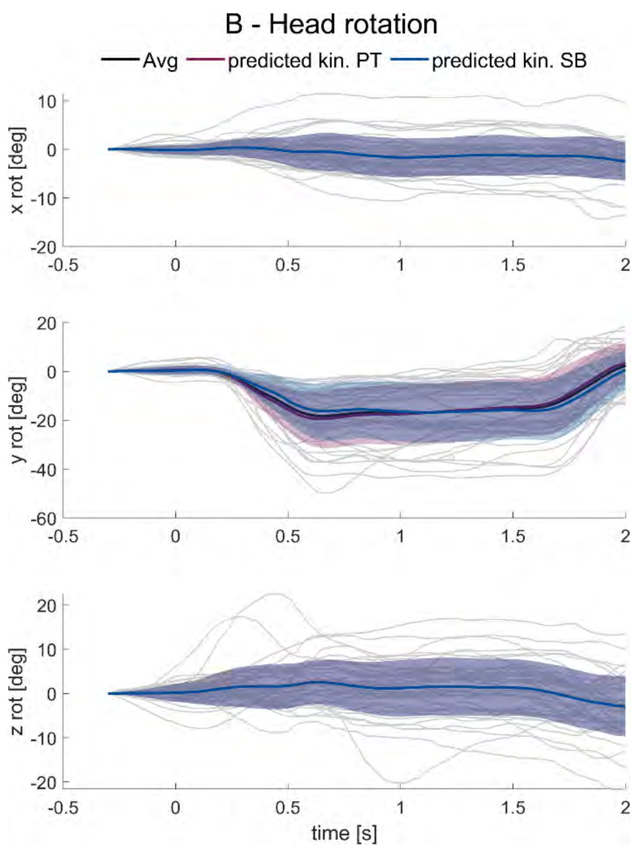
*** p-val<0.001
** p-val<0.01
* p-val<0.05



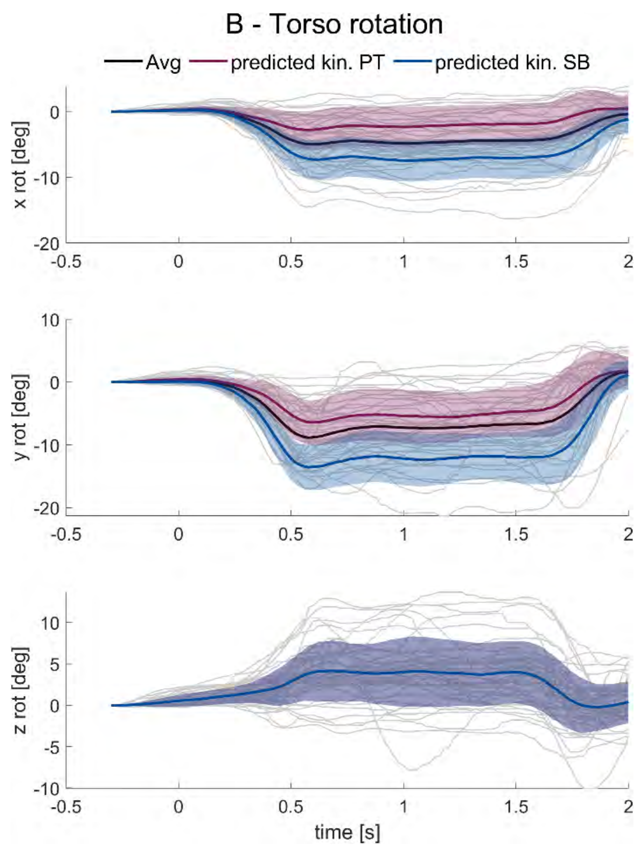
a) Head translation



b) Torso translation

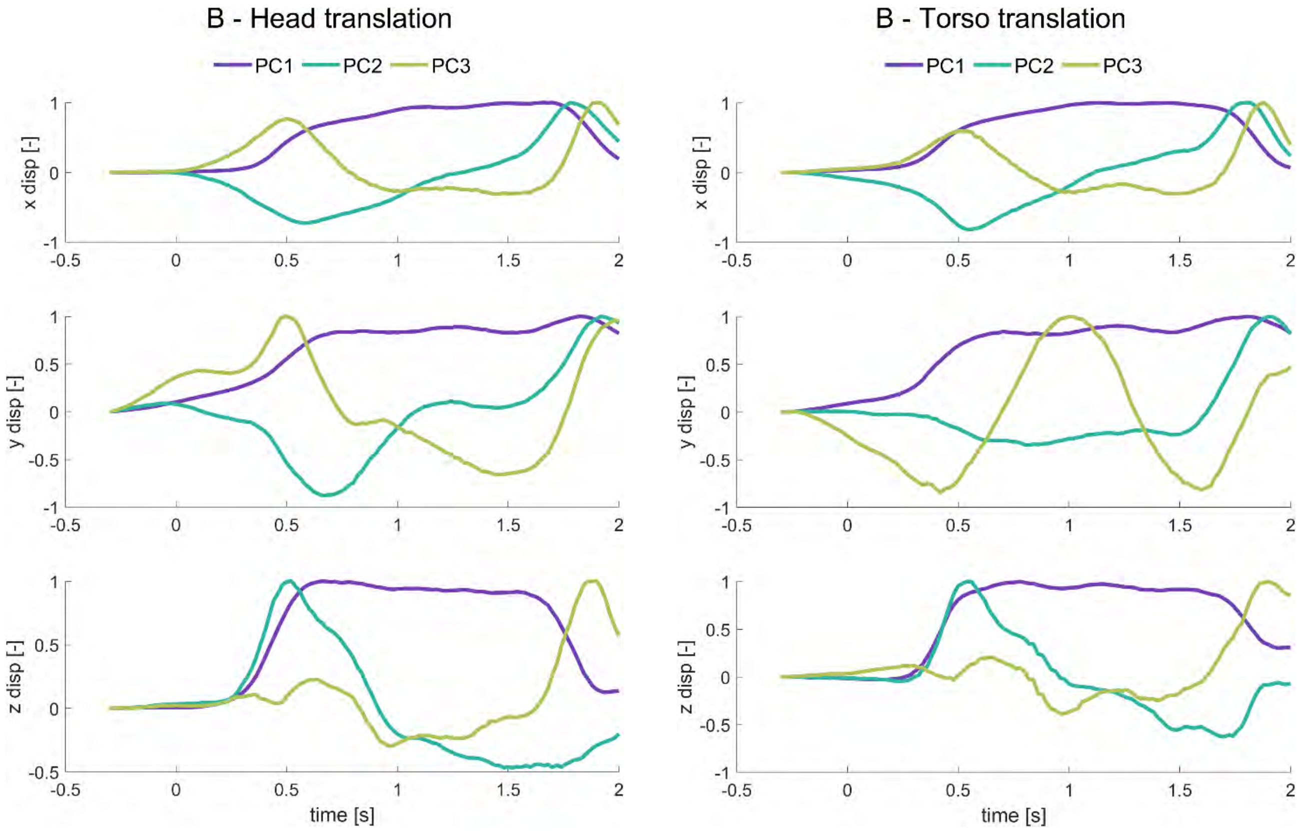


c) Head rotation

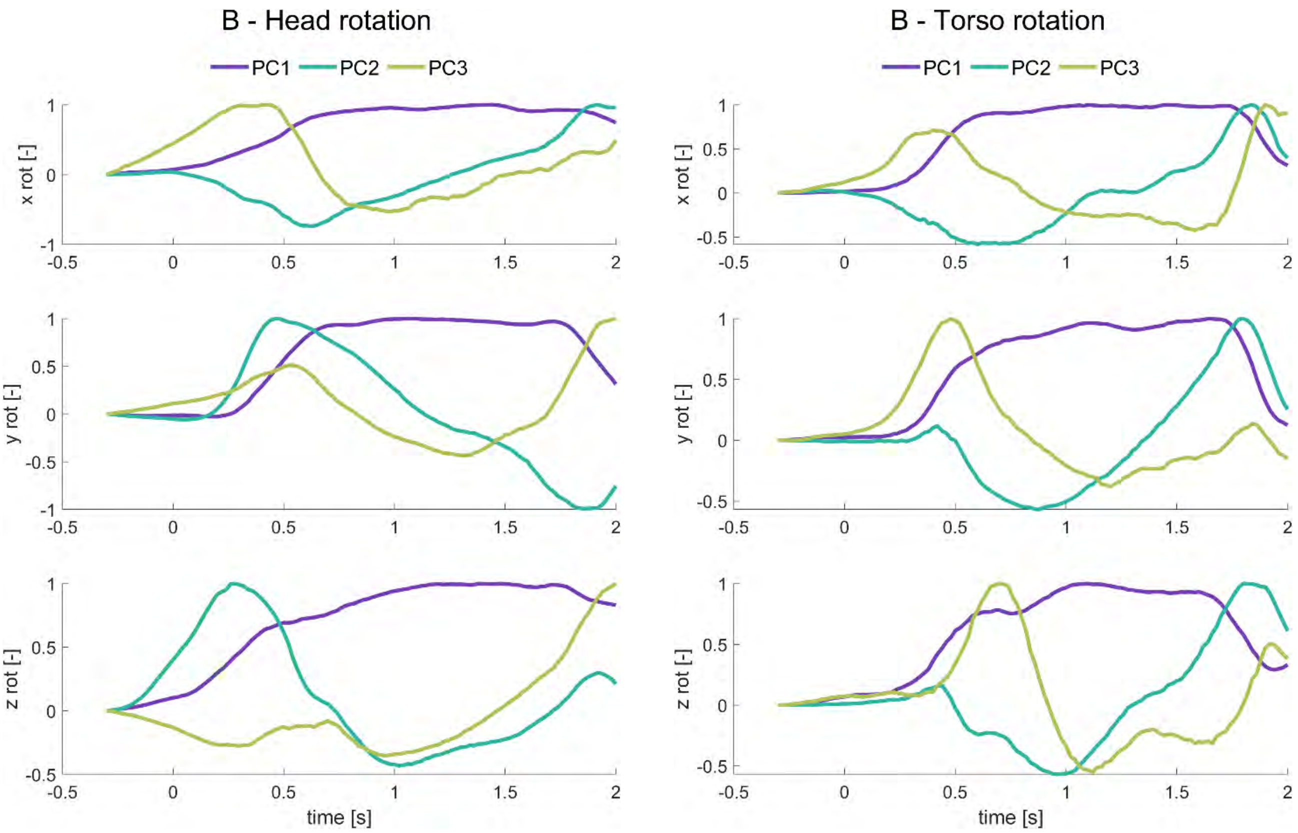


d) Torso rotation

Fig. F. 1 Predicted kinematics (red/blue line) and corridors (filled red/blue) in a braking manoeuvre, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, in a vehicle equipped with a pre-tensioned belt (red) and standard belt (blue). Grey curves are individual kinematics from both manoeuvres with standard and pre-tensioned belt, males and females, and the black curve are the average of these kinematics.

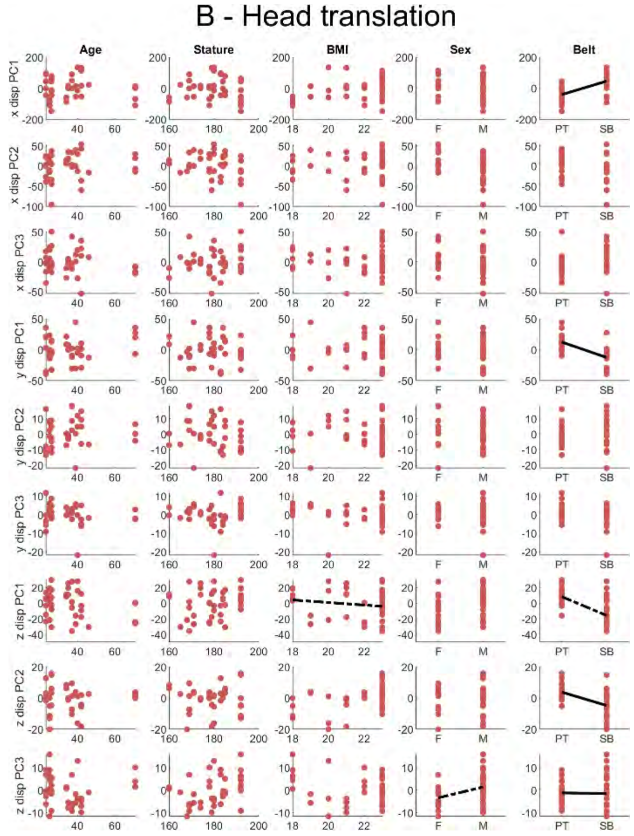


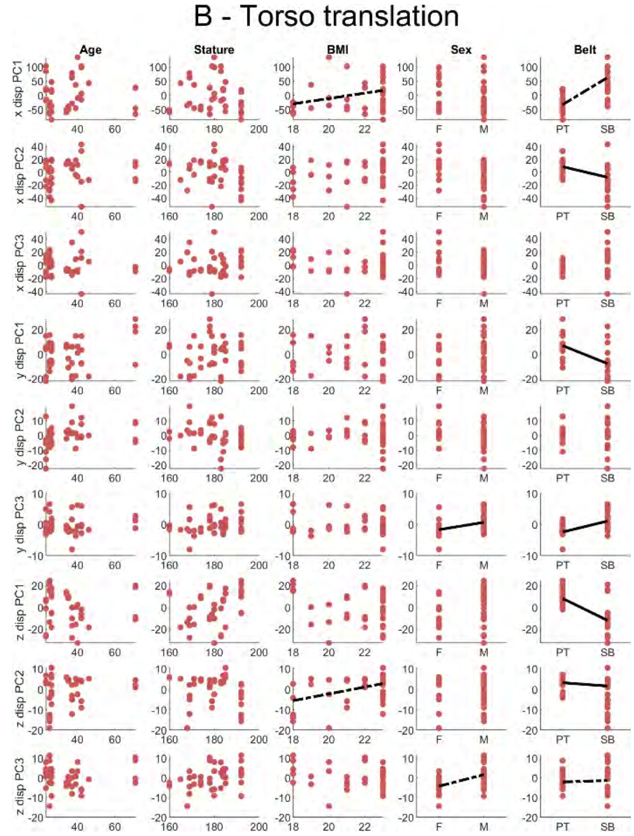
a) Head translation *b) Torso translation*



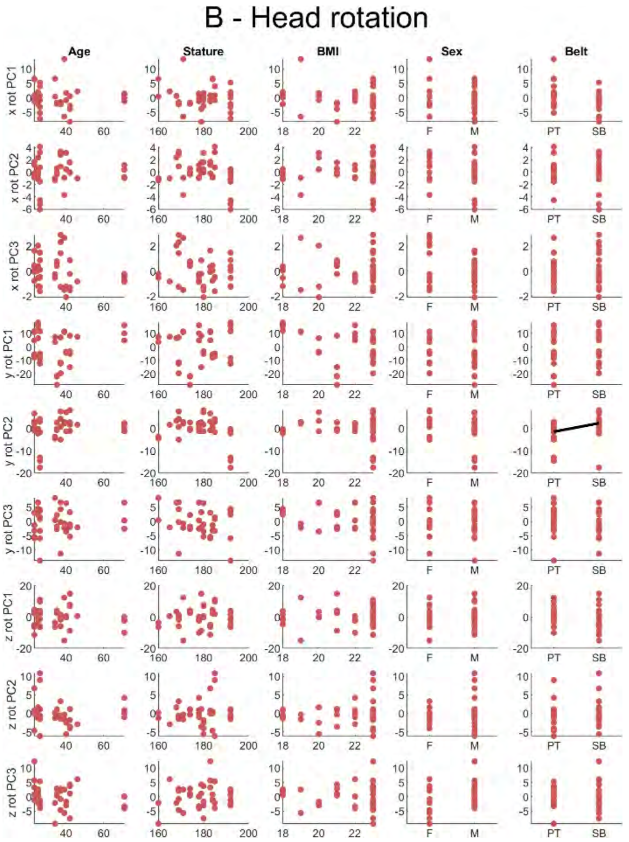
c) Head rotation *d) Torso rotation*

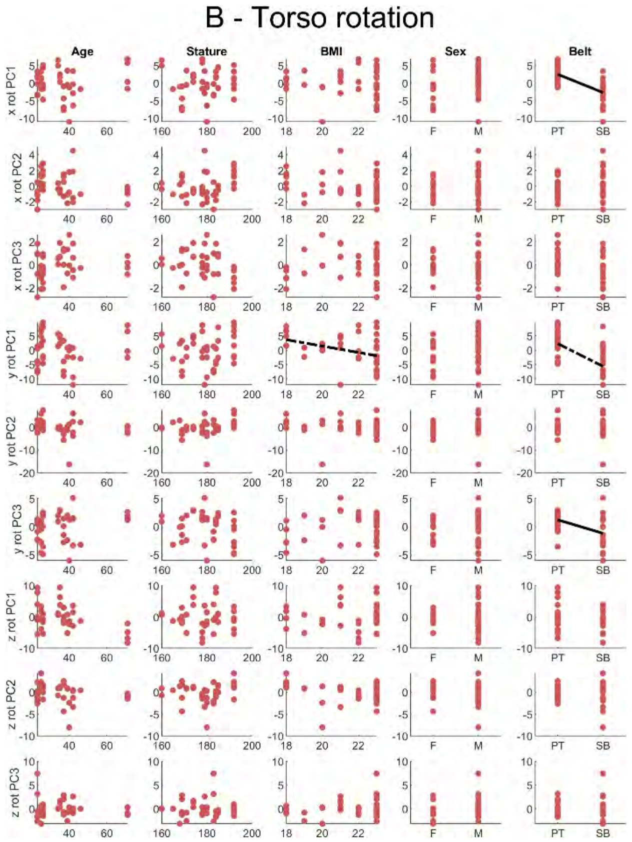
Fig. F. 2 First three principal component vectors for kinematics braking (standard and pre-tensioned belt).





a) Head translation *b) Torso translation*





c) Head rotation *d) Torso rotation*

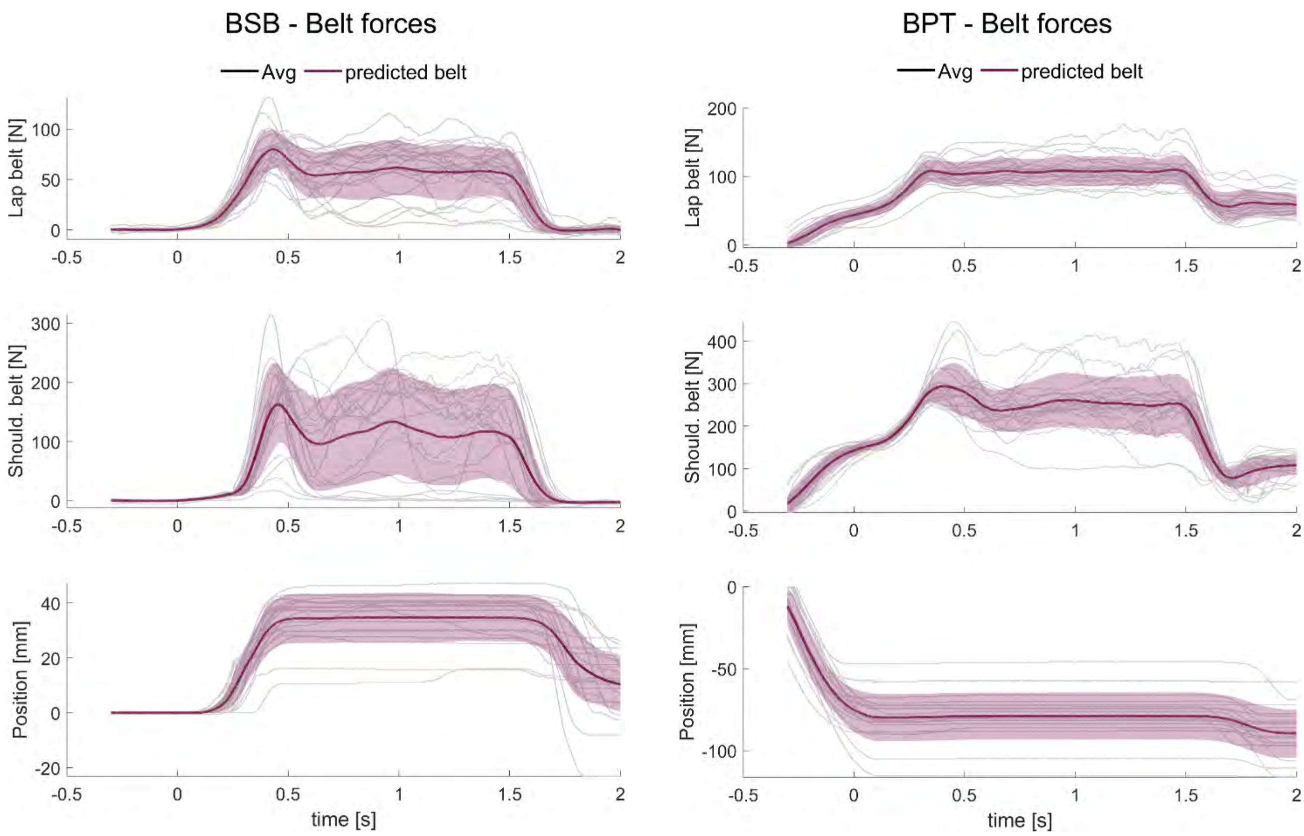
Fig. F. 3 Scatter plots of first three principal component scores for kinematics, and predictors in a braking manoeuvre. For PCs with a predictive model, the line is created with the single predictor changed from the extremes. The baseline used for the other predictors is a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, vehicle equipped with a 50% standard belt. A solid line indicates a significant main effect, a dash-dotted line indicates a non-significant main effect.

TABLE F. II

LINEAR MIXED MODELS FOR BELT FORCES IN BSB.

Comp	PC	p-val	Intercept [mm]	Sex (F=0) [mm]	Stature [mm/cm]	Residual [mm]	Individual specific effect [mm]
Belt position	2	<0.01	-211.0	-31.1**	1.3**	10.3	0.0

*** p-val<0.001
** p-val<0.01
* p-val<0.05



a) BSB *b) LPT*

Fig. F. 4 Predicted belt forces and positions (red line) and corridors (filled red) in a braking manoeuvre with standard (a) and pre-tensioned (b) belt, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. Grey curves are individual belt forces and positions, males and females, and the black curve are the average of these belt forces and positions.

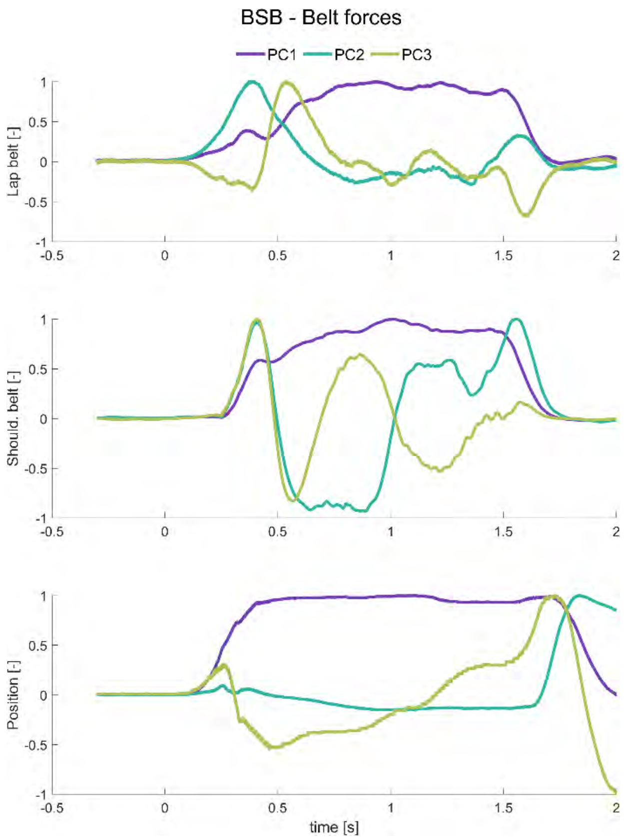


Fig. F. 5 First three principal component vectors for belt forces and position in BSB.

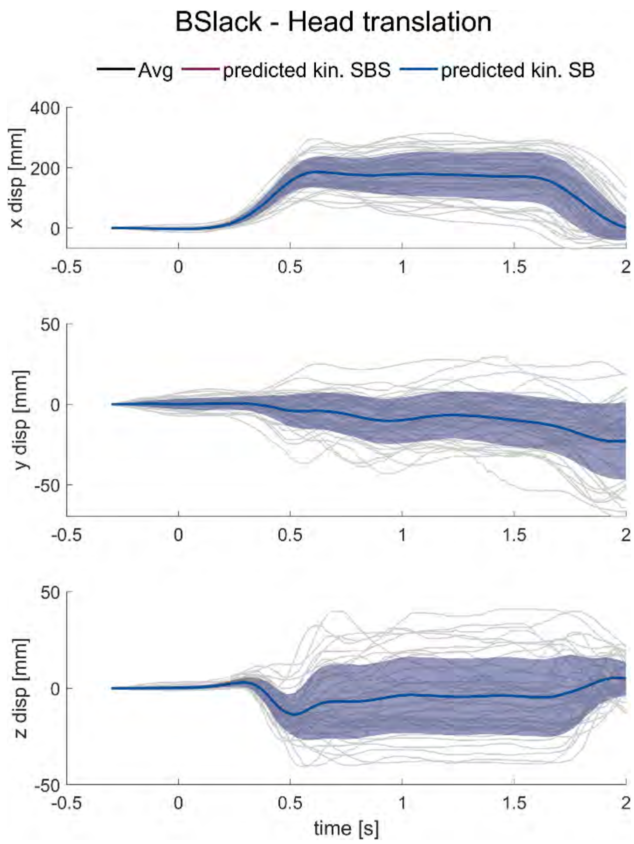
G. Braking, standard and standard slack belt (BSlack)

TABLE G. I

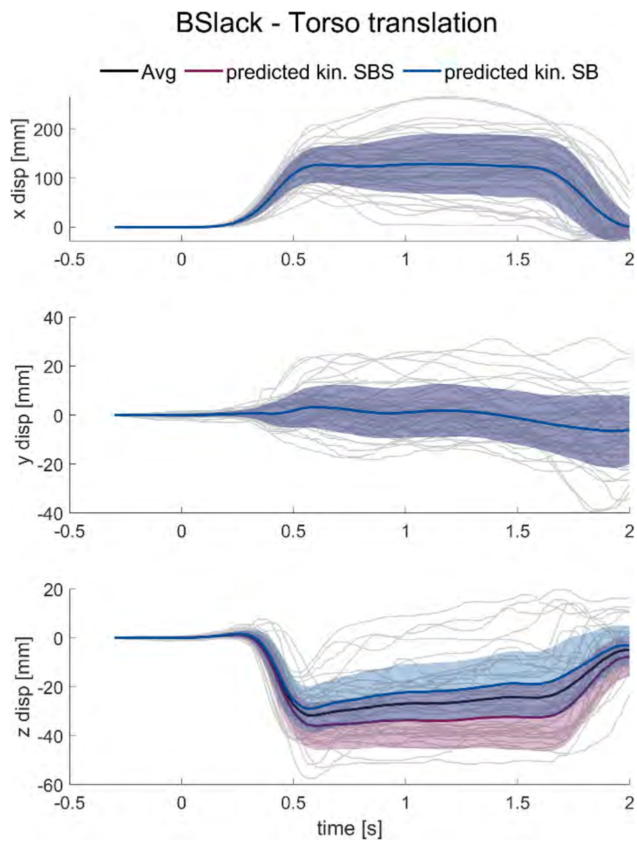
LINEAR MIXED MODELS FOR BRAKING (STANDARD BELT AND STANDARD BELT WITH SLACK)

Comp	**dir**	**PC**	**p-val**	**Intercept [mm]**	**Sex (F=0) [mm]**	**Belt (SB=0) [mm]**	**Sex*Belt**	**Residual [mm]**	Individual specific effect [mm]
Torso transl.	**z**	1	<0.001	4.6	2.8	-20.2***	13.9*	8.2	10.9

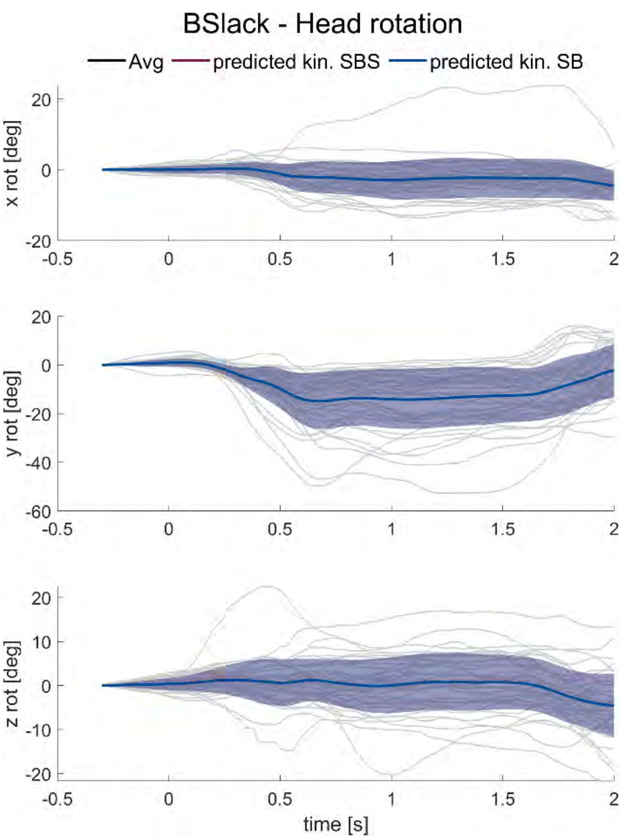
*** p-val<0.001
** p-val<0.01
* p-val<0.05



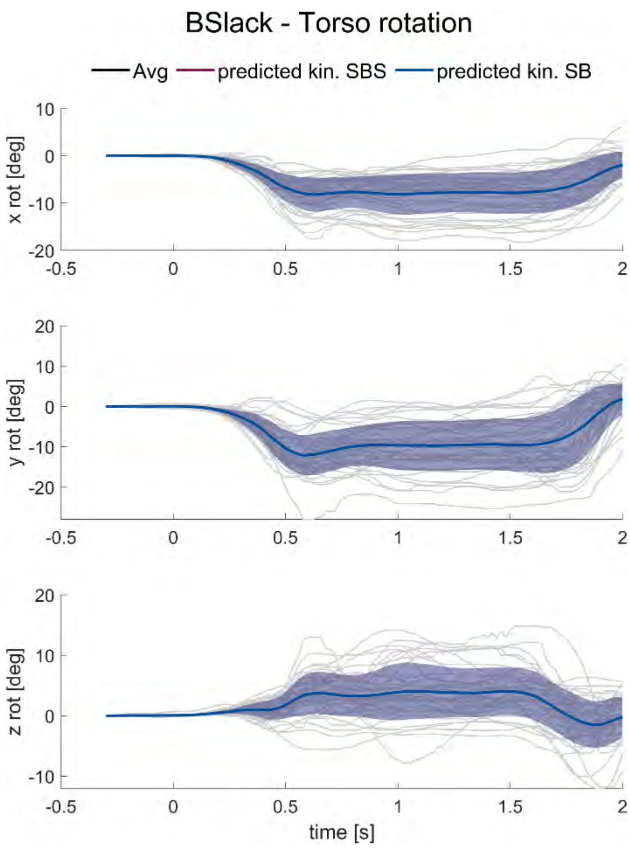
a) Head translation



b) Torso translation

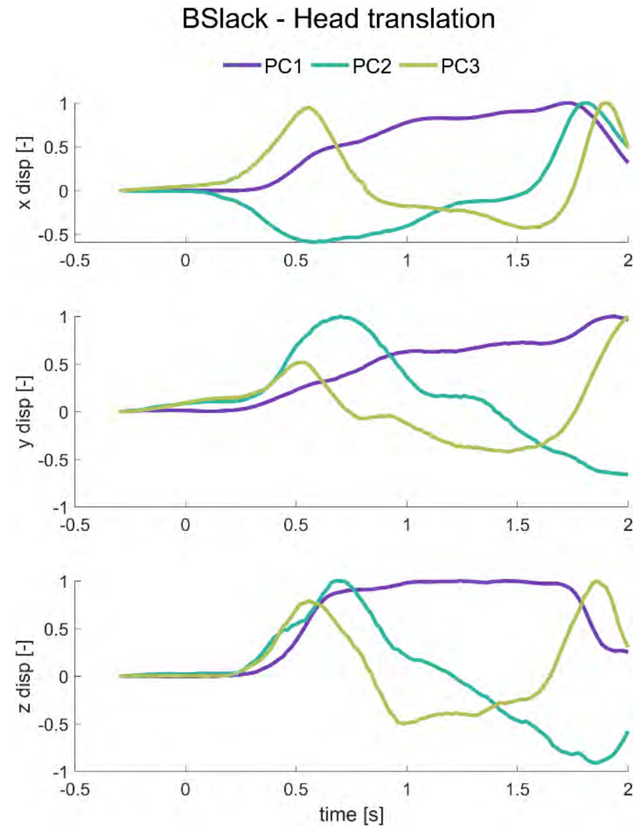


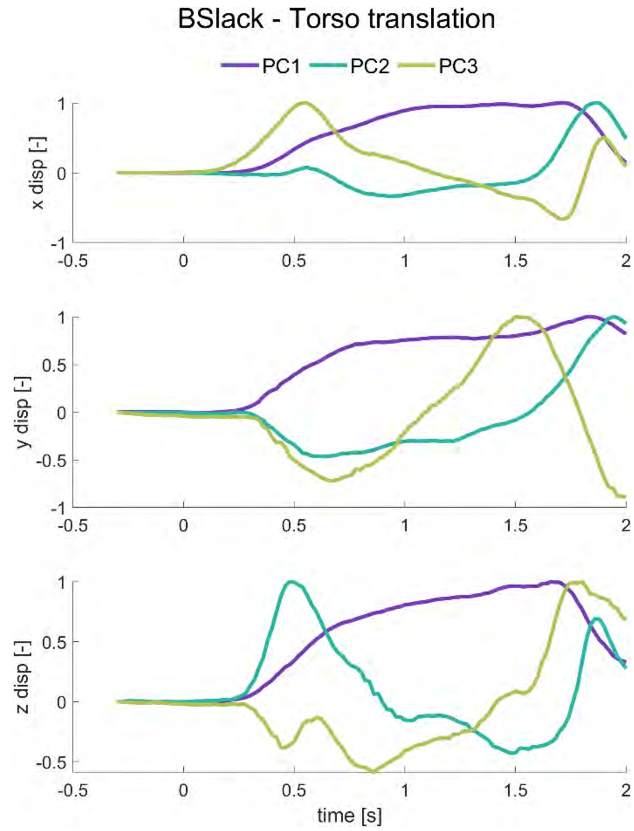
c) Head rotation



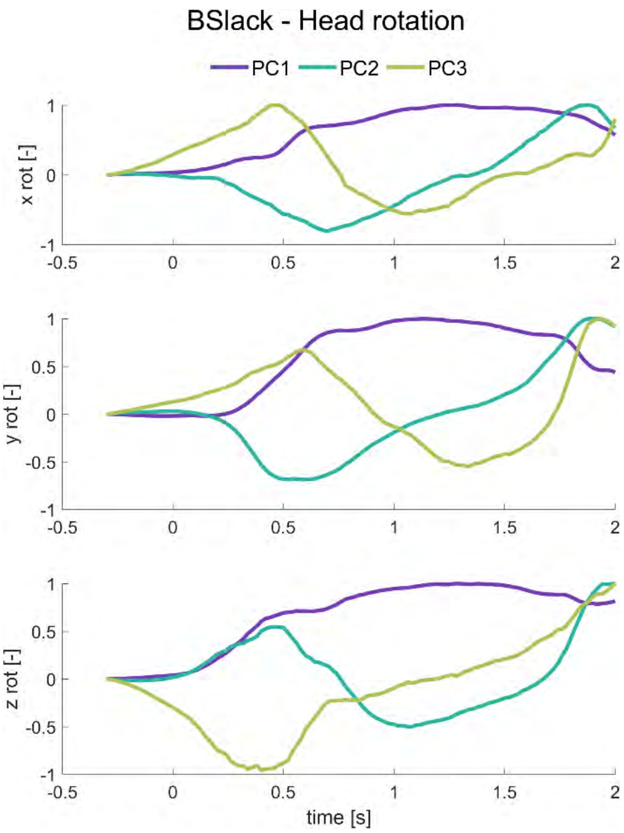
d) Torso rotation

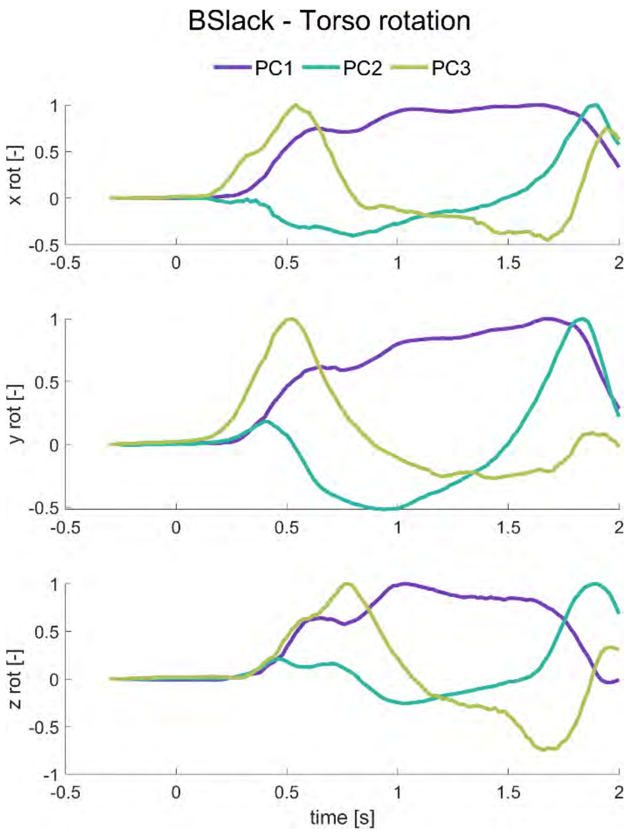
Fig. G. 1 Predicted kinematics (red/blue line) and corridors (filled red/blue) in a braking manoeuvre, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, in a vehicle equipped with a standard belt with slack (red) and standard belt (blue). Grey curves are individual kinematics from both manoeuvres with standard belt and standard belt with slack, males and females, and the black curve are the average of these kinematics.





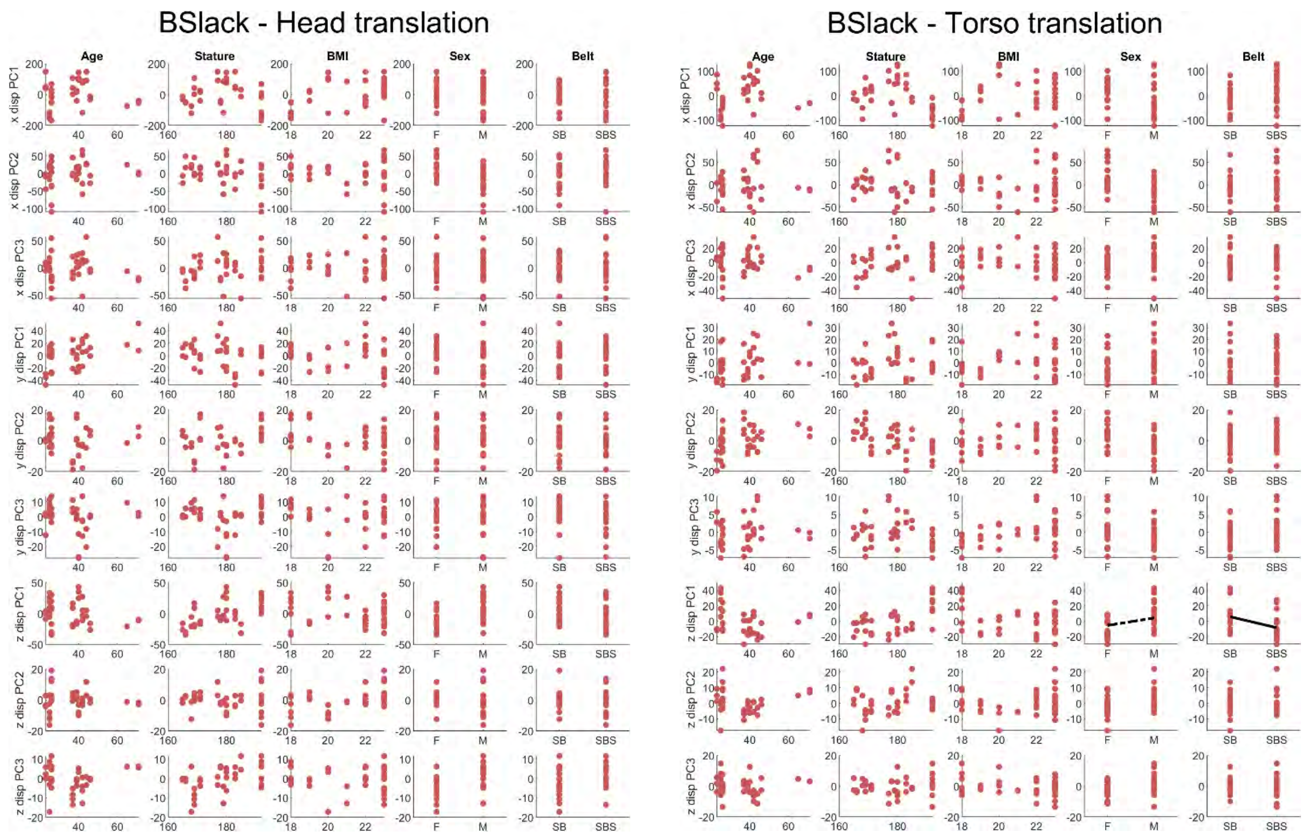
a) Head translation *b) Torso translation*



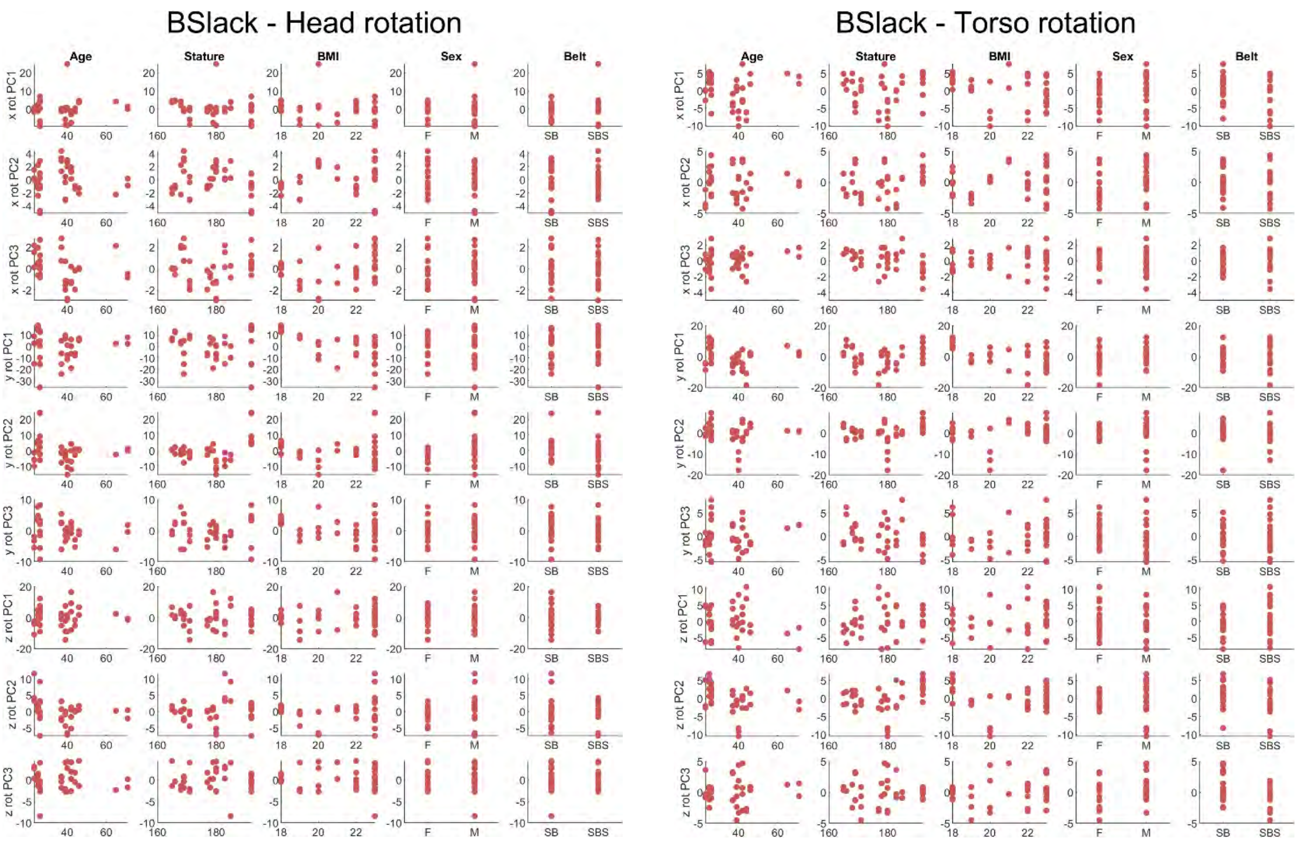


c) Head rotation *d) Torso rotation*

Fig. G. 2 First three principal component vectors for kinematics in braking (standard belt and standard belt with slack).



a) Head translation *b) Torso translation*



c) Head rotation *d) Torso rotation*

Fig. G. 3. Scatter plots of first three principal component scores for kinematics, and predictors, in a braking manoeuvre with standard belt and standard belt with slack. For PCs with a predictive model, the line is created with the single predictor changed from the extremes. The baseline used for the other predictors is a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, vehicle equipped with a 50% standard belt. A solid line indicates a significant main effect, a dash-dotted line indicates a non-significant main effect.

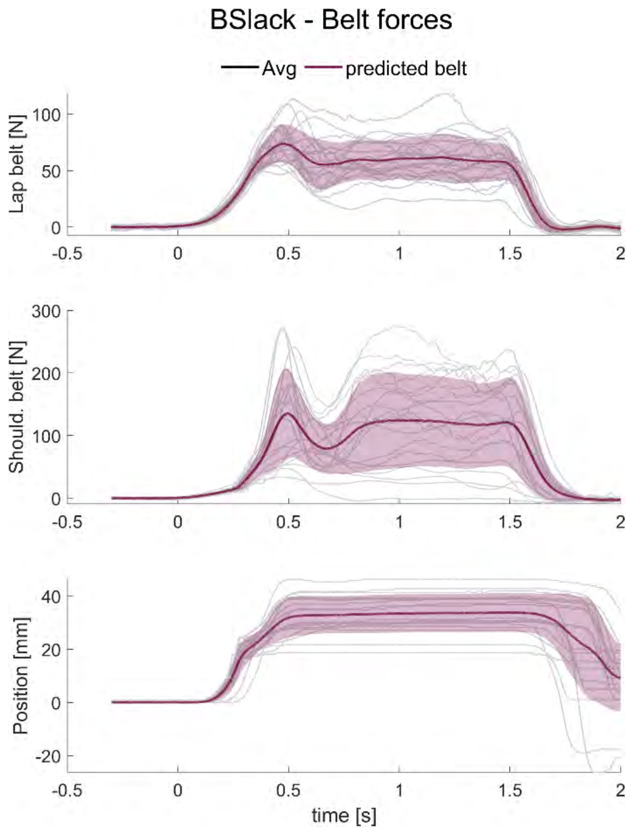


Fig. G. 4. Predicted belt forces and positions (red line) and corridors (filled red) in a braking manoeuvre with standard belt with slack, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. Grey curves are individual belt forces and positions, males and females, and the black curve are the average of these forces and positions.

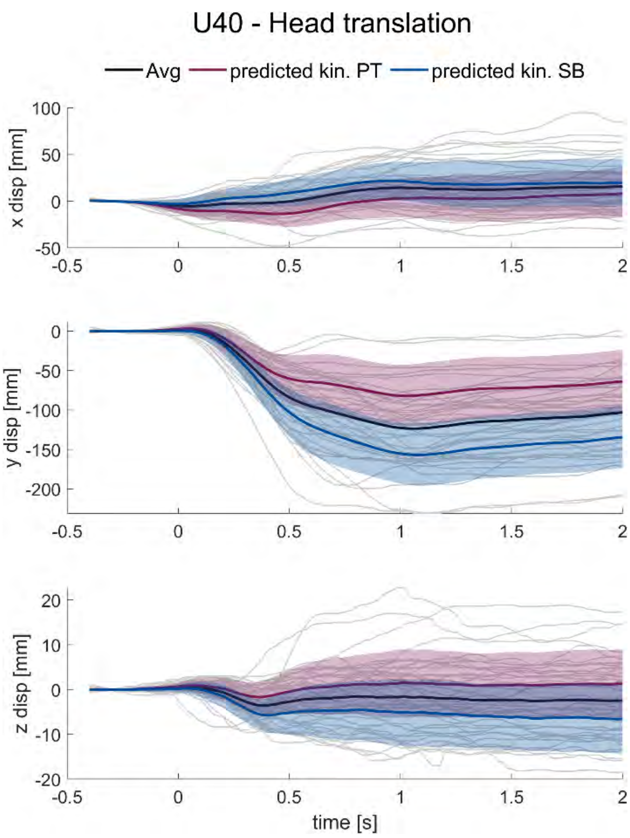
H. U-turn at 40 km/h, standard and pre-tensioned belt (U40)

TABLE H. I
LINEAR MIXED MODELS FOR U-TURN AT 40 KM/H

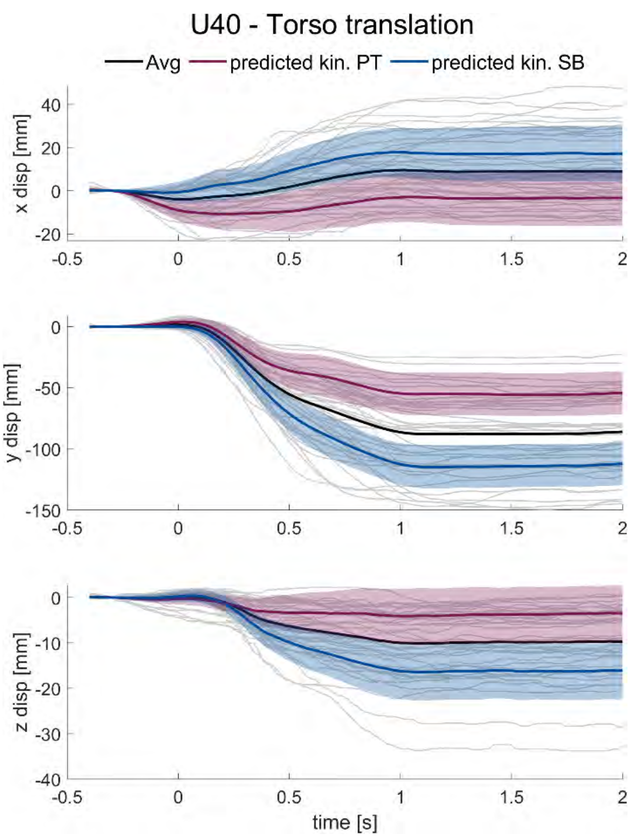
Comp	dir	PC	p-val	Intercept [mm]	Age (years) [mm/years]	Sex (F=0) [mm]	Stature (cm) [mm/cm]	BMI [mm/(kg/m^2)]	Belt [mm]	Sex*Belt [mm]	Stature*Belt [mm/cm]	Residual [mm]	Individual specific effect [mm]
Head transl.	x	1	<0.01	-11.9					19**			16.8	18.9
		2	<0.001	-7.8					13.7***			7.8	3.6
	y	1	<0.001	42.5					-76.5***			24.3	31.6
	z	1	<0.001	3.5					-7.4***			5.3	5.4
		3	<0.01	1.0					-2**			1.8	2.2

Head rot.	**x**	1	<0.01	8.7		-9*			-8.2***	5.7*		4.0	6.4
Torso transl.	**x**	1	<0.001	-148.9			0.8		179.6**		-0.9**	9.3	8.5
		2	<0.001	-2.9					4.8***			2.9	3.5
	y	1	<0.001	8.3	0.7*				-59.7***			12.8	12.0
	z	1	<0.001	6.0					-12.3***			2.6	5.8
		2	<0.001	-35.3			0.2***		41.5***		-0.2***	1.4	0.0
Torso rot.	**x**	1	<0.001	3.5					-6.8***			2.2	2.7
	y	1	<0.001	21.4	0.1**	-2.1*		-1.1***				2.3	0.0
	z	1	<0.001	2.4					-4.4***			1.3	3.4
		2	<0.001	0.7					-1.1***			0.9	0.5

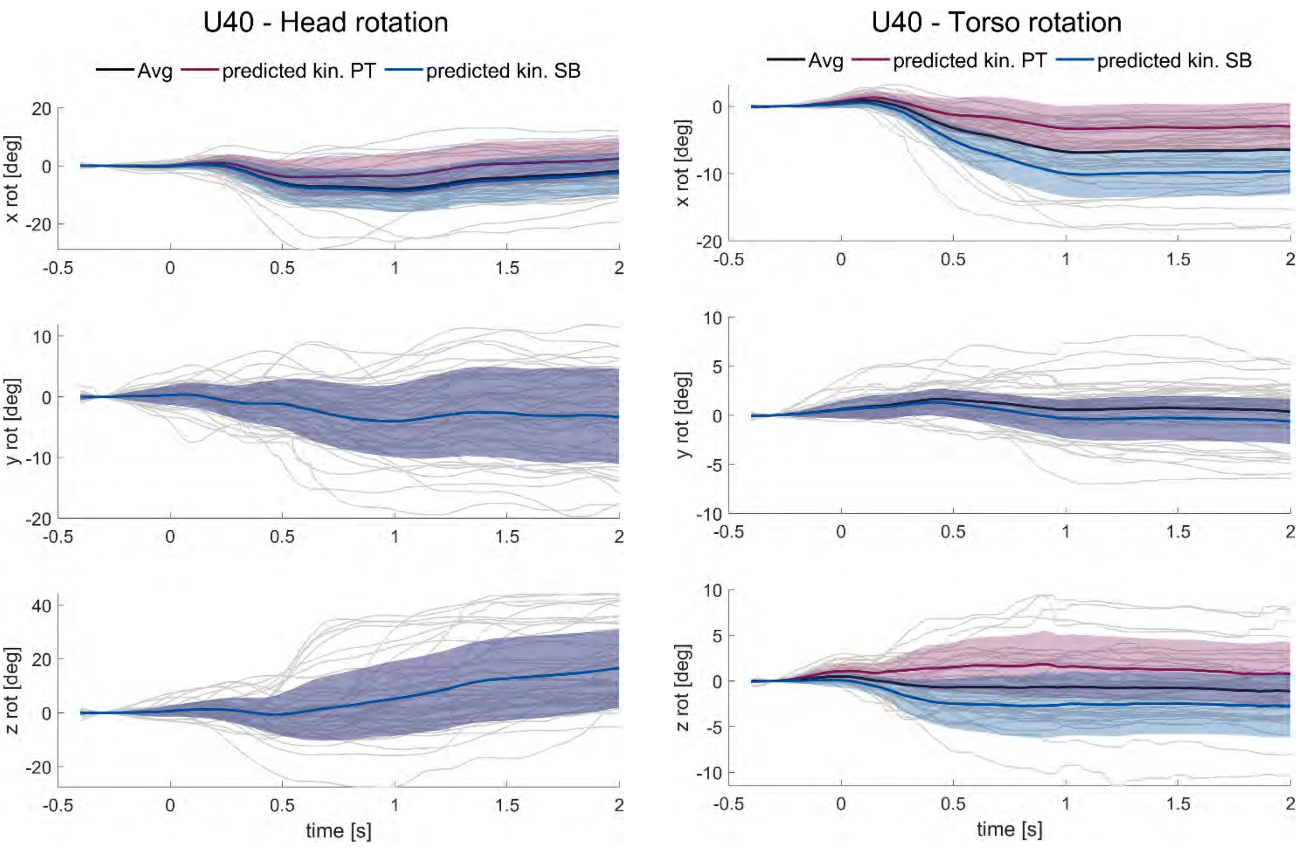
*** p-val<0.001
** p-val<0.01
* p-val<0.05



a) Head translation

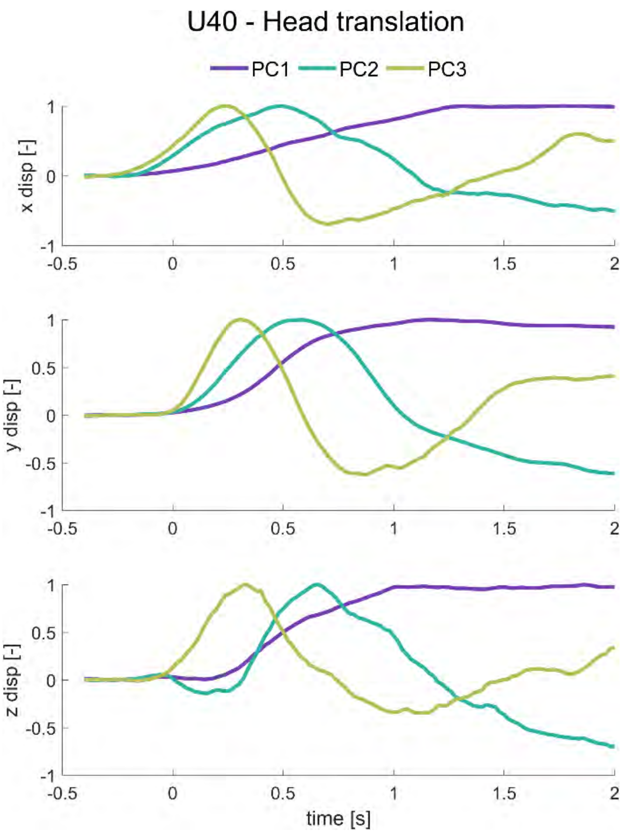


b) Torso translation

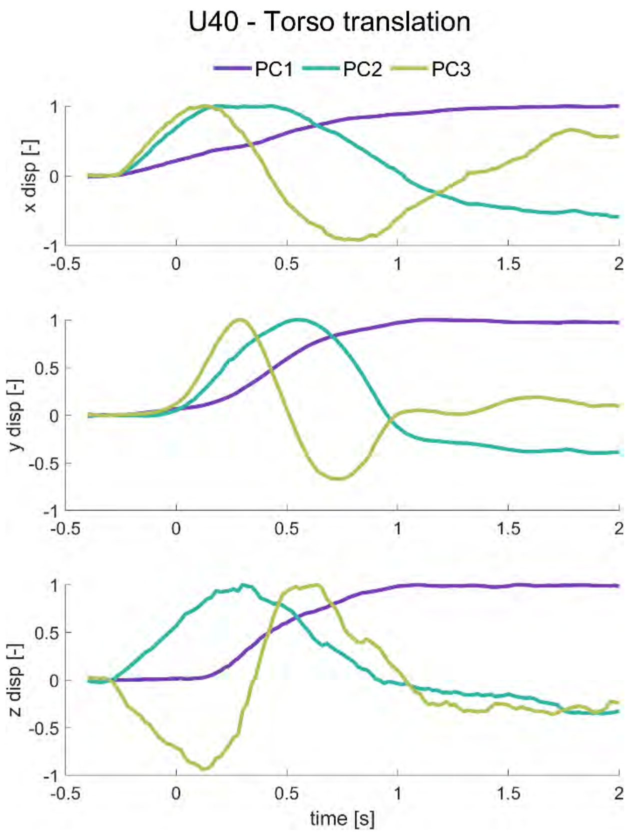


c) Head rotation *d) Torso rotation*

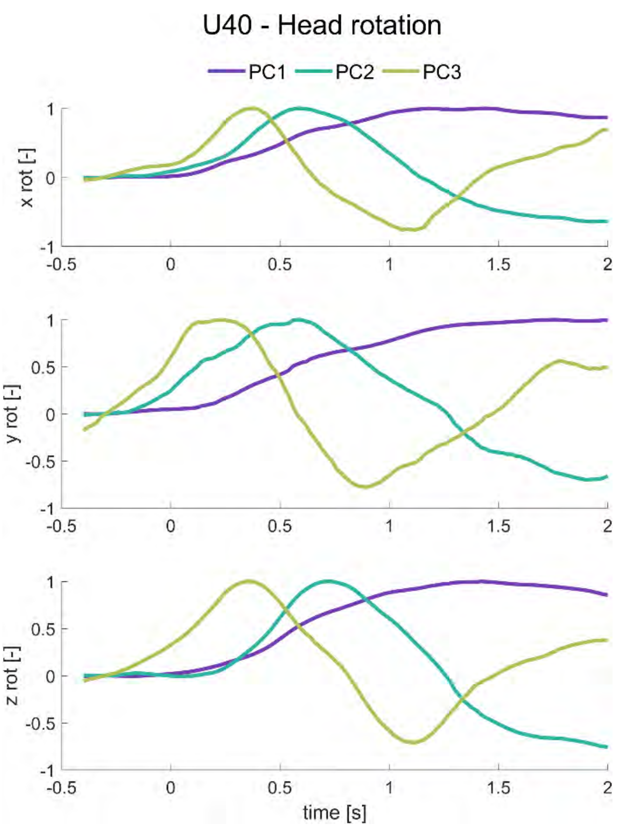
Fig. H. 1 Predicted kinematics (red/blue line) and corridors (filled red/blue) in a U-turn manoeuvre at 40 km/h, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, in a vehicle equipped with a pre-tensioned belt (red) and standard belt (blue). Grey curves are individual kinematics from both manoeuvres with standard and pre-tensioned belt, males and females, and the black curve are the average of these kinematics.



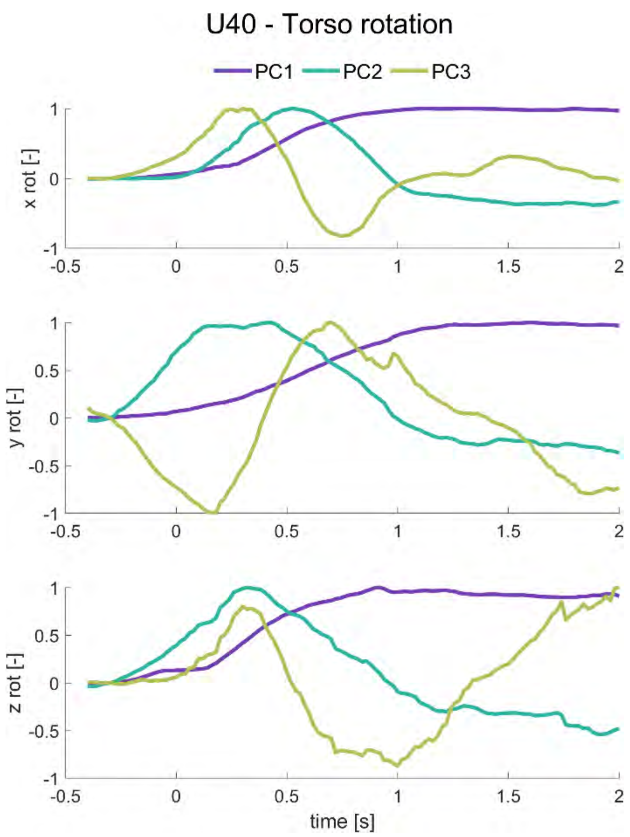
a) Head translation



b) Torso translation

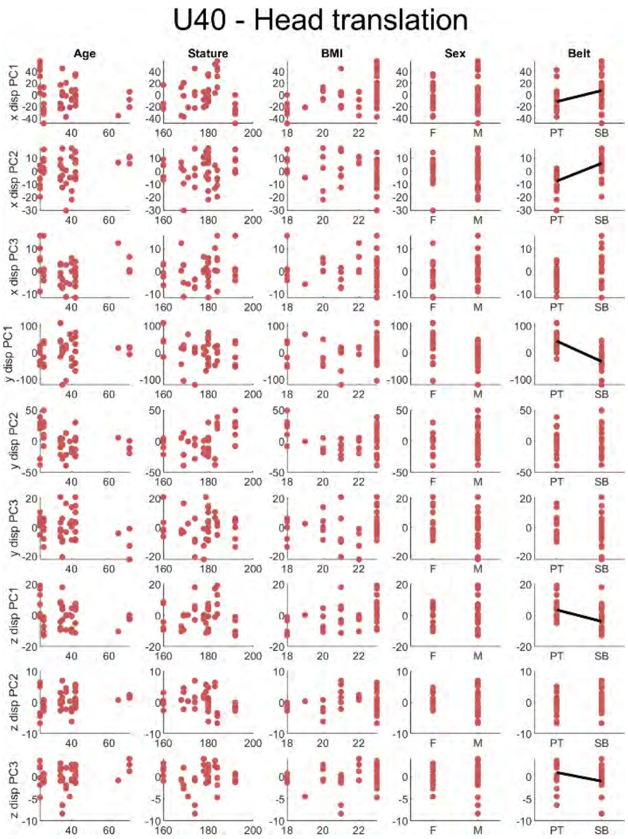


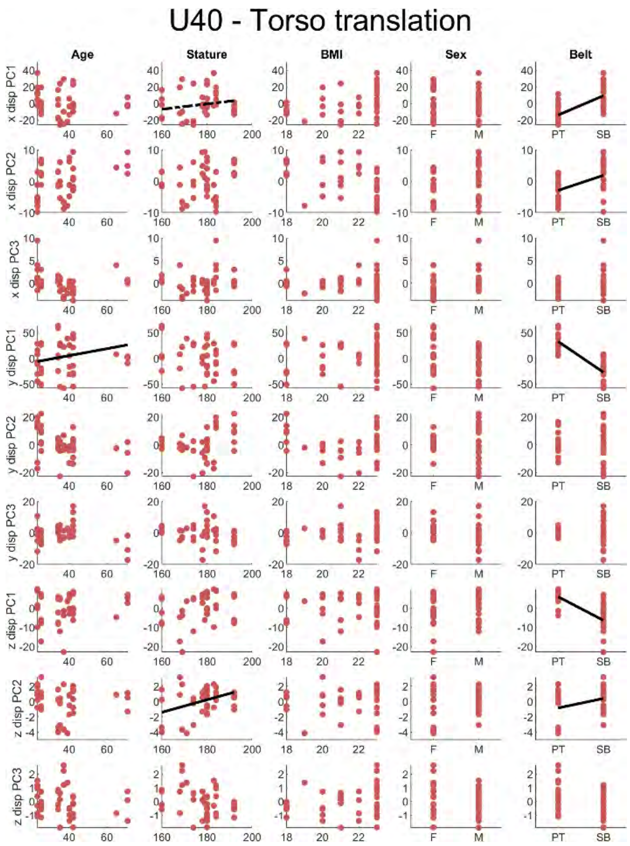
c) Head rotation



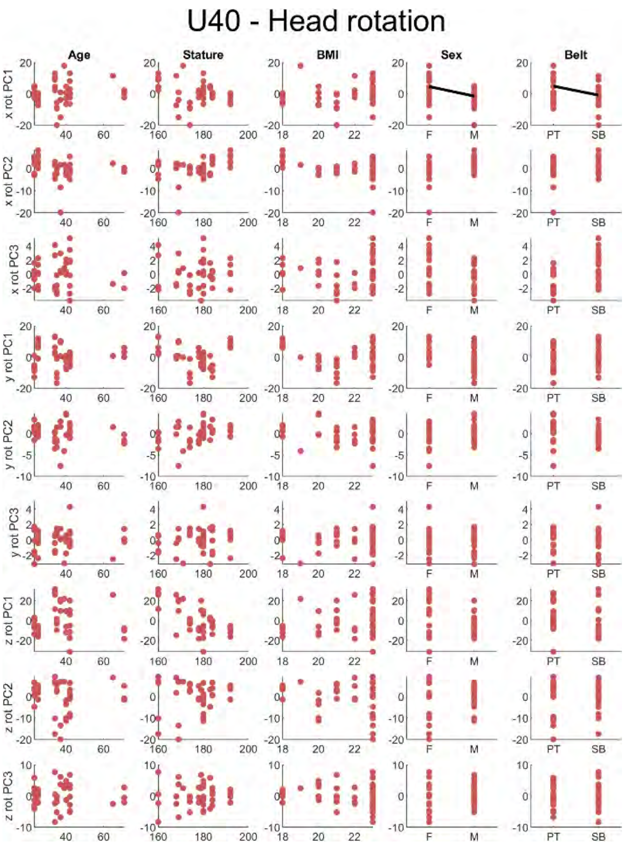
d) Torso rotation

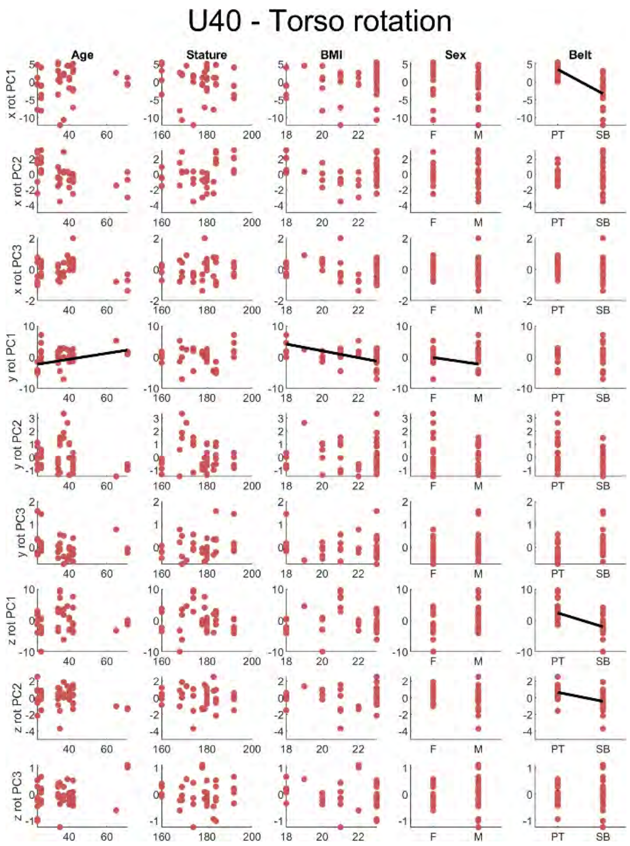
Fig. H. 2 First three principal component vectors for U-turn at 40 km/h (standard and pre-tensioned belt).





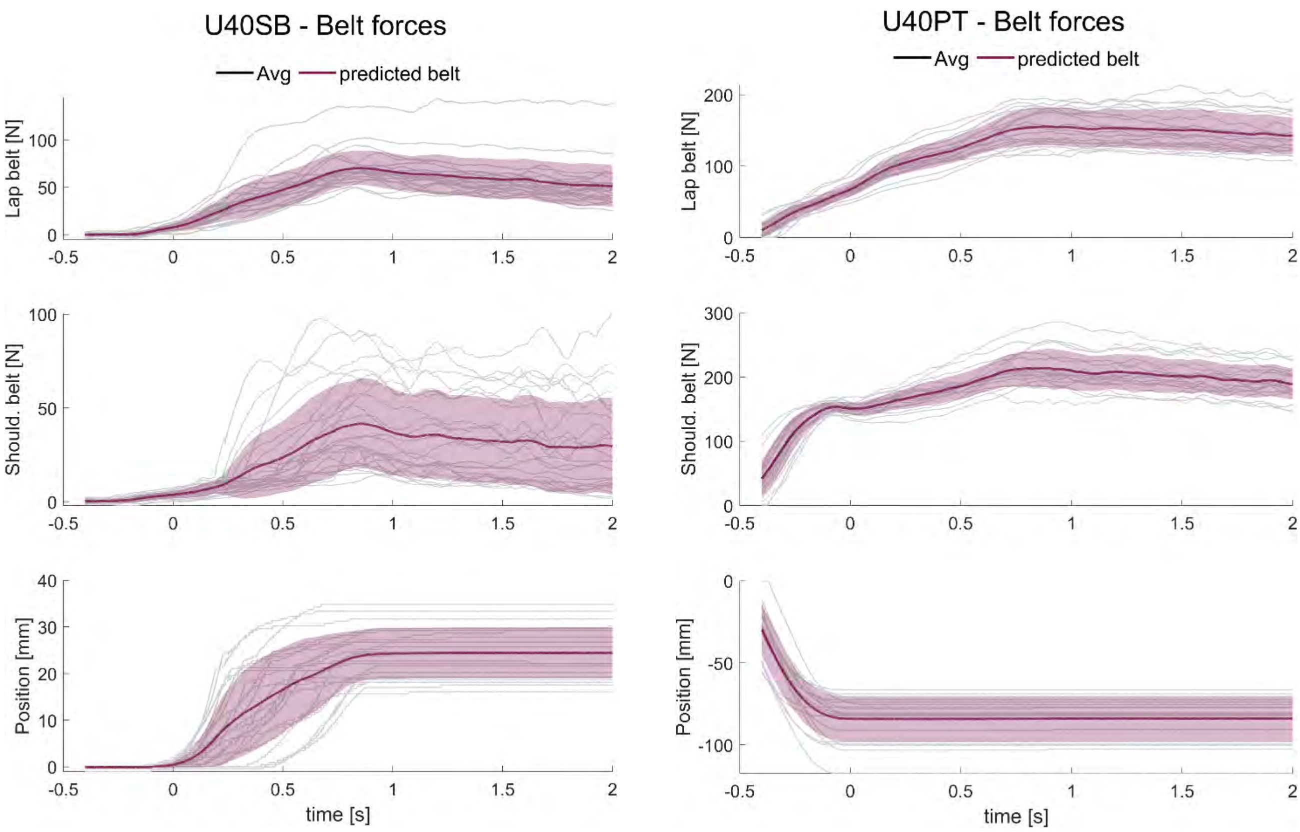
a) Head translation *b) Torso translation*





c) Head rotation *d) Torso rotation*

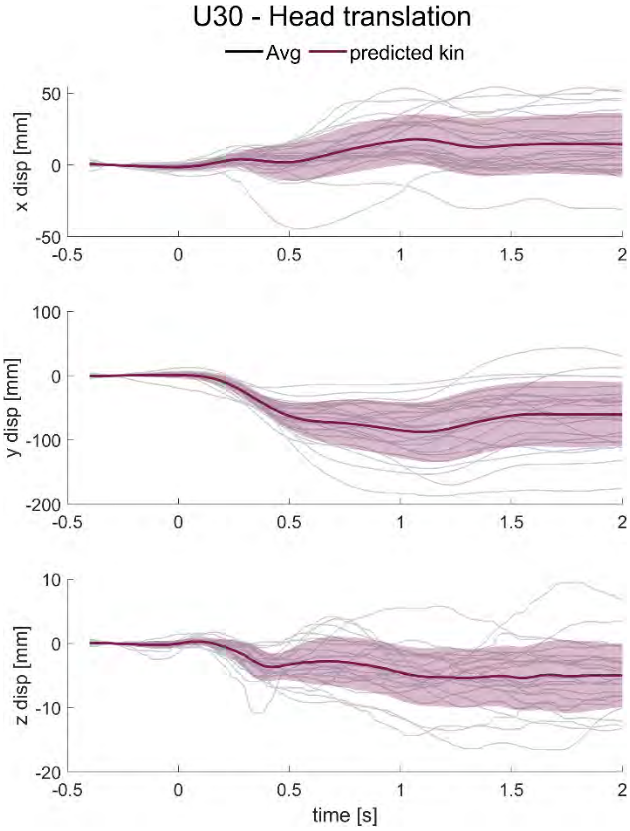
Fig. H. 3. Scatter plots of first three principal component scores and predictors in a U-turn at 40 km/h. For PCs with a predictive model, the line is created with the single predictor changed from the extremes. The baseline used for the other predictors is a 43% male, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, vehicle equipped with a 50% standard belt. A solid line indicates a significant main effect, a dash-dotted line indicates a non-significant main effect.



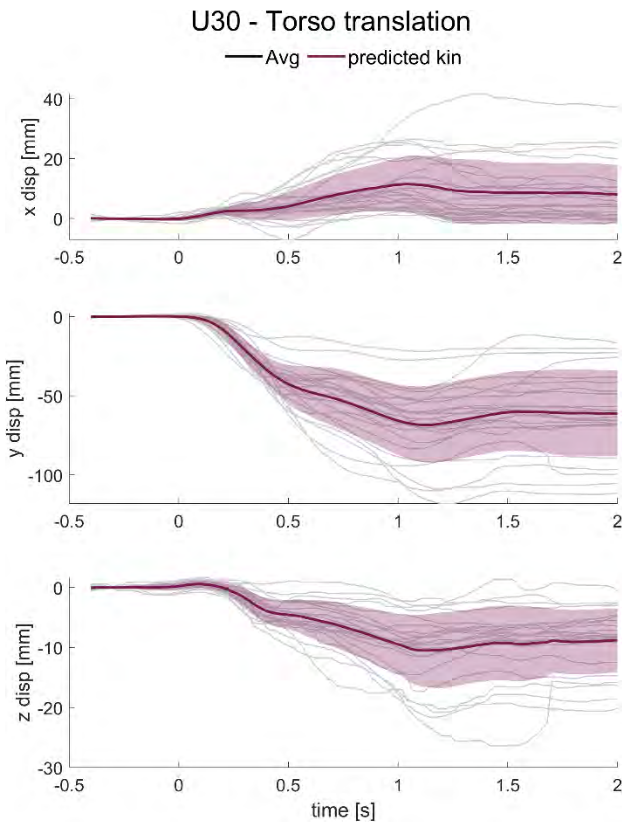
a) U40SB *b) U40PT*

Fig. H. 4. Predicted belt forces and positions (red line) and corridors (filled red) in U-turn manoeuvre at 40 km/h, with standard (a) and pre-tensioned (b) belt, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. Grey curves are individual belt forces and positions, males and females, and the black curve are the average of these belt forces and positions.

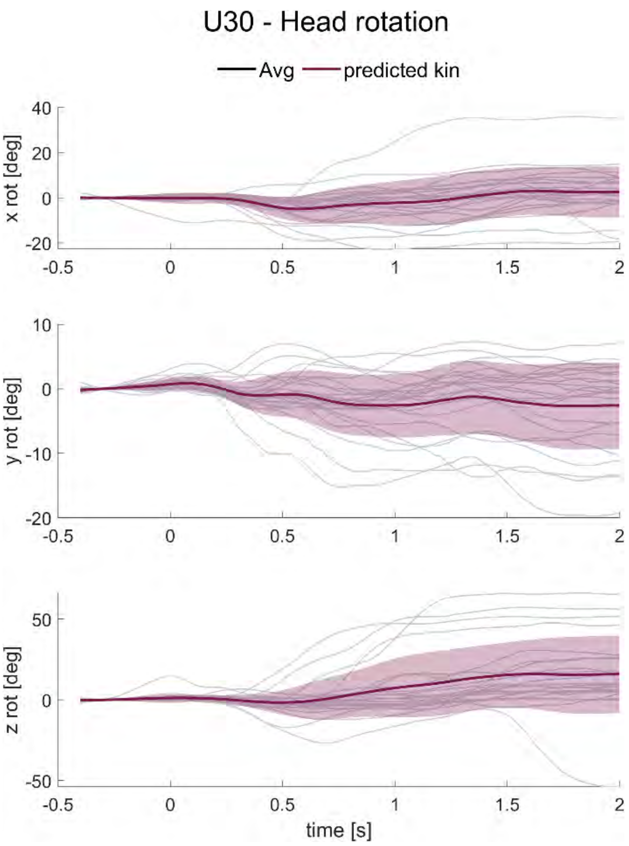
I. U-turn at 30 km/h, standard belt (U30)



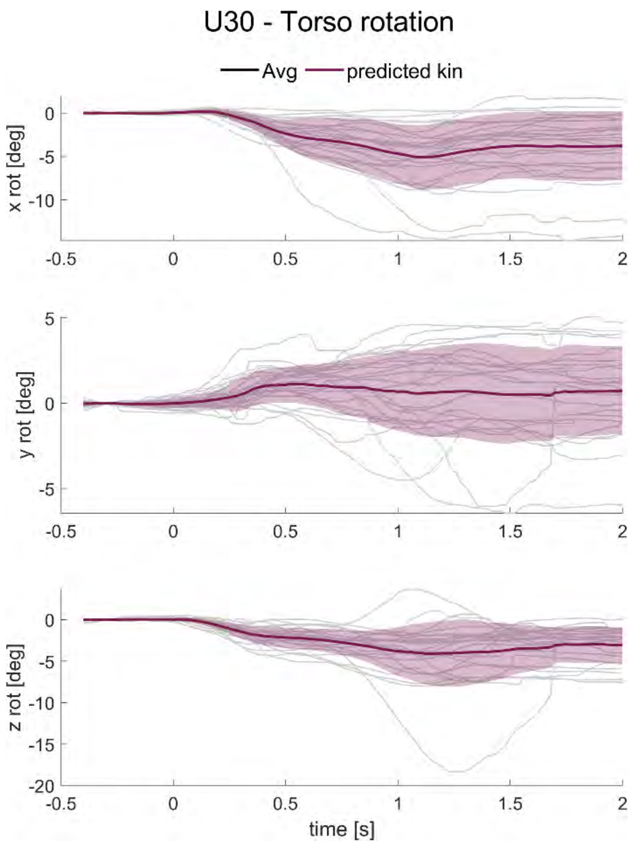
a) Head translation



b) Torso translation

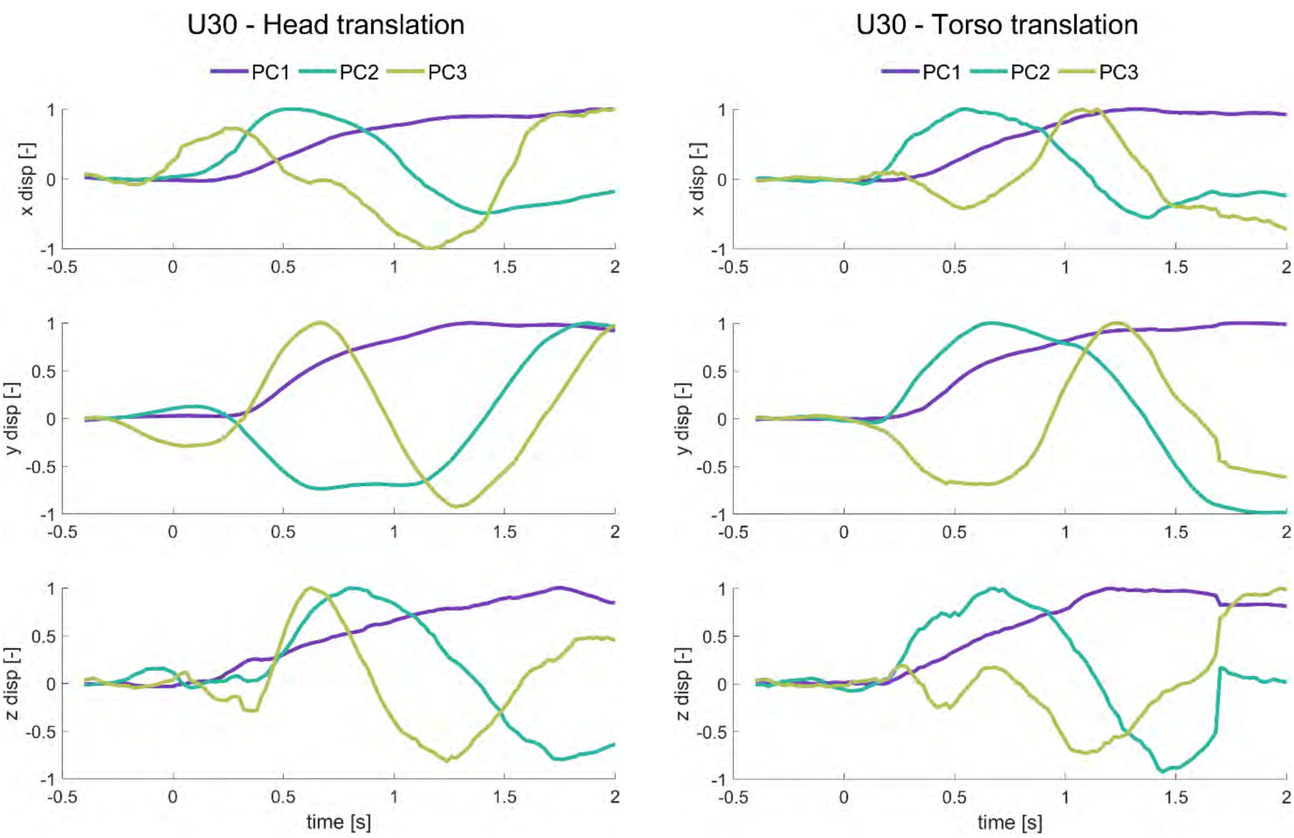


c) Head rotation

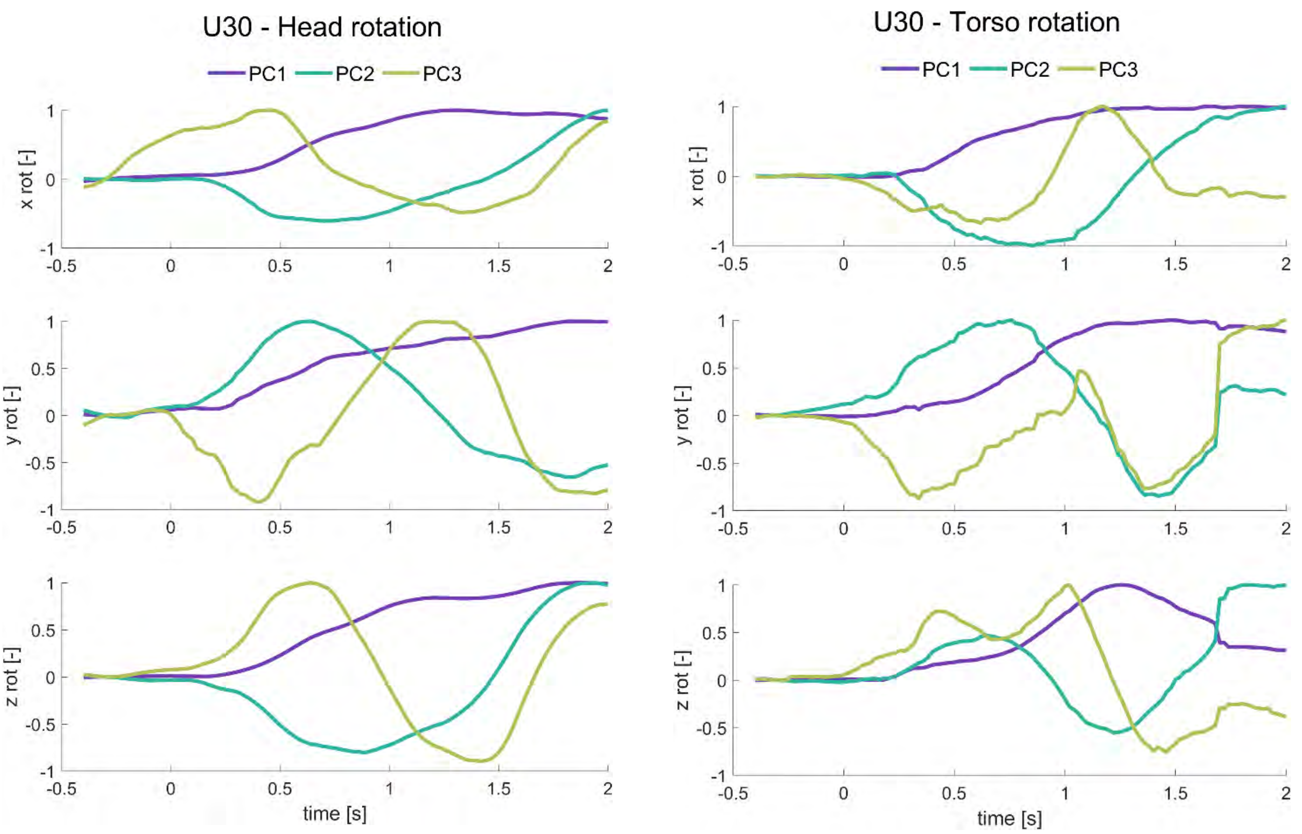


d) Torso rotation

Fig. I. 1 Predicted kinematics (red line) and corridors (filled red) in a U-turn manoeuvre at 30 km/h, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, in a vehicle equipped with a standard belt. Grey curves are individual kinematics, males and females, and the black curve are the average of these kinematics.

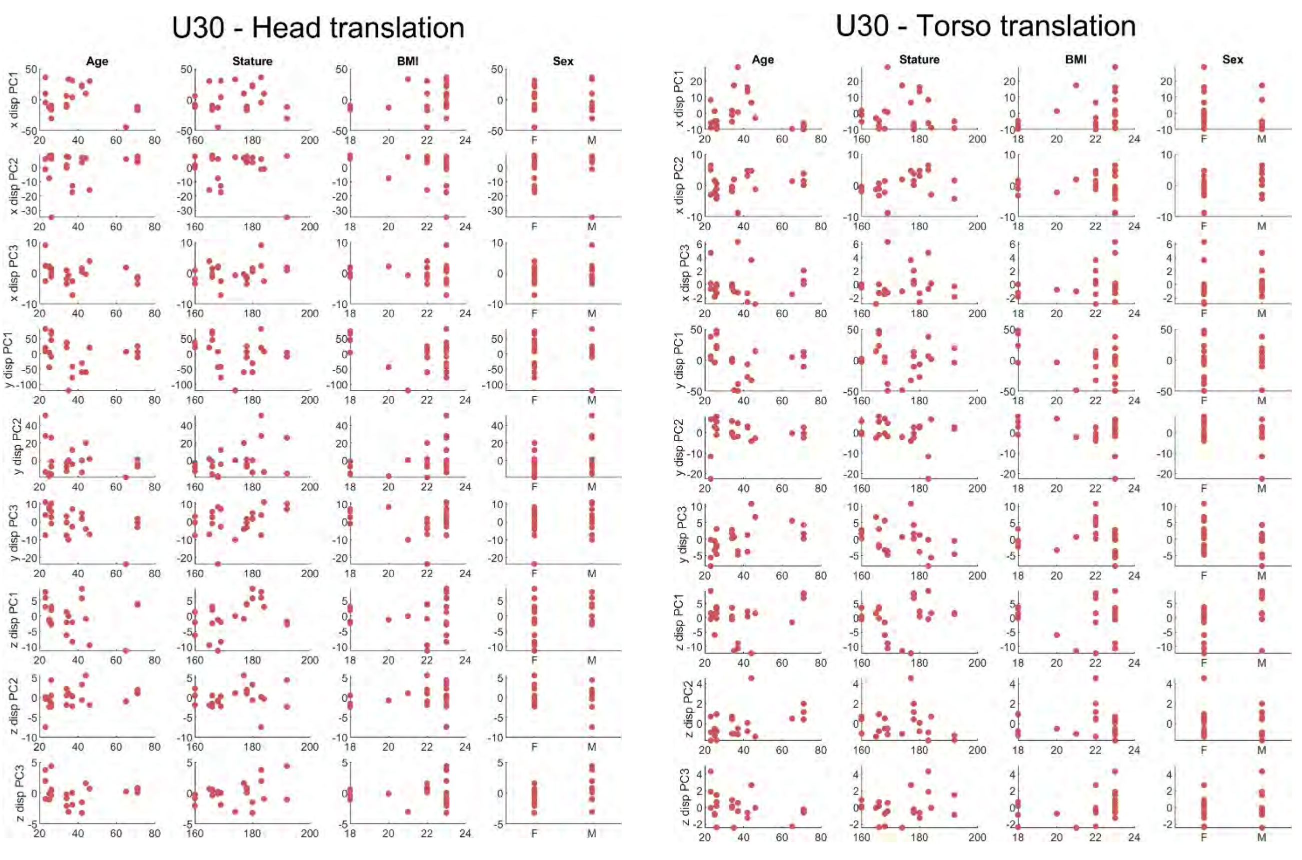


a) Head translation *b) Torso translation*

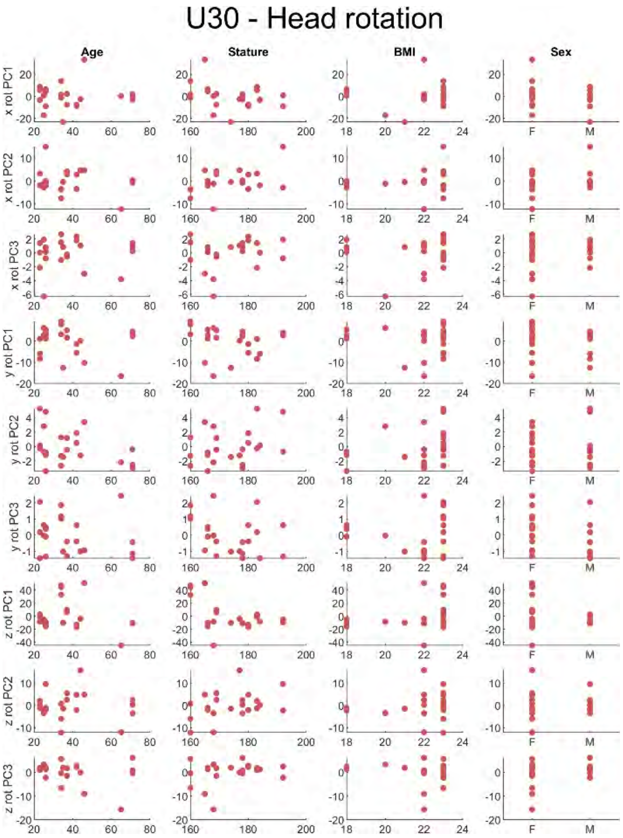


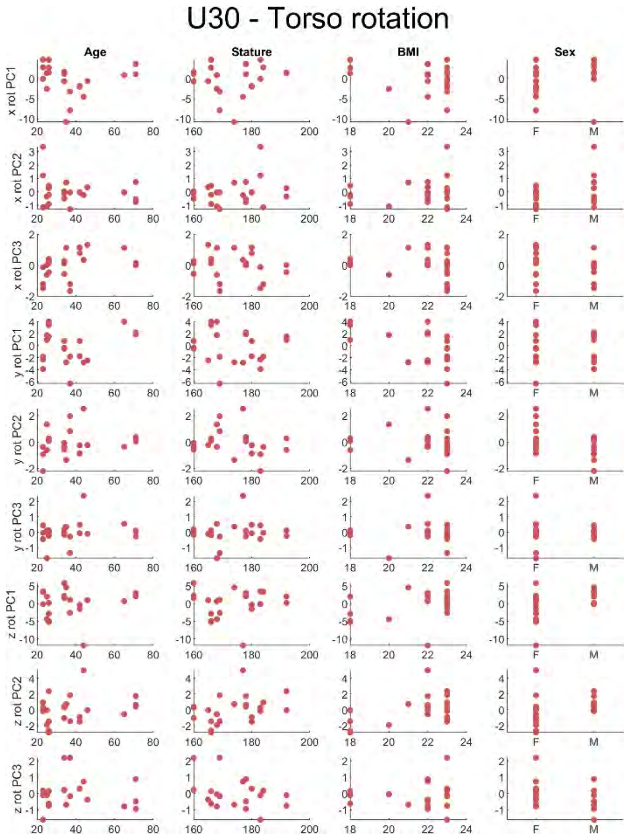
c) Head rotation *d) Torso rotation*

Fig. I. 2 First three principal component vectors for U-turn at 30 km/h (standard belt).



a) Head translation *b) Torso translation*





c) Head rotation *d) Torso rotation*

Fig. I. 3 Scatter plots of first three principal component scores and predictors in a U-turn at 30 km/h. For PCs with a predictive model, the line is created with the single predictor changed from the extreme values of that predictor. The baseline used for the other predictors is a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. A solid line indicates a significant main effect, a dash-dotted line indicates a non-significant main effect.

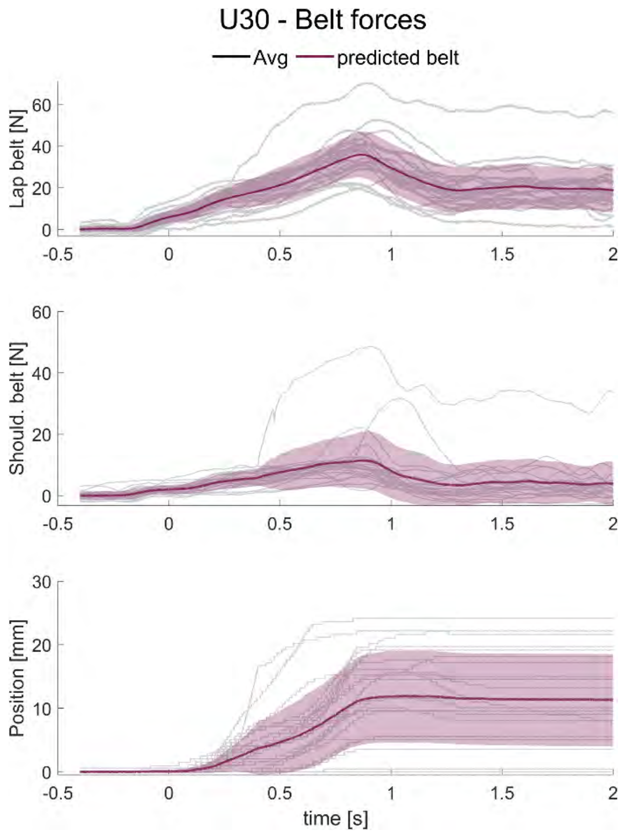
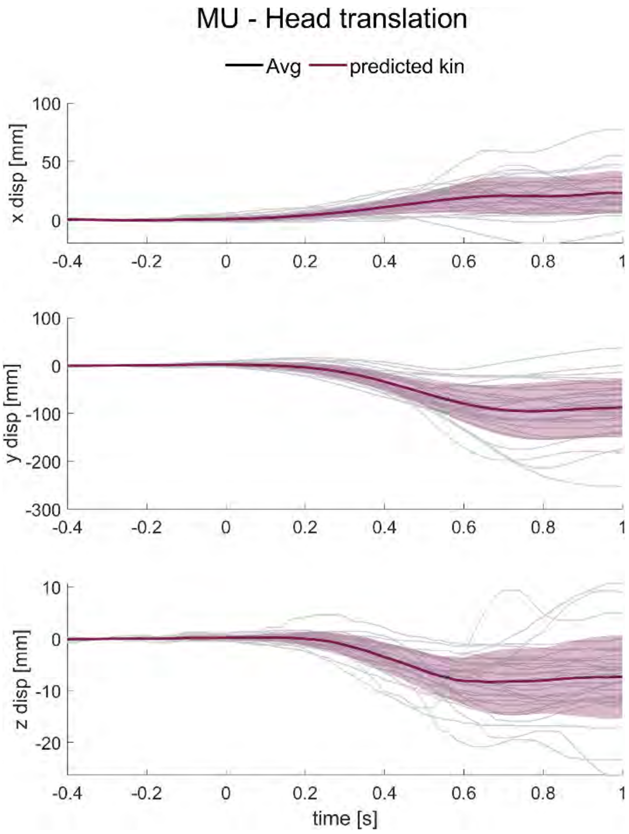
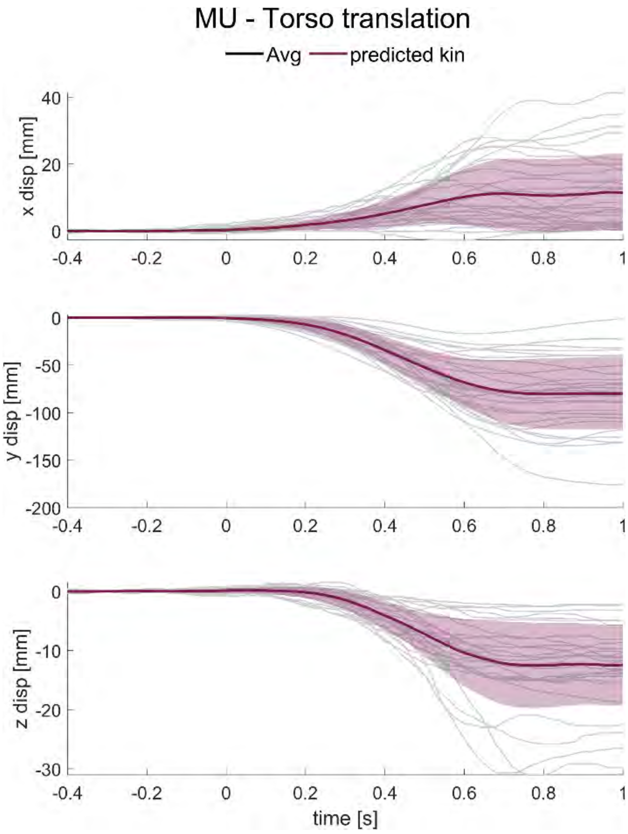


Fig. I. 4 Predicted belt forces and positions (red line) and corridors (filled red) in U-turn manoeuvre at 30 km/h, with standard belt, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. Grey curves are individual belt forces and positions, males and females, and the black curve are the average of these belt forces and positions.

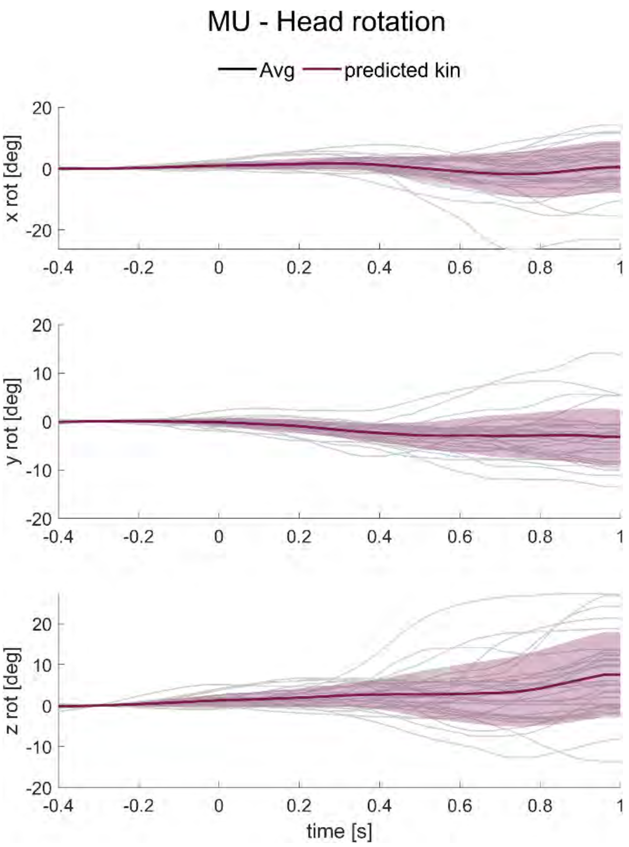
J. Manual U-turn at 40 km/h, standard belt (MU)



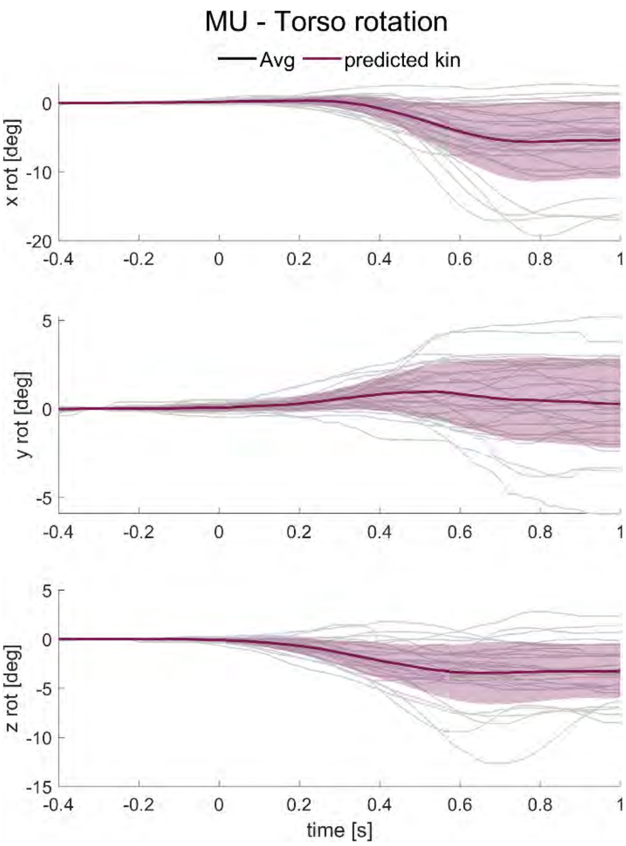
a) Head translation



b) Torso translation

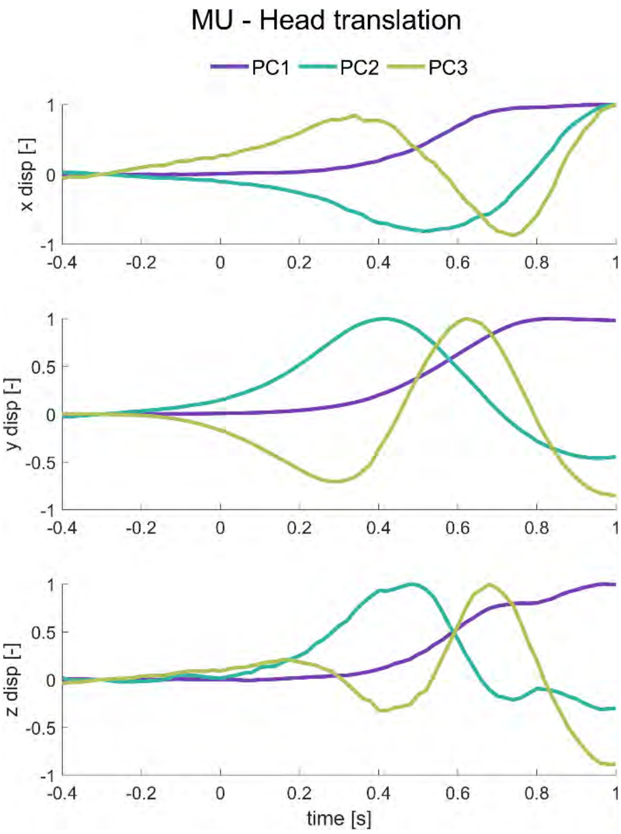


c) Head rotation

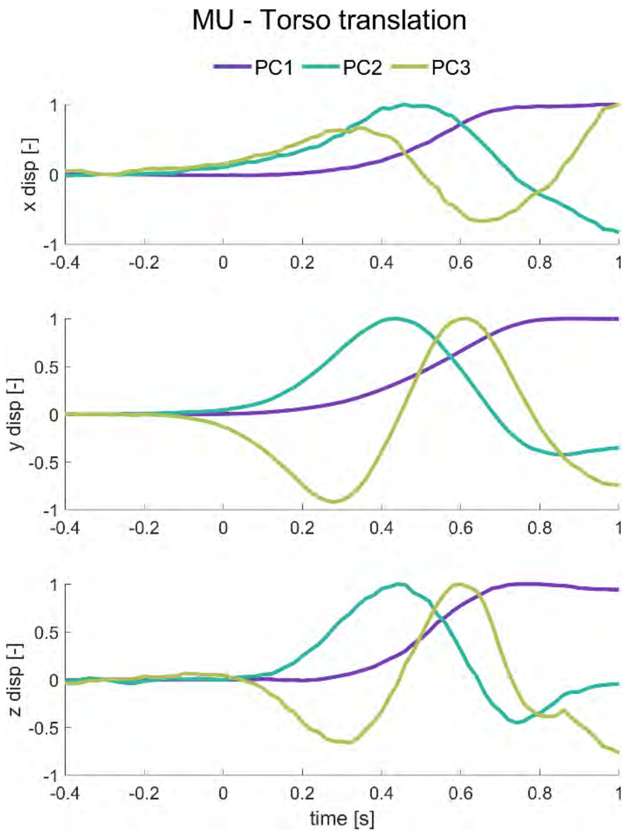


d) Torso rotation

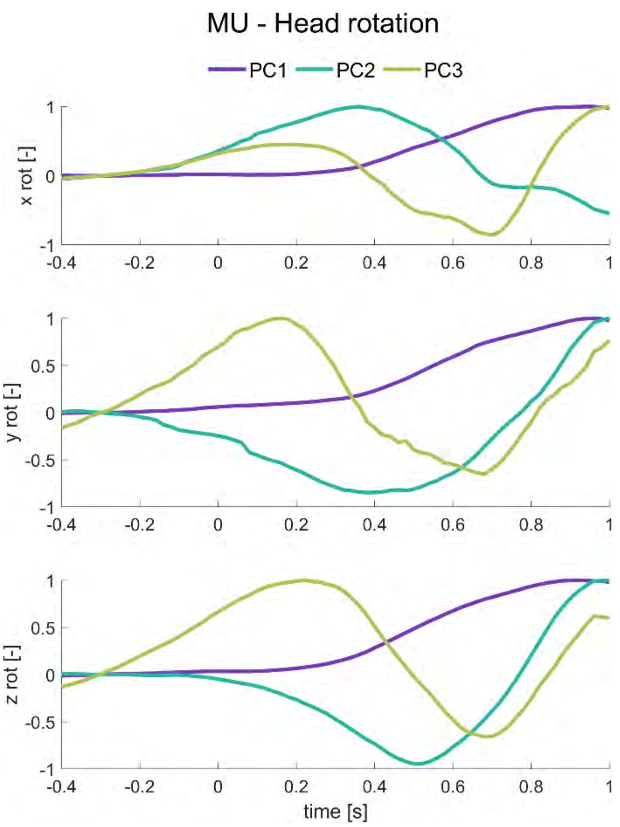
Fig. J. 1 Predicted kinematics (red line) and corridors (filled red) in a manual U-turn manoeuvre at 40 km/h, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2, in a vehicle equipped with a standard belt. Grey curves are individual kinematics, males and females, and the black curve are the average of these kinematics.

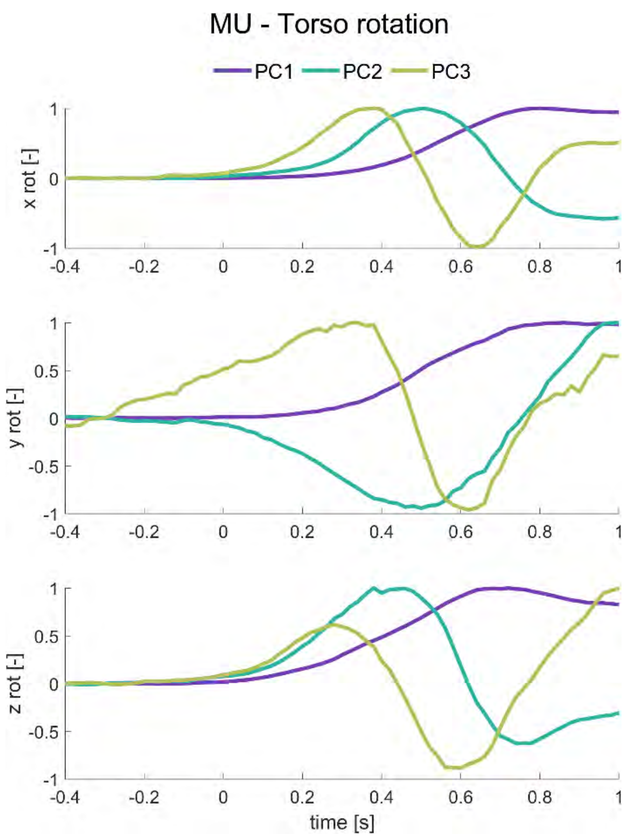


a) Head translation



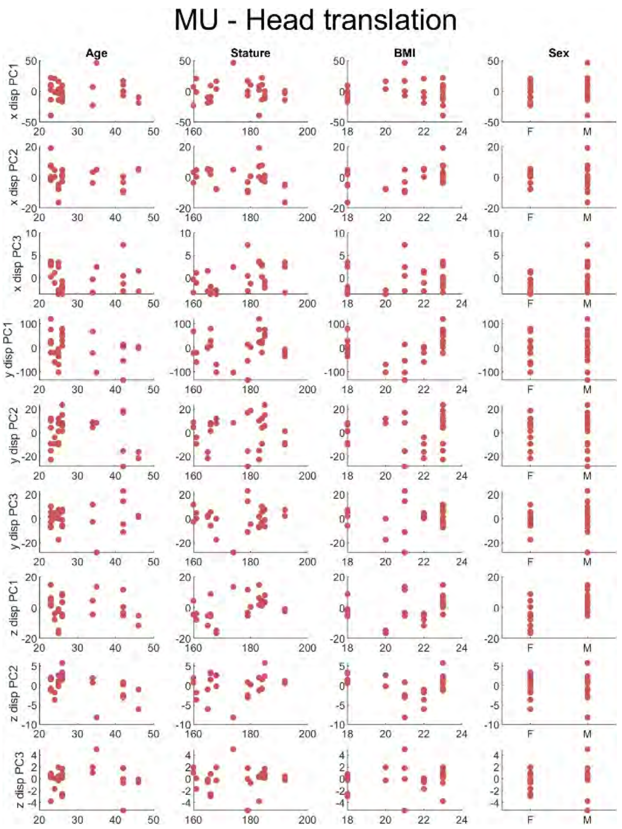
b) Torso translation

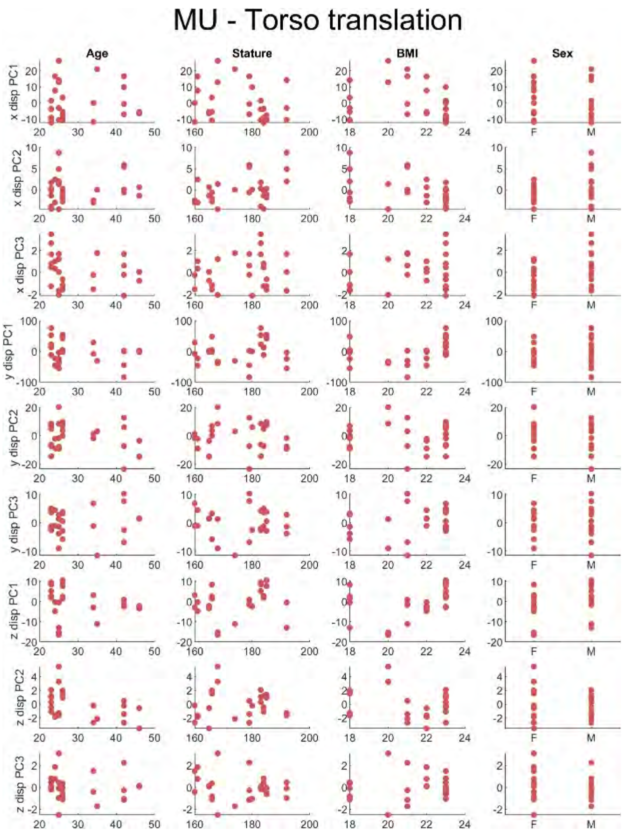




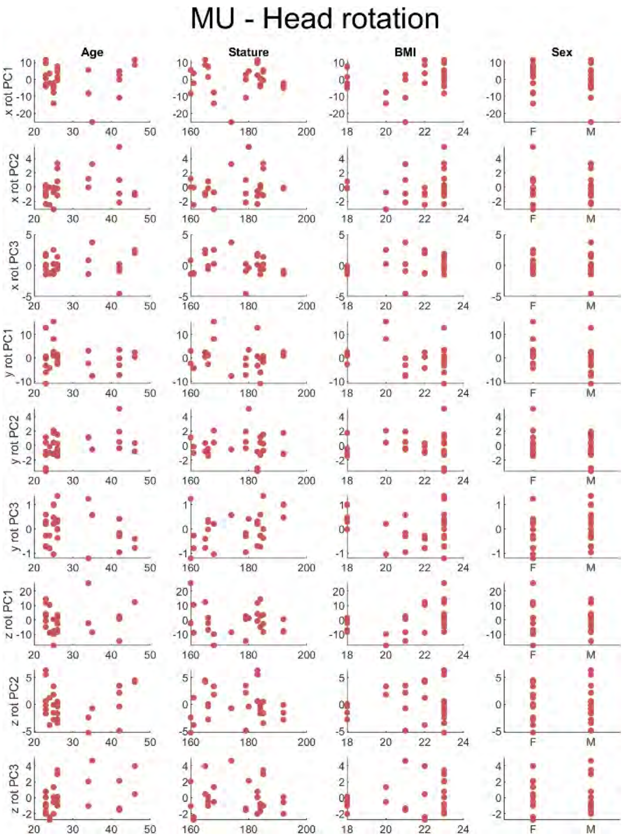
c) Head rotation *d) Torso rotation*

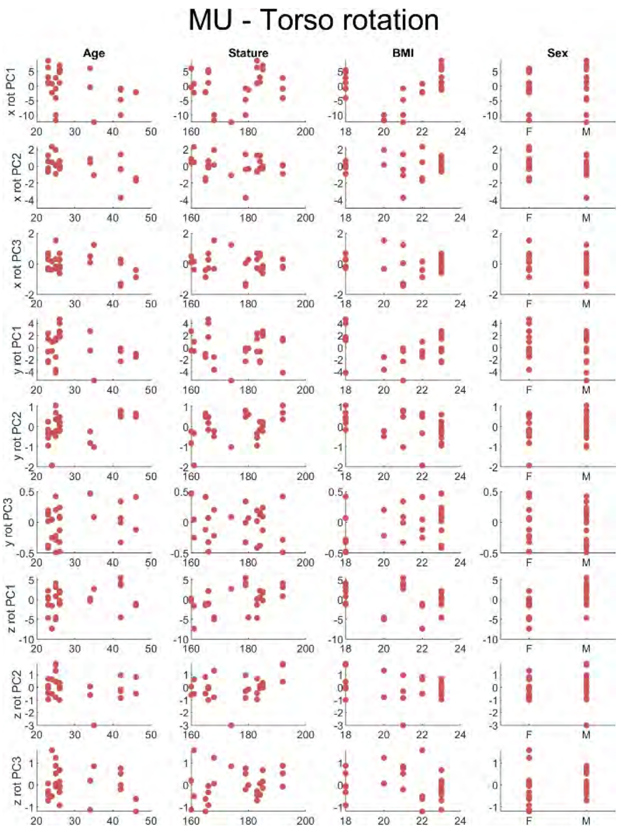
Fig. J. 2 First three principal component vectors for manual U-turn at 40 km/h (standard belt).





a) Head translation *b) Torso translation*





c) Head rotation *d) Torso rotation*

Fig. J. 3 Scatter plots of first three principal component scores and predictors in a U-turn at 30 km/h. For PCs with a predictive model, the line is created with the single predictor changed from the extreme values of that predictor. The baseline used for the other predictors is a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. A solid line indicates a significant main effect, a dash-dotted line indicates a non-significant main effect.

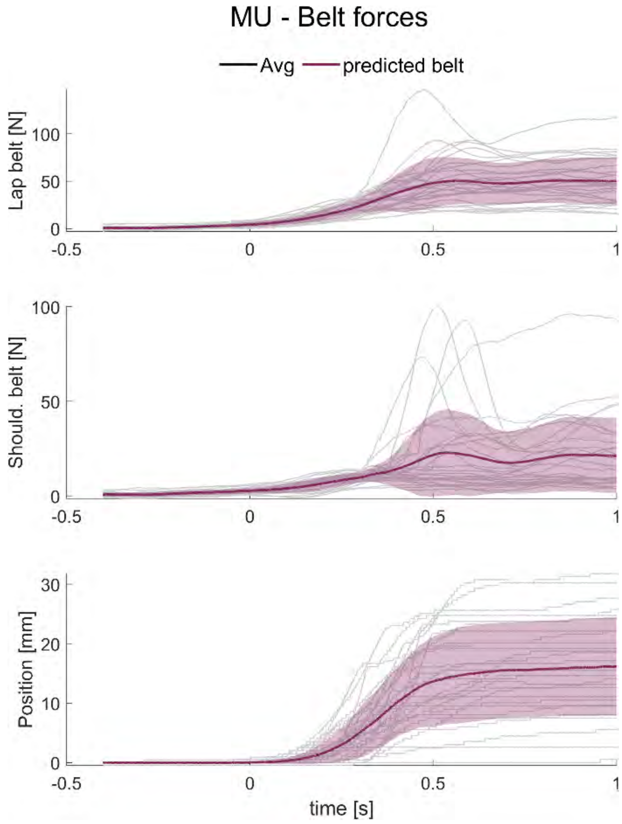


Fig. J. 4 Predicted belt forces and positions (red line) and corridors (filled red) in a manual U-turn manoeuvre at 40 km/h, with standard belt, for a 43% male passenger, 174.5 cm, 36.3 years old, with a BMI of 22.8 kg/m^2. Grey curves are individual belt forces and positions, males and females, and the black curve are the average of these belt forces and positions.

ERRATUM

Passenger Kinematics Variance in Different Vehicle Manoeuvres – Biomechanical Response Corridors Based on Principal Component Analysis

Emma Larsson, Ghazaleh Ghaffari, Johan Iraeus, Johan Davidsson

The plots were not synchronized across acceleration, kinematics, and belt force in the publication. If the data is used together, the values in Table Erratum 1 should be used to shift the plots such that they are synchronized.

TABLE Erratum I

THE TABLE DESCRIBES THE SHIFT NEEDED TO SYNCHRONIZE THE PLOTS BETWEEN ACCELERATIONS, KINEMATICS AND BELT FORCES/POSITION. A POSITIVE VALUE INDICATES THAT THE CURVES SHOULD BE SHIFTED TO A LATER TIME TO SYNCHRONIZE WITH THE OTHER CURVES, A NEGATIVE VALUE INDICATES THAT THE CURVES SHOULD BE SHIFTED TO AN EARLIER TIME.

Manoeuvre	Shift of acceleration [ms]	Shift of kinematics [ms]	Shift of belt forces [ms]
Lane change	0	-100	0
Lane change with braking	0	-100	0
Braking	0	-100	0
U-turn 40 kph	0	0	+200
U-turn 30 kph	0	0	+200
U-turn manual	0	0	+200