Analysis of Individual Variabilities for Lumbar and Pelvic Alignment in Highly Reclined Seating Postures and Occupant Kinematics in a Collision

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Abstract The primary objective of this study was to investigate the effect of the postural change between a normal seating posture and a reclined posture in vehicles by using X-ray to measure individual variabilities of skeletal alignments in a reclined seat. Another objective was to understand the effects of this postural change on injury outcomes. Therefore, human body models representing those individual variabilities were constructed by modifying THUMS ver.4, and occupant kinematics in frontal crashes were analyzed. Three target seating postures were defined, at 24, 35 and 45 degrees. Based on the analysis results of the X-ray data, the lumbar and pelvic alignments of THUMS were modified. Three different reclining angles and skeletal alignment types were compared. At 45 degrees, the forward displacement of whole body and the downward movement of the pelvis were observed. Additionally, the differences in kinematics of the upper body by the different alignment types was also confirmed. Furthermore, more head acceleration, chest rib fractures and lumbar spine stress were observed, as well as a higher risk of submarining. It was found that a reclined posture could significantly affect occupant kinematics and injury outcomes in a collision.

Keywords Reclined posture, individual variabilities, skeletal alignment, occupant kinematics, submarining.

I. INTRODUCTION

In order to mitigate fatalities or serious injuries in the real-world vehicle collisions, it is necessary to understand the effect of seating position and occupant body type/size on injury outcomes. One essential factor to consider is seating posture. Thus far we have reported that seating posture depends on age and body shape by analyzing individual variabilities of human skeletal alignments on an automotive driver seat with its seat-back inclined 24 degrees [1]. Considering the probability of occupants' diverse seating postures in highly automated vehicles, in addition to an occupant in a passenger or 2nd row seat, it is expected there will be increasing use of a highly reclined seating posture. This posture is assumed to promote pelvic rearward rotation and put the occupant close to a horizontal position.

Recent studies on the reclined posture in vehicles have analyzed occupant kinematics and injuries through the use of human body models (HBMs) or post-mortem human subjects (PMHS). These studies indicate that a reclined seating posture induces an increase of upper-body displacement, submarining and so on, resulting in higher injury risk [2-4]. Boyle *et al.* reported that the lap belt angle showed dominant effects on submarining and there is a clear conflict between submarining and lumbar spine force by analyzing the kinematics of Global Human Body Model Consortium (GHBMC) in highly reclined posture during frontal crashes [5]. Richardson *et al.* performed the assessment of PMHS pelvic kinematics and injuries in a reclined seating posture of 50 degrees, and reported variations in pelvic kinematics, such that both forward and rearward pelvic rotation was found, regardless of initially similar positioning of the pelvis [6]. Additionally, they insisted on the necessity of developing injury criteria for lumbar spine and pelvis that include intrinsic variabilities, such as abdomen depth and pelvis shape, and the adaptation of comprehensive restraint paradigms to predict variability of occupant posture [7]. Gepner *et al.* showed a substantial effect of pelvis-flesh attachment in HBMs with a reclined posture on the submarining outcome [8]. However, pelvic rearward rotation in all models was inconsistent with the kinematics in PMHS. Osth *et al.* indicated that in the reclined position, the occupant submarined under the lap-belt and a higher head impact velocity was achieved due to the greater distance to the airbag and seat-belt compared with an upright position.

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However, combination of repositioning a driver occupant from a reclined position to an upright position and adding pre-tension of the seat-belt prior to crash could reduce those injuries [9].
Furthermore, some studies regarding more effective design of restraint systems for the protection of occupants in a reclined posture, such as a load-limiting system, active head restraint and seat-integrated 3-point belt, have been also reported [10-12]. However, there have been few studies to analyze the skeletal alignment of living subjects in a reclined seating posture. The goal of this study was to analyze individual variabilities of subjects' skeletal alignments, especially lumbar spine and pelvis, in reclined seating postures and to investigate occupant kinematics in a frontal collision using modified HBMs.

II. METHODS

Posture Definition and X-ray Facility

Based on the angle of a reclined posture in a previous study and the limitations of the passenger seat in a vehicle with a child car seat in the 2nd row, the reclining angle chosen for this study was 45 degrees, with a seat-track position in which occupants equivalent to AM50 did not feel cramped (Fig. 1a). In our previous study, the X-ray facility with its seat-back inclined 24 degrees and seat pan inclined 21.5 degrees was used as the Mazda design standards in a normal driving posture [1, 13]. In order to reproduce a reclined seating posture in an automotive seat, only the seat-back angle was modified to 45 degrees while the seat pan angle was retained as 21.5 degrees in this study. Moreover, while being X-rayed the subjects were asked to sit back, with their foot on the pedal and footrest, both arms on the armrest, and the back of their head against the headrest (Fig. 1b). The role of the armrest was to prevent bones of upper extremities from overlapping with a vertebra at the time of the X-ray. In order to visualise the position of lap-belt in the X-ray image, lead tapes were put at the middle line of lap belt corresponding to subject's sagittal plane, i.e. middle position, and at the belt section directly in front of the anterior-superior iliac spine (ASIS), i.e. ASIS position. The lap-belt buckle anchorage location for seat-belt fit condition was free to move between 45 degrees and 75 degrees to the horizontal. Subject orientation was adjusted with respect to the X-ray table to achieve a pure lateral view.

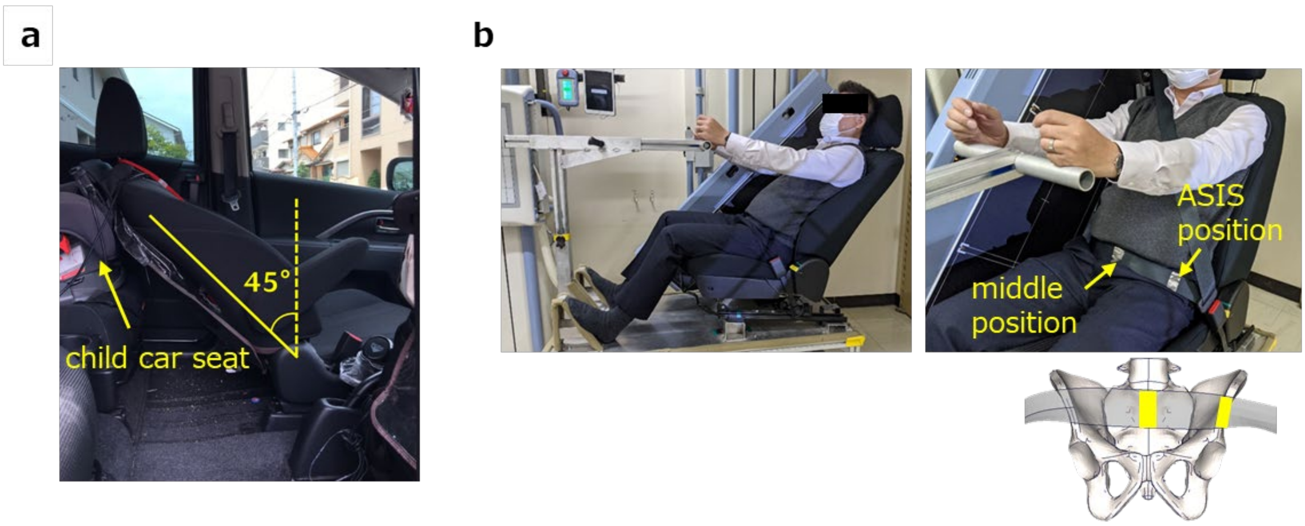

Fig. 1. a. The set-up of reclining seat-back in vehicle and b. The X-ray facility and locations of X-raying in a reclined seating posture.

X-raying and Procedures in this Study

X-ray images were taken using the AeroDR One Shot Stitching (KONICA MINOLTA, Japan), a digital radiography system at the Department of Radiological Technology, Yamaguchi University Hospital. As the X-ray board of this equipment could be rotated from 0 degree to 180 degrees, the board was tilted to the posture of the subjects and they were X-rayed with a single irradiation. All procedures in this study were determined by Yamaguchi University and Mazda Motor Corporation and received prior approval from the ethical committees of both Yamaguchi University Graduate of Medicine and Mazda Motor Corporation.

Subjects

15 asymptomatic volunteers who had no medical history in the vertebral body or pelvis, and who gave informed consent after receiving an explanation of the study and its aims, were subjected to X-ray photography. The subjects consist of 12 males and three females, all aged over 20. Age, gender, stature and BMI of subjects are shown in Appendix, Table A.I.

Image Acquisition and Data Analysis

In the same way as previous studies, the angles from cervical spine to pelvis were measured (Fig. 2). The identification of those angles was performed by an orthopaedic surgeon from Yamaguchi University Hospital. The particular focus of this study was lumbar spine and pelvis. For the lumbar lordosis (LL), the angle between L1 and L5 was measured. For the sacral slope (SS) as the pelvis, the angle between sacrum and the horizontal line was measured [1]. The SS is one of pelvic parameters to decide pelvic orientation as well as the pelvic tilt [13, 14]. For the initial position of lap-belt, X and Z components of distance between ASIS and the upper/rearward edge of the middle or ASIS position of lap-belt were measured [15]. The middle position and ASIS position of individual subjects were plotted in a coordinate system so that the belt path could be predicted based on the relative position between them. The lap-belt angle relative to the horizontal plane was also measured.

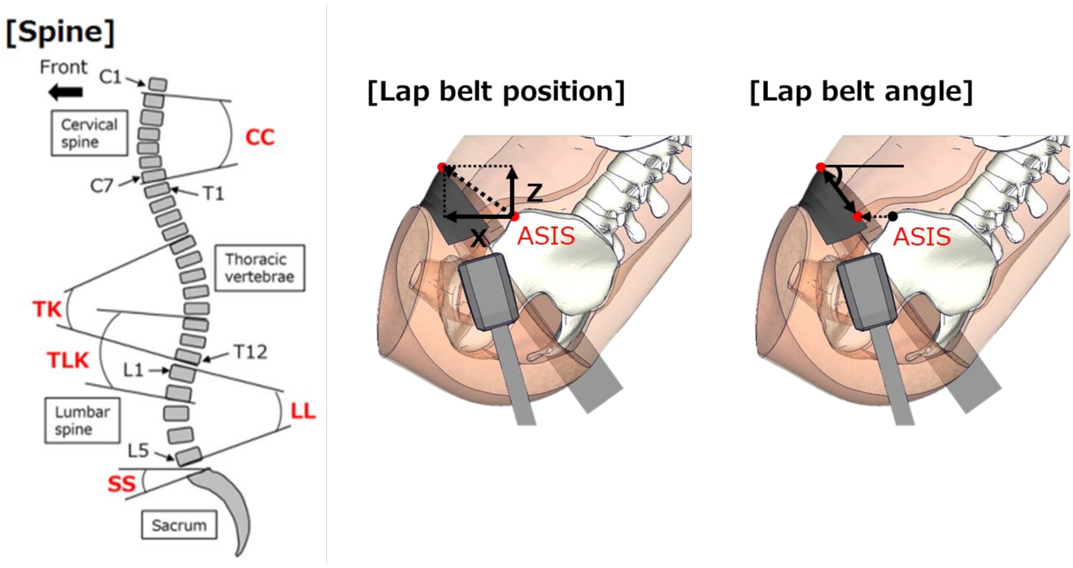

Fig. 2. Measurement items for the spine, initial lap-belt position and lap-belt angle.

Creation of FE-HBMs

In order to consider individual variabilities of subjects' lumbar and pelvic alignments, the angles of LL and SS were focused. For the construction of HBMs in reclined postures, THUMS ver.4 AM50 was modified by three steps, as follows. First, whole body of THUMS ver.4 was rotated at H-point in y-axis until the SS achieved the target angle. During the rotation, CC, TK, TLK, and LL of spine were retained as same as those before the rotation at this moment. Secondly, referring to representative angles of subjects, the alignment of THUMS ver.4 was modified by giving a Prescribed-Motion on the vertebrae of L3 as an inflection point in the lumbar spine. Based on the results of modification, the alignment of LL was adjusted to coincide with subjects' angles. The hands, lower extremities and cervical vertebrae were completely constrained. The thoracic spine was not intentionally controlled with the alignments' change of the lumbar spine. After adjusting the HBM lumbar spine alignment, stresses and strains were zeroed out by restarting with the updated geometry. Finally, the hands and legs were located in appropriate positions. In order to investigate an influence of seating postures on occupant kinematics in a collision, the HBM of 35-degree (35-deg) posture was created with the intermediate angles between a 24-degree normal driving (24-deg) posture and a 45-degree reclined (45-deg) posture (Fig. 3b). Furthermore, to reflect individual variabilities of lumbar and pelvic alignment in a 45-deg posture in THUMS ver.4, three subjects' group with the smallest (Type A), average (Type B) and the largest (Type C) LL angle were selected from the 45-deg regression line in the graph of the relation between LL angle and SS angle. The lumbar and pelvic alignment of THUMS ver.4 was modified to coincide with those angles (Appendix, Table A.II).

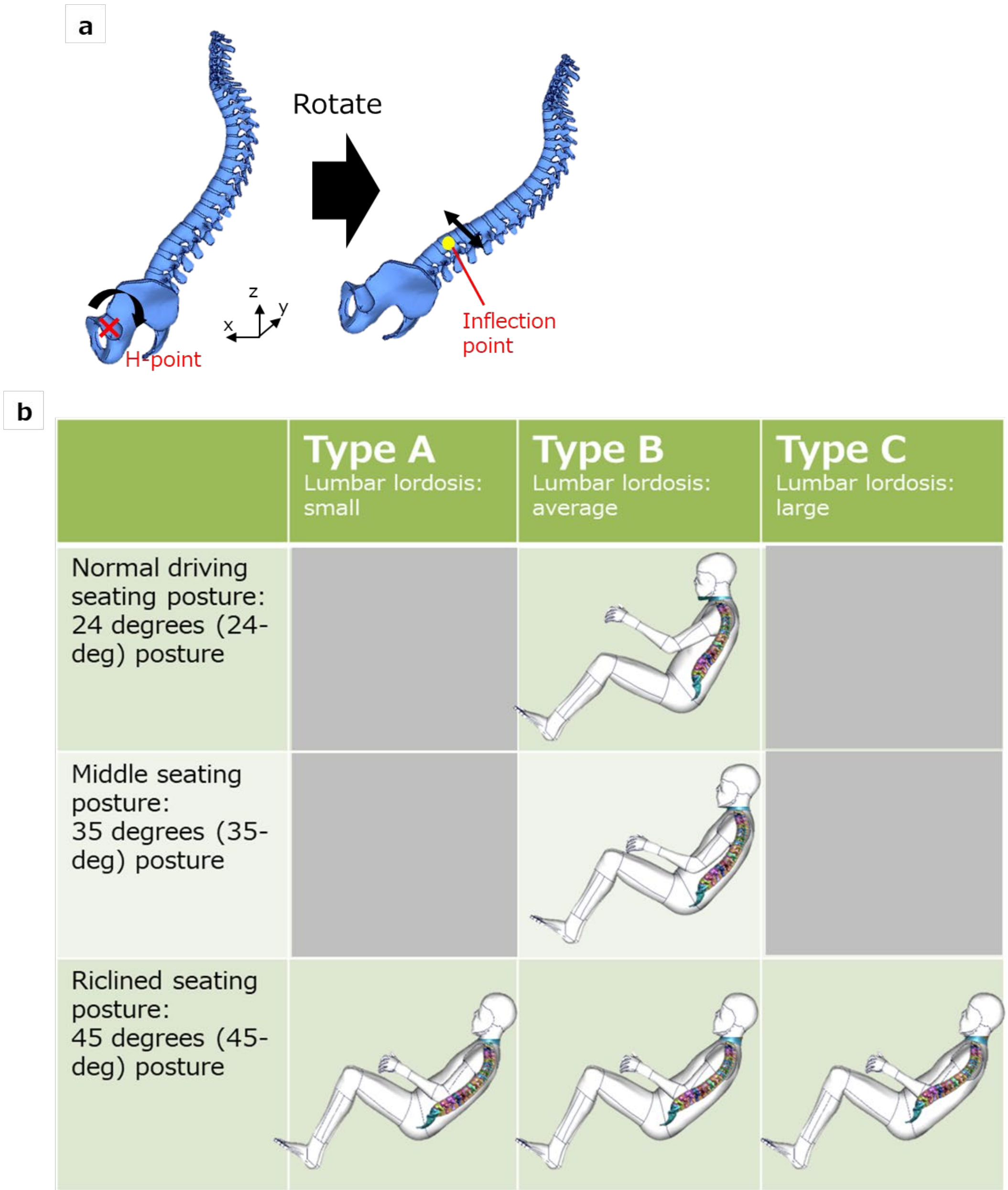

Fig. 3. a. Image showing the method used to construct the models in reclined postures and b. Three HBMs selected from a regression line of a 45-deg posture, and the HBM in a 35-deg posture.

Condition of FE Simulation

In this study, simulations were conducted with the same condition of JNCAP 56 kph full frontal crash (Fig. A.1a). Vehicle models included in simulation were based on Mazda's typical specification, and the 6 DOF accelerations were applied to the vehicle body about its center of gravity (COG) in order to simulate the vehicle kinematics. The acceleration data was obtained from an in-house crash test. The validation results of the simulation model with the Hybrid III AM50 dummy are shown in Fig. A.1b. The similar dummy kinematics and seat-belt forces found in computer aided engineering (CAE) simulation were validated by comparing it to the physical crash test, although the validation of THUMS ver.4 had already been confirmed [15]. Using HBMs with posture transformation, their kinematics in frontal crashes was investigated. Those models were placed in the driver seat and constrained by a seatbelt with pretensioner and load-limiting retractor and without a dynamic locking tongue. Additionally, the occupant was constrained by a knee airbag deployed from the instrumental panel. HBMs in reclined postures were kept away from the accelerator pedal. Positions and angles of pelvis, spine and head depended on the corresponding alignment. The seat-belt was fitted on the chest and pelvis, respectively. Seat cushion was squashed to consider the initial compression by gravity. The simplified seating method implemented in Oasys PRIMER^{TM} was used. However, the initial stress-strain distribution was not considered in this study.

Analysis of Occupant Kinematics

Using the results of FE simulations, the occupant kinematics in full frontal crash were analyzed. For the head, the displacement and acceleration were measured at the COG position of head which is equivalent to that of THOR-50M. For the chest, the displacement of the 6th thoracic vertebra was measured. The fracture locations were estimated by a fracture criterion based on failure strain value defined in HBMs. The fracture criterion was decided referring to rib fracture corridors obtained from previous literatures [16-18]. Additionally, the forces on anterior, middle and posterior location of ribs were also measured to understand the main cause of the rib fracture (Fig. 4a). For the lumbar spine, the von Mises stress distribution of the spine for each posture was analyzed. Furthermore, the vertical load Fz and moment My acting on each lumbar vertebra were calculated (Fig. 4b). For the pelvis, the displacement of the sacrum and lap-belt kinematics for the pelvis were observed. In addition, the abdomen compression rate and rotation angle of pelvis were also measured as parameters related to submarining.

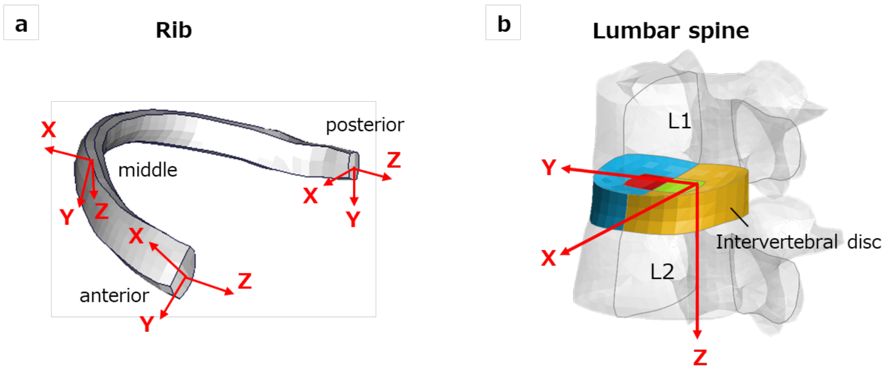

Fig. 4. Measurement position and each direction in local coordinate system for a. rib and b. lumbar spine.

III. RESULTS

Individual variabilities of the skeletal alignment and lap-belt position

To date, the X-ray data of seven subjects were obtained and individual variabilities of those alignments were analyzed. A sample of X-ray images is shown in Fig. 5. The data of angles from the cervical spine to the pelvis are also shown in Appendix, Table A.I.

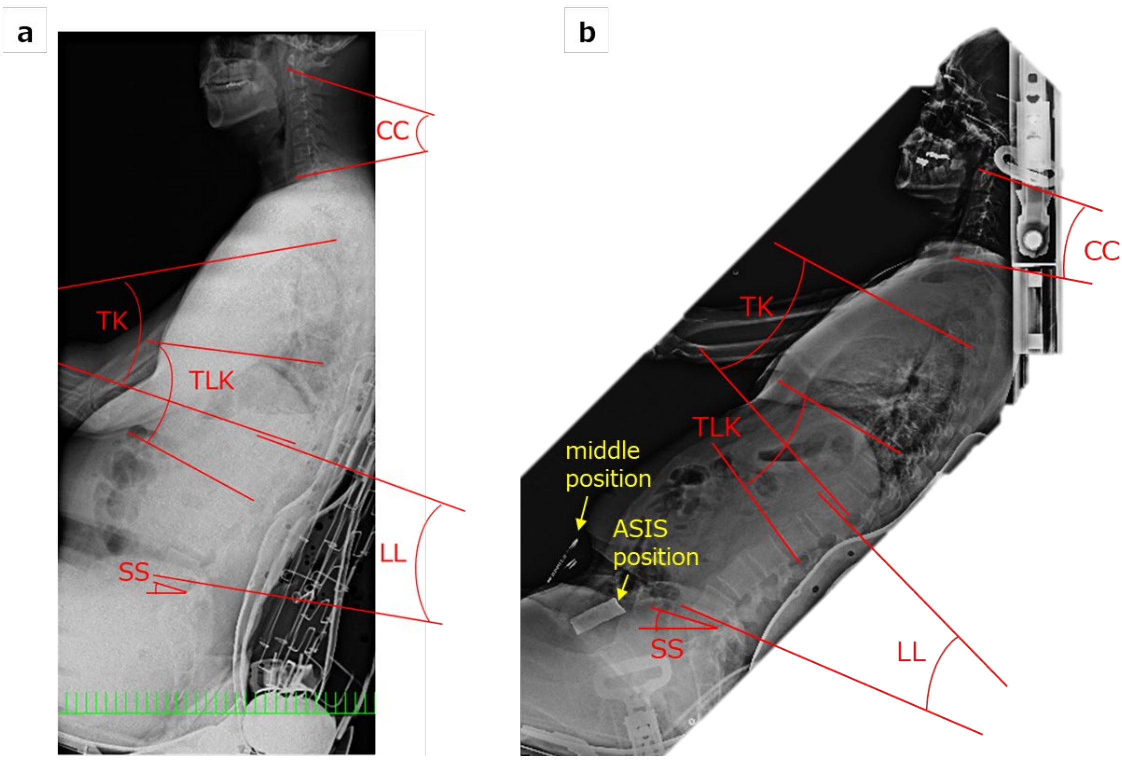

Fig. 5. X-ray image of seating postures at a. 24 degrees and b. 45 degrees.

The relation between LL angle and SS angle from X-ray data is shown in Fig. 6a. Linear regressions were drawn in the graph of each relation in a 24-deg posture or a 45-deg posture. The postural change from a 24-deg posture to a 45-deg posture resulted in more lumbar lordosis and pelvic rearward rotation for all subjects (Fig. 6a). It was also observed that the lap-belt position was higher and closer to ASIS, and that the belt angle was greater (Fig. 6b). Each distance of the lap-belt to ASIS is also shown in Appendix, Table A.III.

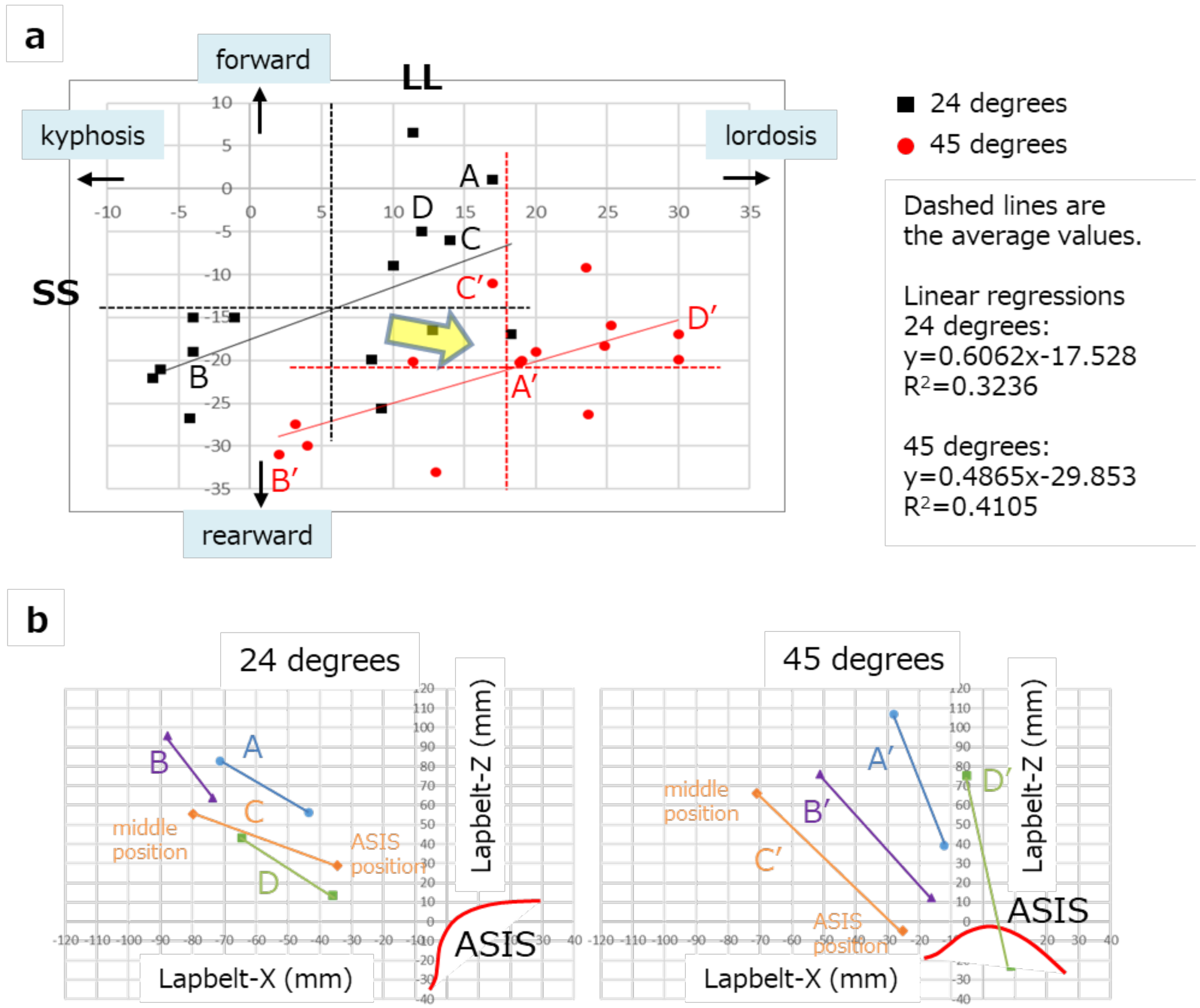

Fig. 6. a. The graph of the relation between LL angle and SS angle and b. The sample of lap-belt position for the ASIS. Each symbol, i.e. A, B, C and D is coincided with those symbols in a graph of Fig. 6a.

Analysis of Occupant Kinematics

Occupant kinematics using the HBMs in a FE vehicle environment are shown in Fig. 7. From the analysis results and comparison of 24-, 35- and 45-deg postures, it was found that the forward displacements of head and chest were increased due to highly reclined posture (Fig. 7a). In fact, the head displacement in a 45-deg posture was 150 mm or more forward than that in a 24-deg posture. Additionally, 50 mm or more forward and 10 mm or more downward movement of the pelvis in a 45-deg posture was observed in comparison with the pelvic movement of a 25-deg posture. From the analysis results and comparison of three types of lumbar and pelvic alignment, i.e. Types A, B, and C in 45-deg, upward movement of upper body was increased in the models with lumbar lordosis (Fig. 7b).

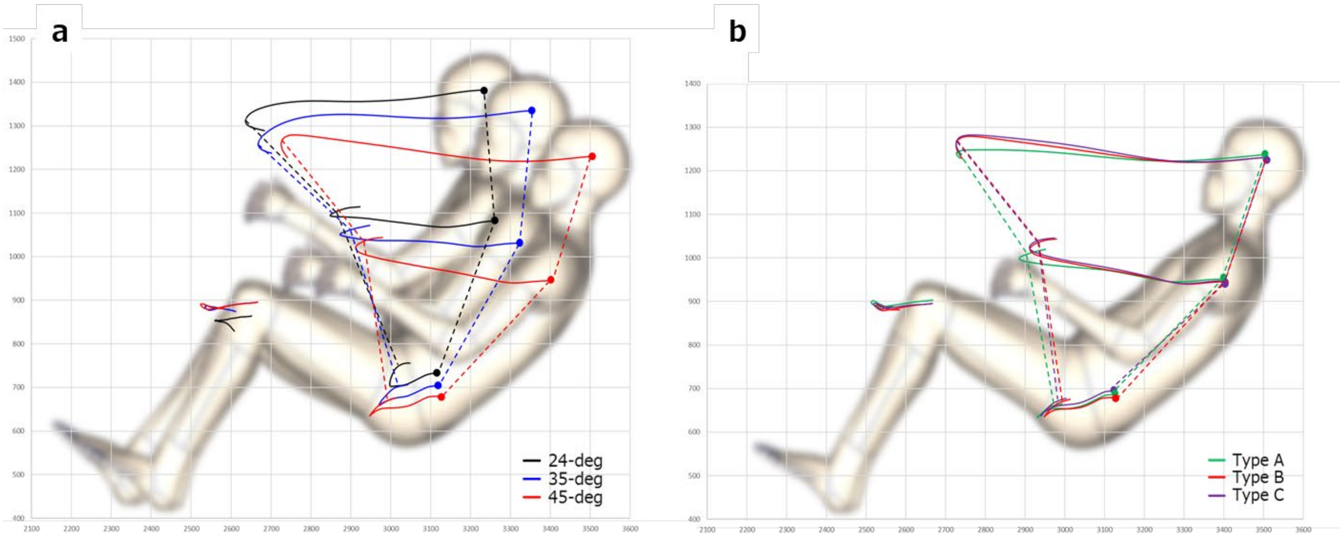

Fig. 7. Occupant kinematics of the head, chest, pelvis and femur: a. reclining angle, b. skeletal alignment.

Head Kinematics

Comparison of the different postures showed that the greater the reclined angle, the greater the increase in the forward displacement of the head. Comparison of the different skeletal alignment for HBMs of Type B and Type C in a 45-deg posture showed the upward movement of head. From the analysis results of maximum acceleration, high head acceleration in z-axis was measured in these HBMs at 97 ms (Fig. 8a). The head injury criterion (HIC) of Type B and Type C in a 45-deg posture was also higher than that of the others (Fig. 8b).

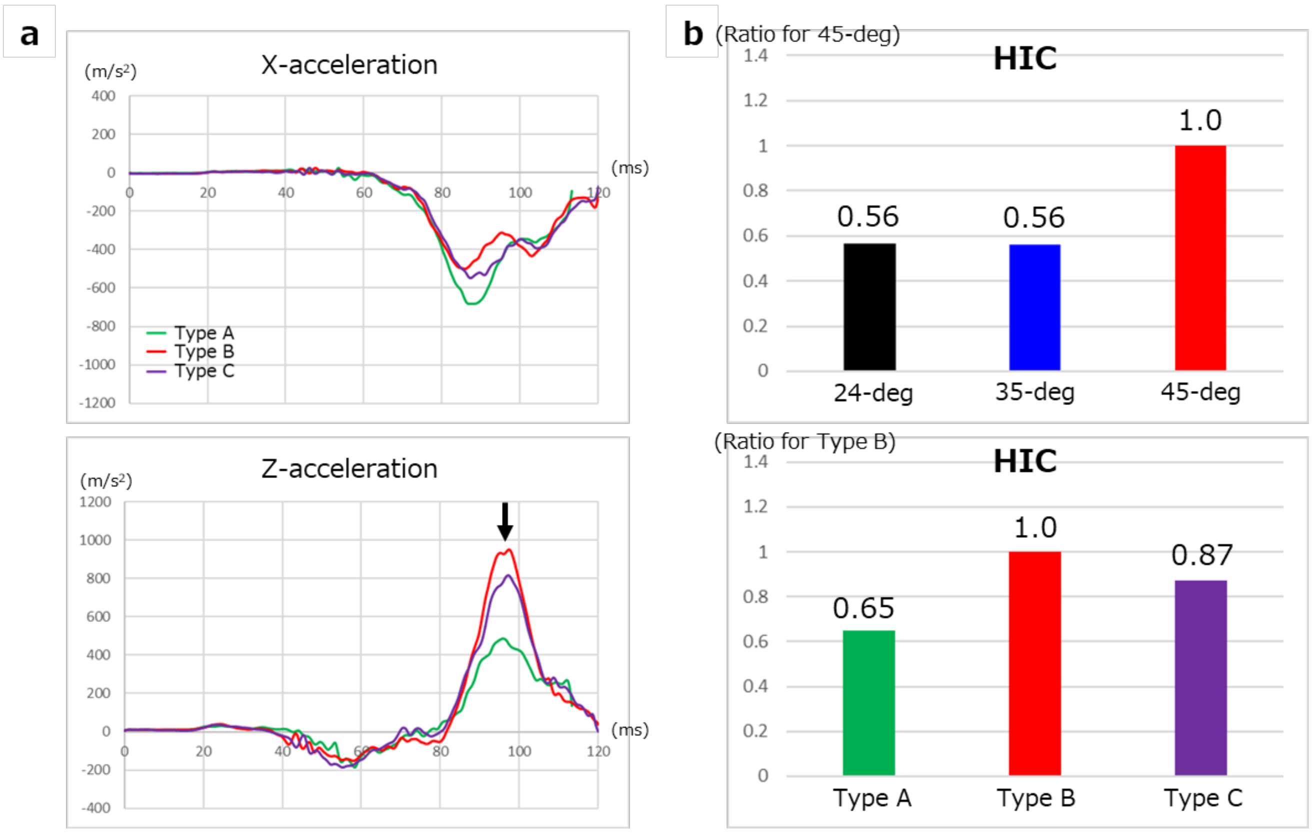

Fig. 8. a. X- and z-acceleration in a 45-deg posture. b. HIC measured in each model. Type B in the lower graph is equivalent to 45-deg in the upper graph.

Chest Kinematics

The patterns of the forward displacement for the chest in each HBM were also similar to those observed for the head. A greater number of rib fractures occurred in Type B and Type C with a 45-deg posture (Fig. 9a). Those fractures were observed on posterior location of lower right ribs, out of the seat-belt path. By analysing the forces on each location of ribs, maximum tension force on those locations of rib fractures were measured above 0.3 kN in x-axis and above 0.5 kN in z-axis at 65 ms (Fig. 9b). All data of the x-, y- and z-axis forces of non-fractured posterior right rib4 and fractured posterior right rib9 as representative forces are shown in Appendix, Fig. A.2.

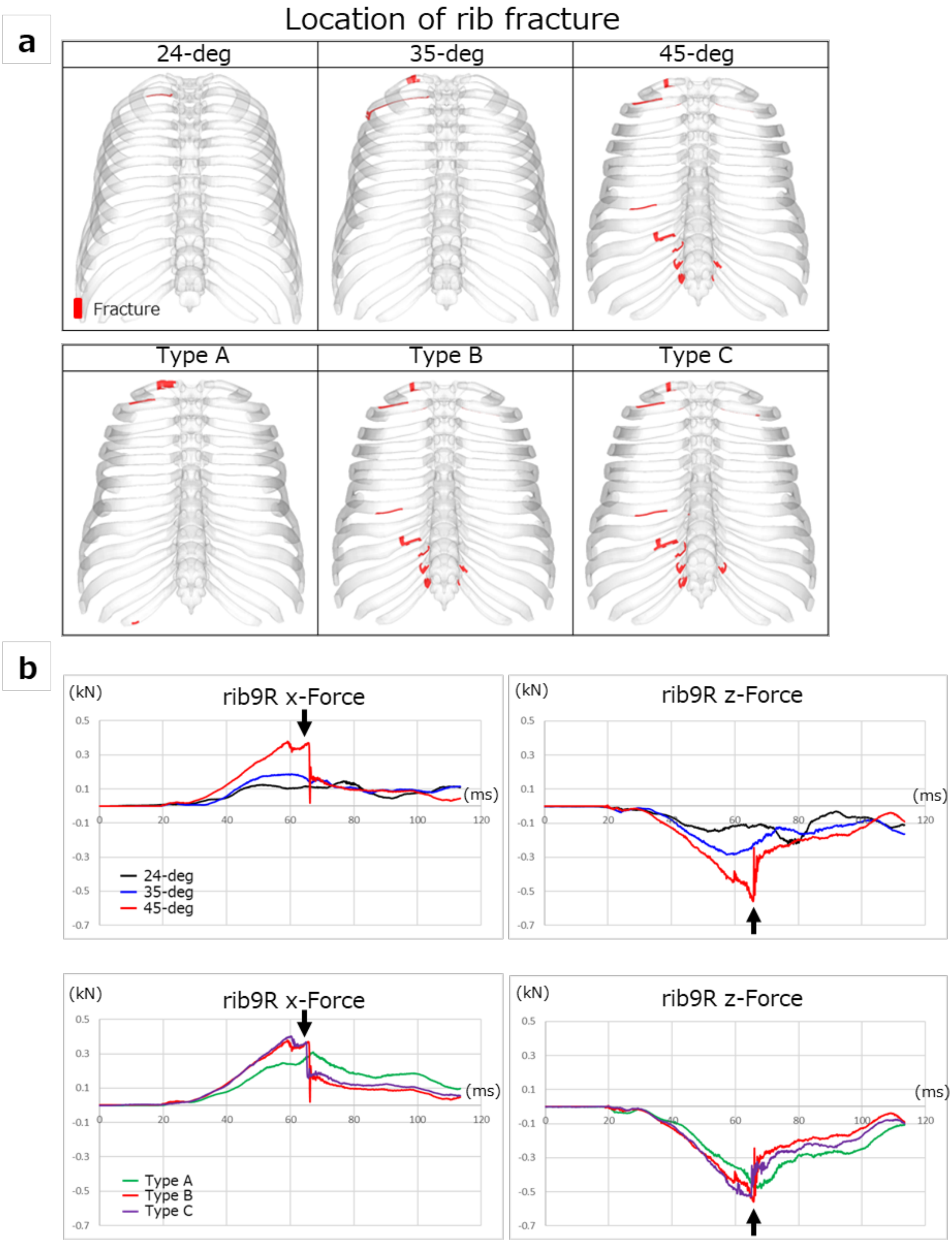

Fig. 9. a. The location of rib fractures in each model. b. The x and z-axis forces on posterior right rib9.

Lumbar Kinematics

The von Mises stress distribution of lumbar spine for each posture and alignment type was analyzed. The greater stress was observed on anterior parts of lumbar spine vertebrae for HBMs with all alignment types in a 45-deg posture (Fig. 10a). Next, the vertical load Fz and flexion moment My acting on each lumbar vertebra were analyzed. The maximum Fz of HBMs in a 45-deg posture was the highest measured, and the load between vertebra L5 and sacrum was 7.8 kN at 85 ms of the rebound phase (Fig. 10b). On the other hand, the maximum My in this posture was also the highest measured and My of 110 Nm at 85 ms between L4 and L5 was observed. These results indicated that the risk of lumbar vertebral fractures in a 45-deg posture is higher than in the other postures.

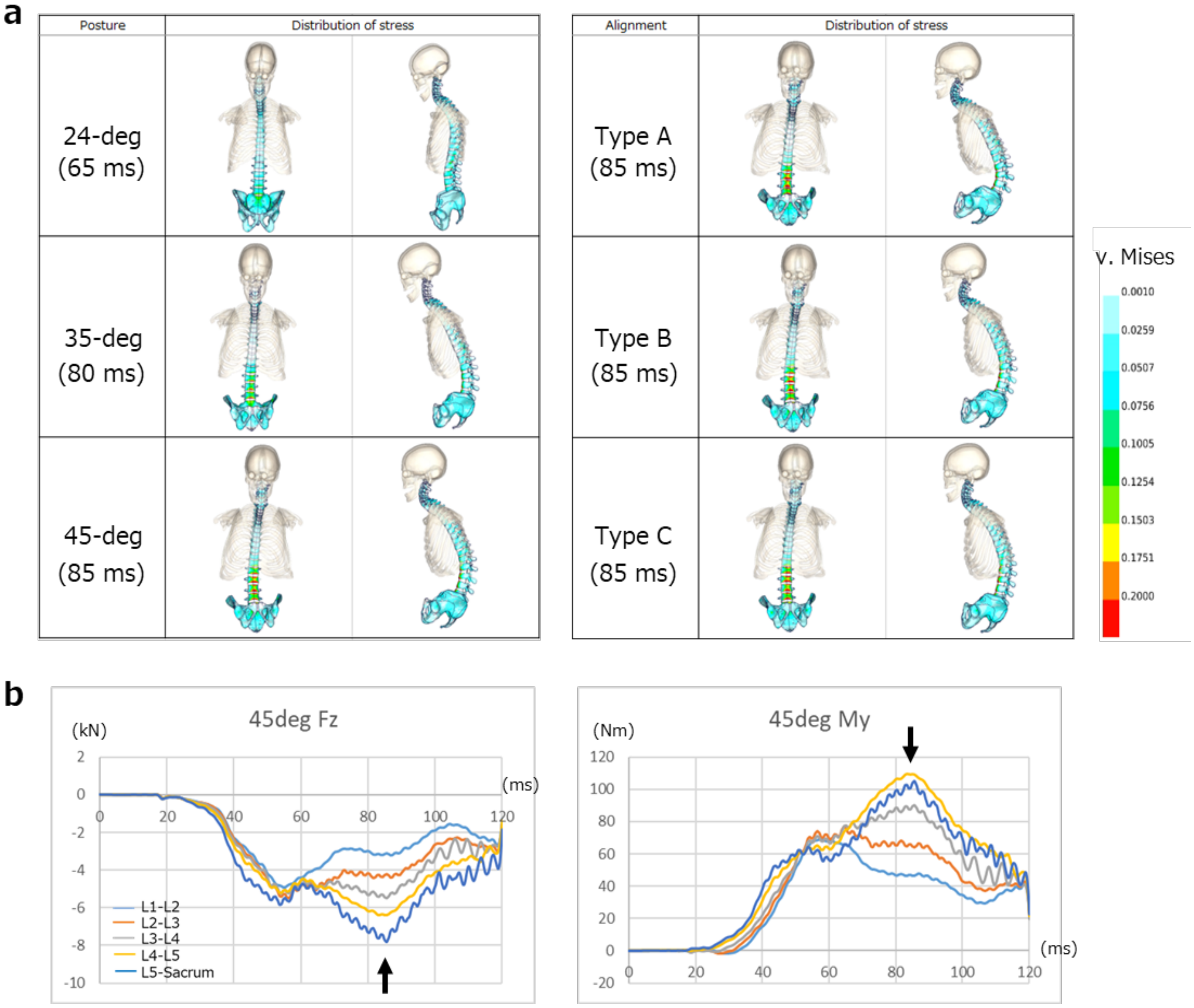

Fig. 10. a. The distribution of stress in the spine of each model. b. Fz and My in a 45-deg posture.

Pelvic Kinematics

From the simulation results of HBMs with different postures, it was found that the greater the reclined angle, the greater the increase in the forward and downward movement of the pelvis were increased. The analysis of lap belt kinematics showed that the lap-belt sliding up was greatly increased in a 45-deg posture, regardless of the alignment type (Fig. 11a), and resulted in submarining. This phenomenon was validated by the abdomen compression rate above 30% and rapid increase of pelvic rearward from 40 ms (Fig. 11b).

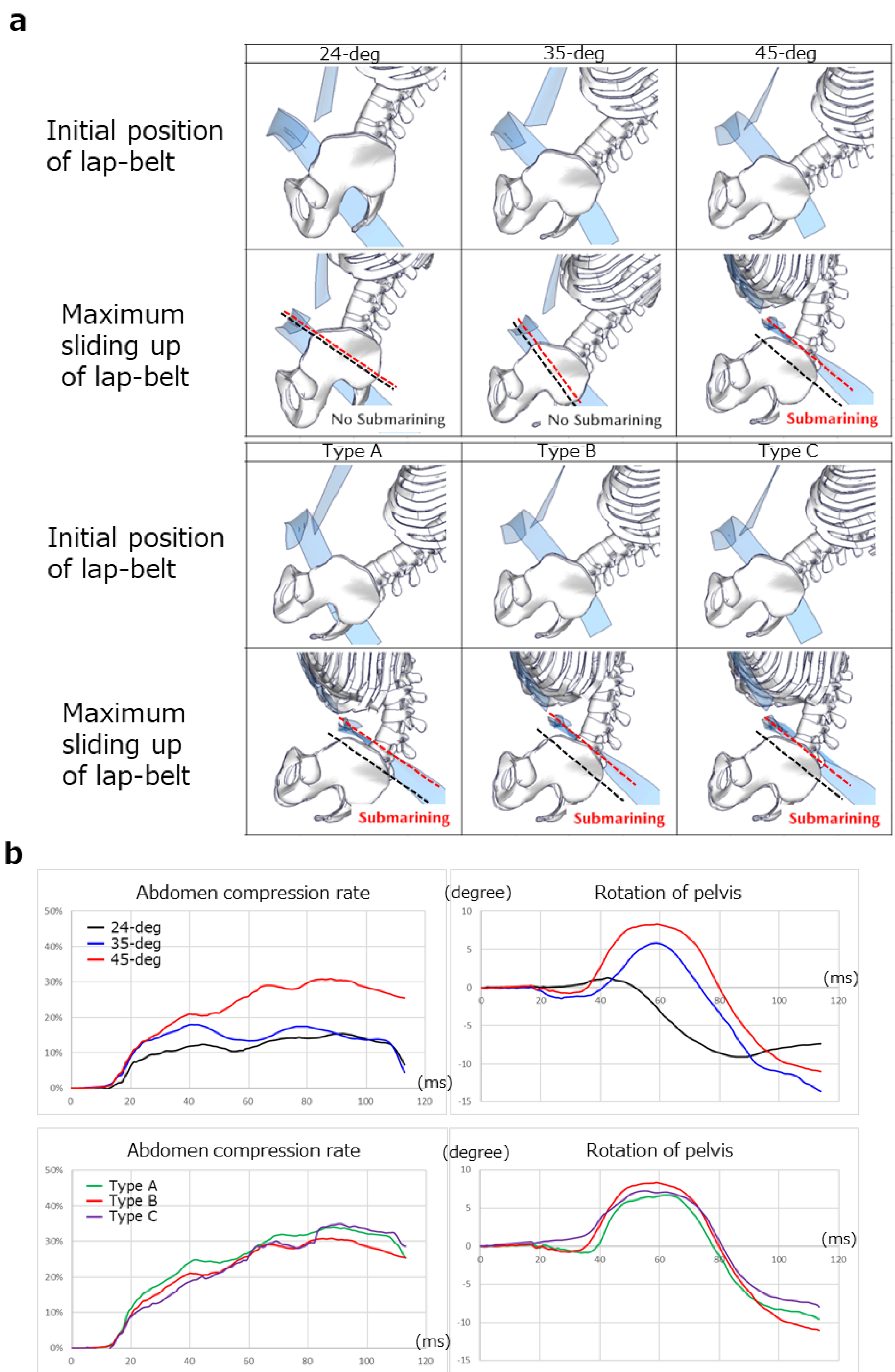

Fig. 11. a. The results of lap-belt and pelvis kinematics. The black dashed line is ASIS position, and the red line is lap-belt position. b. The abdomen compression rate and rotation angle of the pelvis in each model.

IV. DISCUSSION

In this study, individual subjects' skeletal alignment variability was analyzed based on X-ray data. In addition, occupant kinematics and injury outcomes were simulated using HBMs with modified skeletal alignment in different postures. In our previous study, subjects' data of skeletal alignments were collected in an unbiased way in terms of age, stature and BMI [1]. The analysis results for the subjects' alignments concluded that no strong correlation could be observed between alignments and human factors, i.e. age, stature and BMI. In the same way as the previous study, X-ray data of 15 subjects in different postures were obtained and analyzed. The analysis results revealed that the postural change from a 24-deg to 45-deg resulted in not only pelvic rearward rotation but also lumbar lordosis for all subjects (Fig. 6a). Pelvic rearward rotation promotes an increase of SS [13]. A high SS results in lumbar lordosis because the subjects would lean their back on the seatback and their lumbar spine would be strongly pushed forward by the lumbar support. The analysis results for each simulated posture showed that HBMs with strong lumbar lordosis experienced upward movement of the upper body in highly reclined postures (Fig. 7b). In other words, it was concluded that this alignment might affect injury outcomes of the upper body in these postures. Furthermore, trends were observed in that the lap-belt position was higher and the belt angle was greater (Fig. 6b). These trends indicated that it was common for the lap-belt to slide up over the ilium, resulting in submarining.

For the head, the HBMs with strong lumbar lordosis in a 45-deg posture were observed to have upward movement of the head in addition to the increase of forward displacement. By analyzing occupant kinematics from the point of view of skeletal alignment, it was found that the lumbar alignment of these models was changed from straight to kyphosis once that was changed from lordosis to straight. These kinematics induced the upward movement of the head, resulting in the increase of airbag force in z-axis and higher HIC. On the other hand, such a change was not observed in the HBM close to lumbar kyphosis, which kept the same alignment during the crash. For the chest, the trends were similar to those observed for the head. Only the rib fractures of HBMs with strong lumbar lordosis in a 45-deg posture were predicted on posterior location of lower right ribs in addition to upper right ribs on the seat-belt path (Fig. 9a). As shown in Fig. 12a, the forward deformation of lower right ribs was confirmed in these models. It was concluded that left internal organs were pushed out on the right side due to the outside displacement of shoulder-belt position; this deformation on the right side was caused by the protruded liver. As a result, the forward and lateral tension forces were produced on posterior location of lower right ribs.

For lumbar spine, the greater stress was observed from L1 to L5 in the models of a 45-deg posture (Fig. 10a). Two inflection points were confirmed in these models. One of them was between L2 and L3, where more lumbar kyphosis resulted from greater flexion, and the other was between L4 and L5, resulting in the maximum Fz and My. For that reason, it was concluded that the greater stresses were accumulated on whole lumbar spines. From the analysis of the kinematics for the pelvis and lap-belt, submarining was predicted in the HBMs with highly reclined posture (Fig. 11a). In fact, the initial position of lap-belt was higher and the belt angle was greater according to the analysis of X-ray data (Fig. 6b). As shown in Fig. 12b, it was concluded that the component of lap-belt force along the ASIS-AIIS line was produced in an opposite direction due to highly reclined posture. This belt sliding up on the ilium helps the pelvis to rotate more rearward. As a result, submarining was induced. This is demonstrated by the graphs of pelvic rotation (Fig. 11b).

The results from this study will give important insights towards understanding actual skeletal alignment for occupants in a reclined posture and how to protect them from predicted injuries. By investigating individual variabilities of skeletal alignments on occupants with various body shapes, the phenomena specific to highly reclined posture can be identified. Future studies are needed to better understand the effects of these conditions on the occupant kinematics and injury outcomes and to learn how best to protect occupants from these injuries.

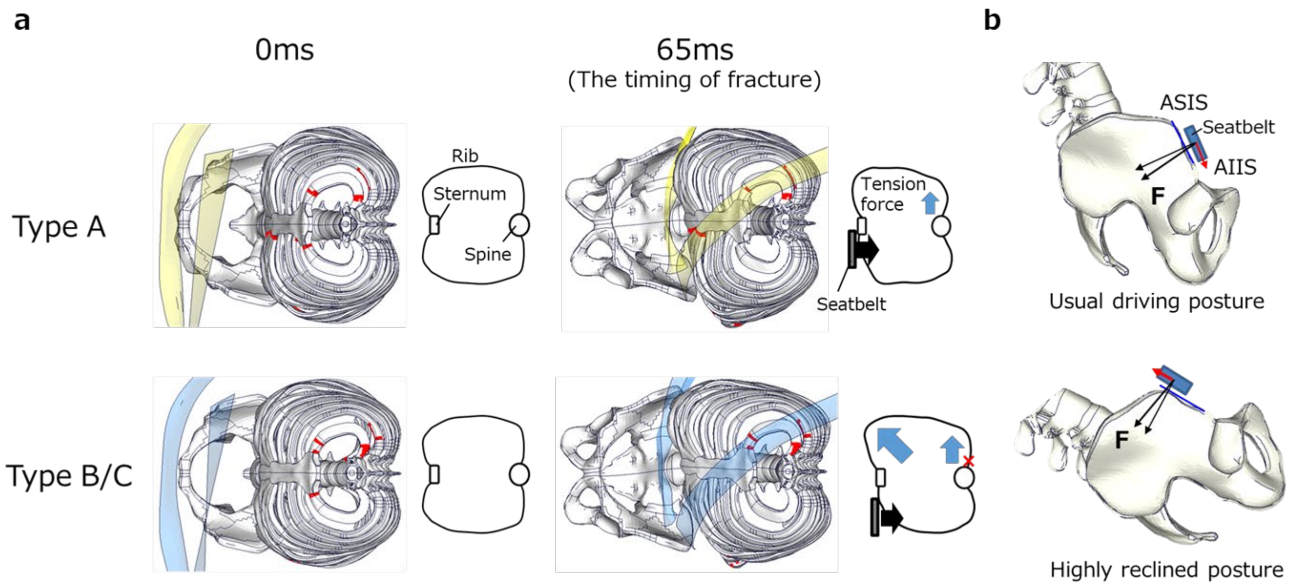

Fig. 12. a. The difference in rib kinematics of Type A and Type B/C. b. The relation between pelvis and lap-belt.

Limitations

As this study deals only with Japanese occupants, the relevance of its findings to other ethnicities is beyond its scope. Furthermore, since X-ray photographs were taken with subjects seated in one type of automotive seat within a short time period, it is not known if the results are applicable to extended periods of riding. The samplings are not complete and further data analysis needs to be done. In X-ray data obtained until now, the number of males was extremely larger than that of females. In this study, the simulations were conducted under the restraint system of a driver seat. Additionally, the results of occupant kinematics, especially the upper body, in simulations should be interpreted only as a trend because this study focused solely on the angle of LL and SS. Future analysis will need to be performed using HBMs modified in the whole skeletal alignment.

V. CONCLUSIONS

In this study, the skeletal alignment of volunteers was analyzed via X-ray. From the analysis of individual variabilities for lumbar and pelvic alignment, it was found that both lumbar lordosis and pelvic rearward were confirmed for all subjects due to highly reclined seating posture. Additionally, trends were also identified in that the lap-belt position was higher and the belt angle was greater. HBMs representing three posture types and three skeletal alignment types, including different postures and alignments, were prepared by modifying THUMS ver.4 AM50. The simulation results indicated that the forward displacements of head, chest and pelvis were increased, and that there was downward movement of the pelvis in a reclined posture. Upward movement of upper body was also observed in this posture. These kinematics, which result from changing the recline angles, affect injury outcomes of vehicle occupants, including HIC, rib fractures, lumbar spine injury and submarining.

VI. ACKNOWLEDGEMENTS

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VIII. APPENDIX

TABLE A.I
THE DATA OF THE ANGLES FROM CERVICAL SPINE TO PELVIS FOR SUBJECTS

gender	stature (cm)	BMI	age	24-deg posture					35-deg posture					45-deg posture				
				CC	TK	TLK	LL	SS	CC	TK	TLK	LL	SS	CC	TK	TLK	LL	SS
Male	162	19.1	39	1.1	-21	-10.3	-6.3	-21	10.4	-35.4	-11.6	8.5	-27	0.8	-18.8	-16.2	23.7	-26.3
Male	164	21.9	29	-15	-15	-11	-4	-19	-17	-17	-5	-1	-24	-13	-9	-3	2	-31
Male	166	20.3	28	0	-20	5	17	1	-11	-21	5	14	-9	-10	-12	8	19	-20
Male	166	30.8	35	-7.8	-19.3	-0.3	11.4	6.5	-0.6	-19.3	4.4	19.1	0.8	0.5	-22.9	6.8	23.5	-9.2
Male	167	22.1	51	11	-40	-6	10	-9	9	-34	-6	11	-15	8	-38	-5	20	-19
Male	168	24.4	44	5.6	-36.9	-19.2	14	-6	0	-27	-16	20	-6	3	-28	-16	17	-11
Male	168	30.8	50	-6.7	-19.2	-3.3	-1.1	-15	-5.5	-22.5	-3.9	5.5	-15.6	-7.4	-22.8	-6.8	11.4	-20.2
Male	169	36.8	31	-6.3	-24.8	-3.6	18.3	-16.9	1.6	-24.8	-1.1	24.8	-12.9	-2.6	-5.6	-28.8	30	-19.9
Male	170	20.1	42	-0.4	-27	-13.9	-6.8	-22.1	-1.1	-19.6	-0.5	14.5	-14.7	-2.5	17.3	7.5	18.9	-20.3
Male	172	25.3	54	-6.9	-14.6	-25	12	-5	-14	-29	-17	23	-11	-17	-37	-16	30	-17
Male	178	17.7	37	7.1	-26.2	-9.3	8.5	-19.9	4	-26.2	-7.4	7	-25.9	1	-17.9	0.9	24.8	-18.3
Male	181	28.9	41	-14	-14	-17	-4	-15	-15	-19	-17	-3	-27	-13	-11	-9	4	-30
Female	152	18.6	45	-11.7	-14.2	-13.3	-4.2	-26.8	-10	-22	-8	0	-31	-14	-25	-9	13	-33
Female	153	19.7	27	-3.9	-26	-12.1	12.8	-16.5	-6.9	-21.5	-8.3	28.7	-19.7	-9.7	-20.3	-5.2	25.3	-15.9
Female	156	18.5	24	0.3	-18.7	-14.3	9.2	-25.6	-3.6	-19.9	-13.7	-2.3	34.1	-7.5	-22.2	-10	3.2	-27.4
Average	166.1	23.7	38.5	-3.2	-22.5	-10.2	5.8	-14	-4	-23.9	-7.1	11.3	-13.6	-5.6	-18.2	-6.8	17.7	-21.2

Angle (+): lordosis/forward
(−): kyphosis/rearward

TABLE A.II
THE DATA OF THE ANGLES FROM CERVICAL SPINE TO PELVIS FOR SUBJECTS

	24-deg	35-deg	45-deg		
			Type A	Type B	Type C
Angle of LL	27	9	2	15	27
Angle of SS	5	-17	-30	-23	-19

TABLE A.III
THE DATA OF THE XZ-COORDINATES FOR THE LAP-BELT POSITION

subject	stature (cm)	BMI	age	24-deg/middle		24-deg/ASIS		45-deg/middle		45-deg/ASIS	
				X	Z	X	Z	X	Z	X	Z
A	166	20.3	28	-71	82	-43	56	-28	107	-12	39
B	172	25.3	51	-88	96	-74	64	-51	76	-16	12
C	168	24.4	41	-80	55	-34	29	-71	66	-25	-5
D	164	21.9	29	-64	43	-36	13	-5	75	9	-23

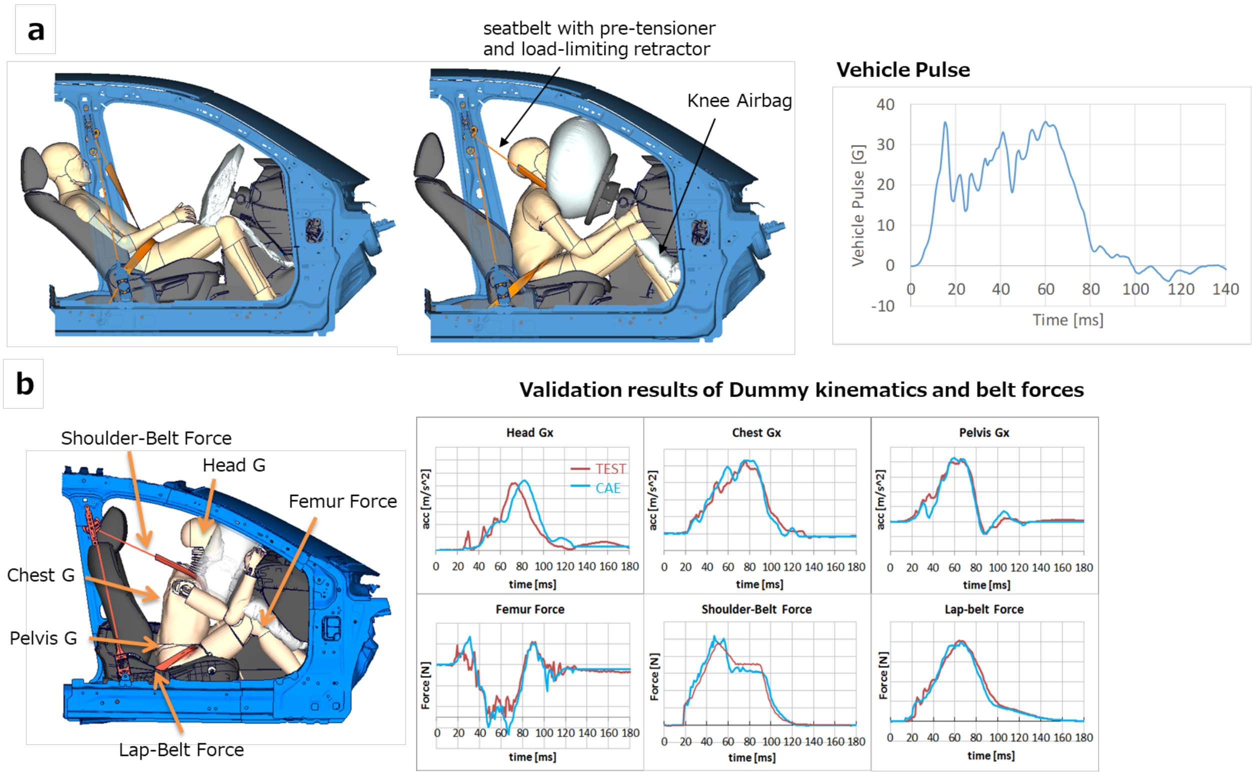

Fig. A.1. a. The FE simulation model and vehicle pulse and b. The kinematics validation results of vehicle model.

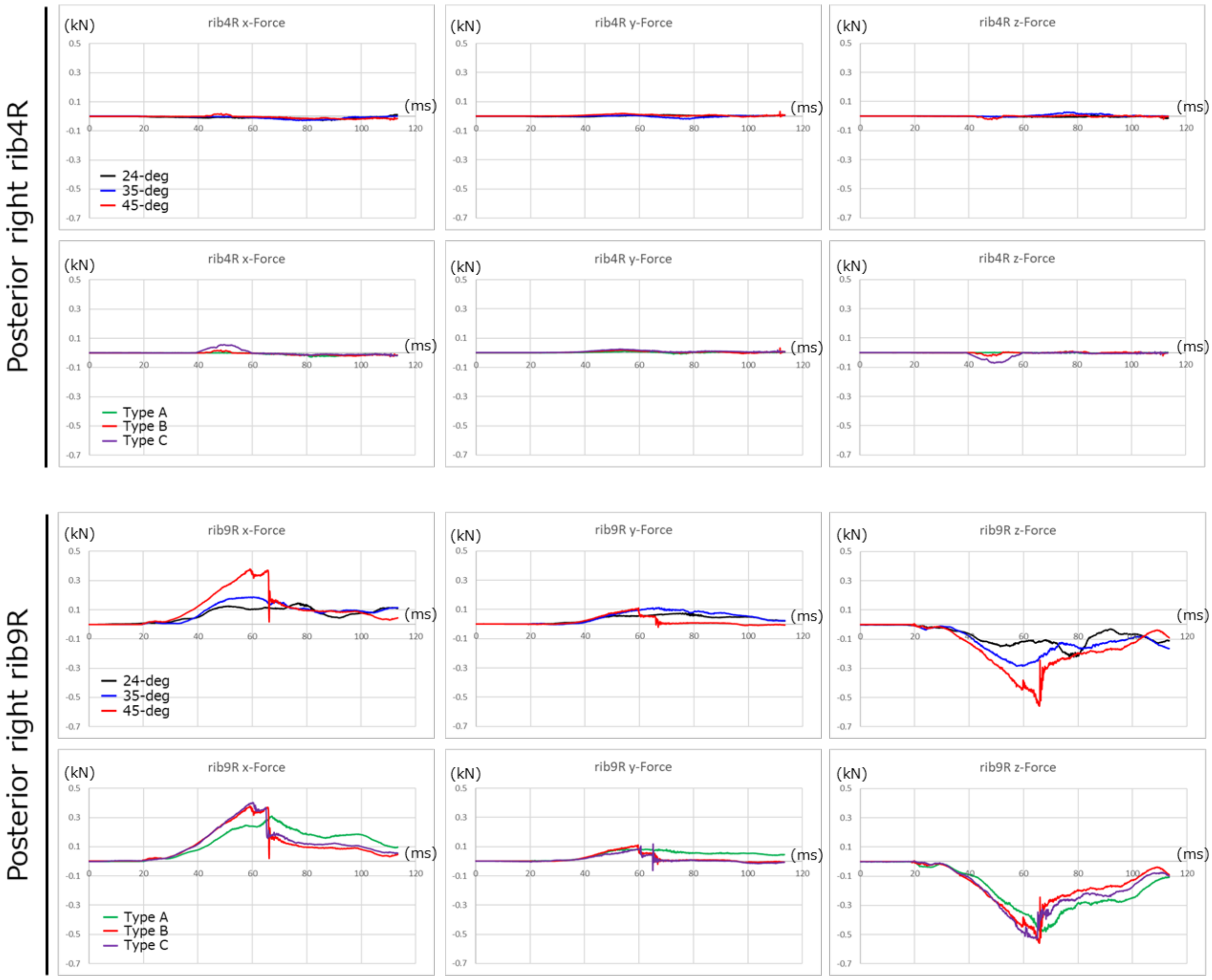

Fig. A.2. The x-, y- and z-axis forces of non-fractured posterior right rib4 and fractured posterior right rib9.