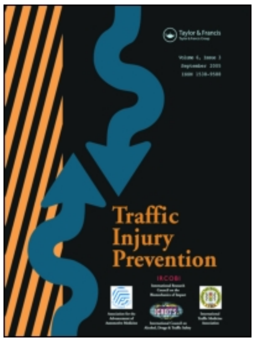

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Effects of whole spine alignment patterns on neck responses in rear end impact

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ABSTRACT
Objective: The aim of this study was to investigate the whole spine alignment in automotive seated postures for both genders and the effects of the spinal alignment patterns on cervical vertebral motion in rear impact using a human finite element (FE) model.
Methods: Image data for 8 female and 7 male subjects in a seated posture acquired by an upright open magnetic resonance imaging (MRI) system were utilized. Spinal alignment was determined from the centers of the vertebrae and average spinal alignment patterns for both genders were estimated by multidimensional scaling (MDS). An occupant FE model of female average size (162 cm, 62 kg; the AF 50 size model) was developed by scaling THUMS AF 05. The average spinal alignment pattern for females was implemented in the model, and model validation was made with respect to female volunteer sled test data from rear end impacts. Thereafter, the average spinal alignment pattern for males and representative spinal alignments for all subjects were implemented in the validated female model, and additional FE simulations of the sled test were conducted to investigate effects of spinal alignment patterns on cervical vertebral motion.
Results: The estimated average spinal alignment pattern was slight kyphotic, or almost straight cervical and less-kyphotic thoracic spine for the females and lordotic cervical and more pronounced kyphotic thoracic spine for the males. The AF 50 size model with the female average spinal alignment exhibited spine straightening from upper thoracic vertebra level and showed larger intervertebral angular displacements in the cervical spine than the one with the male average spinal alignment.
Conclusions: The cervical spine alignment is continuous with the thoracic spine, and a trend of the relationship between cervical spine and thoracic spinal alignment was shown in this study. Simulation results suggested that variations in thoracic spinal alignment had a potential impact on cervical spine motion as well as cervical spinal alignment in rear end impact condition.

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Rear impact; spinal alignment; whiplash; finite element analysis

Introduction

The susceptibility of females to whiplash associated disorder (WAD) has been the focus of numerous epidemiologic studies (Carstensten et al. 2012; Jakobsson et al. 2004; Krafft et al. 2003; Morris and Thomas 1996; O'Neill et al. 1972; Temming and Zobel 1998). These studies show that the risk of sustaining WAD is higher for females than males, even in similar crash conditions. Summarizing the epidemiological literature on WAD, Carlsson et al. (2010) reported that females had up to 3 times higher risk of sustaining WAD compared to males.

WADs occur more frequently in rear end impacts than any other type of automobile impact (Kraft 2002; Watanabe et al. 2000). In order to assess the susceptibility of females to WAD, gender differences in dynamic response of occupants has been analyzed by conducting human volunteer tests in rear end impact conditions (Carlsson et al. 2010, 2011; Linder et al. 2008; Siegmund et al. 1997; Szabo et al. 1994). Ono et al. (2006) investigated cervical spine kinematics related to WAD with sequential x-ray image data obtained by rear impact sled tests with female and male volunteers. Data from the study indicated that females had greater cervical intervertebral displacements with a more pronounced S shape deformation of the cervical spine than males (Sato et al. 2014). Postmortem human head–neck complexes also indicated such gender differences in dynamic vertebral response in rear impact sled conditions (Stemper et al. 2003, 2004).

Experimental investigations have demonstrated the influence of initial cervical postures on neck injury severity (Liu and Dai 1989; Maiman et al. 1983, 2002; Pintar et al. 1995; Yoganandan et al. 1986, 1999). Stemper et al. (2005) showed that elongations of the cervical facet joint ligaments were greater in kyphotic cervical alignment than those in lordotic cervical alignment in simulations with a mathematical head–neck model in rear impact sled test conditions. Hence, the study concluded that cervical kyphosis had a more harmful effect on the risk for WAD than cervical lordosis. Anatomical studies reported that cervical lordotic alignment was shown in a majority, and nonlordotic alignment was 36% (Matsumoto et al. 1998) and 38% (Takeshima et al. 2002) for an asymptomatic population measured in an upright seated position. Matsumoto et al. (1998) reported that

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females presented nonlordotic alignment more frequently than males.

Human volunteer tests have also explained the importance of the interaction between the trunk and seatback to access the potential mechanisms producing WAD in rear end impacts (Ono et al. 1999). Studies with human finite element (FE) models have reported that initial positions of the thoracolumbar spine in a rear end impact affect cervical spine kinematics related to WAD as well as those of the cervical spine (Sato et al. 2010). Alignment of the whole spine is therefore one of the essential key factors for further investigation of WAD. However, the whole spine alignment in automotive seated posture has not been well documented, particularly for females (Chabert et al. 1998).

The aim of this study was to investigate the whole spine alignment in an automotive seated posture for both genders with image data obtained by an upright open magnetic resonance imaging (MRI) system and analyze the effects of average gender specific spinal alignment patterns on cervical vertebral motion in rear impact using a human FE model.

Methods

Effects of spinal alignment patterns on cervical vertebral motion were analyzed by reconstruction FE simulations of the previous sled tests (Ono et al. 2006). The sled tests revealed that cervical intervertebral angular displacements during rear impact were greater for females than males in the same seated posture on a rigid laboratory seat, used to exclude the influence of seat properties and gender differences of occupant posture. In the present study, average spinal alignment patterns for both genders were analyzed from MRI data in a seated posture using multidimensional scaling (MDS) analysis. The posture used was the same as in the previous sled tests. Furthermore, because the previous sled tests were conducted with female volunteers who had approximately AF50 size stature, an occupant FE model of female average size (AF50 size) was developed and validated with respect to female volunteer test data from the previous sled tests (Ono et al. 2006). Then, the spinal alignment of the model was varied between the average female, the average male, and representative alignments of all subjects found by the MDS analysis in order to investigate whether differences in spinal alignment could be contributing to differences in cervical intervertebral angular displacements as reported by Ono et al. (2006). All simulations were conducted with the FE code LS-DYNA (mpp s R6.1.2 LSTC, Livermore, CA).

Spine imaging in seated posture by upright open MRI system

Image data for a seated posture utilized in this study were acquired with an upright open MRI system, as described by Sato et al. (2016). Subjects were 8 female (5 Japanese and 3 European) and 7 male (3 Japanese and 4 European) healthy adult volunteers ranging in age from 21 to 38 years with an average age of 27 years. All subjects had no history of spine injury. The average height and weight were 159.9 cm, 47.8 kg for Japanese female subjects; 162.3 cm, 58.3 kg for European female subjects; 171.4 cm, 64.5 kg for Japanese male subjects; and 175.2 cm, 77.7 kg for European male subjects. The subjects were selected to match as closely as possible the following targets of height and weight. For Japanese subjects, the target height and weight (mean ± SD) were defined as the average Japanese in age from 20 to 40 years, 159 ± 5 cm, 51 ± 6 kg for females and 172 ± 6 cm, 67± 9 kg for males, respectively (Ministry of Education, Culture, Sports, Science and Technology, Japan 2013). The target height and weight for European subjects were set based on the mid-sized female and male in the dummy family defined in the University of Michigan Transportation Research Institute study, 161.8 cm, 62.3 kg for females and 175.3 cm, 77.3 kg for males, respectively (Schneider et al. 1983).

The MRI scans were conducted in an upright open MRI system, Signa SP/i (GE Healthcare Inc.) at Shiga University of Medical Science, Japan, for Japanese subjects and by a Fonar Upright Multi-Position MRI system (Fonar Inc.) at Hospital Universitario HM Montepríncipe (Fundación de Investigación HM Hospitales), Spain, for the European subjects. Subjects were seated on a nonmetallic rigid seat installed in an MRI system. The rigid seat consisting of 2 flat planes had a seatback angle of 20° from the vertical plane and seat pan angle of 10° from the horizontal plane, designed to correspond to the seat used for previous volunteer sled tests under rear end impact (Ono et al. 2006). The volunteer positioning was conducted with the same procedure as the previous volunteer sled tests: volunteers were seated on the rigid seat as deeply as possible and asked to face forward with the Frankfort plane 10° upward from the horizontal in a relaxed state. The femurs (the line between the great trochanter and the center of the knee joint) were set at 25°. Then the spinal column from the mastoid level to the sacrum was scanned with 4 serial images by changing the height of the seat, due to the limitation of the field of view. All procedures for the MRI scanning were approved by the Institutional Review Board of Shiga University of Medical Science, Hospital Universitario HM Montepríncipe, and Japan Automobile Research Institute.

Estimation of the average spine aliment patterns for both genders

Figure 1 shows a scheme of the steps to analyze the spinal alignments by MDS (Miyazaki et al. 2005; Mochimaru et al. 2000) in this study. The spinal alignment was determined by the centers of the vertebral bodies and extracted from the midsagittal images by the medical imaging software OsiriX (Pixmeo, Geneva, Switzerland). For C2 and the sacrum, the midpoint of the inferior or superior surface was used in the definition of the spinal alignment, respectively. Each spinal alignment was rotated and normalized so that C2 was located at 1 on the normalized z-axis with the sacrum at the origin. An interindividual distance between 2 subjects e_{pq} was defined as the sum of squares of Euclidean distances between corresponding vertebral points p_i and q_i from C2 through the sacrum, a total of 22 points, in the normalized coordinate system in Eq. (1).

$$e_{pq} = \sum_{i=1}^{22} (p_i - q_i)^2, \tag{1}$$

where p_i and q_i consist of x and z coordinate values of a corresponding vertebral point for volunteers P and Q. An MDS analysis on the distance matrix D in Eq. (2), representing the

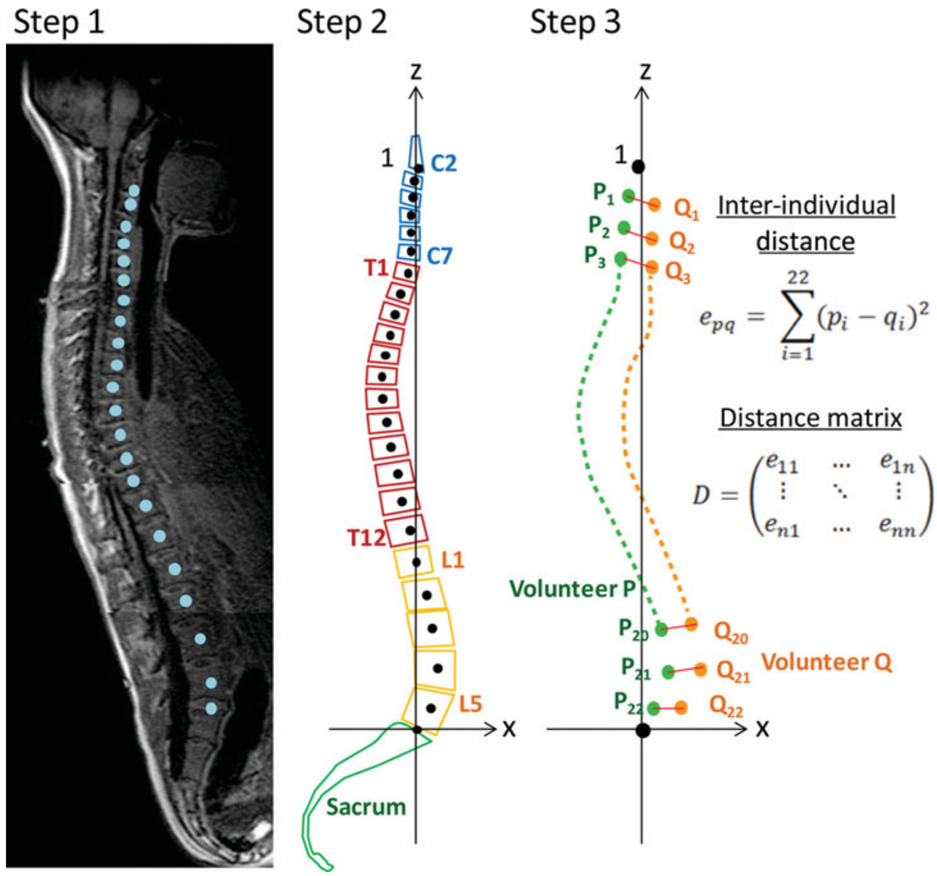

Figure 1. Scheme of the steps to analyze the spinal alignments. Step 1: Extracting the centers of the vertebral bodies from the MRI data. Step 2: Transforming a spinal alignment in the normalized coordinate system. Step 3: Obtaining interindividual distances and the distance matrix.

interindividual distances between all possible pairs of subjects, was carried out.

$$D = \begin{pmatrix} e_{11} & \dots & e_{1n} \\ \vdots & \ddots & \vdots \\ e_{n1} & \dots & e_{nn} \end{pmatrix}, \tag{2}$$

where n means the nth subject. MDS dimensions were provided by characteristic vectors of D. By applying the Young-Householder transformation to D, a scalar product matrix B was obtained. MDS dimensions were provided by characteristic vectors of B. MDS scores of subjects on the MDS dimensions were calculated by characteristic values and vectors of B. In this study, a 2-dimensional distribution map of the spinal alignments was created by 2 MDS dimensions that had the 2 largest characteristic values of B. The MDS dimensions represent independent shape factors that explain the distance relations between subjects most efficiently (Mochimaru et al. 2000), and spinal alignment patterns were investigated based on the MDS scores.

The average spinal alignment patterns for both genders and the representative spinal alignment patterns at the 50% probability ellipsoid on the distribution map by MDS were estimated by weighted average of spinal alignments, represented in Eq. (3). An MDS analysis including the estimated spinal alignment was carried out to obtain the MDS score of the estimated spinal alignment. Then, the weight factor c_j in Eq. (3) was calculated to minimize the difference between the MDS score of the estimated spinal alignment and the target MDS score. The target MDS scores are the average MDS scores for females and males, and the intersections of the 50% probability ellipsoid and the axes of the first or second MDS dimensions.

$$A_{\text{ave}} = \sum_{j=1}^{N} c_j A_j, \tag{3}$$

where A_{ave} is the weighted average of spinal alignments, A_j is the spinal alignment of the jth subject in Eq. (4), and N is the number of subjects.

$$A_j = \begin{pmatrix} x_{j1} & z_{j1} \\ \vdots & \vdots \\ x_{j22} & z_{j22} \end{pmatrix}. \tag{4}$$

Development of AF50 size occupant FE models

An occupant FE model of female average size (162 cm stature and 62 kg weight denoted AF50 size; Carlsson et al. 2014; Schneider et al. 1983) was built based on the Total HUman Model for Safety (THUMS) version 4 AF 05 occupant model developed by Toyota Motor Corporation and Toyota Central R&D Labs (Kitagawa et al. 2015; Toyota Motor Corporation 2011), consisting of approximately 2.3 million elements. In the THUMS series, 5th percentile adult female (AF05) and 50th and 95the percentile adult male (AM50 and AM95) size models are commercially available; the AF50 size is not. The THUMS AF05 occupant model was scaled up to AF50 size with a scaling factor based on body height of 162/154 in X, Y, and Z directions, because the height of the original AF05 model was 154 cm.

The average spinal alignment pattern of the seated posture for females estimated in this study was rotated back to its original positions and implemented in the AF50 model. In the model, the pelvis and sacrum were rotated so that the superior surface of the sacrum was 1.6° upward for the average spinal alignment pattern for females, 9.3° for the average spinal alignment pattern for males, and 5.5° (average of all subjects) for the representative spinal alignment patterns at the 50% probability ellipsoid, corresponding to the respective average from the MRI study. Then, each vertebra was aligned manually from the lower level to the upper level including the surrounding body parts, such as the ribs, organs, and flesh. The angle between the line joining the anterosuperior iliac spine and the anterosuperior edge of the symphysis pubis and the line along the sacrum superior surface remained approximately 57° for the THUMS model, within 48.5 ± 10.2 degrees for human subjects (mean $\pm$ SD; Peleg et al. 2007). Hence, the connectivity between the sacrum and pelvis was not changed in this study. The material properties in the cervical muscles were adjusted according to the material properties published by Yamada (1970) and Chancey et al. (2003), because the model initially was stiffer than female volunteers during the rear impact sled condition. The dynamic response of the AF50 model was validated with respect to the response corridors of female volunteers under rear impact sled condition described in the following subsection. The correlation between the model response and the volunteers' response was analyzed using the correlation and analysis method (CORA Ver 3.6.1; Gehre et al. 2009).

After validation of the AF50 model, the average spinal alignment pattern for males and the representative spinal alignment pattern estimated at the 50% probability ellipsoid were also implemented in the validated AF50 model for a parametric study to investigate the effects of spinal alignment patterns on cervical vertebral motion.

Rear impact simulation

Volunteer rear impact sled tests conducted by Ono et al. (2006) were reconstructed with the AF50 model. This series of rear impact sled tests was conducted with female volunteers of approximately AF50 stature. The change in velocity was 5.8 km/h and peak accelerations of 42 m/s^2, designed to be under a load level that would guarantee the safety of volunteers based on a previous experiment (Ono et al. 1997). The procedures of the volunteer sled tests were approved by the Institutional Review Board of the Medical Department at the University of Tsukuba, Japan. All volunteers gave written informed consent after the protocol including potential risks was explained to them. The complete report of the sled tests was published by Ono et al. (2006). The sled system had a rigid plate seat with a seatback angle of 20° from the vertical mounted on horizontal rails, and volunteers were seated in a relaxed state as described in the former subsection for the MRI scanning. Whole-body kinematics was captured by a high-speed video camera, and cervical vertebral kinematics was analyzed by a cineradiography system. The detailed dynamic response corridors obtained from a reanalysis of the volunteer sled tests are provided by Sato et al. (2014). In order to reconstruct the volunteer sled tests, the AF50 model was seated on a rigid seat model corresponding to the seat in the volunteer sled tests, and the sled acceleration obtained from the tests was used, in combination with gravity load.

Results

Estimated average and representative spinal alignment patterns

The distribution of spinal alignments is shown in Figure A1 (see online supplement). The first and second MDS dimensions of the distribution map explained 67 and 20% of total variance of the spinal alignments, respectively. In order to interpret the first MDS dimension as a shape factor, spinal alignments were compared between subjects who had similar MDS scores on the second MDS dimension but varied on the first MDS dimension (Figures A1b and A1c, for example). The spinal alignments with positive MDS scores on the first MDS dimension had lordotic cervical and more pronounced kyphotic thoracic spine, with a peak of the thoracic kyphosis (the most backward vertebra of the thoracic spine) at the lower vertebra level. Those with negative MDS scores had kyphotic cervical and less-kyphotic thoracic spine with a peak of the thoracic kyphosis at a higher vertebra level. The spinal alignment patterns estimated at the intersections of the 50% probability ellipsoid and the axes of the first MDS dimension (Figure A1e) exhibited the same trend. Therefore, the first MDS dimension explained the curvature of the cervical spinal alignment and degree of thoracic kyphosis with peak vertebra level of thoracic curvature. For the second MDS dimension, a comparison of spinal alignments is shown in Figure A1d. The comparison portrayed a difference of forward/backward position around L1 with similar cervical and upper thoracic spinal alignments. The spinal alignment patterns estimated at the intersections of the 50% probability ellipsoid and the axes of the second MDS dimension (Figure A1f) exhibited the same trend around the middle of the thoracic spine. The second MDS dimension seemed to explain the position of thoracolumbar region with similar cervical and upper thoracic spinal alignments.

The estimated average spinal alignment patterns for both genders are shown in Figure A1g. Most of the female subjects had negative MDS scores on the first MDS dimension. Subjects who had positive MDS scores on the first MDS dimension were mostly male. Therefore, the average MDS score on the first MDS dimension was negative for the females and positive for the males ($P < .1$, t test) The estimated average spinal alignment pattern was slightly kyphotic or almost straight cervical and less-kyphotic thoracic spine for the females and lordotic cervical and more pronounced kyphotic thoracic spine for the males.

Validation of the AF50 model with the average spinal alignment pattern for females

Figure A2 (see online supplement) shows the AF50 model with the average spinal alignment pattern for females and males and representative spinal alignment patterns estimated at the 50% probability ellipsoid, respectively. For validation, the AF50 model with the average spinal alignment for females was utilized.

In comparison with the female volunteer test data (Sato et al. 2014), the head angular displacement (Figure A3d, see online supplement) and the vertebral angular displacement of C1 relative to C7 (Figure A3f) were slightly greater for the AF50 model than the female volunteers after around 100 ms. In general, however, the simulated results show good agreement with the corresponding experimental corridors for head and T1 x-displacement, T1 angular displacement, and vertebral angular displacement of C2 through C6 relative to C7.

Effects of spinal alignment patterns on cervical vertebral motion

Figure 2 portrays the time histories of spine motion in the local coordinate system moving with the sled under the rear impact sled condition. In order to track the spine motion, the spinal alignment with the head center of gravity was extracted from both AF50 models every 20 ms. The spinal alignments for both models were straightened along the seatback until 100 ms. The spine straightening seemed to start from T7 for the model with the female average spinal alignment and L1 for the model with the male average spinal alignment. After 100 ms, rebound of the trunk against the seatback was slightly observed in both models, while the head continued rotating in extension.

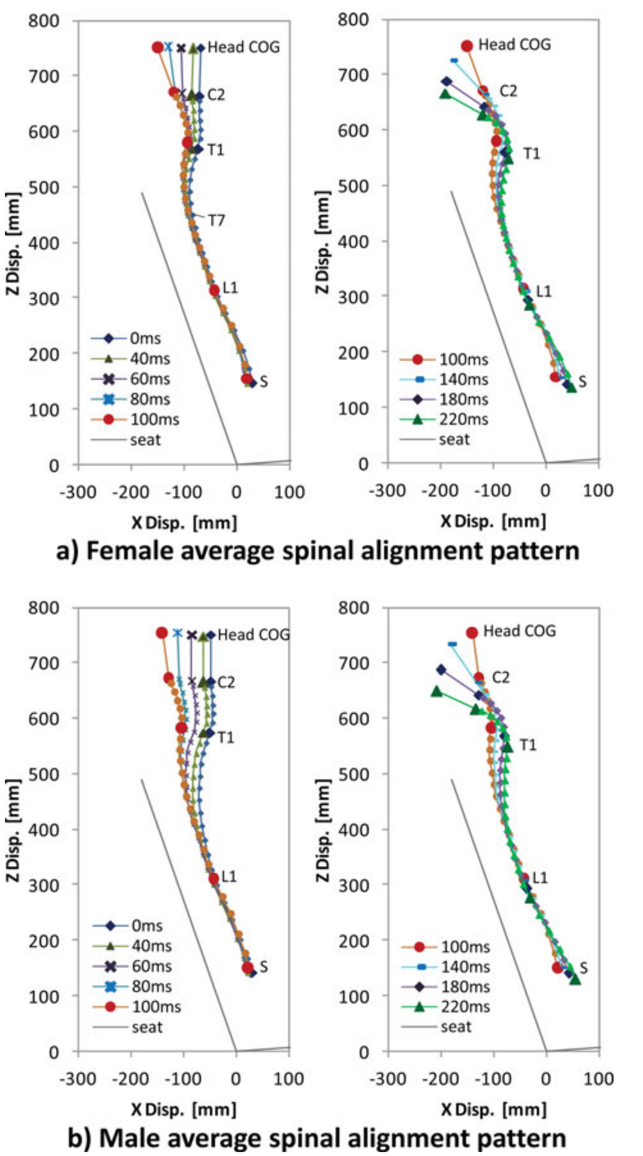

Figure 2. Spine motion of the AF50 occupant model in the local coordinate system moving with the sled with the x-axis in the horizontal and z-axis in the vertical.

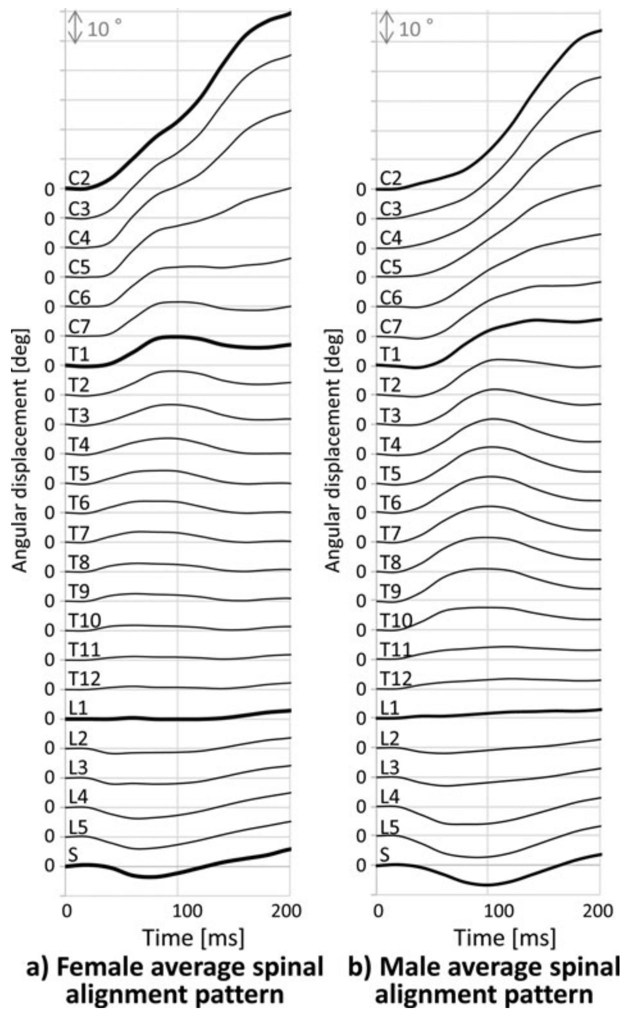

Figure 3. Vertebral angular displacements of the AF50 occupant model. The positive side is extension and negative is flexion against the corresponding initial positions.

Figure 3 indicates the vertebral angular displacements against the corresponding initial positions. In the thoracic spine, vertebrae tended to have a peak of the extension angle until around 100 ms for both models. The timing of the peaks corresponded to the response of spine straightening shown in Figure 2. At 100 ms around the timing of the peaks, intervertebral angular displacements were greater at the upper thoracic vertebrae for the model with the female average spinal alignment and greater at the lower thoracic vertebrae for the model with the male average spinal alignment. In the cervical spine, intervertebral angular displacements were greater for the model with the female average spinal alignment than with the male average spinal alignment, even though the T1 angular displacements for the female average spinal alignment were smaller than for the male average spinal alignment. This trend was observed especially at C4/C5 and C5/C6, for which the female alignment showed intervertebral angles of 3.7° and 3.9°, whereas the male

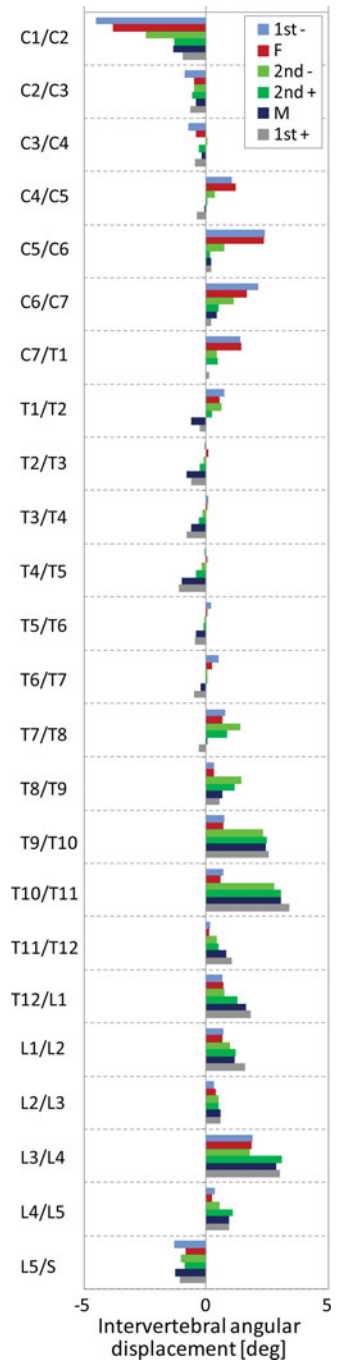

Figure 4. Intervertebral angular displacement at the time of maximum cervical S shape. The positive side is extension and negative is flexion relative to the lower adjacent vertebra. "1st−" and "1st+" indicate the representative spinal alignment patterns estimated at the intersection of the 50% probability ellipsoid and the axes of the first MDS dimension in the negative and positive region the first MDS dimension, respectively. "2nd−" and "2nd+" indicate the representative spinal alignment patterns estimated at the intersection of the 50% probability ellipsoid and the axes of the second MDS dimension in the negative and positive region the second MDS dimension, respectively. "F" and "M" indicate spinal alignments estimated at the average MDS score for females and males, respectively. The maximum cervical S shape occurred around 70–80 ms in each spinal alignment pattern.

alignment showed intervertebral angles of 0.7° and 0.8° at 100 ms.

Figure 4 summarizes intervertebral angular displacements at the time of maximum cervical S shape, defined as the instant when the C2/C3 showed the largest flexion (Stemper et al. 2003). The spinal alignment patterns with slightly kyphotic or almost straight cervical and less-kyphotic thoracic spine ("1st+" and female average) exhibited greater angulation in cervical spine and smaller angulation in thoracic spine than the spinal alignment patterns with lordotic cervical and more pronounced kyphotic thoracic spine ("1st−" and male average). Vertebral motions concentrated in the cervical spine for the spinal alignment patterns with slightly kyphotic or almost straight cervical and less-kyphotic thoracic spine ("1st+" and female average).

Discussion

In this study, the effect of spinal alignment on rear end impact kinematics was investigated through simulations with a female size occupant model with 6 different spinal alignment patterns. The spinal alignment patterns implemented in the occupant model were estimated from MRI data in a seated posture by MDS analysis. The distribution map analysis of the volunteer MRI data (Figure A1) showed that spinal alignment pattern tends to shift from kyphotic cervical and less-kyphotic thoracic spine to lordotic cervical and more pronounced kyphotic thoracic spine with an increase in the MDS score of the first MDS dimension. Previous investigations on the variety of cervical spinal alignment (Headacker et al. 1997; Helliwel et al. 1994; Matsumoto et al. 1998) observed that females were more likely to have a nonlordotic (kyphotic or straight) cervical spine, whereas males were more likely to have a pronounced lordotic cervical spine. Matsumoto et al. (1998) reported a significant correlation between gender and cervical spinal alignment by statistical analysis. In the present study, the estimated spinal alignment pattern was slightly kyphotic or almost straight for females and lordotic for males in the cervical region with lower MDS score of the first MDS dimension for females than males. The spinal alignment around the cervicothoracic junction was also investigated in previous studies (Lee et al. 2014; Park et al. 2015). These studies reported that males had a more forward-inclined T1 than females and decreasing of the T1 inclination was associated with more hypo-lordosis or kyphosis in cervical spinal alignment. The estimated average spinal alignment for males has a more forward inclination around T1 with more lordotic cervical spine than that for females. Accordingly, this study obtained results corresponding to the observation in previous studies.

The spinal alignment pattern affected cervical vertebral motion under rear end impact sled condition (Figures 2–4). The female average spinal alignment showed straightening from a higher thoracic vertebra level than the male average spinal alignment (where straightening occurred at the lower thoracic vertebra levels). This may cause load transmission from the trunk to the head at an earlier stage, and the load provided from the seat back could have a greater effect on the cervical vertebral motion. In addition, vertebral angular displacements concentrated around the cervical spine for the spinal alignment patterns with slightly kyphotic or almost straight cervical and less-kyphotic thoracic spine, whereas it was more concentrated around the lower region of the thoracic spine for the spinal alignment patterns with lordotic cervical and more pronounced kyphotic thoracic spine. Previous studies reported that variations in cervical spinal alignment influenced the cervical spine motion and the severity of injury by conducting experiments with postmortem human subjects and FE analysis (Liu et al.

1989; Maiman et al. 1983, 2002; Pintar et al. 1995; Stemper et al. 2005; Yoganandan et al. 1986, 1999). The cervical spine is linked continuously from the thoracic spine, and a trend of the relationship between cervical and thoracic spinal alignment was shown in this study. Hence, results from the current study suggested that variations in thoracic spinal alignment had a potential impact on cervical spine motion as well as cervical spinal alignment.

The occupant FE models utilized in this study have the same skeletal bone geometry including size. Compiling biomechanical literature on anatomical gender differences with size-matched volunteers (DeRosia 2008; Stemper et al. 2008, 2009; Vasavada et al. 2008), Stemper et al. (2011) reported that females had a more slender neck and smaller vertebral bodies than males, indicating less support in the cervical region. Kitagawa et al. (2015) showed that gender differences in cervical spine motion were affected by anatomical differences rather than muscular strength using FE analysis. Hence, those anatomical differences may contribute to cervical vertebral motion during impact and lead to more pronounced gender differences in intervertebral displacements when applied to the occupant FE models utilized in this study.

The prevalence of neck pain at the cervical zygapophysial joint caused by rear end accidents has been investigated (Barnsley et al. 1995; Liliang et al. 2008; Lord et al. 1996). Chronic pain that the majority of patients experienced occurred at C5/C6. The FE analysis conducted in this study indicated that intervertebral angular displacements were greater for the female average spinal alignment than the male average spinal alignment, especially at C4/C5 and C5/C6. In addition, rear end impact tests with an automotive seat at an impact level similar to that in this study showed that head-to-head restraint contact time was 91 ms for females and 100 ms for males (Carlsson et al. 2010) and 95 ms for males (Pramudita et al. 2007). At around those head-to-head restraint contact timings, intervertebral angular displacements were already greater for the female average spinal alignment than the male average spinal alignment in this study.

Limitations

Validation simulations showed that the model can capture the overall response of human volunteers and therefore it is useful to investigate the effect of an altered spinal alignment as studied in the present article. However, it should be noted that some responses have a somewhat lower correlation with respect to the validation data, such as the C1–C7 rotation (0.58). Hence, in order to be able to quantify the risk of injury with the model, further development and validation might be necessary.

Because FE simulations conducted in this study were carried out with a seat model consisting of rigid planes without a head restraint system, further FE analysis would be needed to assess the vertebral motion with a commercially available automotive seat. In addition, other vehicle interior elements that might affect the posture and seating position, such as different types of vehicles, variations in the seat height, mirror position, steering wheel placement, etc., have not been account for.

The MRI data analyzed in this study were acquired with 8 females and 7 males. The number of subjects was limited in size due to the cost of the MRI scans for each subject. It was insufficient to generalize spinal alignment patterns for a large range of body sizes. Therefore, this study focused on the average body size as a first step for the investigation of spinal alignment patterns.

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APPENDIX

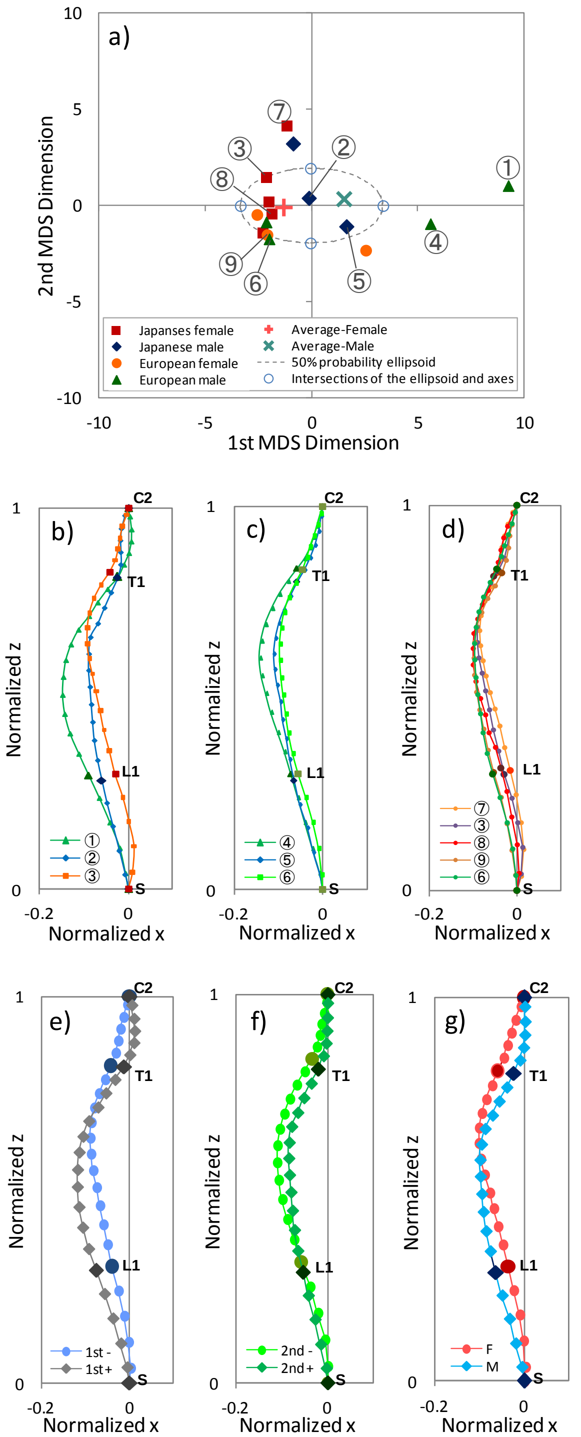

Figure A1. Distribution map of the spinal alignments and comparisons of spinal alignments between b) subject 1, 2 and 3, c) subject 4, 5 and 6, d) subject 3, 6, 7, 8, and 9, e) estimated patterns at the intersections of 50% probability ellipsoid and the axes of the 1st MDS dimension, f) estimated patterns at the intersections of 50% probability ellipsoid and the axes of the 2nd MDS dimension, and g) estimated female average and male average. “1st-“ and “1st+” indicate the representative spinal alignment patterns estimated at the intersection of 50% probability ellipsoid and the axes of the 1st MDS dimension in the negative and positive region the 1st MDS dimension, respectively. “2nd-“ and “2nd+” indicate the representative spinal alignment patterns estimated at the intersection of 50% probability ellipsoid and the axes of the 2nd MDS dimension in the negative and positive region the 2nd MDS dimension, respectively. “F” and “M” indicate spinal alignments estimated at the average MDS score for females and males, respectively.

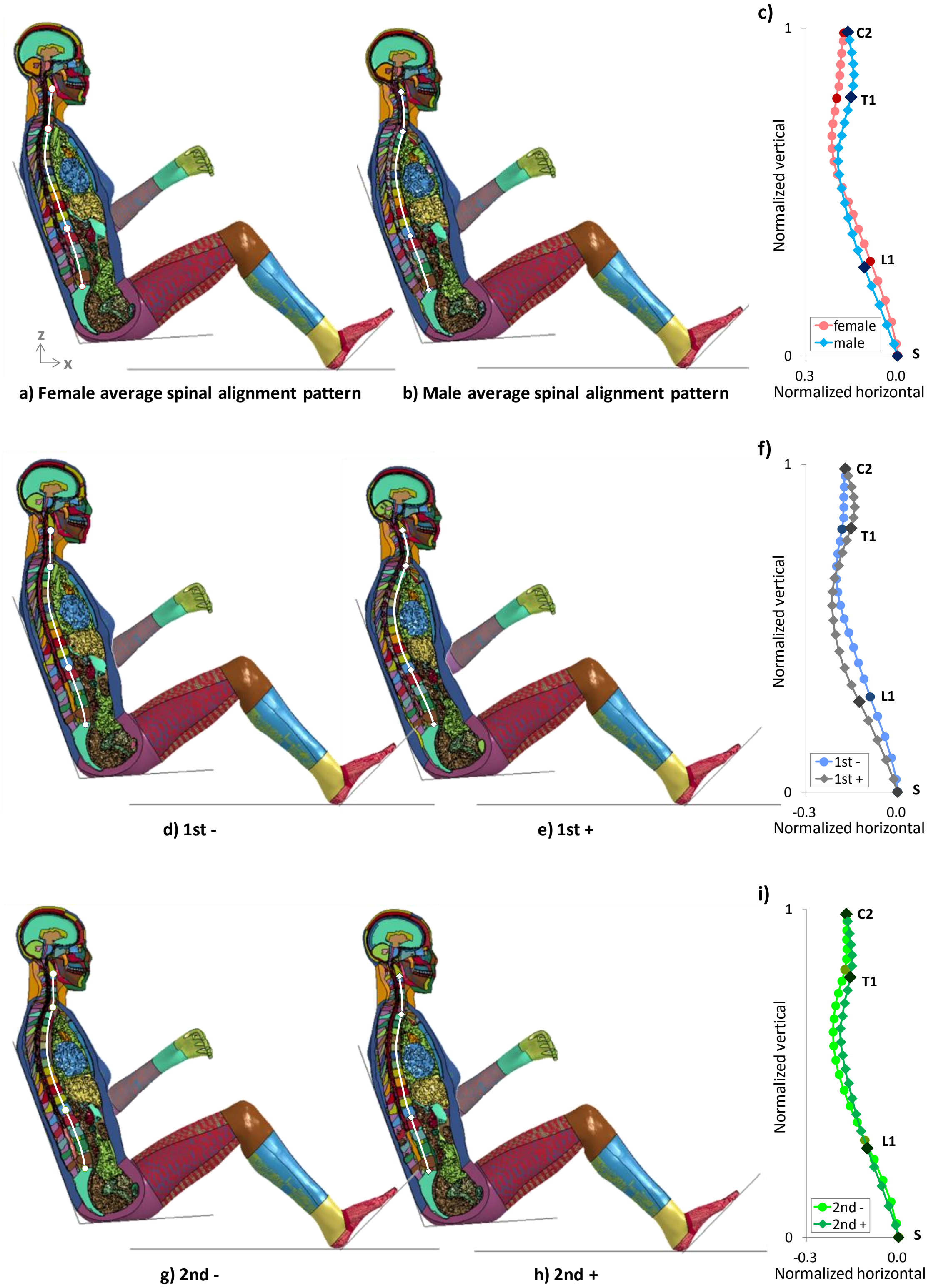

Figure A2. AF 50 size model with a) the average spinal alignment pattern for females and b) males, d) the representative spinal alignment pattern estimated at the intersection of 50% probability ellipsoid and the axes of the 1st MDS dimension in the negative region and e) positive region of the 1st MDS dimension, and g) the representative spinal alignment pattern estimated at the intersection of 50% probability ellipsoid and the axes of the 2nd MDS dimension in the negative region and h) positive region of the 2nd MDS dimension. c), f), i) The estimated spinal alignments by MDS from Figure A1 were rotated back to their original positions, and super imposed to the AF 50 size model in white lines, respectively.

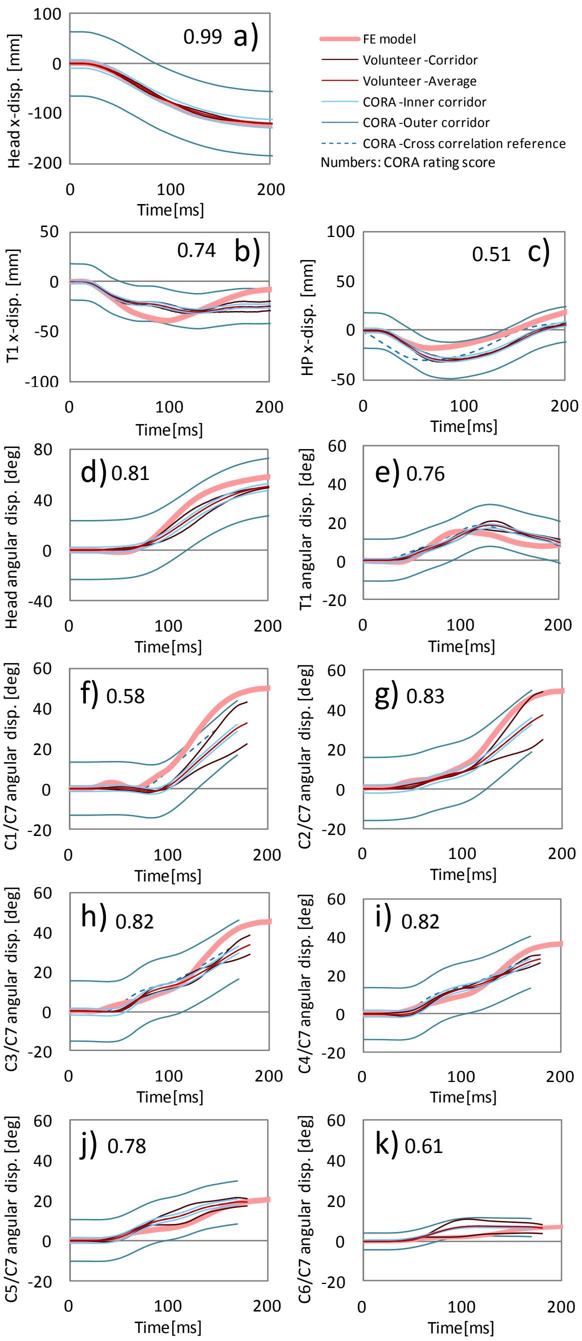

Figure A3. Time histories of dynamic responses for the AF 50 size model with the average spinal alignment pattern for females and the female volunteers under rear end impact sled condition, with the CORA ratings. The CORA rating score was obtained by averaging the scores from the cross-correlation rating and the corridor rating with the same weight factor. The x displacements of a) the head COG, b) the T1 and c) the hip point (HP) were positive forward along the horizontal plane in the local coordinate system moving with the sled. The angular displacements of d) the head COG and e) the T1 were positive extension and negative flexion against the corresponding initial positions. The vertebral angular displacements from f) C1/C7 to k) C6/C7 were positive extension and negative flexion relative to C7. The inner and outer corridors by CORA were created from the average curve ± 0.05 or 0.5 of the peak with the proposed parameter settings in the CORA manual (Gehre et al. 2009). The corridors of the female volunteer sled test data were generated from the average curve ± one standard deviations (SD). The cross-correlation curve coincided with the volunteer's average curve in Figure A3 a), b), d), g), j), and k).