Characteristics of Dynamic Cervical Vertebral Kinematics for Female and Male Volunteers in Low-speed Rear Impact, based on Quasi-static Neck Kinematics

Fusako Sato, Taichi Nakajima, Koshiro Ono, Mats Svensson, Koji Kaneoka

Abstract The purpose of this study is to clarify the dynamic characteristics of inertia-induced cervical vertebral kinematics for both female and male volunteers in low-speed rear impact conditions by comparing quasi-static muscle-induced neck kinematics. Two series of volunteer tests were used. One is data from a rear impact sled test series with 2 females and 4 males. The second set of data is from a voluntary neck bending test series with 4 females and 9 males. Cervical vertebral motions were measured by a cineradiography system. The same volunteers in the first test series also participated in the second test series.

C4/C5 through C6/C7 showed larger extension angle in the peak S shape than maximum voluntary retraction for females. In contrast, the peak S shape was in the maximum voluntary retraction for males. The rearward displacements at C6/C7 in the peak S shape exceeded the maximum voluntary extension for females. The vertebral angular displacement at C5/C6 was greatest in the peak extension and exceeded the voluntary extension, especially for females. The vertebral normalised displacements in X-direction at C5/C6 and C6/C7 showed larger rearward displacements in the peak extension than the voluntary extension, and exceeded the maximum voluntary extension for both genders.

Keywords whiplash, rear impacts, volunteers, neck, cervical vertebral kinematics.

I. INTRODUCTION

Whiplash associated disorder (WAD) caused by vehicle crashes is a worldwide problem. WADs occur in impact from all directions, and more frequently in rear impacts than in any other type of automobile impacts [1-2]. Under such circumstances, preventive measures for WAD in rear impacts have been focused and installed in car seats. In order to reduce the risk of WAD, several types of advanced seat with concepts for whiplash protection have been introduced since the late 1990s [3-6]. As reported by Kullgren [7-8], those types of seat have achieved a reduction of the risk of WAD and proved to be more effective for males than females, according to insurance claims records. The susceptibility of females to WAD has been the focus of many previous studies. Numerous epidemiologic studies have shown that females tend to sustain WAD with higher frequency. Carlsson [9] summarised those studies and reported that the relative injury risk of sustaining WAD was approximately 1.5 to 3 times higher for females compared to males in rear impacts. Harder [10] and Cassidy [11] reported that gender is a significant factor of a longer recovery after sustaining a WAD. Therefore, further investigations to reveal gender differences in the injury biomechanics for WAD are needed in order to prevent WAD more effectively for females as well as males.

The gender differences of dynamic response in rear impacts have been analysed by conducting human volunteer tests, showing females have greater forward accelerations at head and T1 and a more pronounced rebound than males [9][12-15]. Stemper [16] conducted rear impact sled tests with post mortem human head-neck complexes with retro-reflective targets inserted in each vertebra. The study found that the female specimens had larger cervical intervertebral angles and a more pronounced S shape deformation of cervical spine compared to the male specimens. Ono [17] indicated such gender differences on cervical vertebral kinematics based on cineradiography data obtained by rear impact sled tests with female and male volunteers.

Previous studies conducting static experiments have also found gender differences. Females have a larger total range of flexion-extension motion [18-20], with a smaller total range of retraction-protrusion motion [21]. Those studies analysed static end point positions of the cervical spine. Therefore, there is a lack of continuous

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data of cervical vertebral kinematics in quasi-static neck motion, although several studies have acquired cervical kinematics continuously throughout the entire neck motion [22-25].

Ono [26-27] investigated dynamic characteristics of cervical vertebral rotation in rear impact sled testing compared to voluntary muscle-induced neck extension. The study showed that vertebral angle from horizontal plane was largest at C5 around 100 ms under rear impact condition, while vertebral angle was gradually larger from lower to upper vertebrae under voluntary neck extension. However, the study focused on one male volunteer and did not analyse gender differences.

The goal of this study is to clarify the dynamic characteristics of inertia-induced cervical vertebral kinematics for both female and male volunteers in low-speed rear impact conditions by comparing quasi-static muscle-induced cervical vertebral kinematics in voluntary neck motion in order to approach the susceptibility of females to WAD.

II. METHODS

Two series of volunteer tests were used. One is data from a rear impact sled test series with 2 females and 4 males at 6 km/h by Ono [17] (Test Series 1). The second set of data is from a voluntary quasi-static neck bending test series with 4 females and 9 males, which has not been previously published (Test Series 2). The two test series were conducted in the same period, and the same volunteers in Test Series 1 also participated in Test Series 2. Details of the subjects are provided in Table 1. In both test series, sequential X-ray images of cervical vertebral kinematics were acquired by a cineradiography system (Integris Allura BH-5000, Philips Medical System) at the University of Tsukuba Hospital. The time histories of the cervical vertebral kinematics were reanalysed with the sequential X-ray images. The complete description of Test Series 1 [17] and detailed investigations of the overall neck and cervical vertebral kinematics [28] have been published in separate papers.

All subjects gave written informed consent after explanation of the protocol. All procedures in this study were approved by the Institutional Review Board of the Medical Department at University of Tsukuba, and adhered to the guidelines of the Ethics Committee.

TABLE I

DETAILS OF THE VOLUNTEERS IN TEST SERIES 1 AND 2

ID	Test	Sex	Age [year]	Height [cm]	Weight [kg]	Initial C7 angle [deg]
1-I	1 & 2	F	23	164	50	-7
1-II	1 & 2	F	23	162	46	-4
1-III	1 & 2	M	23	176	67	-16
1-IV	1 & 2	M	25	166	61	-10
1-V	1 & 2	M	25	171	57	-25
1-VI	1 & 2	M	24	178	67	-19

ID	Test	Sex	Age [year]	Height [cm]	Weight [kg]	Initial C7 angle [deg]
2-I	2	F	24	166	51	-5
2-II	2	F	23	158	51	-8
2-III	2	M	24	181	77	-15
2-IV	2	M	22	172	69	-22
2-V	2	M	25	173	70	-28
2-VI	2	M	24	172	64	-37
2-VII	2	M	25	172	67	-38

Test Procedures – Test Series 1

Figure 1 shows a schematic of the mini-sled system. The mini-sled system had a rigid seat mounted to a sled on 2 m horizontal rails. The rigid seat, with a seatback angled 20° from the vertical, was accelerated by release of a compressed spring installed on the end of the sled, and decelerated by a hydraulic damper on the anterior part of the rails. The sled acceleration and velocity are shown in Figure 2. The Δ V was 5.8 km/h and the peak acceleration was 42 m/s^2. Volunteers were seated on the rigid seat and asked to relax. The cervical vertebral kinematics was captured at 60 fps by the cineradiography system.

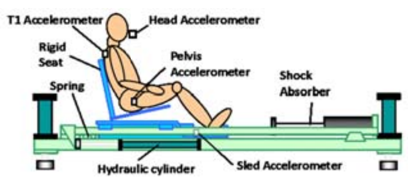


Fig. 1. Scheme of Test Series 1.

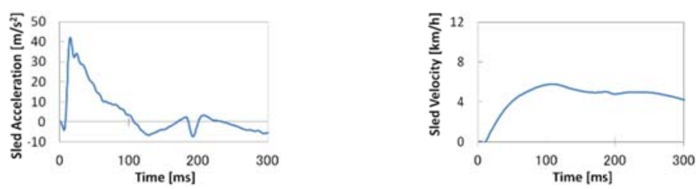


Fig. 2. Time history of the sled acceleration and velocity, Test Series 1.

Test Procedures – Test Series 2

Volunteers were seated on the rigid seat used in Test Series 1 and asked to relax. Volunteers were instructed in moving their cervical spine to three positions in their normal quasi-static physiological motion: 1) maximum extension (face toward ceiling); 2) maximum flexion (chin-to-chest); and 3) maximum retraction (maximal rearward gliding or posterior translation of the head while zero sagittal rotation is maintained) [29]. Volunteers practiced the three motions before testing. Then, sequential X-ray images of their neck motions were acquired at 15 fps by the cineradiography system. The acquisition was conducted only one time in each neck motion to reduce radiation dose as much as possible.

Definitions of the Lower Cervical Vertebra Coordinate Systems

The lower cervical vertebral coordinate system portrayed in Figure 3 was defined, and cervical vertebral kinematics was analysed in the coordinate system in this study. The origin of the coordinate system was at the most inferior and posterior point of the lower vertebral body. Its x-axis was along the inferior surface of the vertebral body along a line posterior point to anterior point of vertebral body. The x-axis is positive forward, and the z-axis positive downward. For the occipital condyle, the lower cervical vertebra coordinate was created with two inferior points, represented as red dots in Figure 4. The initial C7 angle of the x-axis in the global coordinate system was summarised in Table I. In the global and lower cervical vertebra coordinate systems, the positive direction is extension angle and negative flexion angle.

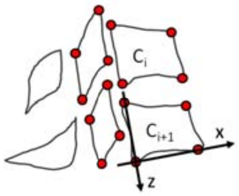


Fig. 3. Definitions of the lower cervical vertebra coordinate systems.

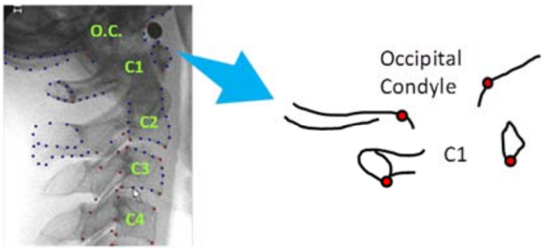


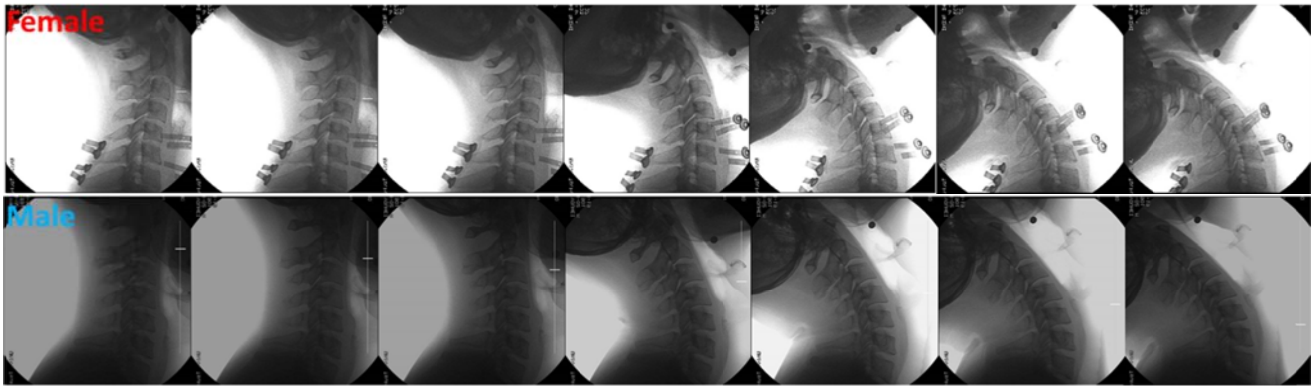
Fig. 4. Digitised points for the Occipital condyle and C1.

Analysis of Cervical Spine Kinematics

Templates of cervical vertebrae and bottom region of the skull around the occipital condyle were prepared for each subject with the initial X-ray image acquired by the cineradiography. The templates shown as blue and red dots in Figure 4 were fitted to each vertebra over sequential X-ray images and four edges of vertebral body and zygapophysial joint were digitised. Those digitised points were represented as red dots in Figure 3 and 4. Two inferior points, represented as red dots in Figure 4, were digitised at the occipital condyle and C1. The midpoint between the two inferior points of each vertebral body was tracked in the lower vertebral coordinate system to obtain the translational displacement of the vertebrae. Then, the translational displacement was normalised by the length between the two inferior points of the adjacent inferior vertebra, represented as red dots in Figure 3. The vertebral angular displacements were calculated as the angle of a line connecting the two inferior points, and done in the global and lower vertebral coordinate system. In order to smooth the digitised raw data, spline interpolation was applied. Plots were extracted at every 10 ms in Test Series 1. For Test Series 2, time was normalised by the time at maximum extension, flexion or retraction, and the duration was divided into 12 sections. Afterwards, the average and standard deviation were calculated at every 10 ms in Test Series 1 and each section in Test Series 2. Differences between genders and between Test Series 1 and 2 were examined for statistical significance using Student's unpaired t-test. The total number of cineradiography images for one test was around 15–20 with 16.67 ms intervals in Test Series 1, and 15–25 with 66.67 ms intervals in Test Series 2. The dose of exposure was 0.016 mGy per frame, and total radiation dose of a series of sequential X-ray images was less than an abdominal computed tomographic scan for normal medical purposes. The resolution of cineradiography images was 1280 x 1024 pixels (approximately 7.3 pixels/mm). The mean errors of the digitised data on the inter-observer variations were 0.7 degrees in rotational angle, 0.44 mm in horizontal direction and 0.25 mm in vertical direction. In the mean error evaluation, an X-ray image was picked up from the sequential X-ray image sets, and observers digitized the same X-ray image.

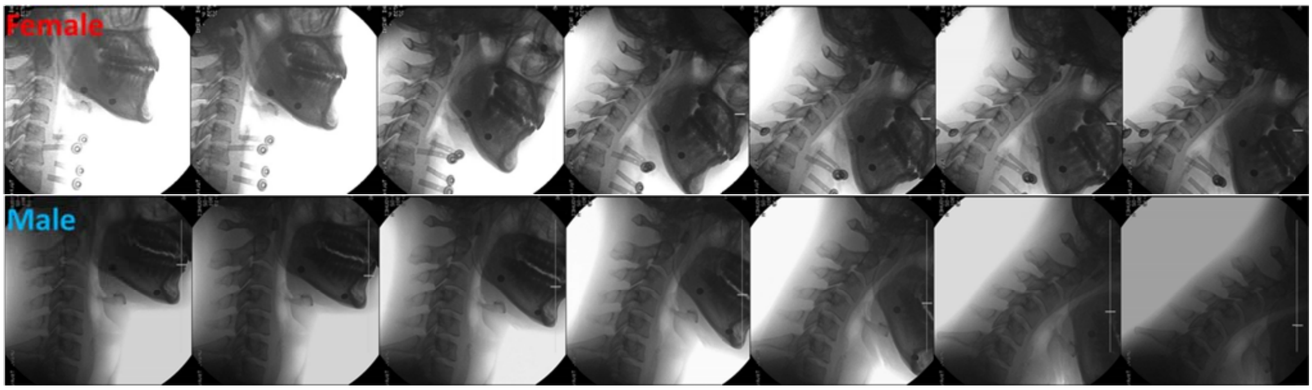
III. RESULTS

Dynamic inertia-induced vertebral kinematics was obtained by analysing sequential X-ray images acquired with a cineradiography in Test Series 1. Details of dynamic inertia-induced vertebral kinematics were reported in our previous study [28]. The data in that study was utilised in comparison between dynamic inertia-induced and quasi-static muscle-induced vertebral kinematics. Figure 5, Figure 6 and Figure 7 show sequential X-ray images in Test Series 2. Quasi-static muscle-induced vertebral kinematics was tracked using these images.



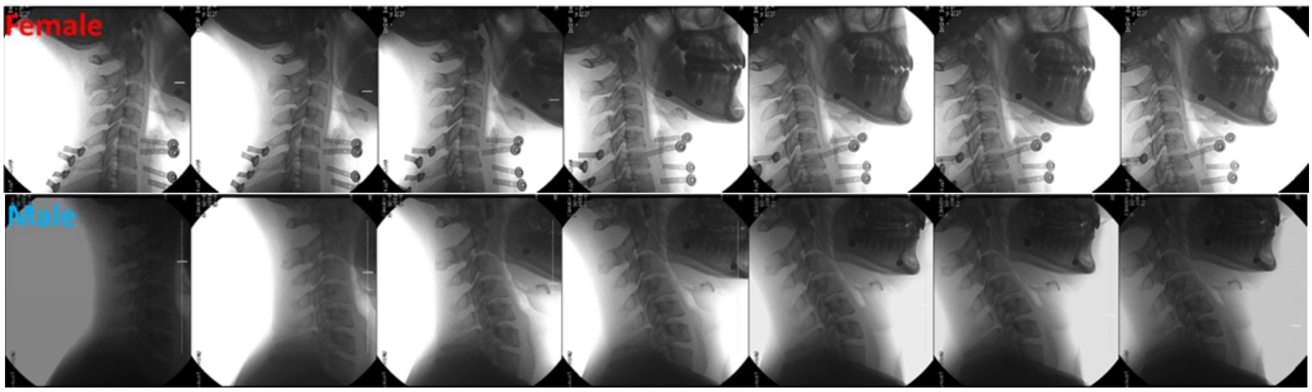
Start Max. extension

Fig. 5. Sequential X-ray images of voluntary neck extension in Test Series 2. The volunteers shown in these images were the same subjects as those reported by Sato [28].



Start Max. flexion

Fig. 6. Sequential X-ray images of voluntary neck flexion in Test Series 2. The volunteers shown in these cineradiography images are the same subjects as those in Fig. 5.



Start Max. retraction

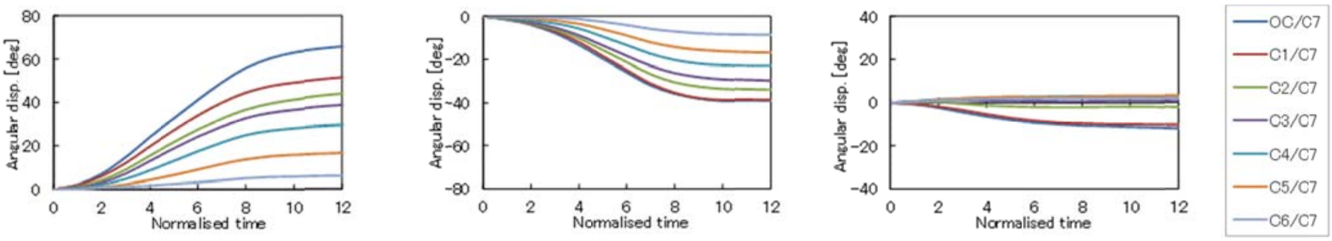
Fig. 7. Sequential X-ray images of voluntary neck retraction in Test Series 2. The volunteers shown in these cineradiography images are the same subjects as those in Fig. 5.

Quasi-static Muscle-induced Vertebral Kinematics

Figure 8 shows the average time histories of the vertebral angular displacement for all participants in voluntary neck extension, flexion and retraction, respectively. The vertebral angular displacements were described relative to C7. The vertebral angular displacements exhibited positive values in voluntary neck extension, and negative values in voluntary neck flexion at all vertebral levels. In voluntary neck retraction, the vertebral angular displacement exhibited negative values at upper vertebrae and positive values at lower vertebrae.

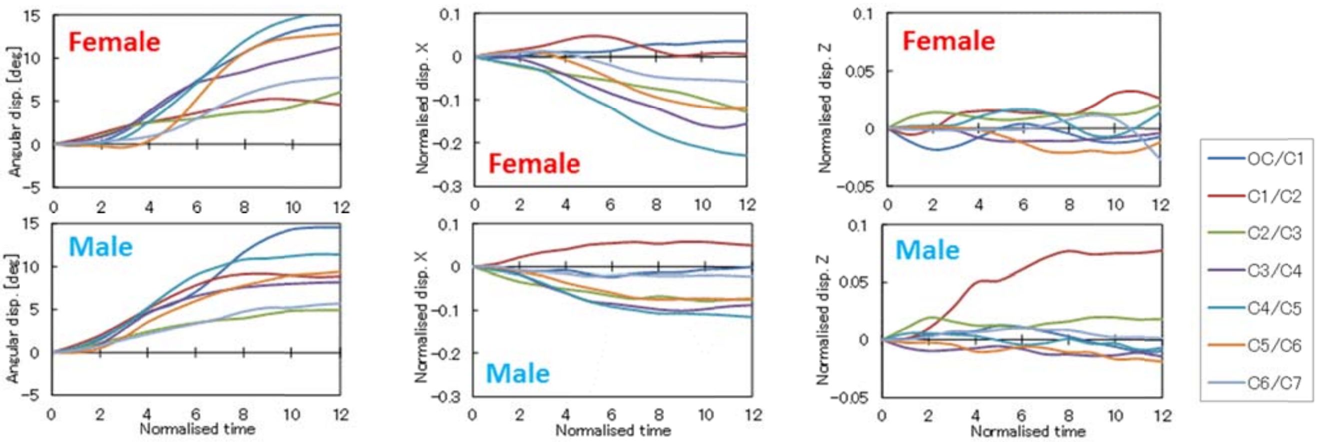
Figure 9, Figure 10 and Figure 11 show the average time histories of the vertebral angular and normalised translational displacement for both genders in their voluntary neck extension, flexion and retraction, respectively. The vertebral displacements were described in the lower cervical vertebra coordinate system. With voluntary neck extension shown in Figure 9, all vertebral segments rotated in extension, except that C5/C6 exhibited flexion angle slightly in the early stage for female. The normalised translational displacement in X-direction was forward at upper vertebral segments, and rearward at lower vertebral segments for both genders. Conversely, in Figure 10, voluntary neck flexion placed all vertebral segments in flexion rotation, except that OC/C1 rotated in extension slightly in the middle stage for female. The normalised translational displacements in X-direction also showed opposite trends, with upper vertebral segments in rearward and lower vertebral segments in forward for both genders. In contrast, with voluntary neck retraction in Figure 11, OC/C1 through C5/C6 rotated in flexion and C6/C7 in extension for females. For males, OC/C1 through C4/C5 rotated in flexion, and C5/C6 and C6/C7 in extension.

Figure 12, Figure 13 and Figure 14 show gender comparisons of the vertebral angular and normalised translational displacement at maximum voluntary neck extension, flexion and retraction, respectively. The vertebral displacements were described in the lower cervical vertebra coordinate system. In Figure 12, OC/C1 and C4/C5 showed the largest extension angle at maximum voluntary neck extension. This result corresponded to previous studies [29-32]. C4/C5 also exhibited the largest rearward displacement. With maximum voluntary neck flexion in Figure 13, C1/C2 was the greatest angular displacement for females, and C5/C6 for males. Maximum voluntary neck retraction shown in Figure 14 produced the most flexion angle at C1/C2, with greater values for females than males. In gender comparisons of angular displacement and normalised translational displacement in X-direction, maximum voluntary neck extension was greater for females than males, and maximum voluntary neck flexion for males than females from C2 through C7, with correspondence to a previous study reported by Yukawa [20].



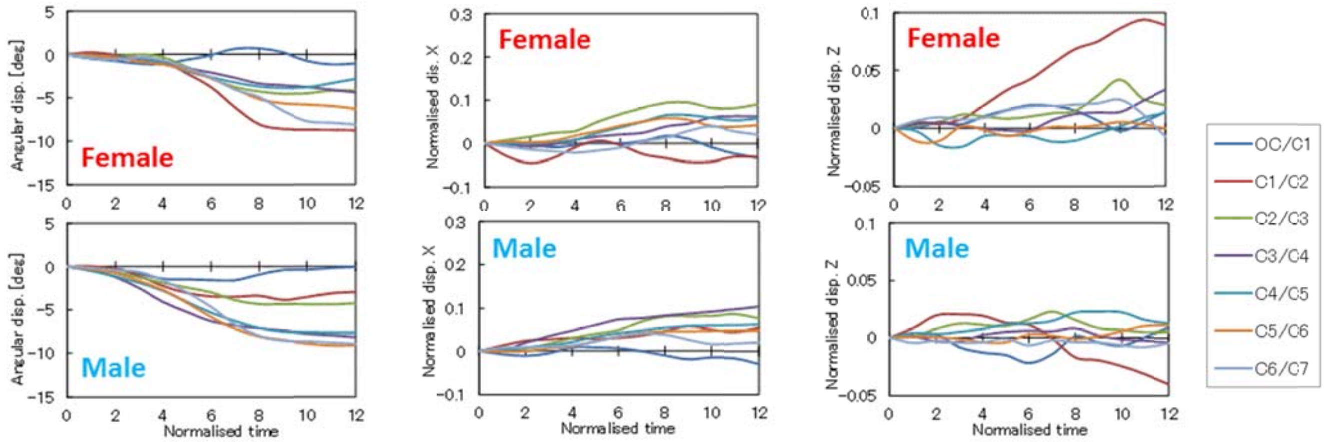
(a) Extension. (b) Flexion. (c) Retraction.

Fig. 8. Average time histories of the vertebral angular displacement relative to C7 for all volunteers in Test Series 2. The positive side is extension angle and negative flexion angle. Figure A1 shows these average time histories for both genders respectively in Appendix.



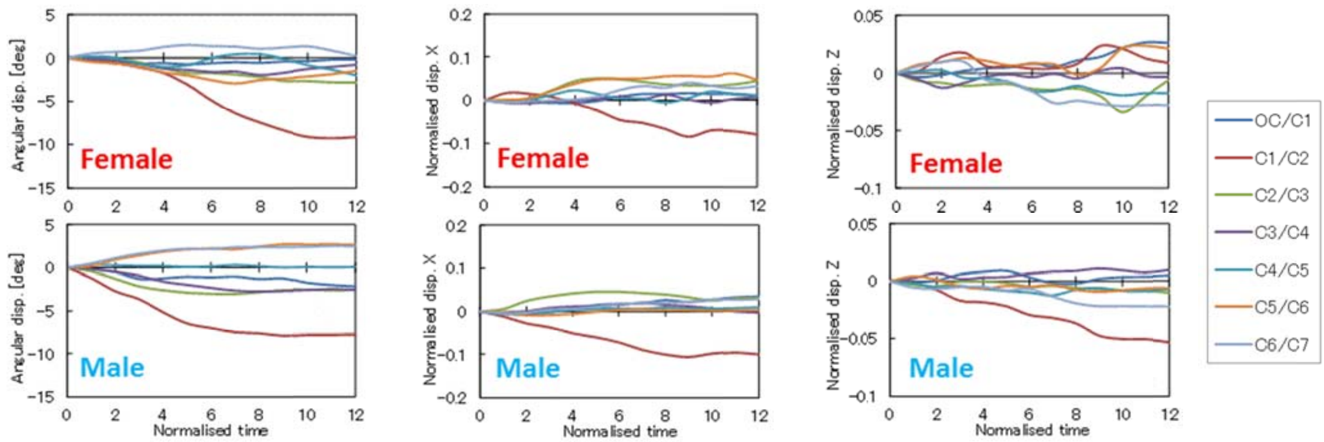
(a) Angular displacement. (b) Normalised translational displacement in X-direction. (c) Normalised translational displacement in Z-direction.

Fig. 9. Average time histories of the vertebral displacement in the lower cervical vertebra coordinate system during voluntary neck extension in Test Series 2. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.



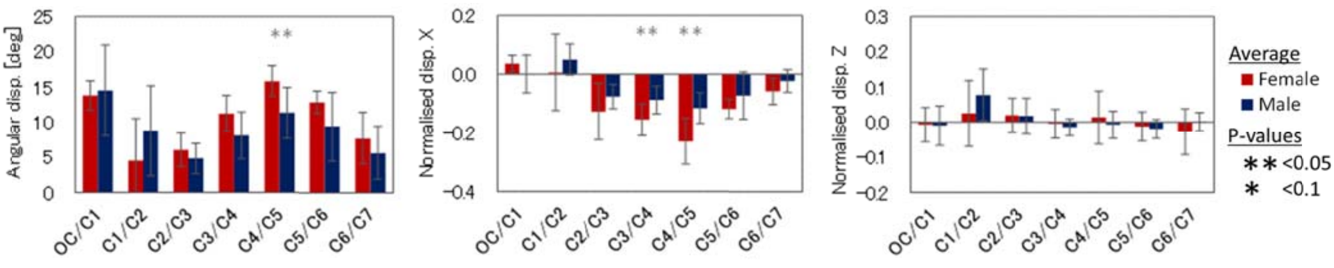
(a) Angular displacement. (b) Normalised translational displacement in X-direction. (c) Normalised translational displacement in Z-direction.

Fig. 10. Average time histories of the vertebral displacement in the lower cervical vertebra coordinate system during voluntary neck flexion in Test Series 2. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.



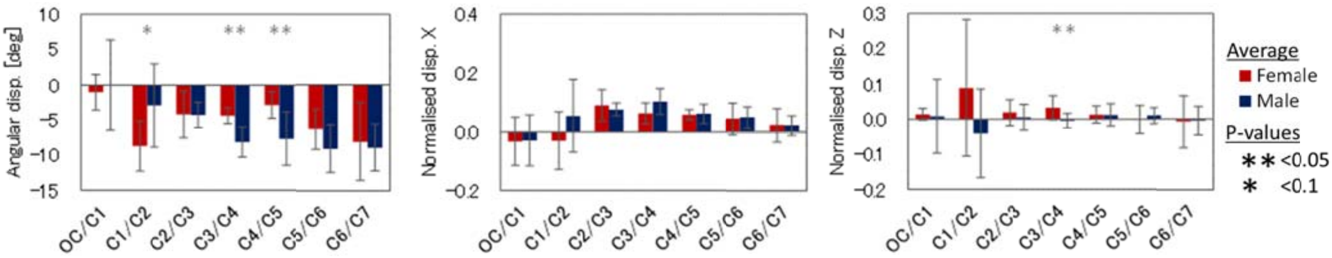
(a) Angular displacement. (b) Normalised translational displacement in X-direction. (c) Normalised translational displacement in Z-direction.

Fig. 11. Average time histories of the vertebral displacement in the lower cervical vertebra coordinate system during voluntary neck retraction in Test Series 2. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.



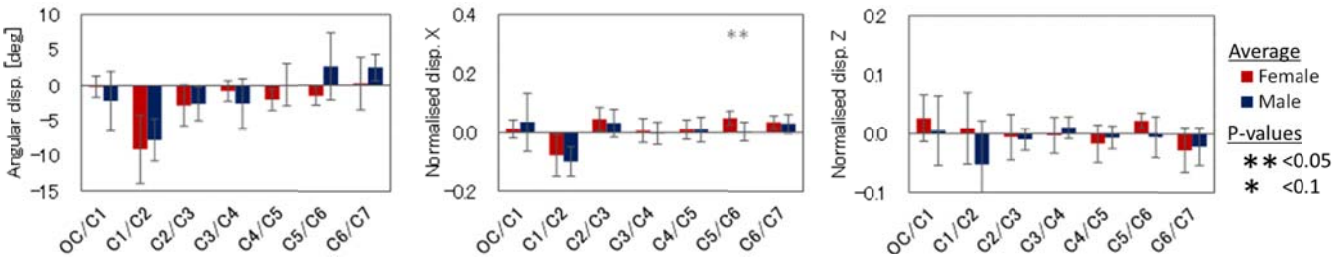
(a) Angular displacement. (b) Normalised translational displacement in X-direction. (c) Normalised translational displacement in Z-direction.

Fig. 12. Gender comparisons of the vertebral displacement in the lower cervical vertebra coordinate system at maximum voluntary neck extension in Test Series 2. The average values in coloured bars, standard deviation in black lines and p-values from t-test. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.



(a) Angular displacement. (b) Normalised translational displacement in X-direction. (c) Normalised translational displacement in Z-direction.

Fig. 13. Gender comparisons of the vertebral displacement in the lower cervical vertebra coordinate system at maximum voluntary neck flexion in Test Series 2. The average values in coloured bars, standard deviation in black lines and p-values from t-test. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.



(a) Angular displacement. (b) Normalised translational displacement in X-direction. (c) Normalised translational displacement in Z-direction.

Fig. 14. Gender comparisons of the vertebral displacement in the lower cervical vertebra coordinate system at maximum voluntary neck retraction in Test Series 2. The average values in coloured bars, standard deviation in black lines and p-values from t-test. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.

Dynamic Inertia-induced Vertebral Kinematics

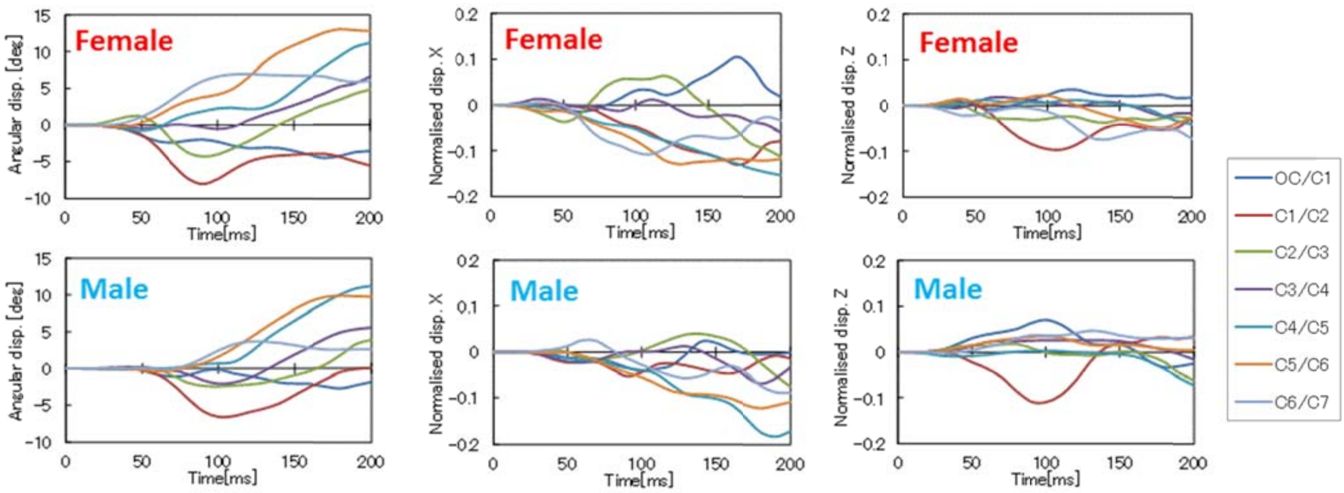
Figure 15 shows the average time histories of the vertebral angular and normalised translational displacement in Test Series 1 for females and males, respectively. The vertebral angular displacement at C1/C2 exhibited the greatest peak flexion angle at time between 90 ms and 100 ms for both genders. At that point in time, OC/C1, C1/C2 and C2/C3 rotated in flexion, while C4/C5, C5/C6 and C6/C7 in extension. Therefore, the cervical spine was exposed to an S shape. The lower neck extension was larger for females than males, giving the female necks a more pronounced S shape. The vertebral normalised displacement in X-direction varied between spinal segments, with larger differences between segments for females than males around the peak S shape. The vertebral normalised displacement in Z-direction at C1/C2 exhibited the greatest peak upward displacement around the peak S shape for both genders.

The dynamic inertia-induced vertebral kinematics described above was compared to the quasi-static muscle-induced vertebral kinematics obtained in Test Series 2. Figure 16 shows the average time histories of the vertebral angular displacement relative to C7 for all participants in Test Series 1. OC and C1 rotated in flexion, with the other vertebrae in extension until 110 ms. Afterwards, all vertebrae rotated in extension. On the other hand, in the quasi-static muscle-induced vertebral kinematics, all vertebrae rotated in extension and no S shape deformation was observed in voluntary neck extension (Figure 8 (a) and Figure 9). The differences of cervical spine response observed in this study corresponded to previous studies reported by Ono [26-27] with one male volunteer. In addition, the voluntary neck retraction showed upper vertebrae rotated in flexion and lower vertebrae in extension, and were similar to S shape in dynamic inertia-induced vertebral kinematics (Figure 8 (c) and Figure 11). Based on these results, the characteristics of dynamic inertia-induced vertebral kinematics was the peak S shape before 100 ms, and then transition from the peak S shape to extension phase [33-39]. The peak S shape was compared to the voluntary neck retraction at its maximum position. In the extension phase, the angular displacement of head (OC) relative to C7 exhibited the greatest peak extension of approximately 35 degrees around 200 ms in the dynamic inertia-induced vertebral kinematics. Therefore, the peak extension was compared to the voluntary neck extension at the same angle as the peak extension angle of head (OC) relative to C7 in dynamic condition.

Figure 17 and Figure 18 show comparisons of the vertebral displacement between the peak S shape and maximum voluntary retraction. C4/C5 through C6/C7 showed larger extension angle in the peak S shape than maximum voluntary retraction for females. C4/C5 and C5/C6 of females exhibited extension in the peak S shape, but flexion in the maximum voluntary retraction. In contrast, the peak S shape was in the maximum voluntary retraction for males. The vertebral normalised displacement in X-direction from C4/C5 through C6/C7 exhibited rearward displacement in the peak S shape, while forward at C5/C6 and C6/C7 for females and C4/C5 through C6/C7 for males in the maximum voluntary retraction. In voluntary neck motion, rearward displacements from C4/C5 through C6/C7 were observed only in voluntary neck extension (Figure 9 and Figure 12). The rearward displacements at C6/C7 in the peak S shape exceeded the maximum voluntary extension for females.

Figure 19 and Figure 20 show comparisons of the vertebral displacement between the peak extension and voluntary extension. The vertebral angular displacements at C4/C5 and C5/C6 were remarkably larger in the peak extension than voluntary extension for both genders. C5/C6 was greatest in the peak extension and exceeded the voluntary extension, especially for females. The vertebral normalised displacements in X-direction at C5/C6 and C6/C7 showed larger rearward displacements in the peak extension than the voluntary extension, and exceeded the maximum voluntary extension for both genders.

Those comparisons described above with Figure 17– Figure 20 were conducted with the data of volunteers who participated in both test series (Volunteer ID: I–VI in Table 1).



(a) Angular displacement. (b) Normalised displacement in X-direction. (c) Normalised displacement in Z-direction.

Fig. 15. Average time histories of the vertebral displacement in the lower cervical vertebra coordinate system in Test Series 1. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.

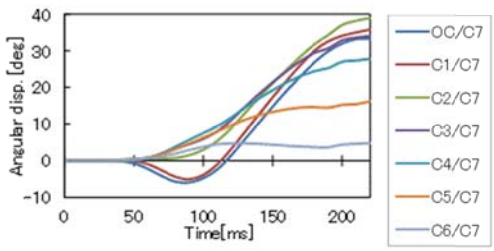
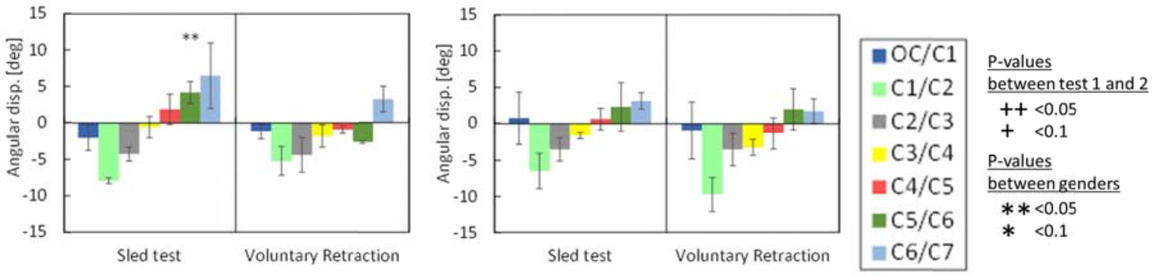
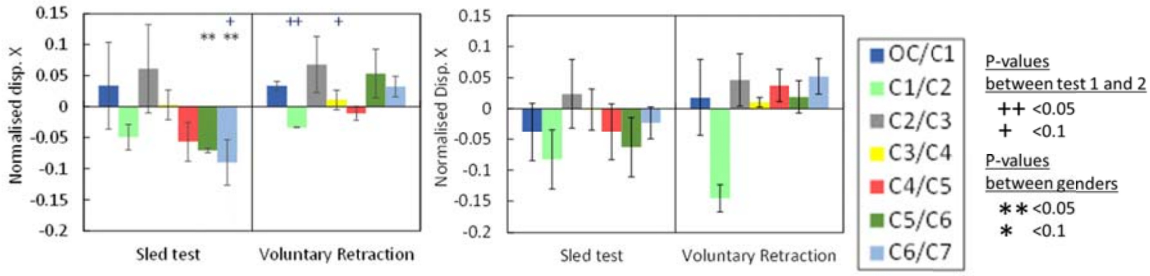


Fig. 16. Average time histories of the vertebral angular displacement relative to C7 for all volunteers in Test Series 1. The positive side is extension angle and negative flexion angle.



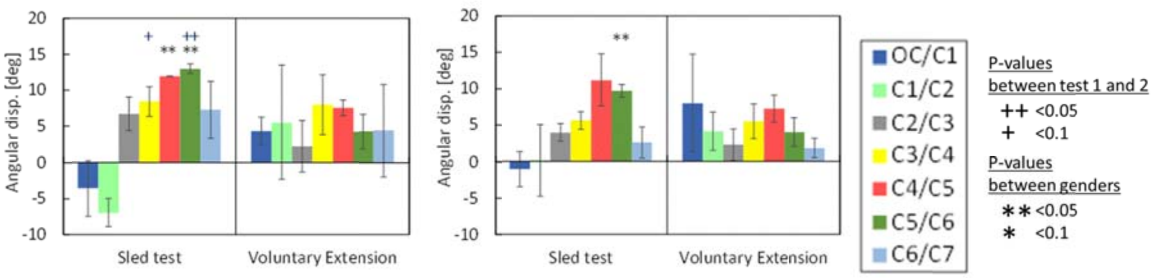
(a) Female. (b) Male.

Fig. 17. Comparison of the vertebral angular displacement in the lower vertebra coordinate system between the peak S shape in Test Series 1 and maximum voluntary retraction in Test Series 2. Average in coloured bars and standard deviation in black lines. The positive side is extension angle and negative flexion angle.



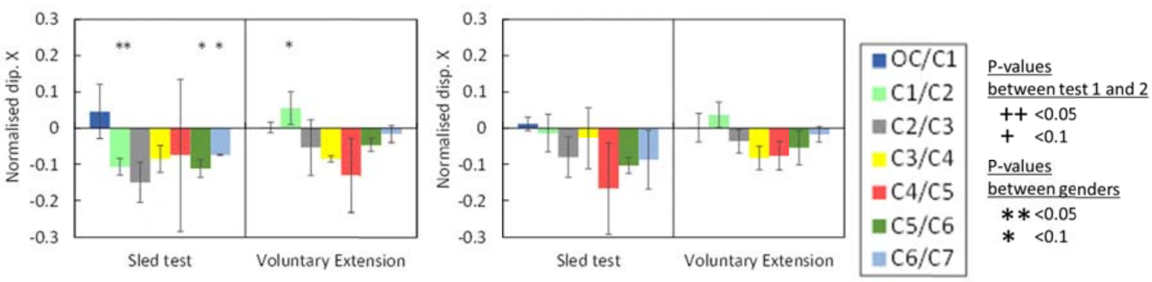
(a) Female. (b) Male.

Fig. 18. Comparison of the vertebral normalised displacement in X-direction in the lower vertebra coordinate system between the peak S shape in Test Series 1 and maximum voluntary retraction in Test Series 2. Average in coloured bars and standard deviation in black lines. The positive side is forward and negative rearward.



(a) Female. (b) Male.

Fig. 19. Comparison of the vertebral angular displacement in the lower vertebra coordinate system between the peak extension in Test Series 1 and voluntary extension in Test Series 2. Average in coloured bars and standard deviation in black lines. The positive side is extension angle and negative flexion angle.



(a) Female. (b) Male.

Fig. 20. Comparison of the vertebral normalised displacement in X-direction in the lower vertebra coordinate system between the peak extension in Test Series 1 and voluntary extension in Test Series 2. Average in coloured bars and standard deviation in black lines. The positive side is forward and negative rearward.

IV. Discussion

In order to clarify the dynamic characteristics of cervical vertebral kinematics under rear impact condition for both genders, the current study compared dynamic inertia-induced cervical vertebral kinematics obtained by low-speed rear impact volunteer tests with quasi-static muscle-induced cervical vertebral kinematics in voluntary neck motions. We assumed that the voluntary neck motions would be non-injurious even though the volunteers were asked to carry out each motion to the maximum limit, but without causing serious discomfort. These voluntary neck motions would in other words generate large intervertebral displacements between adjacent vertebrae that still remained within the sub injurious range. The cervical vertebral motion under inertial loading in sled tests were also sub injurious, but they were involuntary induced to the spinal joints. In case where the range of quasi-static muscle-induced cervical vertebral motion was exceeded, it was hypothesised that this additional vertebral displacement would be potentially harmful. In more severe and injurious real world accidents, it is to be expected that the vertebral motions would follow the same trend as in the sled tests but exceed the voluntary range of motion to an even greater extent and thus cause tissue damage. In addition, tissues have viscoelastic material properties, and stiffens as the loading speed increases. In case where intervertebral displacements under dynamic inertia-induced conditions are the same level as those under quasi-static muscle-induced conditions, it is also to be expected that cervical spine under dynamic inertia-induced conditions would be exposed to more severe loading.

Many previous studies [33-39] have focused on S shape deformation of cervical spine observed during rear impact as the majority of the injury mechanism hypotheses for WAD. The current study showed that the S shape was a main characteristic of dynamic inertia-induced cervical vertebral kinematics. In the S shape phase, upper vertebrae rotated in flexion and lower vertebrae in extension similarly to the voluntary neck retraction. Ordway [29] reported that the voluntary neck retraction produced greater flexion angles at the upper cervical vertebrae than the voluntary neck flexion, and smaller extension angles at the lower cervical vertebrae than the voluntary neck extension. Those trends correspond to results of the Test Series 2 in this study (Figure 12 (a), Figure 13 (a) and Figure 14 (a)). In the voluntary neck retraction, the lower cervical vertebrae reached limits of extension angle, even though those limits were smaller than maximum extension angle observed in voluntary extension. The phenomenon could be caused by interactions between muscles and ligaments and so on around cervical spine, and the S shape beyond the voluntary neck retraction would have a potentially harmful effect on a neck. Therefore, in this study, the peak S shape was compared to the voluntary maximum neck retraction to estimate potential of neck injury.

The fact that the female volunteers exhibited a more pronounced S shape could be part of the explanation as to why females are more susceptible to WAD than men. An increased S shape indicates larger local intervertebral displacements that in turn could cause more severe strain and loading to for instance the facet joints. The more pronounced s-shape will likely cause greater strain on the facet joint capsules and higher pressure magnitudes in the spinal canal during the whiplash motion. These pressure transients have been suggested to be the cause of dorsal root ganglion injuries [40]. These differences between the genders could potentially explain the higher injury risk in females.

Carlsson [9] investigated a rear impact volunteer test series with 11 males and 12 females [13] at the same impact level as that of Test Series 1 in this study. Head to head-restraint contact time was 91 ms for females and 100 ms for males at a ΔV of 8 km/h in that study. Pramudita [41] conducted a rear impact volunteer test series at the same impact level as this study, and reported that head to head-restraint contact time was 95 ms for males with the maximum sled acceleration of 40 m/s^2. This study showed that the peak S shape was observed around those head to head-restraint contact timings. At the peak S shape, C4/C5 through C6/C7 rotated in extension and exceeded maximum voluntary retraction for females. In addition, the rearward displacements at C6/C7 at the peak S shape exceeded the maximum voluntary extension for females. Therefore, the female volunteers in those studies had possibilities to be exposed to pronounced S shape deformation beyond voluntary muscle-induced vertebral kinematics.

Previous studies have investigated the prevalence of neck pain at the cervical zygapophysial joint in rear-end impacts and reported that the majority of patients experienced chronic pain at either C2/C3 [42] or at C5/C6 [42-44]. The study of a rear impact test series with cadavers [45] reported that small damages were found at C5/C6 and C6/C7 level at autopsy. In this study, C2/C3 showed most forward displacement at the peak S shape for females. C5/C6 and C6/C7 exhibited larger extension at the peak S shape and peak extension than voluntary muscle-induced vertebral kinematics, especially for females. In addition, rearward displacements at C5/C6 and C6/C7 exceeded those in the maximum voluntary extension for both genders.

In the future, the vertebral motions obtained in these volunteer tests can be used in the evaluation of human model neck kinematics. It is requisite that future female and male human body models exhibit the same trends as the female and male volunteers respectively. Such human body models will be essential in detailed real world accident reconstructions. There they can give indications of how various vertebral motion and loading parameters correlate to real world injury risk. Once critical vertebral motion and loading parameters have been identified, biofidelic female and male human body models will also become valuable tools in seat and head restraint development.

Limitations

Firstly, the cineradiography data were taken with 2 female and 4 male volunteers in Test Series 1, and 4 female and 9 male volunteers in Test Series 2. It was insufficient to generalise gender characteristics of cervical vertebral kinematics under dynamic and quasi-static conditions. Corridors of vertebral displacements were shown in Appendix, and variations between individual volunteers were not so small as to be negligible. Since all volunteers were in their twenties, is was difficult to discuss gender differences through all ages based on this study. In addition, the collection rate of the cineradiography was much lower than was generally used for impact studies with PMHS [45] in order to conduct the sled testing within no risk from radiation exposure. However, the cineradiography data are valuable and significant in revealing cervical vertebral kinematics. Secondly, in some X-ray images, C1 was partially outside of the frame, such as the last frame of Figure 6. In that case, the template was fitted with visible part in the frame and the kinematics of the vertebra was extracted by digitising the template. Also, effects of the distortion and noise in X-ray images were minimised by superimposing templates. However, there would be still some analytical errors. Thirdly, since the volunteers were not at risk of being injured, the sled pulse was set at a level below causing neck injury. Furthermore, the tests were conducted using an experimental rigid seat without head-restraint. Therefore, extrapolations would be needed to predict the cervical kinematicsusing a commercial vehicle seat with head-restraint under real world accident level.

V. CONCLUSIONS

This study investigated the dynamic characteristics of inertia-induced cervical vertebral kinematics in low-speed rear impact conditions for both genders by comparing quasi-static muscle-induced vertebral kinematics. The following most important findings were obtained.

- The dynamic inertia-induced vertebral kinematics showed the peak S shape at time between 90 ms and 100 ms, and transition from the peak S shape to extension phase for both genders.
- In the quasi-static muscle-induced vertebral kinematics, all vertebrae rotated in extension and no S shape deformation was observed in voluntary neck extension.
- C4/C5 through C6/C7 showed larger extension angle in the peak S shape than maximum voluntary retraction for females. In contrast, the peak S shape was in the maximum voluntary retraction for males.
- The rearward displacements at C6/C7 in the peak S shape exceeded the maximum voluntary extension for females.
- The vertebral angular displacement at C5/C6 was greatest in the peak extension and exceeded the voluntary extension, especially for females.
- The vertebral normalised displacements in X-direction at C5/C6 and C6/C7 showed larger rearward displacements in the peak extension than the voluntary extension, and exceeded the maximum voluntary extension for both genders.

VI. ACKNOWLEDGEMENT

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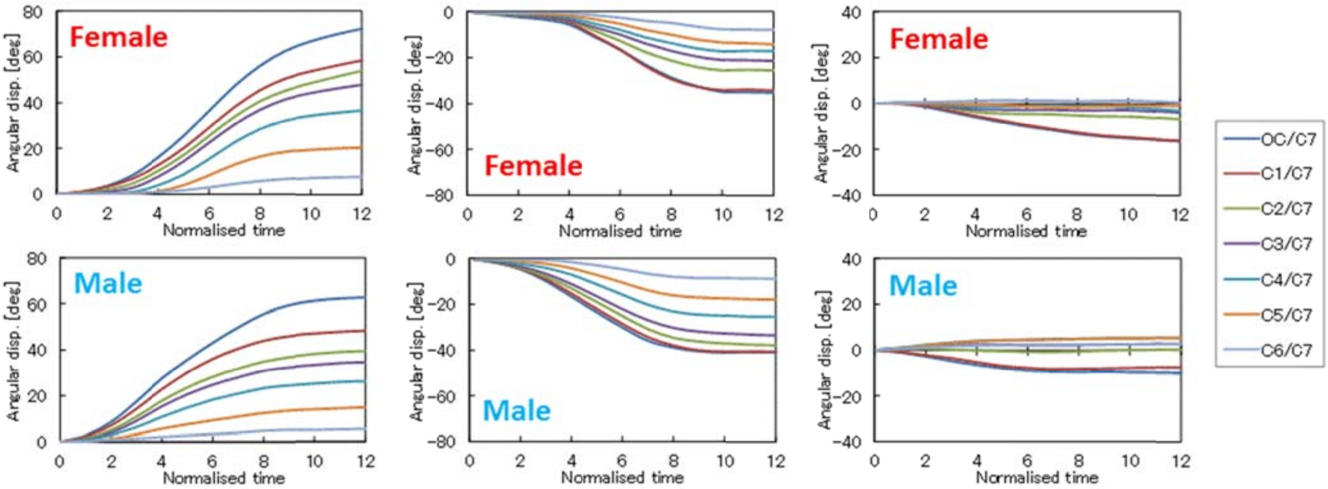
VIII. APPENDIX



(a) Angular displacement. (b) Normalised translational displacement in X-direction. (c) Normalised translational displacement in Z-direction.

Fig. A1. Average time histories of the vertebral angular displacement relative to C7 for females and males in Test Series 2. The positive side is extension angle and negative flexion angle.

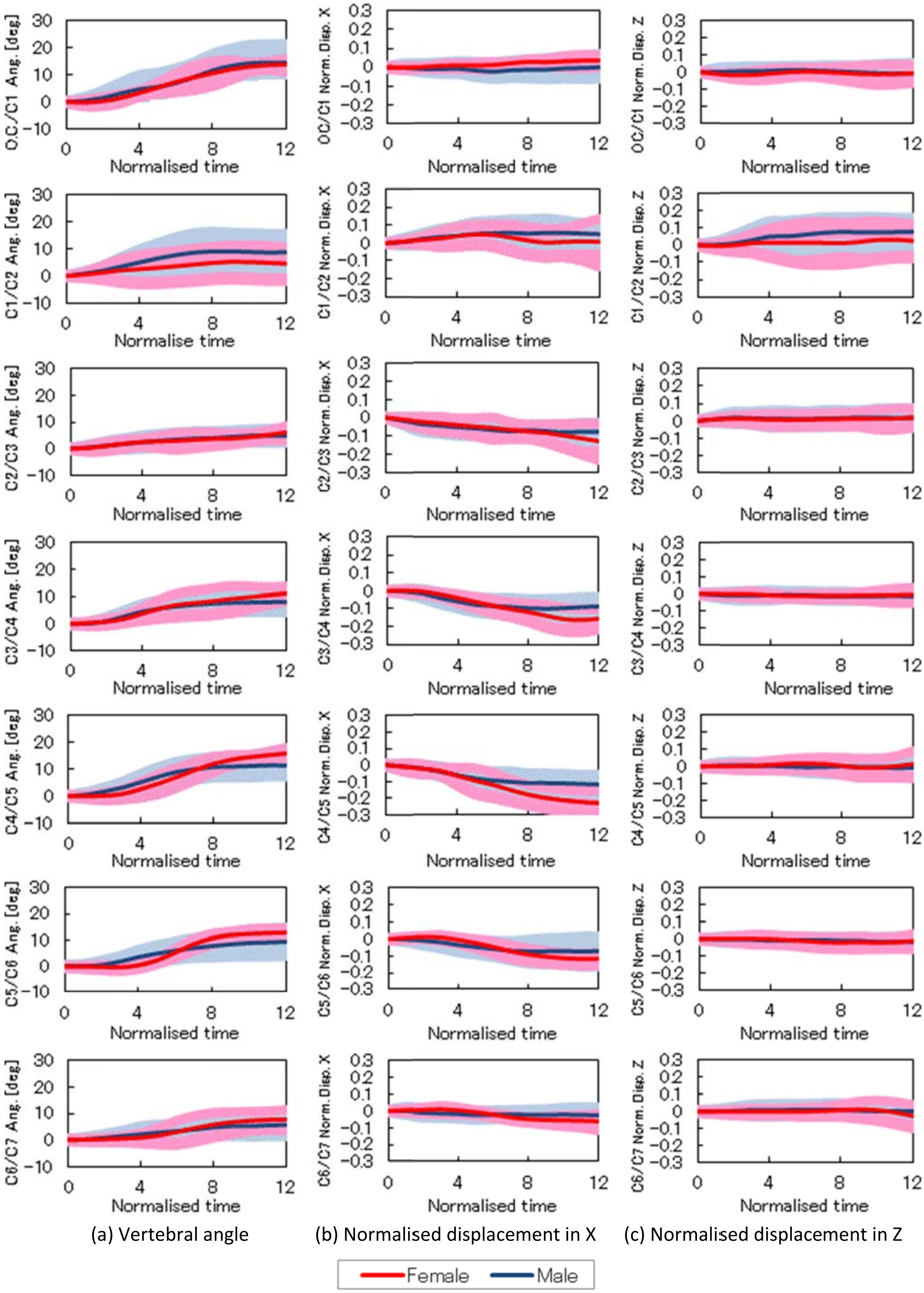
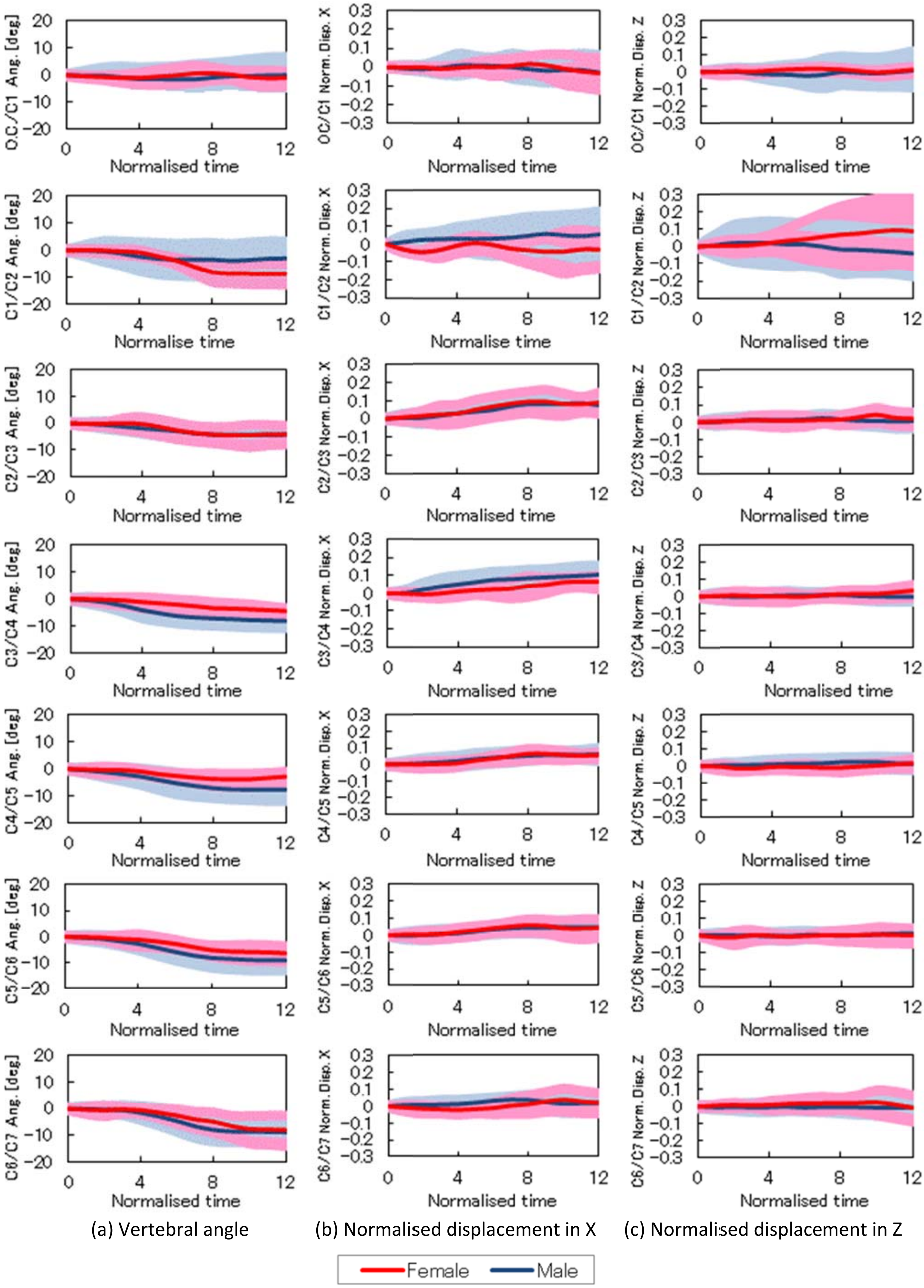
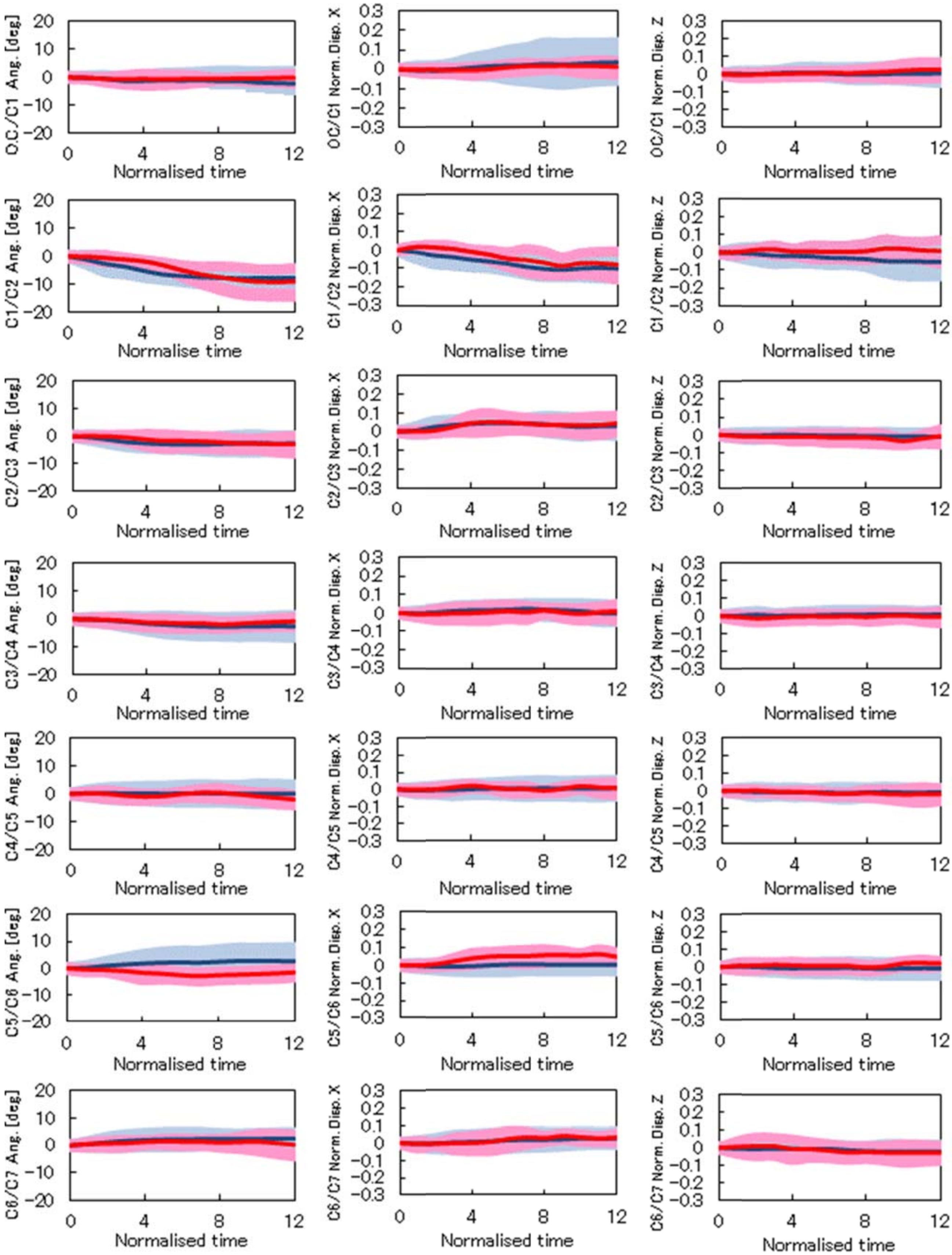


Fig. A2. Time histories of the average and corridor of vertebral displacements in the lower cervical vertebra coordinate system during voluntary neck extension in Test Series 2. The corridors were defined as the average ± one standard deviation from the average. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.



(a) Vertebral angle (b) Normalised displacement in X (c) Normalised displacement in Z

Fig. A3. Time histories of the average and corridor of vertebral displacements in the lower cervical vertebra coordinate system during voluntary neck flexion in Test Series 2. The corridors were defined as the average ± one standard deviation from the average. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.



(a) Vertebral angle (b) Normalised displacement in X (c) Normalised displacement in Z

Female Male

Fig. A4. Time histories of the average and corridor of vertebral displacements in the lower cervical vertebra coordinate system during voluntary neck retraction in Test Series 2. The corridors were defined as the average ± one standard deviation from the average. The x-direction is positive forward. The z-direction is positive downward. For rotation, the positive side is extension angle and negative flexion angle.