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Intervertebral Range of Motion Characteristics of Normal Cervical Spinal Segments (C0-T1) during *In Vivo* Neck Motions

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Abstract

The *in vivo* intervertebral range of motion (ROM) is an important predictor for spinal disorders. While the subaxial cervical spine has been extensively studied, the motion characteristics of the occipito-atlantal (C0-1) and atlanto-axial (C1-2) cervical segments were less reported due to technical difficulties in accurate imaging of these two segments. In this study, we investigated the intervertebral ROMs of the entire cervical spine (C0-T1) during *in vivo* functional neck motions of asymptomatic human subjects, including maximal flexion-extension, left-right lateral bending, and left-right axial torsion, using previously validated dual fluoroscopic imaging and model registration techniques. During all neck motions, C0-1, similar to C7-T1, was substantially less mobile than other segments and always contributed less than 10% of the cervical rotations. During the axial rotation of the neck, C1-2 contributed 73.2±17.3% of the cervical rotation, but each of other segments contributed less than 10% of the cervical rotation. During both lateral bending and axial torsion neck motions, regardless of primary or coupled motions, the axial torsion ROM of C1-2 was significantly greater than its lateral bending ROM ($p<0.001$), whereas the opposite

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Conflict of Interest

The authors declare that there is no conflict of interest.

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Supplementary Material

Appendix A: Cervical Intervertebral Range of Motion Data and Statistical Analysis Results

differences were consistently observed at subaxial segments. This study reveals that there are distinct motion patterns at upper and lower cervical segments during *in vivo* neck motions. The reported data could be useful for the development of new diagnosis methods of cervical pathologies and new surgical techniques that aim to restore normal cervical segmental motion.

Keywords

Occipito-atlantal cervical segment; Atlanto-axial cervical segment; Subaxial cervical segments; Intervertebral range of motion; *In vivo* neck motions; Cervical spine; Spinal kinematics

1. Introduction

The human cervical spine comprises three markedly different intervertebral anatomies, located at the occipito-atlantal (C0-1) segment, the atlanto-axial (C1-2) segment, and subaxial (C2-T1) segments, respectively (Middleditch and Oliver, 2005). The spinal pathologies are distinctly different among these segments (Dickman et al., 1991; Malcolm, 2002). For example, basilar invagination and dislocations are often related to the instability of the occipito-atlanto-axial cervical region (Goel, 2009; Lu et al., 2009; Yang et al., 2014), and disc degeneration at subaxial segments is a major cause of neck pain (Friedenberg and Miller, 1963; Kelly et al., 2012). Accurate knowledge of the intervertebral motions of the entire cervical spine is critical for the evaluation of spinal disorders induced by trauma or degenerative spinal diseases at single or multiple segments (Passias et al., 2011), and for minimization of iatrogenic alterations at the adjacent segments to reduce the risk of secondary surgical interventions (Chung et al., 2014; Hilibrand and Robbins, 2004). Such information can also be useful for planning rehabilitation regimens for patients after conservative/surgical treatments of spinal pathologies (MacWilliams et al., 2014).

In vivo neck / cervical segment motion of asymptomatic subjects has been extensively investigated using various techniques, such as skin marker-based motion analysis (Henmi et al., 2006; Wu et al., 2007), computed tomography (CT)- / magnetic resonance imaging (MRI)-based static imaging (Ishii et al., 2006, 2004; Kang et al., 2019; Zhai et al., 2019), as well as single-/bi-planar X-ray/fluoroscopic imaging (Anderst et al., 2017, 2015, 2013; Iai et al., 1993; Lin et al., 2014; Yu et al., 2019). Most previously reported studies focused on the intervertebral kinematics of the subaxial cervical spine, and showed that each segment has specific motion characteristics (Lin et al., 2014; Yu et al., 2019). However, only a few *in vivo* studies involved the evaluation of the intervertebral ROMs at upper cervical segments (C0-1 and C1-2) using conventional CT/MRI (Ishii et al., 2006, 2004; Kang et al., 2019; Zhai et al., 2019) and using biplanar X-ray/fluoroscopic imaging (Anderst et al., 2017, 2015; Iai et al., 1993) in one or multiple neck motions. Therefore, for the normal cervical spine, it is generally known that an upper cervical segment (C0-1/C1-2) allows a different ROM from that of a lower cervical segment (C2-T1) in certain neck motions (Anderst et al., 2015; Iai et al., 1993; Kang et al., 2019). A holistic investigation of the physiological segment ROM distribution across the entire cervical spine (throughout C0 to T1) during various *in vivo* neck motions has not been reported in the literature.

The objective of this study was to determine the intervertebral ROMs at each cervical segment from C0 to T1 between two maximal positions captured quasi-statically during *in vivo* flexion-extension (FE), left-right lateral bending (LB), and left-right axial torsion (AT) of the neck, using previously validated dual fluoroscopic (DF) imaging and model registration techniques (Mao et al., 2016; Wang et al., 2008). Because the adjacent vertebrae at the C0-1 and C1-2 segments articulate through cartilaginous interface joints without intervertebral discs (Middleditch and Oliver, 2005), it was hypothesized that the ROMs of these two segments differ from those of the subaxial cervical segments.

2. Methods

2.1. Collection of image data

The study was approved by the institutional review board (protocol number: K-2017-008) at Tongji Hospital in Shanghai, China. Ten asymptomatic subjects without prior diagnosed spinal disorders were recruited. Each signed an informed consent form before participating in the study. The skull (C0) and the entire cervical spine (C1-T1) of each subject were scanned using a CT scanner (SOMATOM Definition AS+, Siemens, Forchheim, Germany) in a supine position. The acquired CT images of each subject had a slice thickness of 0.60 mm, an image resolution of 512 pixels $\times$ 512 pixels, and a voxel size of 0.86 mm $\times$ 0.86 mm $\times$ 0.60 mm. After CT imaging, two subjects were excluded, with one subject suffering from congenital block vertebrae causing fusion at the C2-3 segment and one with CT images not qualified for model construction due to the loss of image data in internet transmission. Therefore, eight asymptomatic female subjects (mean age: 33.4 $\pm$ 5.7 years; age range: 28~46 years; mean weight: 52.7 $\pm$ 7.3 kg; mean height: 1.56 $\pm$ 0.06 m; mean body mass index: 21.9 $\pm$ 3.4 kg/m²; smoking status: none) were tested and analyzed in the subsequent data processing. Detailed demographic information was presented in Table 1.

Following the CT scanning, each subject was asked to perform three functional neck motions, including maximal FE, left-right LB, and left-right AT, in their comfortable manners while they stood upright. That is, we did not attempt to impose any specific requirement on the cervical motion performed by the subjects. The cervical spine (C0-T1) of each subject was imaged in each neck position using a DF imaging system according to previously reported protocols (Wang et al., 2008). Two fluoroscopes (BV Pulsera, Philips, Amsterdam, Netherlands) were positioned with their image intensifiers perpendicular to each other. Subjects' maximal neck postures during each neck motion were quasi-statically captured at a frequency of 30 frames per second with a pulse-width of 8 mili-seconds. The high acquisition frequency of the fluoroscopes allowed us to capture neck maximal postures held by subjects no more than one second. It was ensured that all cervical vertebrae and at least the occiput of the skull could be visualized within the field-of-view of both image intensifiers; if any component (vertebra/skull) completely disappeared on an intensifier, we asked the subject to change the standing location until all components could be viewed on both intensifiers. The total exposure dose of CT and DF imaging for each subject was estimated to be 4 mSv, approximately 20% of the average dose limit for occupational exposure in a year (Wrixon, 2008).

2.2. Processing of image data

The CT images were segmented in Amira 6 (Thermo Fisher Scientific, Waltham, MA) to create three-dimensional (3D) anatomical bone models of the skull and cervical spine using a protocol established in our laboratory (Mao et al., 2016; Wang et al., 2008). These 3D skull and vertebral models were imported into a virtual DF imaging environment constructed in MATLAB R2012a (MathWorks, Inc., Natick, MA) that replicated the actual experimental setup (Tsai et al., 2013; Wang et al., 2008). The quality of DF images in this study has been enhanced to enable the 2D-3D registration of the skull and upper cervical vertebrae. As illustrated in Fig. 1, each 3D model was independently translated and rotated in six degrees of freedom (6DOFs), until their projections matched the osseous outlines/features captured on the orthogonal DF images. The resulting 3D models, therefore, represented the *in vivo* positions/orientations of vertebrae in 3D space during various neck motions, as shown in Fig. 2.

To measure 6DOF intervertebral rotations and translations in each cervical spine position, local coordinate systems (CSs) were established at the superior and inferior intervertebral joint articulations or disc endplates using the CT-derived 3D vertebral models in Rhinoceros 5.0 (Robert McNeel & Associates, Seattle, WA). Subsequently, these local CSs were mapped to the registered 3D vertebral models in different neck positions (Fig. 2). For the C0-1 and C1-2 intervertebral articulations (Fig. 3a,b), new definitions of the local CSs based on anatomic landmarks were introduced. The origins of the C0, C1, and C2 CSs were located at the middle point of the line connecting the centroids of the left and right articular surfaces. Within the sagittal plane of the occiput, the superior direction of the C0 CS was perpendicular to the foramen magnum. Within the sagittal planes of C1 and C2 vertebrae, their superior directions were parallel to the C1 articular surface of the anterior arch and to the pivot axis of the C2 odontoid process, respectively. Compared to the CS definitions of the upper cervical segments adopted in previous studies (Anderst et al., 2017; Ishii et al., 2006, 2004; Kang et al., 2019), our definition resulted in different locations of the coordinate origins, but the orientations of the coordinate axes were consistent. For the subaxial segments (Fig. 3c), a well-established definition of the local CSs was adopted from previous works of our group (Mao et al., 2016; Yu et al., 2019). The origins of the CSs were defined at the centroids of the superior and inferior disc footprints. Within the sagittal plane of each subaxial vertebra, the anterior direction was tangent to the convex disc endplate profile.

This study focused on the investigation of maximal primary and coupled rotational ranges of all cervical segments during three typical motions of the neck, *i.e.*, FE, LB, and AT rotations, as shown in Fig. 2. Besides the rotational ROMs, we also measured the ROMs of coupled anterior-posterior, left-right, and superior-inferior translations during each neck motion, and presented these data in Appendix A. According to a previously reported validation study (Wang et al., 2008), the accuracy of DF registration in measuring cadaveric ovine vertebrae was 0.4 mm. The repeatability in reproducing *in vivo* 6DOF kinematics of human lumbar vertebrae using the DF technique was 0.3 mm in translations and 0.7° in orientations (Wang et al., 2008). It should be noted that the accuracy and repeatability of *in vivo* DF measurements depend on the resolution of DF images (Bingham and Li, 2006).

A repeated-measures analysis of variance (ANOVA) with Tukey *post hoc* tests was conducted using the R 3.5.1 software (<http://www.r-project.org>) to compare intervertebral ROMs in each of the 6DOFs between any two segments in FE, LB, and AT tasks, and compare any two rotational/translational ROMs at each segment in FE, LB, and AT tasks. A statistical significance was determined when the p-value is less than 0.05. The results of the statistical analysis can be found in Appendix A.

3. Results

3.1. Cervical intervertebral ROMs in flexion-extension neck motion

In FE neck motion (Table 2), the overall FE ROM measured between C0 and T1 was $94.5 \pm 13.8^\circ$. The primary intervertebral FE ROMs were $6.3 \pm 1.6^\circ$ at C0-1, $13.7 \pm 4.2^\circ$ at C1-2, and $4.1 \pm 2.7^\circ$ at C7-T1. Correspondingly, they contributed $6.6 \pm 1.4\%$, $14.5 \pm 4.4\%$, and $4.5 \pm 2.9\%$ of the overall FE ROM, respectively. The FE ROM of C0-1 was similar to that of C7-T1 ($p=0.113 > 0.05$), and both were significantly smaller than those of all other segments ($p < 0.05$). The FE ROM of C1-2 was significantly smaller than that of C4-5 ($19.4 \pm 2.9^\circ$, $p=0.023$) and significantly greater than that of C2-3 ($9.5 \pm 2.4^\circ$, $p=0.006$) and C7-T1 ($p=0.001$), but no significant difference existed compared to other segments ($p > 0.05$). For subaxial segments, each contributed more than 10% of the overall cervical FE ROM except for C7-T1; the maximal rotation was $19.4 \pm 2.9^\circ$ occurring at C4-5.

As shown in Fig. 4a, the coupled LB and AT rotations were significantly smaller than the primary FE rotation at each cervical segment ($p < 0.05$). There were no significant differences between the coupled LB and AT rotations at all cervical segments ($p > 0.05$).

3.2. Cervical intervertebral ROMs in lateral bending neck motion

In LB neck motion (Table 2), the overall LB ROM measured between C0 and T1 was $60.5 \pm 14.4^\circ$. The primary LB intervertebral ROMs were $1.9 \pm 1.5^\circ$ at C0-1, $7.6 \pm 2.7^\circ$ at C1-2, and $5.0 \pm 2.8^\circ$ at C7-T1, which contributed $2.9 \pm 1.8\%$, $13.2 \pm 6.3\%$, and $8.1 \pm 3.8\%$ of the overall LB ROM, respectively. The LB ROMs of C0-1 were significantly smaller than all other segments ($p < 0.05$). The LB ROM of C1-2 was similar to those of the other subaxial segments ($p > 0.05$), and only significantly smaller than that of C3-4 ($12.4 \pm 3.1^\circ$, $p=0.041$). For subaxial segments, all segments had similar ROMs ($p > 0.05$), except for C7-T1 whose ROM was significantly smaller than others ($p < 0.05$).

As shown in Fig. 4b, the primary LB ROMs were significantly greater than the coupled FE ROMs throughout all segments ($p < 0.05$), except for C0-1 where the opposite significant difference existed ($p=0.032$). On average, the coupled AT ROM ($2.0 \pm 1.5^\circ$) of C0-1 was almost equal to its primary LB ROM ($1.9 \pm 1.5^\circ$). The primary LB ROM ($7.6 \pm 2.7^\circ$) of C1-2 was significantly smaller than its coupled AT ROM ($20.0 \pm 14.7^\circ$, $p=0.037$). In contrast, the primary LB ROMs of subaxial segments were consistently larger than their coupled AT ROMs, although there was no significant difference for C7-T1 ($p=0.125 > 0.05$).

3.3. Cervical intervertebral ROMs in axial torsion neck motion

In AT neck motion (Table 2), the overall AT ROM measured between C0 and T1 was $103.1 \pm 20.1^\circ$. The primary AT intervertebral ROMs were $3.7 \pm 2.2^\circ$ at C0-1, $72.9 \pm 7.6^\circ$ at C1-2, and $1.2 \pm 1.4^\circ$ at C7-T1, which contributed $3.6 \pm 2.0\%$, $73.2 \pm 17.3\%$ and $1.2 \pm 1.3\%$ of the overall AT ROM, respectively. The AT ROM of C1-2 was approximately ten-folds as much as the maximum ROMs of all other segments ($p < 0.001$), occurring at C4-5 and at C5-6. On average, the AT ROMs of C4-5 ($6.5 \pm 1.9^\circ$) and C5-6 ($6.5 \pm 2.1^\circ$) were almost identical; both were significantly greater than the AT ROMs of C0-1 and other subaxial segments ($p < 0.05$), except for C3-4 ($p > 0.05$).

As shown in Fig. 4c, the AT ROM of C0-1 was not significantly different from its FE and LB ROMs ($p > 0.05$). At C1-2, the AT neck task caused a large coupled LB ROM ($21.3 \pm 10.1^\circ$). For C0-1 and subaxial segments, it was noted that their coupled LB ROMs were always larger than their primary AT ROMs, despite the significances only found for C3-4, C4-5, and C6-7 ($p < 0.05$). Except for C0-1, the coupled FE ROMs were significantly lower than the coupled LB ROMs at all segments ($p < 0.05$).

4. Discussion

In this study, the intervertebral ROMs of C0-1, C1-2, and subaxial cervical segments during *in vivo* maximal FE, LB, and AT neck motions were investigated using a combined CT and DF imaging technique. Our measurements indicated that during the three neck motions, both C0-1 and C7-T1 contributed much less rotation ($< 10\%$) to the overall cervical rotation compared to other segments. During the axial rotation of the neck, all segments similarly contributed less than 10% of the overall cervical rotation, except for C1-2, which contributed $73.2 \pm 17.3\%$ of the overall cervical rotation. During both LB and AT neck motions, regardless of primary or coupled motions, the AT ROM of C1-2 was significantly greater than its LB ROM ($p < 0.001$), whereas the opposite differences were observed at subaxial segments. These data partially support our hypothesis that there are unique intervertebral motion behaviors at C0-1 and C1-2 during various neck motions.

Most previous studies on cervical spine kinematics focused on intervertebral motion of only upper or lower cervical segments during specific *in vivo* neck motions (Tables 3-5). For FE neck motion (Table 3), Anderst et al. (2015) and Yu et al. (2019) indicated that the maximal ROMs occurred at C4-5 or C5-6, in agreement with our data. For LB neck motion (Table 4), our data regarding LB ROMs of C3-C7 subaxial segments were only similar to those reported by Lin et al. (2014). For AT neck motion (Table 5), our data only compared favorably with the AT ROMs of C1-2 (3.4°) and C1-2 (72.6°) reported by Ishii et al. (2004). In general, there are variations between our data and others' data on the ROMs of cervical segments and the overall cervical ROMs in each neck motion. The discrepancies in ROMs with other studies may be caused by the differences in experimental setups/procedures (*e.g.*, how to control neck motion), subjects' demographics (*e.g.*, gender and age), and DF image resolutions which affect the accuracy of model registration.

In this study, we measured the ROMs of all cervical segments from a sample of asymptomatic subjects, which enabled us to conduct a consistent comparison of

intervertebral motion patterns of the entire cervical spine. Compared to subaxial segments, we found the distinct kinematic characteristics of C0-1 and C1-2, which can be attributed to their unique anatomies. For C0-1 (Fig. 3a), there is a pair of bilateral condyloid joints in which the C0 inferior oval-shaped articular processes fit into the C1 superior articular hollows (Middleditch and Oliver, 2005). The C0-1 articulation anatomy favors FE motion but constrains LB and AT motions. However, our data showed that the primary FE ROM at C0-1 was only $6.3 \pm 1.6^\circ$ during *in vivo* FE neck motion, in contrast to the allowable FE ROM of approximately 24.5° at C0-1 measured *in vitro* (Panjabi et al., 1988); it implies that soft tissues (ligaments and muscles) surrounding the upper cervical spine may provide additional constraints during neck FE. For C1-2 (Fig. 3b), the median pivot joint formed by the anterior atlas arch and the front odontoid process allows a large range of axial rotation (Middleditch and Oliver, 2005). Correspondingly, the AT ROM of C1-2 accounts for $73.2 \pm 17.3\%$ of the overall C0-T1 ROM in AT neck motion, as measured in this study. The bilateral arthrodial joints of C1-2 are composed of a relatively flat C1 inferior articular surfaces and saddle-shaped C2 superior articular surfaces (Middleditch and Oliver, 2005). Hence, the AT of C1 relative to C2 may facilitate further LB of C1 relative to C2. This behavior should be distinguished from that in AT, where a large coupled contralateral bending occurring at C1-2 compensates for coupled ipsilateral bending generated by all subaxial segments, in order to maintain the horizontal head position (Ishii et al., 2004).

Our data on cervical intervertebral ROMs offer compelling clinical implications into the neck injury mechanisms and the etiologies of neck pathologies. For example, a majority of head/neck injuries during football sports, have been observed during the lateral impact of the head (Banerjee et al., 2004). The ROM of the neck in LB is approximately a half of that in neck FE or AT, and C0-1, C1-2, and C7-T1 are the least mobile segments during the neck LB. Consequently, the head/neck may be less tolerable to lateral impact loads, with C0-1, C1-2, and C1-T1 more vulnerable to injury than other segments. In the case of the stiff neck symptom, neck mobility (primarily in AT) is substantially reduced, but there has been no consensus about the etiology. As a normal C1-2 segment can provide more than 70% of the neck AT, a stiff neck may be associated with a significant limitation to the C1-2 rotation, to mitigate the impingement against inflamed surrounding soft tissues (Gubin et al., 2009). However, it should be acknowledged that the association of injuries/diseases with the allowable neck/segment ROMs requires further investigations by collecting the injury/disease patterns from a large cohort of patients.

The selection of spinal fusion or total disc replacement (TDR) to treat spinal disorders at a subaxial cervical segment markedly influences postoperative performance, including radiological parameters, spinal kinematics, and adjacent segment degeneration (Daniels et al., 2012; Li et al., 2018; Zechmeister et al., 2011). Our data showed that during all functional neck motions, C7-T1 allows the smallest ROMs, indicating that C7-T1 could be more suitable for the fusion treatment; the segments above C7-T1 may favor TDR treatments. Recently, hybrid surgery has been thought to be a promising solution to multi-segment cervical diseases (Grasso, 2015; Hung et al., 2018; Zang et al., 2015). Clinical studies generally suggested that hybrid surgeries, in which the fusions were commonly performed near C7-T1, can be comparable with and even superior to multi-segment fusions

or TDRs (Grasso, 2015; Hung et al., 2018; Zang et al., 2015), consistent with the implication of this study.

Several limitations in this study should be addressed in future investigations. Only eight female participants' image data were available to analyze cervical intervertebral ROMs. It has been demonstrated that cervical spine / segment ROMs are associated with gender (Trott et al., 1996), age (Simpson et al., 2008), or both simultaneously (Dvorak et al., 1991; Lind et al., 1989). To address this limitation requires a large cohort of subjects in future work. Consequently, it could be insufficient to perform clinical diagnoses and provide patient-specific treatment recommendations only based on the data of this study. Furthermore, this study focused on the maximal intervertebral ROMs during various *in vivo* neck motions, whereas the dynamic motion characteristics of C0-1 and C1-2 were not evaluated. Future work should investigate the dynamic intervertebral motion of upper segments and their dynamic contributions to the motion of the entire cervical spine.

In conclusion, we determined the intervertebral ROMs of the cervical spine from C0 to T1 during *in vivo* maximal FE, LB, and AT neck motions using a DF imaging system. For the eight asymptomatic female subjects tested in this study, we demonstrated that the C0-1 and C1-2 featured distinct motion characteristics during these neck motions. Future work should further evaluate the effects of gender and age on neck motion using a larger cohort of subjects. The reported cervical motion measurements in this study could be used to improve the understanding of the cervical function, benchmark post-operative spinal kinematics, and guide patients' rehabilitation to prevent dangerous activity.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

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Fig. 1. Illustration of a C0-T1 cervical spine 3D model, which was registered to the dual fluoroscopic images captured in the neutral position.

Fig. 2. Registered 3D C0-T1 cervical spine models of a subject in different static positions. (a) flexion (*left*) and extension (*right*); (b) left (*left*) and right (*right*) lateral bending; (c) left (*left*) and right (*right*) axial torsion.

Fig. 3.

The definitions of intervertebral local coordinate systems for the C0-1 segment (a), the C1-2 segment (b) and subaxial segments (c) graphically described in the oblique views (*left*) and sagittal cross-section views (*right*). For a better visualization, the occiput separated from the skull was shown in (a). Without loss of generality, only the C3-4 segment, representing a subaxial segment, was presented in (c).

Fig. 4.

The primary/coupled FE, LB, and AT intervertebral rotational ROMs of each cervical segment in FE (a), LB (b), and AT (c) neck tasks. Error bars represent one standard deviation. The black lines indicate that there are significant differences ($p < 0.05$) between two rotational ROMs at each segment (the gray lines indicate no significant differences).

Table 1.

The demographic information of all the eight female asymptomatic subjects in this study (BMI: body mass index; SD: standard deviation).

Subject #	1	2	3	4	5	6	7	8	Mean $\pm$ SD
Age (years)	33	34	46	29	28	34	34	29	33.4 $\pm$ 5.7
Weight (kg)	46.8	55.5	64	45.5	56.6	42.2	58.2	52.7	52.7 $\pm$ 7.3
Height (m)	1.62	1.55	1.52	1.60	1.51	1.45	1.64	1.56	1.56 $\pm$ 0.06
BMI (kg/m ²)	17.8	23.2	27.7	17.8	24.8	20.2	21.6	21.7	21.9 $\pm$ 3.4
Smoking	No	No	No	No	No	No	No	No	N/A

Table 2.

Comparison of the primary intervertebral rotational ROMs (°) at each cervical segment of the entire cervical spine (C0-T1) in FE, LB and AT tasks (mean $\pm$ standard deviation values are presented).

	Primary FE ROM	Primary LB ROM	Primary AT ROM
C0-C1 (a)	6.3 $\pm$ 1.6 ^{<i>b,g</i>}	1.9 $\pm$ 1.5 ^{<i>b,h</i>}	3.7 $\pm$ 2.2 ^{<i>b,e,f</i>}
C1-C2 (b)	13.7 $\pm$ 4.2 ^{<i>a,c,e,h</i>}	7.6 $\pm$ 2.7 ^{<i>a,d</i>}	72.9 $\pm$ 7.6 ^{<i>a,c,h</i>}
C2-C3 (c)	9.5 $\pm$ 2.4 ^{<i>a,b,d,f,h</i>}	11.3 $\pm$ 4.5 ^{<i>a,h</i>}	2.4 $\pm$ 1.6 ^{<i>b,e,f</i>}
C3-C4 (d)	14.9 $\pm$ 4.0 ^{<i>a,c,e,h</i>}	12.4 $\pm$ 3.1 ^{<i>a,b,h</i>}	4.2 $\pm$ 2.7 ^{<i>b</i>}
C4-C5 (e)	19.4 $\pm$ 2.9 ^{<i>a-d,g,h</i>}	9.8 $\pm$ 2.4 ^{<i>a,h</i>}	6.5 $\pm$ 1.9 ^{<i>a-c,g,h</i>}
C5-C6 (f)	17.1 $\pm$ 4.2 ^{<i>a,c,g,h</i>}	10.0 $\pm$ 2.3 ^{<i>a,h</i>}	6.5 $\pm$ 2.1 ^{<i>a-c,g,h</i>}
C6-C7 (g)	12.3 $\pm$ 4.2 ^{<i>a,e,f,h</i>}	10.6 $\pm$ 3.3 ^{<i>a,h</i>}	2.4 $\pm$ 1.2 ^{<i>b,e,f</i>}
C7-T1 (h)	4.1 $\pm$ 2.7 ^{<i>b,g</i>}	5.0 $\pm$ 2.8 ^{<i>a-c,g</i>}	1.2 $\pm$ 1.4 ^{<i>b,e,f</i>}
Overall (C0-T1)	94.5 $\pm$ 13.8	60.5 $\pm$ 14.4	103.1 $\pm$ 20.1

Note:

The letters ("a – h") represent the eight cervical segments from proximal to distal, respectively. The letter superscripts of the primary rotational ROM at a segment indicate that there are the significant differences ($p < 0.05$) when comparing to the ROMs of the segments represented by these letters.

Table 3.

Comparison of the primary FE rotational ROMs (°) at each cervical segment in the FE task measured in the current study with those in previously reported *in vivo* DF measurements of cervical dynamic motion (mean $\pm$ standard deviation values are presented). The demographic information in different studies, including gender and age, is also presented (M: males; F: females; y: years).

	Current study	Anderst et al. (2015)	Yu et al. (2019)
	8 F 33.4 $\pm$ 5.7 y 28-46 y	15M, 14F 27.3 $\pm$ 4.4 y 20-35 y	6 M, 4 F 40.3 $\pm$ 10.9 y
C0-C1	6.3 $\pm$ 1.6		
C1-C2	13.7 $\pm$ 4.2	15.6 $\pm$ 5.8	
C2-C3	9.5 $\pm$ 2.4	12.7 $\pm$ 2.6	
C3-C4	14.9 $\pm$ 4.0	17.1 $\pm$ 3.3	13.8 $\pm$ 4.3
C4-C5	19.4 $\pm$ 2.9	19.5 $\pm$ 3.4	15.1 $\pm$ 5.1
C5-C6	17.1 $\pm$ 4.2	19.7 $\pm$ 3.7	14.5 $\pm$ 7.0
C6-C7	12.3 $\pm$ 4.2	15.8 $\pm$ 4.8	9.2 $\pm$ 4.3
C7-T1	4.1 $\pm$ 2.7	8.3 $\pm$ 3.5	
Overall	94.5 $\pm$ 13.8	119.0 $\pm$ 13.8	

Note:

The overall ROM reported by Anderst et al. (2015) was measured between the head and torso using an optical track system, different from our measurement using the 2D-3D registration technique.

Table 4.

Comparison of the primary LB rotational ROMs (°) at each cervical segment in the LB task measured in the current study with those in previously reported *in vivo* DF/MRI measurements of cervical dynamic motion (mean $\pm$ standard deviation values are presented). The demographic information in different studies, including gender and age, is also presented (M: males; F: females; y: years).

	Current study	Ishii et al. (2006)	Lin et al. (2014)	Anderst et al. (2015)
	8 F 33.4 $\pm$ 5.7 y 28-46 y	6 M, 6 F 23.6 y 20-30 y	6 M, 4 F 22.6 $\pm$ 2.6 y	15M, 14F 27.3 $\pm$ 4.4 y 20-35 y
C0-C1	1.9 $\pm$ 1.5	3.8 (1.9 $\pm$ 0.9)		
C1-C2	7.6 $\pm$ 2.7	3.2 (1.6 $\pm$ 1.3)		
C2-C3	11.3 $\pm$ 4.5	7.4 (3.7 $\pm$ 2.0)		
C3-C4	12.4 $\pm$ 3.1	7.0 (3.5 $\pm$ 1.4)	12.8 (6.4 $\pm$ 2.3)	14.3 $\pm$ 2.8
C4-C5	9.8 $\pm$ 2.4	6.6 (3.3 $\pm$ 1.0)	10.4 (5.2 $\pm$ 1.4)	13.1 $\pm$ 3.2
C5-C6	10.0 $\pm$ 2.3	8.6 (4.3 $\pm$ 1.4)	12.2 (6.1 $\pm$ 1.8)	12.3 $\pm$ 3.2
C6-C7	10.6 $\pm$ 3.3	11.4 (5.7 $\pm$ 1.9)	12.2 (6.1 $\pm$ 1.8)	14.5 $\pm$ 3.9
C7-T1	5.0 $\pm$ 2.8	8.2 (4.1 $\pm$ 2.7)		5.6 $\pm$ 2.4
Overall	60.5 $\pm$ 14.4			83.9 $\pm$ 14.5

Note:

The ROMs in parentheses represent reported one-sided ROMs, which were converted to the two-sided ROMs by multiplying 2, since no significant difference was found in the left and right lateral bending in the corresponding study. The overall ROM reported by Anderst et al. (2015) was measured between the head and torso using an optical track system, different from our measurement using the 2D-3D registration technique.

Table 5.

Comparison of the primary AT rotational ROMs (°) at each cervical segment in the AT task measured in the current study with those in previously reported *in vivo* X-ray/DF/MRI measurements of cervical dynamic motion (mean $\pm$ standard deviation values are presented). The demographic information in different studies, including gender and age, is also presented (M: males; F: females; y: years).

	Current study	Iai et al. (1993)	Ishii et al. (2004)	Lin et al. (2014)	Anderst et al. (2015)	Anderst et al. (2017)	Yu et al. (2019)
	8 F 33.4 $\pm$ 5.7 y 28-46 y	20 M 27.7 y 27-50 y	8 M, 7 F 24.3 y 22-31 y	6 M, 4 F 22.6 $\pm$ 2.6 y	15 M, 14 F 27.3 $\pm$ 4.4 y 20-35 y	13 M, 7 F 28.0 $\pm$ 4.2 y 21-35 y	6 M, 4 F 40.3 $\pm$ 10.9 y
C0-C1	3.7 $\pm$ 2.2	8.0	3.4				
C1-C2	72.9 $\pm$ 7.6	76.0	72.6			73.6 (36.8 $\pm$ 6.7)	
C2-C3	2.4 $\pm$ 1.6						
C3-C4	4.2 $\pm$ 2.7			8.4 (4.2 $\pm$ 1.3)	11.8 $\pm$ 2.1		3.5 $\pm$ 1.7
C4-C5	6.5 $\pm$ 1.9			9.2 (4.6 $\pm$ 1.3)	11.3 $\pm$ 1.7		6.9 $\pm$ 3.8
C5-C6	6.5 $\pm$ 2.1			6.0 (3.0 $\pm$ 1.0)	9.3 $\pm$ 1.9		9.6 $\pm$ 4.1
C6-C7	2.4 $\pm$ 1.2			2.6 (1.3 $\pm$ 0.8)	6.5 $\pm$ 1.7		2.6 $\pm$ 2.5
C7-T1	1.2 $\pm$ 1.4				3.8 $\pm$ 1.2		
Overall	103.1 $\pm$ 20.1				142.8 $\pm$ 13.1		

Note:

The ROMs in parentheses represent reported one-sided ROMs, which were converted to the two-sided ROMs by multiplying 2, since no significant difference was found in the left and right axial torsion in the corresponding study. The overall ROM reported by Anderst et al. (2015) was measured between the head and torso using an optical track system, different from our measurement using the 2D-3D registration technique.