Normal intervertebral segment rotation of the subaxial cervical spine: An in vivo study of dynamic neck motions

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Abstract Background: Accurate knowledge of the intervertebral center of rotation (COR) and its corresponding range of motion (ROM) can help understand development of cervical pathology and guide surgical treatment.
Methods: Ten asymptomatic subjects were imaged using MRI and dual fluoroscopic imaging techniques during dynamic extension-flexion-extension (EFE) and axial left-right-left (LRL) rotation. The intervertebral segment CORs and ROMs were measured from C34 to C67, as the correlations between two variables were analyzed as well.
Results: During the EFE motion, the CORs were located at 32.4°/C6 20.6%, -2.4°/C6 11.7%, 21.8°/C6 12.5% and 32.3°/C6 25.5% posteriorly, and the corresponding ROMs were 13.8°/C6 4.3°/C14, 15.1°/C6 5.1°/C14, 14.4°/C6 7.0°/C14 and 9.2°/C6 4.3°/C14 from C34 to C67. The ROM of C67 was significantly smaller than other segments. The ROMs were not shown to significantly correlate to COR locations (r = 0.243, p = 0.132). During the LRL rotation cycle, the average CORs were at 85.6° ± 18.2%, 32.3° ± 25.3%, 15.7° ± 12.3% and 82.4° ± 31.3% posteriorly, and the corresponding ROMs were 3.5°/C6 1.7°, 6.9° ± 3.8°, 9.6° ± 4.1° and 2.6° ± 2.5° from C34 to C67. The ROMs of C34

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and C67 was significantly smaller than those of C45 and C56. A more posterior COR was associated with a less ROM during the neck rotation ($r = -0.583, p < 0.001$). The ROMs during EFE were significantly larger than those during LRL in each intervertebral level.

**Conclusion:** The CORs and ROMs of the subaxial cervical intervertebral segments were segment level- and neck motion-dependent during the in-vivo neck motions.

**The translational potential of this article:** Our study indicates that the subaxial cervical intervertebral CORs and ROMs were segment level- and neck motion-dependent. This may help to improve the artificial disc design as well as surgical technique by which the neck functional motion is restored following the cervical arthroplasty.

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excluded. Written consent was obtained from all patients before participation in the study. The CORs and ROMs of intervertebral segments (C34, C45, C56 and C67) of each patient were investigated.

Three-dimensional vertebral models

Each patient was scanned in a supine, relaxed position using a 3-T MRI scanner (MAGNETOM Trio; Siemens, Erlangen, Germany) with a spine coil and a proton density–weighted sequence. Three-dimensional (3D) models of the vertebrae from C3 to C7 were constructed using the magnetic resonance images [31] using a solid modelling software (3D slicer, MIT Artificial Intelligence Lab and Brigham and Women’s Hospital, Boston, MA) [32].

In vivo cervical spine kinematics

The dual fluoroscopic imaging system (DFIS) was used to capture the cervical spine motion [33,34]. The DFIS consists of two fluoroscopes (BV Pulsera; Phillips, Bothell, WA, USA) with their imaging intensifiers positioned perpendicular to each other. During the experiment, the patient sat and moved the neck within the field of view of the two fluoroscopes. The neck was imaged while the patient was performing two functional neck motions: 1) extension-flexion-extension (EFE) motion (from maximal extension position to maximal flexion and then extend to maximal extension position) and 2) left-right-left (LRL) rotation (axial rotation from maximal left position to maximal right position and then twisting back to maximal left position) (Figure 1). The images were captured with a frame rate of 30 Hz and an 8-ms pulse. Each patient was exposed to ~0.08-mSv radiation dosage in this study.

The pairs of fluoroscopic images captured during the neck motion were input into a solid modelling software (Rhinoceros; Robert McNeel & Associates, Seattle, WA, USA) and positioned as virtual imaging intensifiers for construction of a virtual DFIS that reproduces the actual DFIS setup [33–35]. The 3D magnetic resonance–based vertebral models were introduced into the virtual DFIS environment and viewed from two virtual cameras that represent the two X-ray sources of the actual DFIS. Each vertebral model could be translated and rotated independently in six degrees of freedom until their projections on the virtual imaging intensifiers matched the corresponding images captured during the experiment to reproduce the actual in vivo vertebral locations. The C1 and C2 vertebrae were not studied as their images were obscured by the skull and mandible. This technique has been validated by the roentgen stereophotogrammetric analysis technique as the gold standard to have a submillimeter accuracy in measurement of dynamic cervical motion [34].

Definition of the CORs and ROMs of the cervical intervertebral segments

The relative coordinate systems of the two endplate surfaces of each intervertebral segment (C34, C45, C56 and C67) (Figure 2-a) were used to calculate the intervertebral segment kinematics [34]. The x-axis was defined towards left, and the y-axis was posteriorly directed to spinous process as x-y plane was parallel to the endplate surface. The geometric centre of each endplate was chosen as the origin of the corresponding coordinate system. The z-axis was defined in the cephalic direction as perpendicular to the x-y plane. For each intervertebral segment, the coordinate system of the upper endplate surface of the inferior vertebra was used as a reference for calculation of the relative motion of the lower endplate of the superior vertebra (Figure 2-b). The static standing neutral posture was used as a reference for calculation of the intervertebral segment motion.

To define the intervertebral segment CORs, the anterior-posterior (AP) axis of the lower endplate of the superior vertebra was projected onto the primary motion plane of the reference coordinate system of the upper endplate of inferior vertebra. The intersection of the projections of the axes of two consecutive motions was represented as the COR of the intervertebral segment.
The COR location was measured as the distance to the geometric centre of the intervertebral segment. The COR was defined positive when posterior and negative when anterior to the intersegment centre. In this study, the COR was normalized to the AP dimension of the intervertebral disc [38] (Figure 2-b).

For the EFE neck motion, the CORs and ROMs were measured during the motion from full extension to flexion position, and the CORs and ROMs were also measured as the patients moved from the full flexion position to the full extension position. The averages of the CORs and ROMs of each intervertebral segment during the motion cycle were defined as the COR and ROM of the segment. The COR and ROM were similarly calculated for each intersegment during the LRL neck motion.

Statistics

To test the differences in COR locations and the ROMs of the 4 intervertebral segments during the EFE motion and LRL rotation, two-way repeated-measures analysis of variance and the Newman–Keuls post hoc test were performed. To test the difference in COR and ROM between motions,
Results

Intervertebral disc dimensions

The disc dimensions of C3 to C6 segments were similar in the AP direction (Table 1). In the medial-lateral direction, the C6 segment was significantly longer than other segments ($p < 0.001$). In the proximal-distal direction, the C6 segment was lower, but not significantly different compared with the other segments.

Intervertebral segmental CORs and ROMs

EFE motion

The average CORs were located at 32.4 ± 20.6, 2.4 ± 11.7, 21.8 ± 12.5 and 23.2 ± 25.5% posterior to the center of the vertebral body for C3, C4, C5 and C6 segments, respectively (Table 2) (Figure 2-a). The COR of C4 was significantly more anterior to its intervertebral center than the other intervertebral segments ($p < 0.001$). The ROMs of the 4 intervertebral segments were 13.8 ± 4.3, 11.1 ± 5.1, 14.4 ± 7.0 and 9.2 ± 4.3° (Table 2). The ROM of C6 segment was significantly less than the other 3 segments.

LRL rotation

The average CORs were located at 85.6 ± 18.2, 32.3 ± 25.3, 15.7 ± 12.3 and 82.4 ± 31.3% posterior to the center of the vertebral body for C3, C4, C5 and C6 segments, respectively (Table 2) (Figure 2-a). The COR of C5 was significantly closer to its intervertebral center than the other intervertebral segments ($p < 0.001$). The ROMs of the 4 intervertebral segments were 3.5 ± 1.7, 6.9 ± 3.8, 9.6 ± 4.1° and 2.6 ± 2.5° (Table 2). The ROM of C6 segment was significantly less than the other 3 segments.

Comparison of EFE motion and LRL rotation

The CORs of C3, C4 and C6 were more posteriorly positioned during the LRL rotation than during the EFE motion ($p < 0.05$) (Table 2). The positions of the CORs of C5 were not significantly different during the two neck motions ($p > 0.05$). The ROMs of each intervertebral

Table 2 The average intervertebral segment COR locations (%) and angular ROMs (°) of the cervical spine during the EFE motion and LRL rotation.

| Segment | EFE motion (a, d, e) | LRL rotation (a, b, d, e, f) |
|---------|---------------------|-----------------------------|
| COR     | C34                 | C45                         |
|         | 32.4 ± 20.6         | -2.4 ± 11.7                 |
|         | 21.8 ± 12.5         | 23.2 ± 25.5                 |
| ROM     | C34                 | C45                         |
|         | 85.6 ± 18.2         | 32.3 ± 25.3                 |
|         | 15.7 ± 12.3         | 82.4 ± 31.3                 |

Significant differences between different intervertebral segments when $p < 0.05$: a for C3 vs. C4, b for C3 vs. C5, c for C3 vs. C6, d for C4 vs. C5, e for C4 vs. C6 and f for C5 vs. C6.

$\bullet$ Represents the statistically significant difference between EFE motion and LRL rotation.

Figure 3 (A) The correlations between the COR locations (%) and corresponding ROMs (°) during the EFE motion of the neck; (B) the correlations between the COR locations (%) and corresponding ROMs (°) during the LRL rotation of the neck. The "0" on the COR axis represents the location of disc center. The -50% represents the anterior edge of disc, whereas the +50% represents the posterior edge of disc. EFE = extension-flexion-extension; LRL = left-right-left; ROM = range of motion.
segment during the EFE motion were significantly larger than during the LRL rotation \(p < 0.05\) (Table 2).

**Correlation of COR locations and corresponding ROMs during EFE and LRL neck motions**

Generally, a closer COR to the disc centre corresponds to a larger ROM (Figure 3). There was no significant correlation \(r = -0.243, p = 0.132\) between the posterior COR positions and the corresponding ROMs of all intervertebral segments of C34 to C67 during the EFE neck motion (Figure 3-a). During the LRL neck rotation, there was a negative correlation \(r = -0.583, p < 0.001\) between these two variables (Figure 3-b).

**Discussion**

This study found that the CORs of C45 and C56 are closer to the intervertebral centres than those of C34 and C67 during the EFE motion and LRL rotation of the neck. The CORs are more posteriorly positioned during the LRL rotation than during the EFE motion at all segments except the C56 level. The ROM of each intervertebral segment is larger during the EFE motion than during the LRL rotation. Generally, a closer position of the COR to the intervertebral centre corresponds to a larger ROM. These data were consistent with our hypothesis that the locations of the CORs are segment specific and neck motion dependent in asymptomatic healthy cervical spines.

Previous studies have investigated the CORs of the cervical vertebral columns primarily during the flexion-extension motion of the neck [22–28]. The CORs were generally shown to be close but posterior to the endplate centres via measurement of plain radiographs captured at static flexion and extension postures [22,23]. In a recent study of the instantaneous CORs of the cervical vertebrae during dynamic neck flexion-extension motion, the mean locations of the CORs measured from the inferior vertebral body centres were found to change increasingly posteriorly from C34 to C67 during the flexion-extension of the neck [28]. In general, our data were consistent with the data reported in literature on neck flexion-extension. However, our data showed that the mean intervertebral segmental COR of the C45 was slightly anterior to the disc centre \(-2.4\%) during the flexion-extension of the neck. It is difficult to make a direct comparison between various studies of cervical spine because different studies used different experimental setups and measured the intervertebral motion using different methods. No data have been reported on the cervical intervertebral segment rotation during neck axial rotation.

The data found in this study may have interesting clinical implications. Most contemporary TDRs were designed using the ball–socket joint concept that has designed articulation path of the device [39–41]. This mechanical design concept may not be compatible to the large range of COR location variations as shown at different intervertebral segments and during different neck motions. For example, Duggal et al. [42] found that a TDR at C56 could result in significant increases in global spinal ROM compared with preoperative evaluations in a patient follow-up study. Skepholm et al. [43] investigated the intervertebral ROM using an in vivo computed tomography study and reported that the treated intervertebral ROM of the C56 was similar to that of the C45 but statistically larger than that of the C67. This could be explained by the fact that the CORs of C56 were located close to the intervertebral centre. Our data and the findings of Dvorak et al. [44] also showed that the C56 and C45 were the more mobile than other levels in the subaxial cervical spine.

However, our data also indicated that the COR locations of the C34 and C67 were more posterior than C45 and C56 during rotations of the neck. In general, a more posteriorly positioned COR corresponded to a smaller ROM. Therefore, to achieve a large ROM, the TDR may need to be positioned close to the intervertebral segment centre. Current TDRs may not be suitable for treatment of C34 and C67 as it is difficult to achieve the posterior CORs of the two segments using these devices. No study has compared the clinical outcome of cervical TDRs when applied to different segments. Future improvement of motion preservation treatments for cervical diseases may need to consider the variations of motion characteristics of different intervertebral segments during different neck motions.

There are several limitations to this study. First, C12 and C23 were not included in the analysis because of the obstruction of their images by the mandibular and occipital bones in certain postures along the neck motion path. Second, only 10 asymptomatic patients were investigated with age ranged from 30 to 59 years. Future studies should include more patients with a wider range of age to investigate the effects of age on cervical spine biomechanics. Finally, we investigated the intervertebral segment CORs of the cervical spine during two functional neck motions. In future, the cervical spine should also be investigated during dynamic walking, the most common loading condition experienced during daily life.

**Conclusion**

This study investigated the intervertebral segmental CORs and ROMs of the subaxial cervical spine during two neck functional motions. The locations of the CORs during the dynamic EFE motion and axial LRL rotation were shown to be segment level specific and neck motion dependent. The intervertebral segmental CORs of C45 and C56 were located closer to the geometrical centres than those of C34 and C67. The ROMs were larger during the EFE motion than during the LRL rotation at each intervertebral level. A more posteriorly positioned COR was corresponding to a smaller ROM during the LRL rotation. The data obtained in this study could provide insights into the improvement of motion preservation prosthesis design and surgical implantation techniques that is aimed to restore normal neck function and prevent adjacent segment degeneration after the cervical spine surgery.

**Author contributions statement**

Each of the coauthors has involved in the design of the study, data analyses, interpretation of data and writing of
the manuscript. All authors have read and approved the final submitted manuscript.

Ethical review committee statement

This research was approved by the Partners Human Research Committee (Protocol Number: 2012PO02508/MGH).

Conflicts of interest statement

There is no conflict of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jot.2018.12.002.

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