Three-dimensional analysis of cervical spine segmental motion in rotation

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Abstract

Introduction: The movements of the cervical spine during head rotation are too complicated to measure using conventional radiography or computed tomography (CT) techniques. In this study, we measure three-dimensional segmental motion of cervical spine rotation *in vivo* using a non-invasive measurement technique.
Material and methods: Sixteen healthy volunteers underwent three-dimensional CT of the cervical spine during head rotation. Occiput (Oc) – T1 reconstructions were created of volunteers in each of 3 positions: supine and maximum left and right rotations of the head with respect to the bosom. Segmental motions were calculated using Euler angles and volume merge methods in three major planes.
Results: Mean maximum axial rotation of the cervical spine to one side was 1.6° to 38.5° at each level. Coupled lateral bending opposite to lateral bending was observed in the upper cervical levels, while in the subaxial cervical levels, it was observed in the same direction as axial rotation. Coupled extension was observed in the cervical levels of C5-T1, while coupled flexion was observed in the cervical levels of Oc-C5.
Conclusions: The three-dimensional cervical segmental motions in rotation were accurately measured with the non-invasive measure. These findings will be helpful as the basis for understanding cervical spine movement in rotation and abnormal conditions. The presented data also provide baseline segmental motions for the design of prostheses for the cervical spine.

Key words: cervical spine, segmental motion, coupled motion, rotation, *in vivo*.

Introduction

One of the fundamental functions of the cervical spine is to assist and control motion of the head and neck. When the kinematics of the neck is disrupted, the abnormal motion may contribute to clinical symptoms. Many investigators have provided data in support of the hypothesis that abnormalities in intervertebral motion provide important diagnostic information in the evaluation of patients reporting neck or related complaints [1-6]. Although disorders of the cervical spine can affect motion in many different geometric planes, abnormalities in sagittal plane motion have been the focus of most research. Flexion-extension radiographs are commonly used in clinical practice to help identify abnormalities in motion within patients with suspected cervical spine disorders [7]. There has been some controversy as to whether excessive motion on flexion-extension radiographs is associated with low neck pain or degenerative disc disease

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[6, 7]. Spinal instability, and axial rotational instability in particular, has been implicated in the pathogenesis of chronic low neck pain.

Axial rotation of the cervical spine is complicated by accompanying concomitant motions in lateral bending, flexion-extension, and translations, as so-called coupled motion [8]. The use of radiographs has been shown to be limited by poor accuracy and impracticality of measuring out-of-plane rotations [9, 10]. In addition, the range of motion measured in many radiographic studies is affected by the variability in voluntary efforts that the subject applies at the time of examination and also can be limited because of pain. Other two-dimensional methods for measuring axial rotation, as opposed to flexion-extension, have involved magnetic resonance imaging (MRI) scanning of subjects in various rotated positions [11, 12]. While these studies were non-invasive and controlled for voluntary motions, they could only determine changes in vertebral motion around one axis. It has been suggested that coupled motions could play an important role in determining spinal instability [13]. In this study, we measured the three-dimensional segmental motion of the cervical spine during rotation *in vivo* using a non-invasive measurement technique. These findings will be helpful as the basis for understanding cervical spine movement in rotation and abnormal conditions. The presented data also provide baseline segmental motions for the design of prostheses for the cervical spine.

Material and methods

Acquisition of 3D CT

Sixteen healthy, asymptomatic volunteers participated in the current study (mean age: 26.5 ±3.4 years (mean ± SD); 8 males and 8 females). Each subject signed an approved informed consent form. Computed tomography (CT) was used to calculate three-dimensional motion of the cervical vertebral bodies for this study. Subjects were placed supine on the CT table and asked to rotate their heads from neutral to maximum rotation while 3D images were obtained. Subjects always rotated their head on a plane perpendicular to the CT table by keeping both of their eyes on the positioning beam of the CT machine throughout head rotation, and their shoulders were fixed to the table with the band. If the extreme rotations were severely uncomfortable for the subjects, a lower value for full rotation would be used and recorded for subsequent analysis.

Processing of 3D CT image

The 1.0-mm-thick axial slices from the CT scanner were imported into a three-dimensional reconstruction software package (Mimics, Materialise Inc., Ann Arbor, MI), where a threshold level to define the cortical shell was selected. Each vertebral body was segmented based on the threshold level. These reconstructions were then imported into the software package ProEngineer 2000i (Parametric Technology Corp., Needham, MA) where a three-dimensional solid model was created and the principal moment, principal axes and centroid of each vertebra were calculated. Using the theory of rigid body mechanics, the principal axes at the centroid of a solid body were rotated with that body so that the amount of rotation was determined. The inertial property values were then input into a custom program (Matlab, MathWorks Inc., Novi, MI) that used Euler angles to determine initial rotations and translations about the centroid between two vertebral bodies based on methods described by Panjabi *et al.* and other authors [14]. A volume merge method was created with custom software program in Microsoft Visual C++. NET 2003 with Microsoft Foundation Class programming environment (Microsoft Corp., Redmond, WA) and was further used to refine the above-mentioned Eigen vector method [15]. In the volume merge method, a vertebral body in the neutral position (the moving vertebra) was virtually rotated and translated toward the same body in a rotated position (the stationary target).
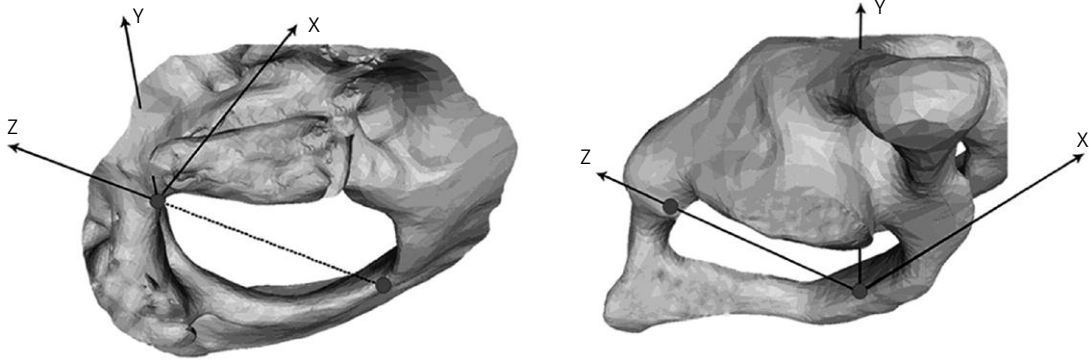
Coordinate system

Three major axes of rotation were examined (flexion-extension, lateral bending, and axial rotation) for each vertebral body. An order of axial/flexion-extension/lateral bending rotation was used in this study for determining the Euler angles [16, 17]. Positive values indicated left axial rotation, left lateral bending, and flexion. In addition, translations of the centroid from neutral position to rotated positions were calculated in the three major planes (frontal, x; sagittal, y; and axial, z). Positive values for translations were left, posterior, and superior motions (Figures 1 and 2).

Evaluation of accuracy

Mean absolute rotational error was 0.01° for flexion-extension, 0.01° for lateral bending, and 0.005° for axial rotation. Mean absolute translational error was 0.02 mm for superoinferior translation, 0.01 mm for anteroposterior translation, and 0.02 mm for lateral translation.

Motion analysis

Segmental rotations and translations were calculated as the motion from supine to either left or right rotations. Analysis for rotations and translations was performed using a one-way analysis of variance with Fisher's *post hoc* test to determine

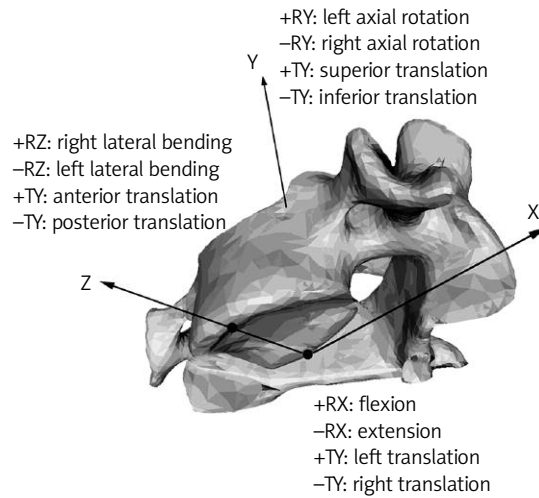**Figure 1.** Anatomical orthogonal coordinate system for Oc and C1

differences based on spinal level and direction of motion. The significance level was set to $p < 0.05$ for all analyses.

Results

Mean (± SD) angle of axial rotation of the head (Oc-T1) from neutral to maximum was 65.3° ±5.2°. Coupled lateral bending in the same direction as axial rotation was 15.1° ±3.6° and coupled flexion was 16.7° ±3.9°. Means and standard deviations for ranges of intervertebral motions to one side are displayed in Figures 3 and 4.

Axial rotation

Mean maximum axial rotation at each level of the axial cervical spine to one side was 2.4° ±1.8° at Oc–C1, 38.5° ±4.7° at C1–C2, 3.1° ±1.1° at C2–C3, 4.0° ±1.6° at C3–C4, 5.3° ±1.5° at C4–C5, 4.6° ±1.8° at C5–C6, 2.3° ±1.3° at C6–C7, and 1.6° ±0.9° at C7–T1. Maximum axial rotation was thus greater in C3–C4, C4–C5 and C5–C6 than in other levels.

+RY: left axial rotation
–RY: right axial rotation
+TY: superior translation
–TY: inferior translation

+RZ: right lateral bending
–RZ: left lateral bending
+TY: anterior translation
–TY: posterior translation

+RX: flexion
–RX: extension
+TY: left translation
–TY: right translation

Figure 2. Anatomical orthogonal coordinate system for lower cervical spine

Coupled lateral bending

Coupled lateral bending with axial rotation was observed in the same direction as axial rotation at
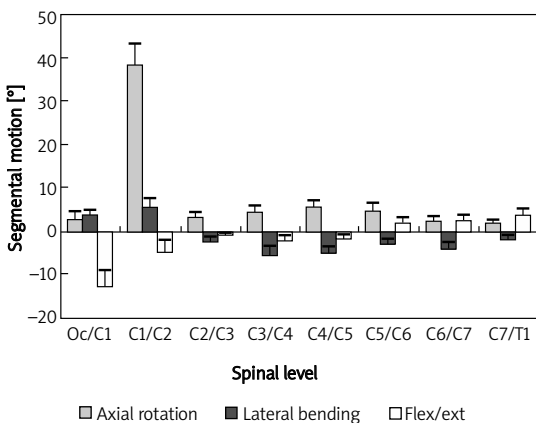
Figure 3. Segmental spine rotation for 16 asymptomatic subjects. Coupled lateral bending (LB) (+) represents the opposite direction of axial rotation (AR); coupled flexion-extension (F-E) (+) represents flexion
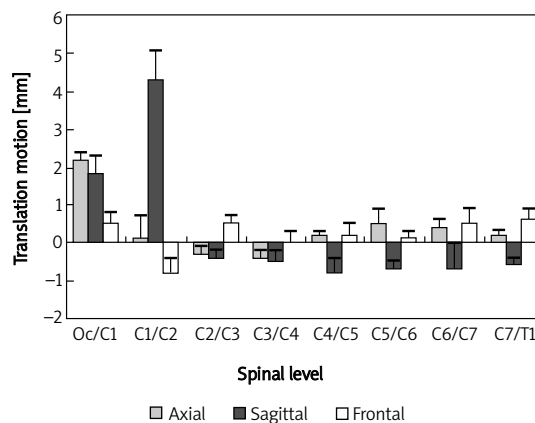
Figure 4. Segmental spine rotation for 16 asymptomatic subjects. Coupled translation (+) represents superior for superoinferior translation (SI-T), the same direction in the axial rotation for lateral translation (LT), and anterior for anteroposterior translation (AP-T)

all levels except for Oc–C1 and C1–C2. The means of lateral bending during maximum head rotation were 3.6° ±1.3° at Oc–C1, 5.4° ±2.0° at C1–C2, 2.7° ±1.3° at C2–C3, 5.9° ±2.2° at C3–C4, 5.4° ±1.8° at C4–C5, 3.1° ±1.1° at C5–C6, 4.2° ±1.6° at C6–C7, and 2.2° ±1.4° at C7–T1. Similar to axial rotation, all participants displayed a greater degree of coupled lateral bending at C3–C4, C4–C5, C5–C6, and C6–C7 than in the other levels.

Coupled flexion-extension

Extension coupled with axial rotation occurred in the upper and middle cervical region (Oc–C1 12.9° ±3.8°, C1–C2 4.9° ±2.6°, C2–C3 1.1° ±1.0°, C3–C4 2.4° ±1.3°, C4–C5 2.0° ±1.2°), while in the lower cervical region, flexion was coupled with axial rotation (C5–C6 1.6° ±1.4°, C6–C7 2.2° ±1.2°, C7–T1 3.5° ±1.5°).

Coupled translations

Lateral translation coupled with axial rotation at the origin of coordinates was observed in the direction opposing axial rotation at all levels except for Co–C1, C1–C2 (Oc–C1 1.8 ±0.5 mm, C1–C2 4.3 ±0.8 mm, C2–C3 0.4 ±0.2 mm, C3–C4 0.5 ±0.3 mm, C4–C5 0.8 ±0.4 mm, C5–C6 0.7 ±0.2 mm, C6–C7 0.7 ±0.3 mm, C7–T1 0.6 ±0.2 mm). Coupled superoinferior translation of Oc relative to C1 with axial rotation was observed in superior (mean 2.2 ±0.2 mm) directions. Other coupled anteroposterior and superoinferior translation with axial rotation was hardly seen.

Discussion

To measure these coupled motions, several studies have attempted to delineate coupling motion patterns of the cervical spine during rotation. More invasive techniques involve inserting wires into the spinous process of subjects to determine three-dimensional motion [18]. While this method has proven more accurate than radiographs, its invasive nature limits its widespread clinical use. Other researchers have used biplanar radiography, where subjects are filmed from two directions simultaneously and three-dimensional motions are determined from anatomic landmarks in corresponding images [19, 20]. There has been some concern with the accuracy of determining anatomic landmarks for biplanar radiography, as well as a lack of equipment for this method in typical clinical settings. Panjabi et al. [21], and Moroney et al. [22] observed in cadaver studies that axial rotation of the cervical spine accompanies lateral bending in the same direction as axial rotation, but no detailed descriptions of coupled flexion-extension were reported. In these in vitro studies, however, the cervical spines without the muscles might not accurately reflect physiological cervical motion. Mimura et al. attempted to document in vivo coupled motion with axial rotation using biplanar radiography but failed to accurately demonstrate complex coupled motion, as their methods depended greatly on subjective assessments by the examiner in tracking bony landmarks on plain radiographs [23]. To combat some of these limitations to three-dimensional motion measurement, Lim et al. developed a three-dimensional imaging technique using parallel computed tomography (CT) scans to determine rotations and translations in individual cadaveric cervical vertebrae [9]. The authors illustrated that accurate measurements (1 mm and 1°) can be made using CT in vitro.

In our study, a non-invasive method was introduced to measure the in vivo cervical segmental rotation and translation with high accuracy. It has overcome several limitations of previous in vitro methods, such as the necessity to disrupt soft tissues for implantation of markers or rods, and a lack of physical muscular force [8]. The method used in the current study was a combination of the Eigen vector method and the volume merging method. The Eigen vector method was used in a previous study for measurement of orientation of a three-dimensional computer cervical vertebral model created by cadaveric cervical vertebrae [9]. The accuracy of this method was expected to be 1° under in vitro conditions, which was large in comparison to the expected cervical segmental motions in vivo.

Table I. Comparison of mean range (SD) of axial rotation on one side (°)

		Oc–C1	C1–C2	C2–C3	C3–C4	C4–C5	C5–C6	C6–C7	C7–T1
In vitro									
W&P (1978)	Cadaver	0	47	9	11	12	10	9	8
Panjabi *et al.* [26]	Cadaver	0	38.9	1.6	2.6	3.4	2.6	1.5	–
In vivo									
Dvorak *et al.* [14]	CT	4	41.5	3 (2.5)	6.5 (2.3)	6.7 (2.3)	7.0 (2.4)	5.4 (2.3)	2.2 (2.1)
Mimura *et al.* [28]	Bi-plane X-ray	–4	38	3.7	2.9	2.1	2.7	3.2	–
Present study	3D CT	2.4 (1.8)	38.5 (4.7)	3.1 (1.1)	4.0 (1.6)	5.3 (1.5)	4.6 (1.8)	2.3 (1.3)	1.6 (0.9)

The segmental motions measured in previous studies have been less than 2°, especially in axial rotation [24]. Therefore, we have implemented a volume merge method in an effort to refine the accuracy of the Eigen vector method. Similar methods have been used for *in vivo* measurement of kinematics of carpal bone, knee joint, hip joint and cervical spine with high accuracy [25-31].

Studies which have measured segmental rotation due to an external axial rotation are rare. Previous representative data for axial rotation of the cervical spine are shown in Table I. *In vivo*, results from conventional CT present larger values at all levels compared with our results except C2–C3 [12, 32]. Conventional CT allows an alignment of the gantry only in the sagittal plane, not in the frontal plane. Tilted vertebrae could be transected obliquely to a different extent in the axial plane, owing to coupled motion [8]. This would impair the measurement of pure axial rotation, potentially leading to these differences in results. Conversely, an *in vivo* study by Mimura *et al.* [23] and an *in vitro* study by Panjabi *et al.* [21] yielded smaller values of axial rotation than our investigation except C1–C2. Those different results compared with ours might come from small head rotation (52.5° between occiput and C7 to one side) in the former and the small loads applied for axial torque (a pure moment of 1 Nm for axial torsion) in the latter. In an *in vitro* study, Miura *et al.* [33] recommended a pure moment of 4 Nm for axial torque to simulate *in vivo*-like cervical motions, and our results support this concept.

The present study has several potential limitations. First, the study included only a small number of healthy, young persons. Therefore, no comparable data can be determined for an elderly group of asymptomatic persons. Second, the persons were positioned supine, not in the upright position. The differences of postures may have an effect on spinal motions.

In conclusion, we have studied three-dimensional, *in vivo* motions in healthy individuals and revealed that three-dimensional cervical segmental motions can be accurately measured with a non-invasive method. These findings will be helpful as the basis for understanding cervical spine movement in rotation and abnormal conditions. The presented data also provide baseline segmental motions for the design of prostheses for the cervical spine.

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