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BIOMECHANICS

In Vivo Three-Dimensional Kinematics of the Cervical Spine During Head Rotation in Patients With Cervical Spondylosis

Yukitaka Nagamoto, MD,* Takahiro Ishii, MD, PhD,† Hironobu Sakaura, MD, PhD,‡ Motoki Iwasaki, MD, PhD,‡ Hisao Moritomo, MD, PhD,‡ Masafumi Kashii, MD, PhD,§ Takako Hattori, MD,* Hideki Yoshikawa, MD, PhD,‡ and Kazuomi Sugamoto, MD, PhD*

Study Design. Kinematics of the cervical spine during head rotation was investigated using 3-dimensional (3D) magnetic resonance imaging (MRI) in patients with cervical spondylosis (CS).

Objective. To demonstrate *in vivo* 3D kinematics of the spondylotic cervical spine during head rotation.

Summary of Background Data. Several *in vivo* studies have identified kinematic differences between normal and spondylotic subjects, but only two-dimensional flexion/extension motion has been investigated. Differences of *in vivo* 3D cervical motion during head rotation between normal and spondylotic subjects have yet to be clarified.

Methods. Ten healthy volunteers (control group) and 15 patients with CS (CS group) underwent 3D MRI of the cervical spine with the head rotated to 5 positions (neutral, ±45° and ±maximal head rotation). Relative motions of the cervical spine were calculated by automatically superimposing a segmented 3D MRI of the vertebra in the neutral position over images for each position using volume registration. The 3D motions of adjacent vertebra were represented with 6 degrees of freedom by Euler angles and translations on the coordinate system.

Results. Compared with the control group, the CS group showed significantly decreased mean axial rotation and mean coupled lateral bending at C5–C6 and C6–C7 and significantly increased mean coupled lateral bending at C2–C3 and C3–C4, although both the groups showed the same pattern of coupled motions.

Conclusion. The *in vivo* 3D kinematics of the spondylotic cervical spine during head rotation was accurately depicted and compared with those of healthy cervical spines for the first time.

Key words: kinematics, coupled motion, cervical spondylosis, volume registration. **Spine 2011;36:778–783**

From the *Department of Orthopaedic Biomaterial Science Osaka University Graduate School of Medicine; †Department of Orthopaedic Surgery, Kaizuka City Hospital, Kaizuka; ‡Department of Orthopaedics, Osaka University Graduate School of Medicine; and §Department of Orthopaedic Surgery, Toyonaka Municipal Hospital, Shibahara, Toyonaka, Osaka, Japan.

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Address correspondence and reprint requests to Yukitaka Nagamoto, MD, Department of Orthopaedic Biomaterial Science, Osaka University Graduate School of Medicine, 2-2 Yamadaoka, Suita, Osaka 5650871, Japan; E-mail: 7gam0to@gmail.com

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The human cervical spine is composed of highly specific tissues and structures, which together provide the extensive range of motion and considerable load-carrying capacity required for physical activities of daily living (ADL). This is 1 reason why degenerative changes in the cervical spine start as early as middle age and affect more than 95% of patients older than 65 years.[1] Even though nerve root or cord compression develops in 10% to 15% of the population,[2] the pathophysiology of cervical spondylosis (CS) remains poorly understood.[3]

Achieving a better understanding of this pathophysiology requires clarification of the differences in kinematics between the normal and spondylotic cervical spine. Several kinematic studies associated with aging and/or degeneration of the cervical spine have been reported using simple extension and flexion radiography,[4–7] motion analysis,[8] cineradiography,[9] and magnetic resonance imaging (MRI).[10] However, most of these studies have investigated only 2-dimensional flexion/extension motion, and 3-dimensional (3D) analysis using a motion analyzer has been vague and indirect. No study comparing in vivo 3D cervical motion during head rotation between normal and spondylotic subjects has been conducted, despite the importance of these motions in ADL. This is because of the difficulty in measuring *in vivo* cervical segmental motion, particularly during head rotation and lateral bending, which involves complex 3D motions called "coupled motion." We have developed a 3D MRI system to evaluate the *in vivo* 3D kinematics of the spine[11–14] and have already reported accurate *in vivo* 3D kinematics of the normal cervical spine using this method.[11–13] The objectives of this study were to investigate *in vivo* 3D kinematics of the spondylotic cervical spine during head rotation and to compare those with kinematics of the healthy cervical spine.

MATERIALS AND METHODS

Subjects in this study comprised 10 healthy volunteers (control group) and 15 patients with CS (CS group). The 10 healthy volunteers (5 men, 5 women; mean age, 25.1 years; range, 22–31 years) had neither neck pain nor any medical history of cervical spine disorders. As for the control group, all subjects were included in our previous publications[11–13] and retrospective analysis was performed. The 15 patients (7 men, 8 women; mean age, 60.2 years; range, 41–70 years) had been referred to our institution because of axial and/or neurologic symptoms and showed radiographic findings of CS as follows: loss of disc space height; spondylotic bars; foraminal osteophytes; and kyphosis. Subjects with a history of cervical spine surgery, trauma, tumors, infection, rheumatoid arthritis, or ossification of the posterior longitudinal ligament were excluded. All study protocols were approved in advance by the institutional review board.

Each subject was placed supine on the MRI table and underwent 3D MRI in 5 positions with the head rotated 0° (neutral position), 45°, and maximally to the left and right. All subjects were instructed to rotate the head as perpendicular as possible to the axis of the body trunk, and the shoulders were fixed to the table with a band. In the control group, MRI was performed using a 1.0-T commercial magnetic resonance system (Signa LX; General Electric, Milwaukee, WI). A 3D fast-gradient recalled acquisition in the steady state sequence was used with the following settings: repetition time, 8.0 ms; echo time, 3.3 ms; slice thickness, 1.5 mm; no interslice gap; flip angle, 10°; field of view, 24 cm; and 256 × 224 in-plane acquisition matrix. In the CS group, MRI was performed using a 1.5-T commercial magnetic resonance system (MAGNETOM Espree; Siemens, Erlangen, German). A 3D multiecho data imaging combination sequence was used with the following settings: repetition time, 40.0 ms; echo time, 20.0 ms; slice thickness, 1.3 mm; no interslice gap; flip angle, 12°; field of view, 24 cm; and 256 × 226 in-plane acquisition matrix. All subjects provided informed consent to undergo 3D MRI for the kinematics study and those for whom MRI proved difficult to perform because of axial and/or neurologic symptoms were excluded. All examinations were performed by the first or second author.

MRI data were saved in Digital Imaging and Communications in Medicine format and transmitted to a computer workstation, where image processing was performed using software developed in our laboratory (Virtual Place M series; Medical Imaging Laboratory, Tokyo, Japan). The method used in this study has been fully described in previous reports[11–13] and is, therefore, only described briefly here. This method showed high accuracy as follows: 0.24° for flexion/extension, 0.31° for lateral bending, 0.43° for axial rotation, 0.52 mm for superoinferior translation, 0.51 mm for anteroposterior translation, and 0.41 mm for lateral translation.[11] As a result of image processing (volume registration method), 3D motions of each vertebra expressed as a matrix were obtained. For easier comprehension of complicated 3D motions, relative 3D cervical motions of all motion segments were calculated by converting the matrix obtained by image processing into a matrix representing relative motion with respect to the inferior adjacent vertebra, and these motions were expressed in 6 degrees of freedom by Euler angles with the sequence of yaw (X)-pitch (Y)-roll (Z) and translations using a previously defined coordinate system as follows: the z-axis of occipital bone (Oc) was parallel to the line connecting anterior and posterior borders of the foramen magnum, with anterior considered positive. The y-axis was defined as perpendicular to the z-axis, with superior being positive. The x-axis was positive to the left. The coordinate system of C1 was defined using 2 points: the posteroinferior border of the anterior arch and the anteroinferior border of the posterior arch. Origins were located at the anterior border of the foramen magnum on Oc and the posteroinferior border of the anterior arch on C1. The coordinate system of subaxial cervical vertebrae was defined as follows: the origin was located at the most inferior point on the posterior wall of the vertebral body in the midsagittal plane. The z-axis was defined as the line connecting anterior and posterior points in the inferior plane of the vertebral body, with anterior considered positive. The y-axis was defined as perpendicular to the z-axis, with superior being positive. The positive x-axis was directed to the left (Figure 1).[11–13] The coordinate system was always set with moving vertebrae (suprajacent vertebra of the functional spinal unit) in this study. Mean values and standard

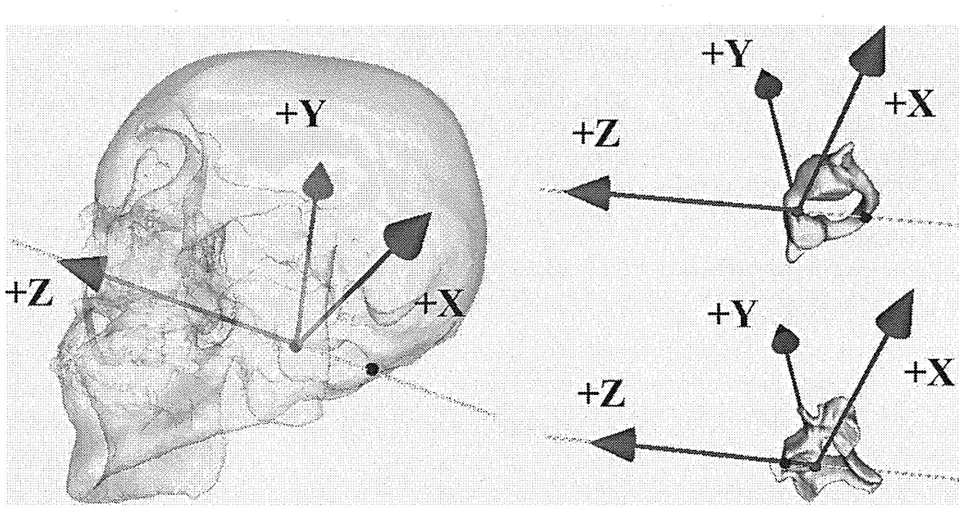

Figure 1. Anatomic orthogonal coordinate system for Oc, C1, and subaxial cervical vertebrae (C5). The methods have been fully described in previous studies.

TABLE 1. Rotations by Spinal Level for Control and CS Groups at 45° Head Rotation

	Oc–C1	C1–C2	C2–C3	C3–C4	C4–C5	C5–C6	C6–C7	C7–T1
AR								
Control(°)	0.4 ± 2.1	29.4 ± 3.2	0.5 ± 0.4	2.1 ± 0.5	2.4 ± 0.9	2.6 ± 0.7*	1.6 ± 0.7*	0.8 ± 0.6
CS(°)	0.2 ± 1.1	28.8 ± 3.7	0.9 ± 0.5	2.0 ± 0.7	2.0 ± 0.8	1.1 ± 0.7*	0.6 ± 0.3*	0.7 ± 0.3
Cp LB								
Control(°)	−4.0 ± 1.4*	−3.8 ± 1.8†	0.7 ± 1.2*	2.7 ± 0.7†	3.1 ± 0.8	2.8 ± 1.1*	2.5 ± 1.6†	0.5 ± 0.9
CS(°)	−2.3 ± 0.8*	−5.7 ± 1.6†	2.2 ± 1.0*	3.8 ± 1.2†	2.5 ± 1.3	1.3 ± 0.9*	1.3 ± 0.9†	0.6 ± 0.6
Cp F/E								
Control(°)	−5.4 ± 2.7†	−3.4 ± 2.0	−0.6 ± 1.0	0.8 ± 1.2	−1.1 ± 2.0	0.7 ± 1.5	1.0 ± 1.4†	0.8 ± 1.1
CS(°)	−7.7 ± 2.4†	−4.9 ± 2.8	−0.7 ± 0.4	−0.9 ± 0.7	−1.0 ± 1.1	−0.1 ± 0.7	0.5 ± 0.8†	1.3 ± 0.9

**P* < 0.01.
†*P* < 0.05.
AR indicates axial rotation; Cp LB, coupled lateral bending; Cp F/E, coupled flexion/extension; CS, cervical spondylosis.

deviations for range of motion to 1 side were computed in each group. Segmental motions were calculated as the average of the sum between left and right motions for coupled extension flexion, coupled anteroposterior translation, and coupled superoinferior translation, using constant codes between left and right rotation, and also calculated as the average difference between left and light motions for main axial rotation, coupled lateral bending, and lateral translation, using differing codes between left and right rotation.

In addition, degree of head rotation was measured accurately on the absolute spatial coordinate system using volume registration of the occiput. A 3D animation of each subject was also constructed to facilitate an understanding of these complex motions using methods that have been fully described in previous studies.[11–13]

Comparisons of rotations and translations by spinal level between groups were performed using the nonparametric Mann-Whitney *U* test. Values of $P < 0.05$ were considered statistically significant.

RESULTS

Mean (±standard deviation) maximal head rotation was 72.0 ± 5.3° in the control group and 63.4 ± 8.9° in the CS group. As a large range of mobility was identified between groups, only kinematics at 45° of head rotation was compared.

Main Axial Rotation at 45° Head Rotation

Significant decreases in axial rotation were observed at C5–C6 and C6–C7 in the CS group at both 45° (Table 1 and Figure 2).

Coupled Lateral Bending at 45° Head Rotation

In both groups, coupled lateral bending opposite to head rotation to 1 side was observed in the upper cervical spine, whereas the subaxial cervical spine displayed coupled lateral bending in the same direction as head rotation (Table 1 and Figure 3). Significant decreases in coupled lateral bending were observed at Oc–C1, C5–C6, and C6–C7, and significant increases were also observed at C1–C2, C2–C3, and C3–C4 in the CS group compared with the control group.

Coupled Flexion/Extension at 45° Head Rotation

In both groups, extension coupled with head rotation to 1 side occurred in the upper and middle cervical spine, whereas in the lower cervical spine, flexion was coupled with head rotation (Table 1 and Figure 4). Significant decreases in coupled flexion/extension were observed at C6–C7, and significant increases were observed at Oc–C1 in the CS group compared with the control group.

Coupled Translations at 45° Head Rotation

Although coupled translations were barely seen and most of these values were beyond the limit of accuracy and too small to analyze statistically, concerning lateral translation, the CS group showed a tendency toward larger motion in the middle

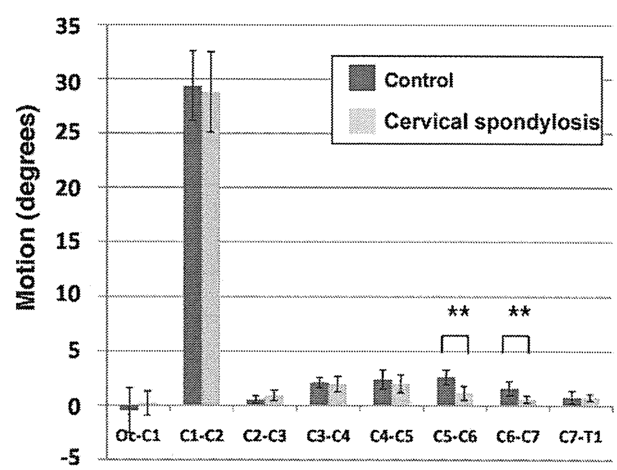

Figure 2. Main axial rotation by spinal level for the Control and CS groups at 45° head rotation. Data represent mean ± standard deviation. $*P < 0.05$ and $**P < 0.01$.

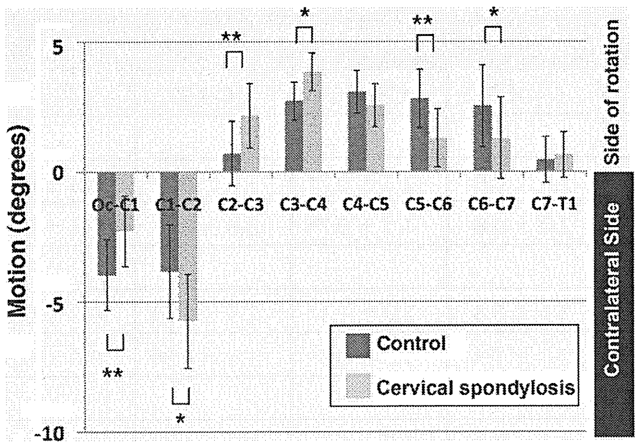

Figure 3. Coupled lateral bending by spinal level for the Control and CS groups at 45° head rotation. Data represent mean ± standard deviation. $^*P < 0.05$ and $^{**}P < 0.01$.

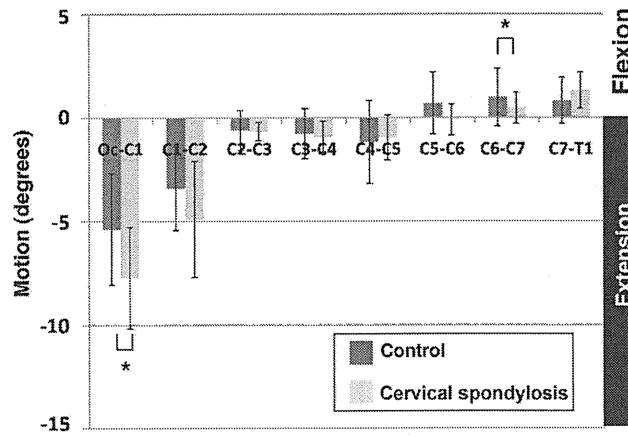

Figure 4. Coupled flexion/extension by spinal level for the Control and CS groups at 45° head rotation. Data represent mean ± standard deviation. $^*P < 0.05$ and $^{**}P < 0.01$.

cervical spine compared with the control group (Table 2 and Figure 5).

DISCUSSION

Hypomobility at the Lower Cervical Segments in the Degenerative Cervical Spine

General agreement is seen in the literature that the most commonly involved level is at C5–C6, followed by C6–C7 with increasing age.[4,15,16] Degenerative changes are speculated to arise most frequently at these levels because maximum distribution of axial load occurs at the lower cervical levels representing the sites of lordotic inversion.[10,17,18] To the best of our knowledge, few studies have addressed the *in vivo* kinematic changes of cervical motion segments after degeneration, despite a number of 2-dimensional flexion/extension motion studies of the normal cervical spine. Dvorak *et al*[4] showed significant hypomobility in sagittal rotation at C6–C7 in subjects with degenerative spine based on a functional flexion/extension radiographic study. Miyazaki *et al*[10] revealed that decreased segmental motion during extension-flexion starts at C4–C5 and C5–C6 with increasing age in a kinetic MRI study. No studies have clarified the kinematic changes occurring head rotation, because of the difficulties inherent in measuring such 3D motions *in vivo*. This study succeeded in detecting kinematics of the cervical spine during head rotation in patients with CS using a unique method. Comparison with healthy cervical spines yielded comparable results to previous cervical flexion/extension motion studies, showing significant decreases in main axial rotation and coupled lateral bending during headrotation at C5–C6 and C6–C7 segments in the CS group. These results indicate that in the lower cervical spine of the CS group, which is vulnerable to degeneration, motion segments might have already been in the stabilization phase put forward by Kirkaldy-Willis and Farfan[19] and hypomobility might have been present.

As for main axial motion, significant compensatory motions were barely seen at the suprajacent segments. However, the question arises as to where compensation occurs, because both groups were compared at 45° fixed head rotation. Total cervical motion at 45° fixed head rotation and the

TABLE 2. Coupled Translations by Spinal Level for Control and CS Groups at 45° Head Rotation

	C2–C3	C3–C4	C4–C5	C5–C6	C6–C7	C7–T1
Lateral translation						
Control (mm)	0.2 ± 0.0	−0.2 ± 0.0	−0.4 ± 0.1	−0.5 ± 0.0	−0.3 ± 0.1	−0.2 ± 0.0
CS (mm)	−0.2 ± 0.2	−0.6 ± 0.3	−0.5 ± 0.2	−0.5 ± 0.4	−0.3 ± 0.1	−0.2 ± 0.0
Superoinferior translation						
Control (mm)	−0.1 ± 0.1	−0.1 ± 0.2	−0.0 ± 0.3	0.1 ± 0.3	0.3 ± 0.3	0.2 ± 0.5
CS (mm)	−0.2 ± 0.1	−0.1 ± 0.2	−0.1 ± 0.1	−0.0 ± 0.1	0.1 ± 0.2	0.1 ± 0.2
Anteroposterior translation						
Control (mm)	−0.1 ± 0.2	−0.1 ± 0.2	−0.0 ± 0.3	0.2 ± 0.3	0.4 ± 0.4	0.3 ± 0.7
CS (mm)	−0.1 ± 0.1	−0.1 ± 0.2	−0.1 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1

CS indicates cervical spondylosis.

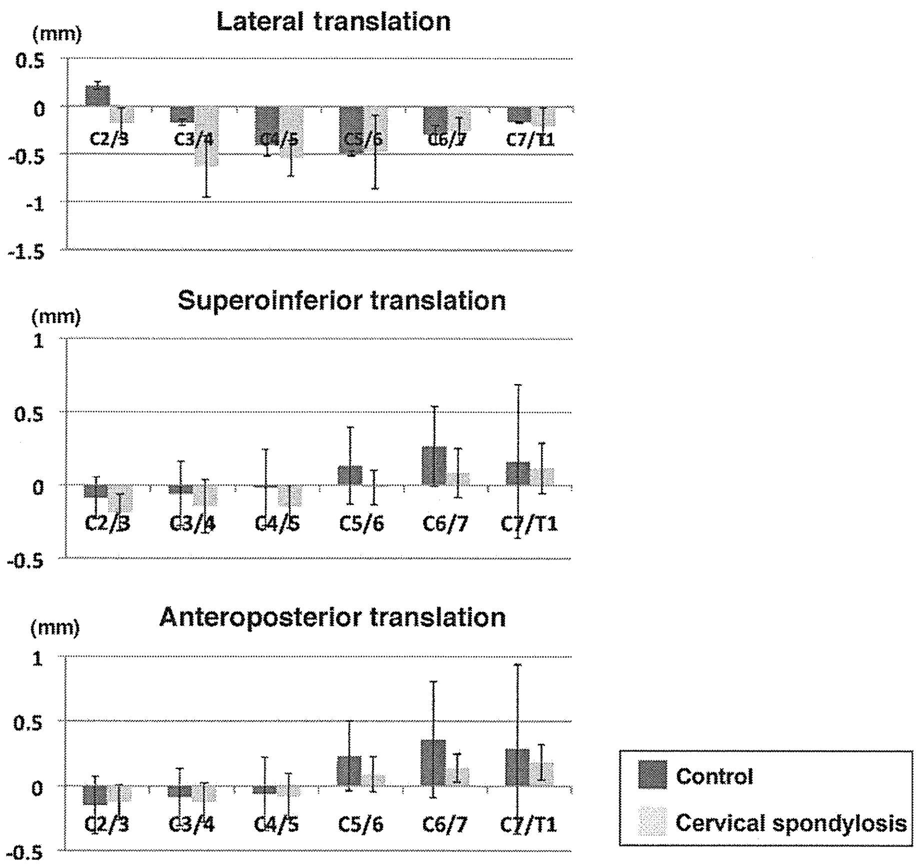

Figure 5. Coupled translations by spinal level for the Control and CS groups at 45°. Intervertebral motions are expressed in mm.

contribution ratio ([total cervical rotation {°}/head rotation {°}] × 100) was 38.9° (89%) in the control group and 36.4° (83%) in the CS group. Slight but significant decreases in motion were identified in the CS group ($P < 0.01$, nonparametric Mann-Whitney *U* test). Given the above findings, some compensation can safely be said to occur beyond the upper thoracic spine, but the precise location at which compensation occurred could not be identified.

Coupling Pattern of the Degenerative Cervical Spine

Although coupling patterns provide important clues for the detection of selected elements of spine pathology,[20] coupled motion is thought to be difficult to assess precisely because of the complex 3D motions and *in vivo* explorations have been rare. White and Panjabi[21] described abnormal coupled motion as 1 feature of abnormal spine kinematics. As we have already succeeded in accurately detecting 3D coupled motion of the cervical spine *in vivo*, we investigated coupled patterns of the spondylotic cervical spine during head rotation and compared the results with those of the healthy cervical spine. Although almost the same coupling patterns were identified in both groups, the spondylotic cervical spine showed significant hypomobility in axial and lateral directions at the lower cervical spine and significant lateral hypermobility, including coupled lateral bending at the middle cervical spine (Table 3). The fact that hypermobility in lateral directions was observed at the middle cervical spine in the CS group compared with the control group indicates that intervertebral mechanical stresses are increased in lateral directions at the middle cervical spine. As head axial rotation movements are reportedly half as frequent as flexion/extension movements and just as frequent as lateral bending movements,[22] head axial rotation movements are often repeated during ADL. Given these considerations, repetition of head rotation in ADL might have promoted degenerative changes of the middle cervical spine in the CS group.

This study has several limitations. First, the information was not obtained from true real-time imaging in the upright position. Second, the study was conducted using a small sample size. Third, patients were grouped together in the CS group despite a wide degree of variation in age, deformity, and symptoms. In this regard, further research focused more specifically on a particular subject group should be undertaken to elucidate details of the natural history of cervical

TABLE 3. Summary of Coupling Pattern for the CS Group Compared With the Control Group

	Main Motion	Coupled LB	Coupled F/E
Upper (Oc–C2)	N	N	N
Middle (C2–C5)	N	Increased	N
Lower (C5–T1)	Decreased	Decreased	N

LB indicates lateral bending; F/E, flexion/extension; N, no marked difference between groups; CS, cervical spondylosis.

spine motion after degeneration. Fourth, there might be some differences between the images obtained from the 2 different scanners in the 2 groups. Despite all these limitations, no other approaches to kinematic analysis have provided the kind of information given in this study, and these findings thus represent a step toward a better understanding of CS.

In conclusion, we accurately determined *in vivo* 3D kinematics of the spondylotic cervical spine during head rotation and compared the results with kinematics for the healthy cervical spine for the first time. Comparison with healthy cervical spine yielded comparable results with previous cervical flexion/extension motion studies, significant decreases in main axial rotation, and coupled lateral bending during head rotation at C5–C6 and C6–C7 segments in the spondylotic cervical spine. Although almost the same coupling patterns were observed in both groups, significant hypomobility in axial and lateral directions at the lower cervical spine and significant hypermobility in lateral directions at the middle cervical spine were apparent in the spondylotic cervical spine. Because hypermobility in lateral directions at the middle cervical spine in the CS group were thought to reflect increased intervertebral mechanical stresses, repeated head rotation in ADL might contribute to the progression of degenerative changes in the middle cervical vertebrae of the spondylotic cervical spine.

➢ Key Points

- *In vivo* 3D kinematics of the spondylotic cervical spine during head rotation was investigated for the first time.
- Almost the same coupling patterns were observed in both healthy and spondylotic cervical spine.
- Significant hypomobility at the lower cervical segments were observed in the spondylotic cervical spine; significant decreases in main axial rotation and coupled lateral bending at C5–C6 and in coupled flexion/extension as well as main axial rotation and coupled lateral bending at C6–C7.
- On the contrary, significant hypermobility in lateral directions were observed at the middle cervical segments in the spondylotic cervical spine; significant increases in coupled lateral bending at C2–C3 and C3–C4.

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References

1. Garfin SR. Cervical degenerative disorders: etiology, presentation, and imaging studies. *Instr Course Lect* 2000;49:335–8.
2. Kolstad F, Myhr G, Kvistad KA, et al. Degeneration and height of cervical discs classified from MRI compared with precise height measurements from radiographs. *Eur J Radiol* 2005;55:415–20.
3. Muhle C, Metzner J, Weinert D, et al. Classification system based on kinematic MR imaging in cervical spondylitic myelopathy. *AJNR Am J Neuroradiol* 1998;19:1763–71.
4. Dvorak J, Panjabi M, Grob D, et al. Clinical validation of functional flexion/extension radiographs of the cervical spine. *Spine* 1993;18:120–7.
5. Holmes A, Wang C, Han ZH, et al. The range and nature of flexion-extension motion in the cervical spine. *Spine* 1994;19:2505–10.
6. Dai L. Disc degeneration and cervical instability. Correlation of magnetic resonance imaging with radiography. *Spine* 1998;23:1734–8.
7. Lind B, Sihlbom H, Nordwall A, et al. Normal range of motion of the cervical spine. *Arch Phys Med Rehabil* 1989;70:692–5.
8. Dvorak J, Antinnes JA, Panjabi M, et al. Age and gender related normal motion of the cervical spine. *Spine* 1992;17:S393–8.
9. Cheng JS, Liu F, Komistek RD, et al. Comparison of cervical spine kinematics using a fluoroscopic model for adjacent segment degeneration. Invited submission from the Joint Section on Disorders of the Spine and Peripheral Nerves, March 2007. *J Neurosurg Spine* 2007;7:509–13.
10. Miyazaki M, Hong SW, Yoon SH, et al. Kinematic analysis of the relationship between the grade of disc degeneration and motion unit of the cervical spine. *Spine* 2008;33:187–93.
11. Ishii T, Mukai Y, Hosono N, et al. Kinematics of the upper cervical spine in rotation: *in vivo* three-dimensional analysis. *Spine* 2004;29:E139–44.
12. Ishii T, Mukai Y, Hosono N, et al. Kinematics of the subaxial cervical spine in rotation *in vivo* three-dimensional analysis. *Spine* 2004;29:2826–31.
13. Ishii T, Mukai Y, Hosono N, et al. Kinematics of the cervical spine in lateral bending: *in vivo* three-dimensional analysis. *Spine* 2006;31:155–60.
14. Fujii R, Sakaura H, Mukai Y, et al. Kinematics of the lumbar spine in trunk rotation: *in vivo* three-dimensional analysis using magnetic resonance imaging. *Eur Spine J* 2007;16:1867–74.
15. Shedid D, Benzel EC. Cervical spondylosis anatomy: pathophysiology and biomechanics. *Neurosurgery* 2007;60:S7–13.
16. Friedenberg ZB, Edeiken J, Spencer HN, et al. Degenerative changes in the cervical spine. *J Bone Joint Surg Am* 1959;41:61–70.
17. Gallucci M, Limbuci N, Paonessa A, et al. Degenerative disease of the spine. *Neuroimaging Clin N Am* 2007;17:87–103.
18. Jager HJ, Gordon-Haris L, Mehring UM, et al. Degenerative change in the cervical spine and load-carrying on the head. *Skeletal Radiol* 1997;26: 475– 81.
19. Kirkaldy-Willis WH, Farfan HF. Instability of the lumbar spine. *Clin Orthop Relat Res* 1982;(165):110–23.
20. Cook C, Heqedus E, Showalter C, et al. Coupling behavior of the cervical spine: a systematic review of the literature. *J Manipulative Physiol Ther* 2006;29:570–5.
21. White AA, Panjabi MM. *Clinical Biomechanics of the Spine*. 2nd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 1990.
22. Sterling AC, Cobian DG, Anderson PA, et al. Annual frequency and magnitude of neck motion in healthy individuals. *Spine* 2008;33:1882–8.

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Patient satisfaction with surgery for cervical myelopathy due to ossification of the posterior longitudinal ligament

Clinical article

Takahito Fujimori, M.D.,[1] Motoki Iwasaki, M.D., Ph.D.,[1] Shinya Okuda, M.D., Ph.D.,[2] Yukitaka Nagamoto, M.D.,[1] Hironobu Sakaura, M.D., Ph.D.,[1] Takenori Oda, M.D., Ph.D.,[2] and Hideki Yoshikawa, M.D., Ph.D.[1]

[1]Department of Orthopaedic Surgery, Osaka University Graduate School of Medicine; and [2]Department of Orthopaedic Surgery, Osaka Rosai Hospital, Osaka, Japan

Object. Surgical results in cervical myelopathy caused by ossification of the posterior longitudinal ligament (OPLL) evaluated with a patient-based method have not yet been reported. The purpose of this study was to examine patient satisfaction with surgery for cervical myelopathy due to OPLL and to clarify factors related to satisfaction.

Methods. Clinical data in 103 patients (74 male and 29 female) who underwent surgery for cervical OPLL were retrospectively reviewed. The average age at surgery was 57 years, and the average follow-up period was 9.3 years. Outcomes were assessed using an original satisfaction questionnaire, the conventional Japanese Orthopaedic Association (JOA) scoring system, the JOA Cervical Myelopathy Evaluation Questionnaire, the 36-Item Short Form Health Survey, and the hospital anxiety and depression scale. Spearman rank correlation coefficients for 5-scale patient satisfaction against outcome measures were calculated to test relationships between variables. All variables were compared between the satisfied (responses of very satisfied or satisfied) and dissatisfied (responses of dissatisfied or very dissatisfied) groups. Parameters exhibiting a significant Spearman rank correlation or difference between the groups were entered in a stepwise logistic regression analysis model, with satisfaction as the dependent variable.

Results. Sixty-nine patients were included in the analysis. There was not a significant difference in clinical data between these 69 study patients and the other 34 patients. Fifty-five patients (80%) were satisfied with the results of the surgery, and 58 patients (84%) reported that their condition was improved by the surgery. All patients who reported being very improved were either very satisfied or satisfied with the results of surgery. Quality of life (QOL), physical function (PF), and role physical (RP) were significantly correlated with patient satisfaction. The dissatisfied group had significantly more severe pain; lower maximum conventional JOA scores; lower maximum recovery rates; worse lower-extremity function (LEF); reduced QOL; and lower PF, RP, and vitality scores. Stepwise logistic regression analysis showed that PF, QOL, LEF, and maximum recovery rate based on JOA score were correlated with satisfaction.

Conclusions. Eighty percent of patients were satisfied with the surgical results after treatment of cervical myelopathy due to OPLL. Surgery for cervical OPLL was effective, as evaluated by both doctor- and patient-based methods. Patient satisfaction was related to QOL, PF (especially LEF), and improvement. *(DOI: 10.3171/2011.1.SPINE10649)*

Key Words • **ossification of the posterior longitudinal ligament** • **patient satisfaction** • **myelopathy** • **surgical outcome** • **cervical spine** • **Japanese Orthopaedic Association Cervical Myelopathy Evaluation Questionnaire**

Ossification of the posterior longitudinal ligament of the cervical spine (termed cervical OPLL) is one of the major disorders that causes myelopathy. It has previously been reported that surgical treatments are effective for cervical OPLL with appropriate indications.[8–10,23] Other studies have reported 50% to 70% recovery rates according to the conventional JOA scoring system.[17,18,25] However, all of these previous reports included only evaluations by doctor-based methods. Recently, patient-based evaluation methods have drawn much attention for investigations of effectiveness of treatments in many medical fields. Because the concept of patient-based evaluation did not exist when the conventional JOA scoring system was developed, patient satisfaction, QOL, and psychological components are not evaluated in the conventional JOA scoring system. Given this background, the JOA produced a new evalu-

Abbreviations used in this paper: HAD = hospital anxiety and depression; JOA = Japanese Orthopaedic Association; JOACMEQ = JOA Cervical Myelopathy Evaluation Questionnaire; LEF = lower-extremity function; NRS = numerical rating scale; OPLL = ossification of the posterior longitudinal ligament; PF = physical function; QOL = quality of life; RP = role physical; SF-36 = 36-Item Short Form Health Survey; UEF = upper-extremity function; VAS = visual analog scale.

ation method for cervical myelopathy: the JOACMEQ, a patient-based, multidimensional and statistically validated scoring system.[3–6]

Evaluation from the patient's viewpoint has become essential for discussion of the effects of treatment. Although there have been many reports of high patient satisfaction with total hip or knee arthroplasty,[11,16] lumbar disc herniation,[21,26] lumbar canal stenosis,[27] and scoliosis,[1] no study has reported the surgical results of cervical OPLL evaluated with a patient-based method. In the present study, surgical treatments for cervical OPLL were evaluated using a patient-based method, focusing on patient satisfaction. The purpose of this study was first to investigate patient satisfaction with cervical OPLL surgery, and second to identify factors related to satisfaction.

Methods

Patient Population

A questionnaire was mailed to 103 consecutive patients with cervical OPLL (74 male and 29 female) who had undergone surgery between 1981 and 2007. The average age at surgery was 57 years, and the average follow-up period was 9.3 years. No patients were treated by the first author. All patients presented with signs of cervical myelopathy, such as spastic gait disturbance and/or clumsiness of the hands. The surgical procedure was selected appropriately, depending on the occupying ratio and range of compression. Anterior decompression and fusion was performed in 30 cases and laminoplasty in 73 cases.

The first author, as an independent observer, mailed a set of survey sheets to all 103 patients and collected the 72 completed sheets. Informed consent was obtained from the patients, and the study was approved by the internal review board of our institution.

Outcome Measures and Questionnaires

The conventional JOA scoring system and recovery rate were used to evaluate pre- and postoperative outcomes of cervical myelopathy as a doctor-based evaluation method.[28] The occupying ratio of OPLL was used as a radiographic assessment. Complications were defined as neurological deterioration, CSF leakage, epidural hematoma, and dislocation of grafted bone.

A set of 4 survey sheets included the following: 1) an original satisfaction questionnaire; 2) a JOACMEQ scoring sheet; 3) an SF-36 scoring sheet; and 4) an HAD scale. In the original patient satisfaction questionnaire, patients were asked to select from among the following 5 options for closed-type questions: 1) very good; 2) good; 3) fair; 4) bad; and 5) very bad *(Appendix)*. For open-type questions, patients were asked whether they were satisfied or dissatisfied, and they wrote their responses freely. Pain was evaluated on an NRS of 0–5 in the neck, arms, and legs; a score of 0 indicated no pain, whereas a score of 5 indicated intolerable pain.

The JOACMEQ has 5 functional scores (cervical spine function, UEF, LEF, bladder function, and QOL), which are obtained for corresponding domains according to previously reported formulas.[3–6] Each functional score ranges from 0 to 100, with higher scores indicating better conditions. The JOACMEQ also includes 100-mm VASs for pain or numbness in the neck, chest, arms, or hands, and from the chest to the toes. A score of 0 indicates no symptoms, and a score of 100 indicates the worst conceivable symptoms.

The SF-36 is a widely used measure for health-related QOL consisting of 8 scales, with higher scores indicating a better condition:[12–14,24] PF, RP, bodily pain, social functioning, general health perceptions, vitality, role emotional, and mental health. The HAD scale is a measure for anxiety and depression.[7,29]

Statistical Analysis

To confirm that the 69 patients included in the study were an appropriate sample, demographic data were compared with those of the 34 patients not included in the analysis (Mann-Whitney U-test, and Fisher exact probability test). Spearman rank correlation coefficients for 5-scale patient satisfaction against all outcome measures were calculated to test relationships between variables. Patients were divided into 2 groups: satisfied (responses of very satisfied or satisfied) and dissatisfied (responses of dissatisfied or very dissatisfied). The 2 groups were compared over all variables of the conventional JOA scoring system, the JOACMEQ, pain scale, SF-36, and HAD scale (Mann-Whitney U-test, Fisher exact probability test, and Pearson chi-square test). Parameters that exhibited a significant correlation or difference were entered in a stepwise logistic regression analysis model, with satisfaction as the dependent variable. The predefined significance for inclusion in the next step of the regression model was 0.2. Statistical analyses were conducted with JMP version 8.0.1 software (SAS Institute, Inc.), and a p value less than 0.05 was considered significant.

Results

Response Rate and Patient Demographic Data

Of the 103 patients who underwent surgery and to whom questionnaires were mailed, 75 received the survey sheets. From these 75 patients, 72 sets of survey sheets were collected. Of the remaining 31 patients, 13 had died, 15 were lost to follow-up, and 3 did not return the survey sheets, for a response rate of 96% (72 of 75). No patient died because of surgical complications. Of the 72 responders, 69 patients fully completed the survey; the remaining 3 patients could not complete the survey sheets due to neurovascular disease or dementia, although their family members partly filled in the questionnaire on the patients' behalf. According to the returned questionnaires, all of these 3 patients were satisfied with the surgery. These incompletely answered survey sheets were not included in further statistical analysis (Fig. 1). To verify these 69 patients as an appropriate sample, the demographic data and conventional JOA scores at the last follow-up were compared between the 69 study participants and the other 34 patients (Table 1). Although the 34 patients who were not included tended to have lower scores, this difference was not statistically significant.

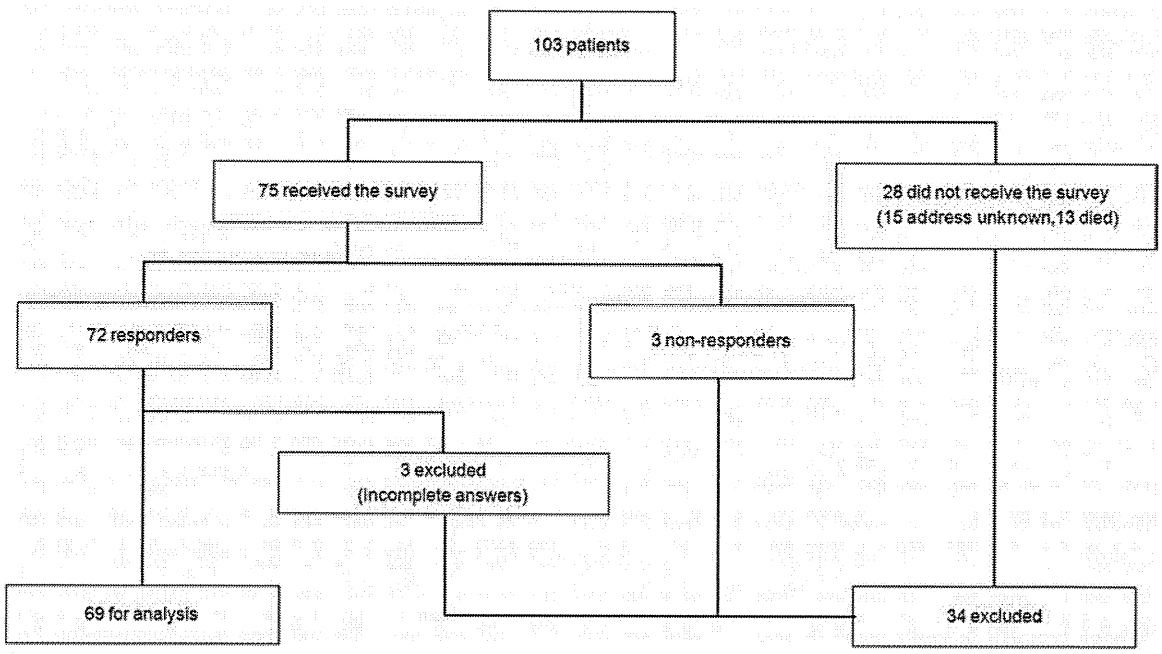

Fig. 1. Chart showing the study population. Of the 103 patients who underwent surgery and to whom the questionnaires were mailed, 69 were included in the analysis.

Patient Satisfaction

Fifty-five (80%) of the 69 participants reported being very satisfied (16%) or satisfied (64%) with the results of surgery, 7 (10%) were neither satisfied nor dissatisfied, and 7 (10%) were dissatisfied or very dissatisfied (Fig. 2). All of the patients who were very satisfied reported that their condition was very improved (13%) or improved (2.9%) by surgery. Of the satisfied patients (64%), 57% reported being very improved or improved by surgery, and 7% reported being neither improved nor worsened by surgery.

TABLE 1: Demographic data for patients included in the satisfaction study and other patients who were excluded*

Variable	Study Patients	Other Patients	p Value
no. of patients	69	34	
age at op (yrs)	57.0 ± 7.9	58.7 ± 8.4	0.3†
age at FU (yrs)	70.0 ± 8.8	72.6 ± 10.4	
sex (M/F)	49:20	25:9	1‡
no. of procedures (ACDF/lam)	23:46	7:27	0.3‡
avg range of vertebrae/laminae per op (ACDF/lam)	3:5.5	3:5.8	1‡
FU (yrs)	9.3 ± 5.0	8.2 ± 4.4	0.5†
conventional JOA score			
preop	9.8 ± 2.4	8.4 ± 3.4	0.08†
postop	13.8 ± 2.2	13.1 ± 2.4	0.09†
max	14.5 ± 1.9	13.8 ± 2.0	0.05†
postop recovery rate (%)	54.1 ± 27.1	53.4. ± 31.2	0.1†
max recovery rate (%)	65.4 ± 24.2	60.8 ± 23.7	0.3†
occupying ratio (%)	51.4 ± 14.6	46.0 ± 12.9	0.08†
complication (no. of cases)	14	4	0.4‡

* Unless otherwise indicated, values are expressed as the mean ± SD. Abbreviations: ACDF = anterior cervical decompression and fusion; avg = average; FU = follow-up; lam = laminoplasty (posterior approach).
† According to the Mann-Whitney U-test.
‡ According to the Fisher exact probability test.

Fifty-eight patients (84%) reported that their condition was very improved or improved by surgery (Fig. 3). All of the patients who reported being very improved were very satisfied (13%) or satisfied (10%) with the results of surgery. Of the patients whose condition had improved (60.8%), 52% reported that they were very satisfied or satisfied with surgery, but 4% reported that they were neither satisfied nor dissatisfied, and the other 4% reported that they were dissatisfied with surgery.

Fifty-six patients (81%) reported that they would definitely or probably recommend surgery if family or friends suffered from the same disease (Fig. 4).

Correlation Coefficients of Satisfaction

Leg pain (rated by NRS; −0.25), QOL (based on JOACMEQ; 0.26), PF (based on SF-36; 0.33), and RP (based on SF-36; 0.25) were significantly weakly correlated with patient satisfaction. No other variables were significantly correlated with patient satisfaction. Correlates are summarized in Table 2. Of the 3 items used for assessment of pain, leg pain (rated by NRS) was strongly negatively correlated with QOL (based on JOACMEQ), and PF, RP, and bodily pain (based on SF-36).

Comparison Between the Satisfied and Dissatisfied Groups

To identify parameters related to dissatisfaction, clinical data were compared between the satisfied and dissatisfied groups (Table 3). There were no significant differences in age, sex, surgical procedure, follow-up period, complications, or depression prevalence between the 2 groups. In

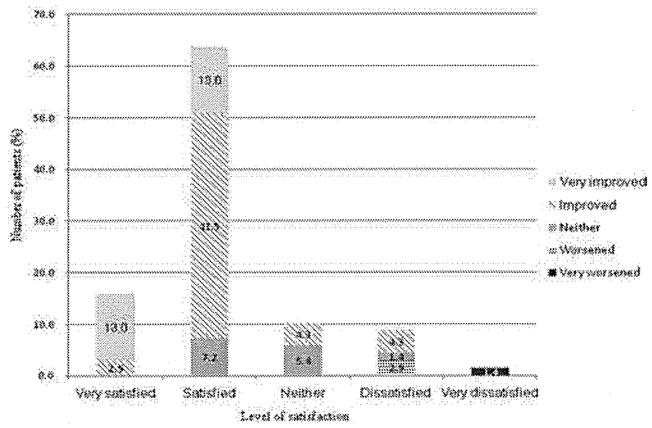

Fig. 2. Bar graph showing patient satisfaction with surgery. Eleven patients (15.9%) reported being very satisfied with the results of surgery, 44 (63.7%) were satisfied, 7 (10.1%) were neither satisfied nor dissatisfied, 6 (8.7%) were dissatisfied, and 1 (1.4%) was very dissatisfied.

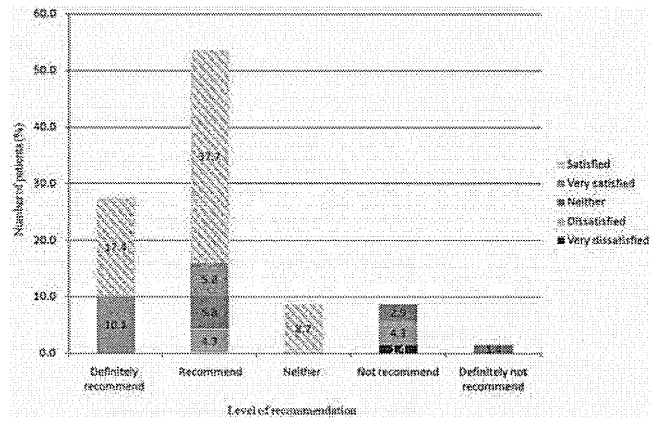

Fig. 4. Bar graph showing patients recommending surgery. Nineteen patients (27.5%) reported that they would definitely recommend the surgery, 37 (53.6%) would probably recommend the surgery, 6 (8.7%) would neither recommend nor not recommend the surgery, 6 (8.7%) would probably not recommend the surgery, and 1 (1.4%) would definitely not recommend the surgery.

patients assessed using the conventional JOA scoring system, the dissatisfied group had a significantly lower maximum score and a lower maximum recovery rate. In those assessed using the JOACMEQ, the dissatisfied group had significantly reduced LEF and QOL. In patients assessed using SF-36, the dissatisfied group showed significantly lower PF, RP, and vitality. Pain in all 3 items of the NRS was significantly more severe in the dissatisfied group than in the satisfied group. The difference in postoperative conventional JOA scores between the 2 groups was close to significant ($p = 0.05$). Reasons for dissatisfaction as recorded in responses to open-type questions are summarized in Table 4.

Logistic Regression Analysis

All parameters that were significantly correlated with satisfaction or showed significant differences between the satisfied and dissatisfied groups were entered in a stepwise logistic regression analysis model, with satisfaction as the dependent variable. Based on the results of stepwise logistic regression analysis, the following variables were correlated with satisfaction: 1) PF (based on SF-36); 2) QOL (based on JOACMEQ); 3) LEF (based on JOACMEQ); and 4) maximum recovery rate (based on conventional JOA). The adjusted R^2 was 0.5, indicating that this model explained 50% of the variation in satisfaction as dependent (Table 5).

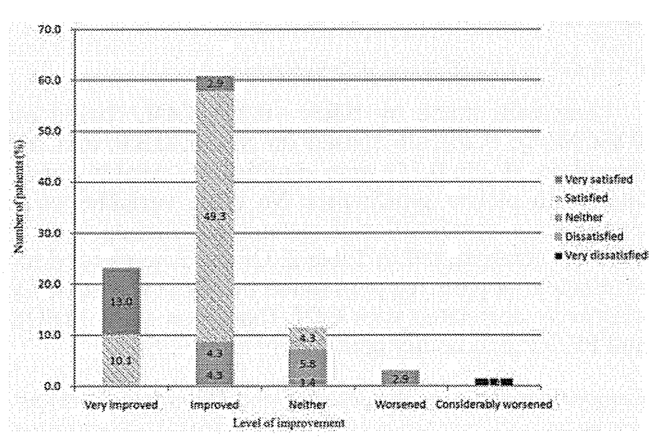

Fig. 3. Bar graph showing patients whose condition was improved by surgery. Sixteen patients (23.1%) reported being very improved by the surgery, 42 (60.8%) were improved, 8 (11.5%) were neither improved nor worsened, 2 (2.9%) were worsened, and 1 (1.4%) was considerably worsened.

Discussion

To the best of our knowledge, no previous study has reported patient satisfaction with surgery for cervical OPLL that was evaluated using a patient-based method. Patient satisfaction with surgery for cervical spondylotic myelopathy has been reported to range from approximately 75% to 90%.[2,20,22] Riew et al.[20] reported an 89.8% satisfaction rate after arthroplasty for myelopathy due to single-level compression by cervical spondylosis or disc herniation in middle-aged patients. Sampath et al.[22] reported a 75% satisfaction rate after surgery for cervical myelopathy due to multilevel compression. In the present study, 80% of patients with cervical myelopathy due to multilevel compression of OPLL were satisfied with the surgical results. This positive result suggests that surgical treatment for cervical OPLL was effective according to both patient- and doctor-based evaluation. Based on statistical analysis, factors associated with satisfaction could be classified into the following general categories: QOL, PF, and improvement.

As suggested by the comparatively large Spearman rank correlation coefficient and small p value in the present study, QOL (based on JOACMEQ) was a key parameter of satisfaction. Physical function (based on SF-36) is a scale that mainly evaluates QOL and walking ability. Therefore, PF and LEF (based on JOACMEQ) are also important factors associated with satisfaction. In previous studies, as typified by the Grip and Release Test, UEF has been regarded as a representative parameter of myelopathy because it has been shown to correlate with other functional scores such as total or LEF in the conventional JOA scoring system.[19] However, in the present study, the

TABLE 2: Correlation coefficients of satisfaction in patients with cervical myelopathy due to OPLL*

	JOA Score		Recovery Rate		Pain Score (NRS)			JOACMEQ Score					SF−36 Score							
Parameter	Max	Postop	Max	Postop	Neck	Arm	Leg	CF	UEF	LEF	BF	QOL	PF	RP	BP	GH	VT	SF	RE	MH
satisfaction	0.08	0.03	0.10	0.08	−0.16	−0.15	−0.25	0.10	0.07	0.17	0.03	0.26	0.33	0.25	0.07	0.02	0.15	0.02	0.15	0.13
JOA score																				
max		0.88	0.88	0.69	−0.38	−0.38	−0.35	0.07	0.32	0.36	0.16	0.42	0.32	0.36	0.29	0.24	0.32	0.26	0.33	0.25
postop			0.77	0.78	−0.44	−0.41	0.37	0.20	0.37	0.44	0.16	0.47	0.37	0.39	0.37	0.21	0.30	0.32	0.31	0.25
recovery rate																				
max				0.83	0.41	0.32	−0.23	0.07	0.21	0.24	0.03	0.34	0.22	0.24	0.28	0.22	0.25	0.18	0.21	0.15
postop					−0.53	−0.42	−0.25	0.29	0.35	0.36	0.13	0.43	0.32	0.34	0.42	0.28	0.28	0.30	0.27	0.19
pain score (NRS)																				
neck						0.71	0.54	−0.48	−0.38	−0.34	−0.28	−0.62	−0.26	−0.38	−0.68	−0.31	−0.37	−0.26	−0.31	−0.31
arm							0.56	−0.55	−0.49	−0.35	−0.36	−0.66	−0.31	−0.47	−0.53	−0.40	−0.44	−0.35	−0.46	−0.42
leg								−0.39	−0.38	−0.43	−0.4	−0.73	−0.39	−0.49	−0.7	−0.40	−0.48	−0.34	−0.45	−0.44
JOACMEQ score																				
CF									0.62	0.43	0.44	0.44	0.38	0.44	0.49	0.43	0.39	0.40	0.40	0.35
UEF										0.75	0.45	0.58	0.59	0.58	0.48	0.42	0.44	0.61	0.59	0.48
LEF											0.46	0.63	0.76	0.68	0.45	0.33	0.49	0.66	0.69	0.57
BF												0.50	0.43	0.42	0.43	0.32	0.42	0.46	0.44	0.41
QOL													0.59	0.69	0.73	0.67	0.80	0.63	0.71	0.72
SF−36 score																				
PF														0.78	0.44	0.29	0.46	0.61	0.67	0.49
RP															0.53	0.38	0.65	0.76	0.80	0.65
BP																0.38	0.60	0.59	0.48	0.52
GH																	0.63	0.37	0.45	0.55
VT																		0.67	0.71	0.84
SF																			0.76	0.74
RE																				0.81

* BF = bladder function; BP = bodily pain; CF = cervical spine function; GH = general health; MH = mental health; RE = role emotional; SF = social functioning; VT = vitality.

TABLE 3: Comparison between satisfied and dissatisfied groups*

Parameter	Satisfied Group	Dissatisfied Group	p Value
no. of patients	55	7	
age at op (yrs)	56.4 ± 7.9	57.3 ± 6.6	0.7
age at FU (yrs)	69.3 ± 5.5	69.9 ± 7.9	
sex (M/F)	41:14	5:2	1
op procedure (ACDF/lam)	19:36	2:5	1
FU (yrs)	9.7 ± 5.1	10.4 ± 4.9	0.8
conventional JOA score			
preop	9.8 ± 2.4	9.0 ± 2.8	0.5
postop	13.8 ± 2.3	12.2 ± 2.0	0.05
max	14.6 ± 2.0	13.3 ± 1.1	0.02†
postop recovery rate (%)	55.0 ± 27.8	34.7 ± 31.2	0.1
max recovery rate (%)	67.4 ± 24.5	50.7 ± 17.5	0.03†
occupying ratio (%)	51.6 ± 14.5	51.7 ± 18.1	0.9
complication (no. of cases)	11	2	0.6
JOACMEQ score			
CF	47.5 ± 31	37.1 ± 32	0.4
UEF	76.6 ± 22.3	64.0 ± 24.3	0.2
LEF	62.5 ± 26.8	42.0 ± 20.5	0.04†
BF	71.9 ± 25.4	54.7 ± 27.7	0.1
QOL	55.7 ± 17.2	28.6 ± 13.2	0.0009†
NRS score			
neck	1.8 ± 1.6	2.9 ± 0.7	0.03†
arms	1.3 ± 1.3	2.6 ± 1.4	0.02†
legs	1.6 ± 1.5	3.7 ± 1.1	0.02†
VAS score			
neck	4.2 ± 3.1	5.3 ± 2.3	0.3
chest	1.4 ± 2.2	0.9 ± 1.4	0.5
arms or hands	3.6 ± 2.8	4.3 ± 3.3	0.6
chest to toe	3.5 ± 3.1	5.6 ± 2.9	0.08
SF-36 score			
PF	60.3 ± 28.1	22.1 ± 18.9	0.003†
RP	65.7 ± 28.7	25.9 ± 25.6	0.003†
BP	57.2 ± 24.2	35.4 ± 18.0	0.05
GH	51.0 ± 17.1	44.1 ± 23.2	0.5
VT	58.1 ± 20.1	39.3 ± 19.0	0.03†
SF	72.3 ± 28.0	53.6 ± 25.7	0.09
RE	69.6 ± 29.4	42.9 ± 42.6	0.1
MH	69.2 ± 20.9	52.1 ± 22.5	0.05
HAD score‡			
anxiety (definite/doubtful)	5:14	1:3	0.9
depression (definite/doubtful)	31:5	8:2	0.3

* Unless otherwise indicated, values are expressed as the mean ± SD.
† Statistically significant ($p < 0.05$).
‡ Values represent the number of patients whose scores denoted definite anxiety or depression, versus those with doubtful scores.

Spearman rank correlation coefficient for LEF was larger than that for UEF. Also, there was no significant difference in UEF between satisfied and dissatisfied patients. In responses to open-type questions, many patients wrote that the reason why they were dissatisfied was because they could not move by themselves. These details suggest that LEF correlates more directly with satisfaction than UEF.[12] In our experience, many patients decide to undergo surgery because of their fear of being unable to walk. Perhaps because gait disturbance in daily life is a more compelling problem than hand clumsiness, especially in elderly or disabled patients, LEF correlated more strongly with patient satisfaction.

In the present study, the satisfied group had a significantly higher maximum score and maximum recovery rate according to the conventional JOA scoring system. Using a stepwise logistic regression analysis model, we chose maximum recovery rate (conventional JOA) as the independent variable, with satisfaction as the dependent variable. No patients reported being worsened in either the satisfied group or in the neither satisfied nor dissatisfied group. These results suggest that treatment effects as reflected by improvements in conventional JOA score were associated with satisfaction.

There was still controversy over the selection of anterior or posterior surgery for cervical OPLL. In the present study, anterior surgery was basically selected when the occupying ratio of OPLL was greater than 60%, according to previous reports.[9,10,15] As a result, selection of surgical procedures was not a factor influencing patient satisfaction. Appropriate indications for anterior or posterior surgery might lead to successful results in doctor- and patient-based evaluation methods.

Our study had some limitations. First, although the vast majority (96%) of patients who received survey sheets responded, data from 31 patients could not be collected because of the patient's death or an unknown address. If all of these 31 patients were dissatisfied with the results of surgery in the worst-case scenario, the satisfaction rate would decline to 56%. However, in the best-case scenario, the satisfaction rate would rise to 86%. Second, although a stepwise method was used, there was a possibility that multicollinearity existed in the logistic regression analysis. Because some of the JOACMEQ was created with SF-36 as a reference, PF (based on SF-36) might correlate with LEF on the JOACMEQ.

Unlike NRS, there was no significant difference in VAS scores on the JOACMEQ between the satisfied and dissatisfied groups. This discrepancy was thought to have been caused by the fact that the VAS score reported on the JOACMEQ included numbness as well as pain. Numbness was more common, and might be a more acceptable postsurgery symptom than pain for patients with cervical OPLL. Because it was repeatedly explained when obtaining informed consent that numbness was difficult to improve with surgery, patients were thought to be more accepting of numbness. It was reported that unrealistic expectations for surgery decreased satisfaction, and therefore sufficient understanding of the expected results was important for patient satisfaction.[26]

TABLE 4: Summary of clinical data in dissatisfied and neither satisfied nor dissatisfied groups*

Satisfaction	Sex	Age at FU (yrs)	Op Procedures	JOACMEQ Score CF	UEF	LEF	BF	QOL	Reasons (open-type question)
very dissatisfied	M	60	lam	5	53	50	63	15	shoulder stiffness, deterioration of symptoms, difficulty walking
dissatisfied	M	81	lam	0	32	9	13	28	restriction of ROM of neck, difficulty walking
	M	80	lam	20	68	45	94	34	leg numbness
	M	63	lam	100	95	36	38	40	leg numbness & pain
	F	79	lam	50	42	32	38	8	back, neck, & leg pain
	M	68	ACDF	45	95	77	81	45	dislocation of grafted bone & reop, restriction of ROM of neck due to added posterior fusion, leg numbness due to peroneal nerve injury
	F	68	ACDF	40	63	56	56	30	arm & leg pain, difficulty walking
neither satisfied nor dissatisfied	M	81	lam	35	74	55	31	50	difficulty walking
	M	88	lam	5	79	41	50	34	difficulty walking
	F	75	lam	15	42	14	75	44	difficulty walking
	F	65	lam	100	95	59	100	91	difficulty walking
	F	76	lam	25	95	95	94	89	restriction of ROM of neck
	F	83	ACDF	30	37	9	19	32	difficulty walking
	F	61	ACDF	85	95	68	100	31	leg pain

* ROM = range of motion.

Conclusions

The present study demonstrated that 80% of patients were satisfied with the results of surgery for cervical myelopathy due to OPLL. Patient satisfaction was related to QOL, PF (especially LEF), and improvement. Surgery for cervical OPLL was effective when evaluated both by doctor- and patient-based methods.

Appendix: Original Satisfaction Questionnaire

Q1. Are you satisfied with the result of the surgery?
Very satisfied
Satisfied
Neither satisfied nor dissatisfied
Dissatisfied
Very dissatisfied
What are you satisfied or dissatisfied with?

Q2. How has your condition changed since the surgery?
Very improved
Improved
No change
Worsened
Considerably worsened
What are the changes?

Q3. Would you recommend the surgery to a family member or friend suffering from the same disease?
Definitely recommend
Probably recommend
I don't know
Would not recommend
Definitely would not recommend
Why would you recommend or not recommend the surgery?

Q4. Where do you experience body pain?
Neck to shoulders
Arms or hands
Lower body (buttocks, legs, knees)
Please rate the pain:
0: No pain
1: Slight pain
2: Modest pain
3: Moderate pain
4: Severe pain
5: Intolerable pain

TABLE 5: Stepwise logistic regression analysis model with satisfaction as the dependent variable

Parameter (scoring system)*	Chi-Square Value (likelihood ratio test)	p Value
PF (SF-36)	6.4	0.01
QOL (JOACMEQ)	6.4	0.01
LEF (JOACMEQ)	5.1	0.02
max recovery rate (JOA)	1.8	0.18

* Adjusted R^2 = 0.5.

Disclosure

The manuscript does not contain information about medical device(s) or drug(s). Other funds (The Investigation Committee on the Ossification of Spinal Ligaments of the Japanese Ministry of Health, Labor, and Welfare) were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript. This study was performed with the aid of the Investigation Committee on the Ossification of the Spinal Ligaments of the Japanese Ministry of Health, Labor, and Welfare. The institutional review board of the authors' institute approved this study.

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Fujimori, Iwasaki. Acquisition of data: Fujimori, Okuda, Oda. Analysis and interpretation of data: Fujimori. Drafting the article: Fujimori. Critically revising the article: Fujimori, Nagamoto, Sakaura. Reviewed final version of the manuscript and approved it for submission: Iwasaki, Yoshikawa. Statistical analysis: Fujimori.

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References

1. Bridwell KH, Shufflebarger HL, Lenke LG, Lowe TG, Betz RR, Bassett GS: Parents' and patients' preferences and concerns in idiopathic adolescent scoliosis: a cross-sectional preoperative analysis. **Spine 25:**2392–2399, 2000
2. Chagas H, Domingues F, Aversa A, Vidal Fonseca AL, de Souza JM: Cervical spondylotic myelopathy: 10 years of prospective outcome analysis of anterior decompression and fusion. **Surg Neurol 64 (Suppl 1):**S30–S36, 2005
3. Fukui M, Chiba K, Kawakami M, Kikuchi S, Konno S, Miyamoto M, et al: Japanese Orthopaedic Association Cervical Myelopathy Evaluation Questionnaire (JOACMEQ): Part 2. Endorsement of the alternative item. **J Orthop Sci 12:**241–248, 2007
4. Fukui M, Chiba K, Kawakami M, Kikuchi S, Konno S, Miyamoto M, et al: Japanese Orthopaedic Association Cervical Myelopathy Evaluation Questionnaire (JOACMEQ): Part 4. Establishment of equations for severity scores. Subcommittee on low back pain and cervical myelopathy, evaluation of the clinical outcome committee of the Japanese Orthopaedic Association. **J Orthop Sci 13:**25–31, 2008
5. Fukui M, Chiba K, Kawakami M, Kikuchi S, Konno S, Miyamoto M, et al: JOA Back Pain Evaluation Questionnaire (JOABPEQ)/JOA Cervical Myelopathy Evaluation Questionnaire (JOACMEQ). The report on the development of revised versions. April 16, 2007. **J Orthop Sci 14:**348–365, 2009
6. Fukui M, Chiba K, Kawakami M, Kikuchi S, Konno S, Miyamoto M, et al: An outcome measure for patients with cervical myelopathy: Japanese Orthopaedic Association Cervical Myelopathy Evaluation Questionnaire (JOACMEQ): Part 1. **J Orthop Sci 12:**227–240, 2007
7. Hatta H, Higashi A, Yashiro H, Ozasa K, Hayashi K, Kiyota K, et al: [A validation of the Hospital Anxiety and Depression Scale.] **Jpn J Psychosom Med 38:**309–315, 1998 (Jpn)
8. Iwasaki M, Kawaguchi Y, Kimura T, Yonenobu K: Long-term results of expansive laminoplasty for ossification of the posterior longitudinal ligament of the cervical spine: more than 10 years follow up. **J Neurosurg 96 (2 Suppl):**180–189, 2002
9. Iwasaki M, Okuda S, Miyauchi A, Sakaura H, Mukai Y, Yonenobu K, et al: Surgical strategy for cervical myelopathy due to ossification of the posterior longitudinal ligament: Part 1: Clinical results and limitations of laminoplasty. **Spine 32:** 647–653, 2007
10. Iwasaki M, Okuda S, Miyauchi A, Sakaura H, Mukai Y, Yonenobu K, et al: Surgical strategy for cervical myelopathy due to ossification of the posterior longitudinal ligament: Part 2: Advantages of anterior decompression and fusion over laminoplasty. **Spine 32:**654–660, 2007
11. Kim TK, Chang CB, Kang YG, Kim SJ, Seong SC: Causes and predictors of patient's dissatisfaction after uncomplicated total knee arthroplasty. **J Arthroplasty 24:**263–271, 2009
12. King JT Jr, McGinnis KA, Roberts MS: Quality of life assessment with the medical outcomes study short form-36 among patients with cervical spondylotic myelopathy. **Neurosurgery 52:**113–121, 2003
13. King JT Jr, Roberts MS: Validity and reliability of the Short Form-36 in cervical spondylotic myelopathy. **J Neurosurg 97 (2 Suppl):**180–185, 2002
14. Latimer M, Haden N, Seeley HM, Laing RJ: Measurement of outcome in patients with cervical spondylotic myelopathy treated surgically. **Br J Neurosurg 16:**545–549, 2002
15. Liu T, Xu W, Cheng T, Yang HL: Anterior versus posterior surgery for multilevel cervical myelopathy, which one is better? A systematic review. **Eur Spine J** [epub ahead of print], 2010
16. Mancuso CA, Salvati EA, Johanson NA, Peterson MG, Charlson ME: Patients' expectations and satisfaction with total hip arthroplasty. **J Arthroplasty 12:**387–396, 1997
17. Matsuoka T, Yamaura I, Kurosa Y, Nakai O, Shindo S, Shinomiya K: Long-term results of the anterior floating method for cervical myelopathy caused by ossification of the posterior longitudinal ligament. **Spine 26:**241–248, 2001
18. Ogawa Y, Toyama Y, Chiba K, Matsumoto M, Nakamura M, Takaishi H, et al: Long-term results of expansive open-door laminoplasty for ossification of the posterior longitudinal ligament of the cervical spine. **J Neurosurg Spine 1:**168–174, 2004
19. Ono K, Ebara S, Fuji T, Yonenobu K, Fujiwara K, Yamashita K: Myelopathy hand. New clinical signs of cervical cord damage. **J Bone Joint Surg Br 69:**215–219, 1987
20. Riew KD, Buchowski JM, Sasso R, Zdeblick T, Metcalf NH, Anderson PA: Cervical disc arthroplasty compared with arthrodesis for the treatment of myelopathy. **J Bone Joint Surg Am 90:**2354–2364, 2008
21. Ronnberg K, Lind B, Zoega B, Halldin K, Gellerstedt M, Brisby H: Patients' satisfaction with provided care/information and expectations on clinical outcome after lumbar disc herniation surgery. **Spine 32:**256–261, 2007
22. Sampath P, Bendebba M, Davis JD, Ducker TB: Outcome of patients treated for cervical myelopathy. A prospective, multicenter study with independent clinical review. **Spine 25:**670–676, 2000
23. Seichi A, Chikuda H, Kimura A, Takeshita K, Sugita S, Hoshino Y, et al: Intraoperative ultrasonographic evaluation of posterior decompression via laminoplasty in patients with cervical ossification of the posterior longitudinal ligament: correlation with 2-year follow-up results. Clinical article. **J Neurosurg Spine 13:**47–51, 2010
24. Singh A, Crockard HA: Comparison of seven different scales used to quantify severity of cervical spondylotic myelopathy and post-operative improvement. **J Outcome Meas 5:**798–818, 2001–2002
25. Tani T, Ushida T, Ishida K, Iai H, Noguchi T, Yamamoto H: Relative safety of anterior microsurgical decompression versus laminoplasty for cervical myelopathy with a massive ossified posterior longitudinal ligament. **Spine 27:**2491–2498, 2002
26. Toyone T, Tanaka T, Kato D, Kaneyama R, Otsuka M: Patients' expectations and satisfaction in lumbar spine surgery. **Spine 30:**2689–2694, 2005
27. Yamashita K, Ohzono K, Hiroshima K: Patient satisfaction as an outcome measure after surgical treatment for lumbar spinal stenosis: testing the validity and discriminative ability in terms of symptoms and functional status. **Spine 31:**2602–2608, 2006
28. Yonenobu K, Abumi K, Nagata K, Taketomi E, Ueyama K: Interobserver and intraobserver reliability of the Japanese Orthopaedic Association scoring system for evaluation of cervical compression myelopathy. **Spine 26:**1890–1895, 2001
29. Zigmond AS, Snaith RP: The hospital anxiety and depression scale. **Acta Psychiatr Scand 67:**361–370, 1983

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Address correspondence to: Takahito Fujimori, M.D., Department of Orthopaedic Surgery, Osaka University Graduate School of Medicine, 2-2 Yamadaoka, Suita, Osaka 565-0871, Japan. email: takahito-f@hotmail.co.jp.

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ORIGINAL ARTICLE

In vivo three-dimensional segmental analysis of adolescent idiopathic scoliosis

Takako Hattori · Hironobu Sakaura · Motoki Iwasaki · Yukitaka Nagamoto · Hideki Yoshikawa · Kazuomi Sugamoto

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Abstract

Introduction An accurate assessment of three-dimensional (3D) intervertebral deviation is crucial to the better surgical correction of adolescent idiopathic scoliosis (AIS). However, a precise 3D study of intervertebral deviation has not been previously reported.

Objective The purpose of the present study is to evaluate the intervertebral coronal inclination, axial rotation and sagittal angulation of AIS using 3D bone models and a local coordinate system.

Materials and methods 3D bone models of the thoracic and lumbar spine of ten AIS patients were constructed using computed tomography. The local coordinate axis was determined semi-automatically for each vertebra. By using these local coordinates, the intervertebral deviation angles were calculated in the coronal, axial and sagittal planes and projected to subjacent local coordinates.

Result The intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region, and larger near the junctional region. Concerning the sagittal plane deformity, the constant tendency was not recognized.

Conclusion Using a local coordinate system for the vertebra of AIS, we measured the 3D intervertebral coronal, axial and sagittal deviation of the thoracolumbar spine and found that the change in the intervertebral inclination angle in the coronal plane increased toward the apical region and decreased toward the junctional region, and that the converse tendency was noted for the axial intervertebral rotational angle. This analysis provides an improved 3D guide for the surgical correction of AIS.

Keywords Idiopathic scoliosis · Three-dimensional · Intervertebral deviation · Local coordinate system

T. Hattori (✉) · Y. Nagamoto · K. Sugamoto
Division of Orthopaedic Biomaterial Science, Osaka University Graduate School of Medicine, 2-2, Yamadaoka, Suita, Osaka 565-0871, Japan
e-mail: takako-hattori@umin.ac.jp

H. Sakaura · M. Iwasaki · H. Yoshikawa
Department of Orthopaedics, Osaka University Graduate School of Medicine, 2-2, Yamadaoka, Suita, Osaka 565-0871, Japan

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional (3D) deformity associated with lateral deviation in the coronal plane, thoracic hypokyphosis in the sagittal plane and rotation in the axial plane [3, 4, 25]. However, two-dimensional evaluation of AIS remains the mainstay of most studies of AIS [10, 18]. In 2008, Modi et al. [18] reported the wedging angle of both the vertebral body and intervertebral disc and correlated the apical wedging angle and the severity of the curve in 150 AIS patients using only anteroposterior radiographs in the standing position. For evaluation in the transverse plane, Kotwicki et al. [10] used only a single axial slice from a computed tomography (CT) scan at the apex to measure the rotational angle and the intravertebral deformation. The asymmetry in the shape of the vertebral body and spinal canal and rotational deformity in the axial plane in AIS patients further contribute to the inaccuracy of such assessments of the vertebral axis in the two-dimensional plane.

3D evaluation of AIS is also gaining popularity. The in vitro 3D reconstruction of cadaveric vertebrae using 3D morphometric analysis [21–23], such as vertebral wedging, pedicle width, pedicle length, pedicle height, pedicle inclination and facet surface, is a recent example. In addition, several studies concerning 3D reconstruction of the spine using biplane radiographic images have been reported [2, 8, 9]. The method proposed by Kadoury et al. enabled 3D reconstruction from biplane radiographs. Although their studies involve 3D analysis of an in vivo model, their reconstructed bone models used anthropometric data and not patients' bones.

An accurate assessment of 3D intervertebral deviation is crucial to the better surgical correction of the deformity. Although there have been some studies regarding intervertebral deviation of AIS [5, 7, 24], no detailed 3D study using an in vivo model of AIS has been reported. Therefore, the present study aimed to develop a local coordinate system for the AIS vertebra and to evaluate the in vivo 3D intervertebral deviation in the coronal, axial and sagittal planes in order to provide guidance for its surgical correction.

Materials and methods

Patients

We examined spinal CT images from consecutive ten patients with AIS who were scheduled for corrective surgery. The patients included two males and eight females, with an age range of 12 to 19 years (mean 14.7 years) at the time of operation. Before CT imaging, anteroposterior (AP) plain radiographs were taken in the upright position. On AP radiographs, the measured mean Cobb's angles were 62.5° (range 29°–77°) at the thoracic curvature and 50.3° (range 30°–73°) at the lumbar curvature. According to King's classification [11], the curves were type I in two patients, type II in one, type III in six and type IV in one. Risser sign [15] showed grade 0 in two, grade 3 in four, and grade 4 in four patients. Nash and Moe's vertebral rotation [19] of the apex showed grade + in one, grade ++ in seven, and grade +++ in two patients.

The protocol was approved by the institutional boards of the hospital and fully informed consent was obtained from all participants.

CT image acquisition

Prior to surgery, all ten patients underwent CT scans of the entire deformed spine in the supine position. Scans were performed using a helical CT scanner (Light Speed VCT, General Electric, Maukesha, WI). The slice thickness was 0.625 mm, the tube voltage was 120 kV and the amperage was 90 mA. The data were saved in a standard DICOM (Digital Imaging and Communications in Medicine) format. The estimated radiation dose for the patients using this scanning protocol was 5.2 mSv.

Construction of 3D surface bone models

To construct the 3D bone models, we performed a segmentation procedure. Segmentation extracts bone regions and associates each region with individual bones. The anatomic structure or region of interest must be delineated and separated so that it can be viewed individually. Regions of individual bones were segmented semiautomatically using a software program for image analysis (Virtual Place-M; AZE Ltd, Tokyo, Japan). We then obtained the surface models of the vertebrae by applying 3D surface generation of the bone cortex [18, 20].

Axis configuration of local anatomic coordinate system

In order to measure the deviation in three dimensions between adjacent vertebrae, we first established the axis of the local coordinate system for each vertebra by first calculating the centroid of the vertebra automatically and designating it as the origin of the coordinate axis (Fig. 1a). Next, the planar approximation of the superior endplate was calculated using the least-squares method and we estimated a plane parallel to the superior endplate via the origin (Fig. 1b). On that plane, a line from both the centroid and the point which divided the front part of the vertebral body into half (using the least-squares method) formed the z axis (Fig. 1c), with 'anterior' as the 'positive' direction. A line perpendicular to the z axis pointing to the left formed the x axis. Finally, the y axis was defined as a line perpendicular z–x plane (Fig. 1d).

Measurement of intervertebral coronal plane deformity

The intervertebral coronal inclination between adjacent vertebrae was defined as the angle between adjacent x axes projected on the subjacent local coordinate x–y plane. From T1–T2 to L4–L5, each intervertebral coronal inclination was measured. For example, the adjacent inclination in the coronal plane of T8–T9 represented the angle between x axes of T8 and T9 projected to the x–y plane of T9 (Fig. 2). All adjacent intervertebral angles were measured automatically.

Measurement of intervertebral axial plane deformity

The intervertebral rotation in the axial plane between adjacent vertebrae was defined as the angle between adjacent z axes projected on the subjacent local coordinate z–x plane. From T1–T2 to L4–L5, each intervertebral axial rotation angle was measured. For example, the adjacent rotation in the axial plane of T8–T9 represented the angle between z axes of T8 and T9 projected to the z–x plane of

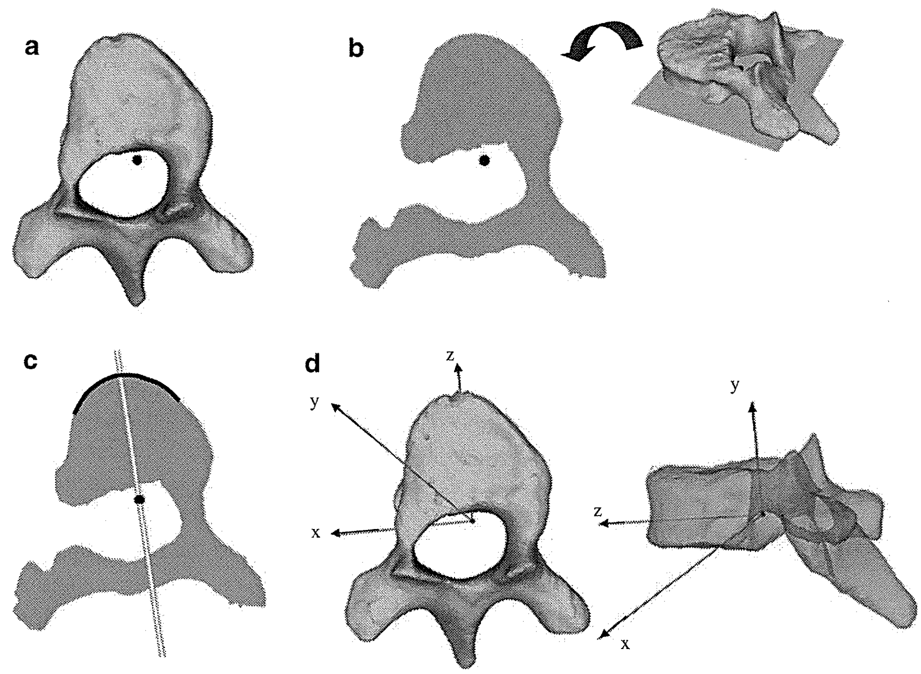

Fig. 1 The method used to establish the local coordinate system. **a** The *black sphere* is a centroid of the vertebra that is defined as the origin of the coordinate axis. **b** The cross-sectional surface of the vertebra; the planar approximation of the superior endplate was calculated using the least-squares method, and we estimated a plane parallel to the superior endplate via the origin. **c** In the cross-sectional plane, the z axis is defined as a line between the centroid and the point that divides the front portion of the vertebral body in half. **d** A line perpendicular to the z axis and pointing to the left on the plane forms the x axis. Finally, the y axis pointing cranial is defined as a line perpendicular to the z–x plane

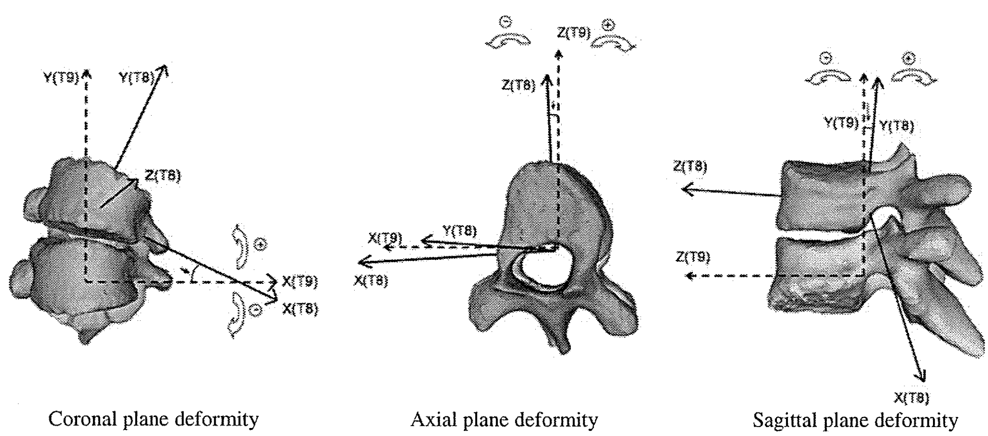

Fig. 2 The T8 and T9 bone models and each local coordinate axis. The *solid lines* present the axis of T8, and the *broken lines* present the axis of T9. *Left* the intervertebral coronal inclination. The figure faces the subjacent vertebral x–y plane; the intervertebral coronal inclination angle (*arrow*) is defined as the angle between two adjacent x axes projected on the subjacent x–y plane. *Middle* the intervertebral axial rotation. The figure faces the subjacent z–x plane; the intervertebral axial rotational angle (*arrow*) is defined as the angle between adjacent z axes projected on the subjacent z–x plane. *Right* the intervertebral sagittal angulation. The figure faces the subjacent y–z plane; the sagittal intervertebral angulation (*arrow*) is defined as the angle between adjacent y axes projected on the subjacent y–z plane

T9 (Fig. 2). All adjacent intervertebral angles were also measured automatically.

Measurement of intervertebral sagittal plane deformity

The intervertebral angulation in the sagittal plane between adjacent vertebrae was defined as the angle between adjacent y axes projected on the subjacent local coordinate y–z plane. From T1–T2 to L4–L5, each intervertebral sagittal angulation was measured. For example, the adjacent angulation in the sagittal plane of T8–T9 represented the angle between y axes of T8 and T9 projected to the y–z plane of T9 (Fig. 2). All adjacent intervertebral angles were also measured automatically.

Results

Intervertebral coronal plane deformity

The left side of Fig. 3 shows the amount of change between each intervertebral coronal inclination for all ten patients. These results indicate that the intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. The maximum intervertebral change at apical region was 20.2° (absolute value), the minimum change at junctional region was 0°. Figure 4 shows two representative cases (Case 3 and Case 10). The 3D models of both the thoracic and lumbar spine and the intervertebral angle in the coronal and axial planes are shown in Fig. 4. The x axis of the graph to the left of the bone model represents the intervertebral inclination angle in the coronal plane. The 'plus' direction of the graph means that the x axis of the suprajacent vertebra is directed in the 'plus' direction in relation to the subjacent vertebral y axis. Similarly, the minus direction of the graph means that the adjacent vertebral x axis is directed in the minus direction in relation to the y axis of the subjacent vertebra (Fig. 2).

Intervertebral axial plane deformity

The middle of Fig. 3 shows the amount of change between each intervertebral axial rotation for all patients. As the converse to the intervertebral coronal deformity, the intervertebral rotation in the axial plane was smaller near the apical region and larger near the junctional region. The maximum intervertebral change at junctional region was 12.6° (absolute value), the minimum change at apical region was 0°. The angle to the plus direction represents the amount of axial rotational change in the clockwise rotation of the suprajacent vertebra to subjacent z–x plane. On the other hand, when the suprajacent vertebral body rotates to the counterclockwise for the subjacent vertebral body, the change in the angle of the adjacent vertebral body is directed in the minus direction (Fig. 2). The amount of changes between adjacent vertebral axial rotation of two representative cases (Case 3 and Case 10) are shown in the graphs to the right of the bone models (Fig. 4).

Intervertebral sagittal plane deformity

The right side of Fig. 3 shows the amount of change between each intervertebral sagittal angulation for all the patients. Concerning the sagittal plane deformity, the constant tendency was not recognized. The 'plus' represents that the y axis of the suprajacent vertebra is directed in the minus direction in relation to the subjacent vertebral z axis. It means that the suprajacent vertebral bodies located in extension to subjacent vertebral bodies on subjacent y–z planes (Fig. 2).

Discussion

Idiopathic scoliosis is a complex spinal deformity characterized by lateral curvature of the spine associated with axial vertebral rotation. Recent 3D evaluations of the spine

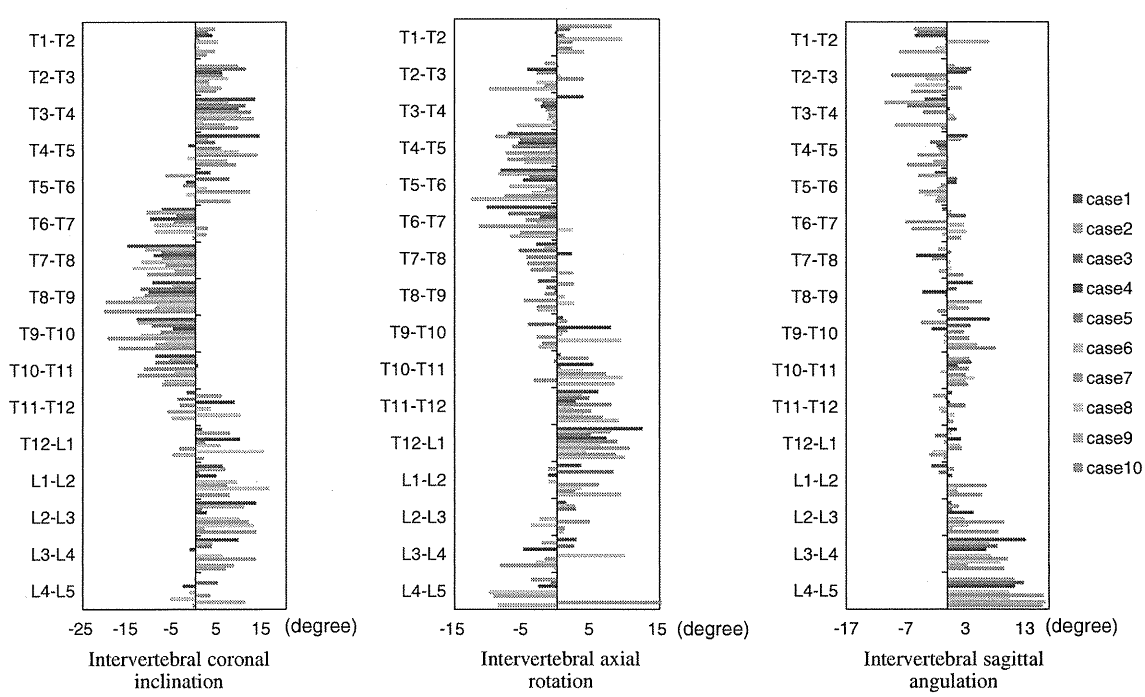

Fig. 3 The intervertebral deviation of the each adjacent vertebrae of all ten patients. The x axes show the each intervertebral deviation angles of all patients in coronal, axial and sagittal plane. The intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region, and larger near the junctional region. Concerning the sagittal plane deformity, the constant tendency was not recognized

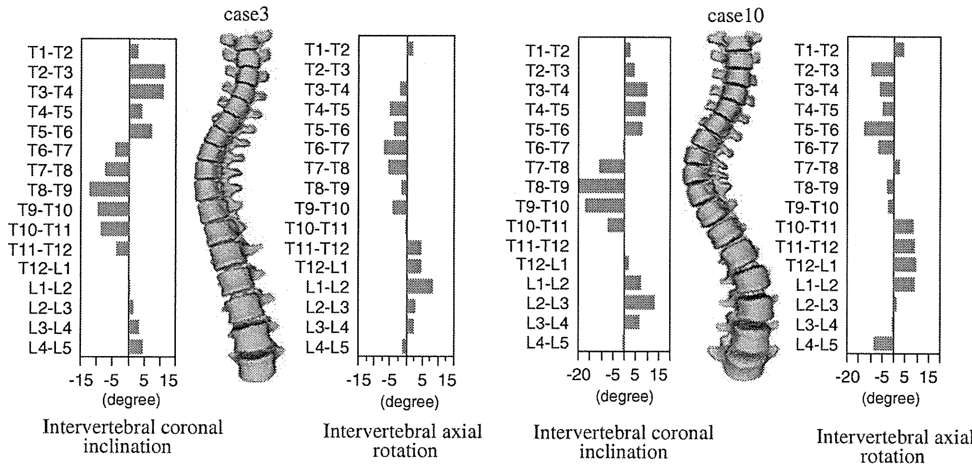

Fig. 4 Two representative cases. The bone models of both the thoracic and lumbar spine are shown in the *center*, and the *left sided graph* represents the intervertebral inclination angle in the coronal plane; the *right sided graph* represents the intervertebral rotational angle in the axial plane. *Left* case 3, *Right* case 10

in patients with AIS have been performed [8, 9, 21–23]. As morphometric studies, Parents et al. [21–23] created a 3D reconstruction of a large number of cadaveric bones, and compared normal vertebrae with the vertebrae of AIS. For example, vertebral wedging increased progressively toward the apex and pedicles located on the concavity were found to be significantly thinner than normal specimens [21–23]. In addition, the evaluation of global 3D correction between pre- and post-operative spinal 3D shape was also reported by Kadoury et al. [8, 9]. They reconstructed 3D models using bi-planar radiographs, and examined the difference among four operative methods. Steib et al. also performed 3D studies about the 3D change before and after surgical correction by in situ contouring technique using the reconstructed 3D models from bi-planar radiographs [6, 7, 16, 27]. However, these methods lacked accuracy since their method required only about 6–20 landmarks when reconstructing the bone models. Although an accurate assessment of 3D intervertebral deviation is crucial to the better surgical correction of the deformity, no detailed 3D study using an in vivo model of AIS has been reported.

Our results indicate the different deviation patterns between the intervertebral coronal plane deformity and intervertebral axial plane rotation. The intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region and larger near the junctional region. In 1994, Dubousset also showed that the intervertebral axial rotation reached its maximum at the extremities and its minimum at the apex [5]. However, the simple finite element models of only one case were used in the study and it is not known how to measure the intervertebral deviation [5]. Therefore, using the precise 3D evaluation method, we can show that the change in the intervertebral inclination angle in the coronal plane increased toward the apical region and decreased toward the junctional region, and that the converse tendency was noted for the axial intervertebral rotational angle in AIS patients for the first time.

There is a limitation in our method. The bone models were constructed from CT images taken in the supine position. Troell et al. [28] examined the radiographs of 287 girls with AIS and found that their mean Cobb angle, measured at standing position, was approximately 9° larger than that in the supine position, and the difference was 45° in the maximum. Yazici et al. [29] also showed that the average Cobb angle on a standing radiograph was approximately 16° larger than that in the supine position and they found that a rotational angle of 22.75° on the standing radiograph and 16.78° in the supine position. However, our results compared coronal with axial deviation under the same condition as supine. Though it is conceivable that the degree of the spinal deformity may be small in the supine position, it would appear that the features obtained from our study are not different from those obtained in the standing position.

The results in the present study can be applied to the surgical correction of AIS. The concave rod rotation maneuver, introduced by Cotrel and Dubousset, is generally concluded with derotation vertebral procedures. It's well accepted that rotation of precontoured concave rod (counter-clockwise) by alone has poor rotation improvement [1, 12–14, 17, 26]. Moreover, Kadoury et al. concluded that scoliosis also involves transverse plane rotation of the vertebrae in the opposite direction. In order to derotate the vertebrae, moments in the opposite sense should also be applied to the vertebrae [9]. According to our result, it might be easier to correct the rotation of each vertebra from the end vertebra to the apex using direct vertebral rotation technique.

Conclusion

We propose a new local coordinate system for deformed vertebrae of AIS. By using this coordinate system, the 3D intervertebral deviation in the coronal, axial and sagittal planes were measured. We found that the intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region and larger near the junctional region.

Conflict of interest None.

References

1. Asghar J, Samdani AF, Pahys JM, D'andrea LP, Guille JT, Clements DH, Betz RR (2009) Computed tomography evaluation of rotation correction in adolescent idiopathic scoliosis: a comparison of an all pedicle screw construct versus a hook-rod system. Spine 34:804–807
2. Benameur S, Mignotte M, Parent S, Labelle H, Skalli W, Guise J (2002) 3D biplanar statistical reconstruction of scoliotic vertebrae. Stud Health Technol Inform 91:281–285
3. Carpineta L, Labelle H (2003) Evidence of three-dimensional variability in scoliotic curves. Clin Orthop Relat Res 412:139–148
4. Cruickshank JL, Koike M, Dickson RA (1989) Curve patterns in idiopathic scoliosis. A clinical and radiographic study. J Bone Joint Surg [Br] 71:259–263
5. Dubousset J (1994) Three-dimensional analysis of the scoliotic deformity. In: Weinstein SL (ed) The pediatric Spine: Principles and Practices. Raven Press, New York, pp 479–496
6. Dumas R, Mitton D, Laporte S, Dubousset J, Steib JP, Lavaste F, Skalli W (2003) Explicit calibration method and specific device designed for stereoradiography. J Biomech 36:827–834
7. Dumas R, Steib JP, Mitton D, Lavaste F, Skalli W (2003) Three-dimensional quantitative segmental analysis of scoliosis corrected by the in situ contouring technique. Spine 28:1158–1162
8. Kadoury S, Cheriet F, Laporte C, Labelle H (2007) A versatile 3D reconstruction system of the spine and pelvis for clinical assessment of spinal deformities. Med Bio Eng Comput 45:591–602
9. Kadoury S, Cheriet F, Beauséjour M, Stokes IA, Parent S, Labelle H (2009) A three-dimensional retrospective analysis of the evolution of spinal instrumentation for the correction of adolescent idiopathic scoliosis. Eur Spine J 18:23–37
10. Kotwicki T, Napiontek M (2008) Intravertebral deformation in idiopathic scoliosis a transverse plane computer tomographic study. J Pediatr Orthop 28:225–229
11. King HA, Moe JH, Bradford DS, Winter RB (1983) The selection of fusion levels in thoracic idiopathic scoliosis. J Bone Joint Surg Am 65:1302–1313
12. Labelle H, Dansereau J, Blellefleur C, de Guise J, Rivard CH, Poitras B (1995) Peroperative three-dimensional correction of idiopathic scoliosis with the Cotrel–Dubousset procedure. Spine 15:1406–1409
13. Lenke LG, Bridwell KH, Baldus C, Blanke K, Schoenecker PL (1992) Cotrel–Dubousset instrumentation for adolescent idiopathic scoliosis. J Bone Joint Surg Am 74:1056–1067
14. Lenke LG, Bridwell KH, O'Brien MF, Baldus C, Blanke K (1994) Recognition and treatment of the proximal thoracic curve in adolescent idiopathic scoliosis with Cotrel–Dubousset instrumentation. Spine 15:1589–1597
15. Little DG, Sussman MD (1994) The Risser sign: a critical analysis. J Pediatr Orthop 14:569–575
16. Mitton D, Landry C, Véron S, Skalli W, Lavaste F, Guise JA (2000) 3D reconstruction method from biplanar radiography using non-stereocorresponding points and elastic deformable meshes. Med Biol Eng Comp 38:133–139
17. Moens P, Vanden Berqhe L, Fabry G, Bellemans J (1995) The Cortel–Dubousset device: prospective study on derotation. Rev Chir Orthop Reparatrice Appar Mot 81:428–432
18. Modi HN, Suh SW, Song HR, Lee SH, Yang JH (2008) Differential wedging vertebral body and intervertebral disc in thoracic and lumbar spine in adolescent idiopathic scoliosis—a cross sectional study in 150 patients. Scoliosis 3:11
19. Nash CL, Moe JH (1969) A study of vertebral rotation. J Bone Joint Surg Am 54:223–229
20. Oka K, Moritomo H, Murase T, Goto A, Sugamoto K, Yoshikawa H (2005) Patterns of carpal deformity in scaphoid nonunion: a 3-dimensional and quantitative analysis. J Hand Surg [Am] 30:1136–1144
21. Parent S, Labelle H, Skalli W, Latimer B, Guise J (2002) Morphometric analysis of anatomic scoliotic specimens. Spine 27:2305–2311
22. Parent S, Labelle H, Skalli W, Guise J (2004) Thoracic pedicle morphometry in vertebrae from scoliotic spines. Spine 29:239–248
23. Parent S, Labelle H, Skalli W, Guise J (2004) Vertebral wedging characteristic changes in scoliotic spines. Spine 29:E455–E462
24. Perdriolle R (1979) *La* scoliose: *Son* e'tude Tridimensionnelle. Ed. Maloine, Paris
25. Perdriolle R, Vidal J (1987) Morphology of scoliosis three-dimensional evolution. Orthopedics 10:909–915
26. Sawatzky BJ, Tredwell SJ, Jang SB, Black AH (1998) Effects of three-dimensional assessment on surgical correction and on hook strategies in multi-hook instrumentation for adolescent idiopathic scoliosis. Spine 23:201–205
27. Steib JP, Dumas R, Mitton D, Skalli W (2004) Surgical correction of scoliosis by in situ contouring: a detorsion analysis. Spine 29:193–199
28. Torell G, Nachemson A, Haderspeck-Grib K, Schultz A (1985) Standing and supine Cobb measures in girls with idiopathic scoliosis. Spine 10:425–427
29. Yazici M, Acaroglu ER, Alanay A, Deviren V, Cila A, Surat A (2001) Measurement of vertebral rotation in standing versus supine position in adolescent idiopathic scoliosis. J Pediatr Orthop 21:252–256