

Three-Dimensional Spinal Cord Volume Mobility on Dynamic Cervical CT Myelography Is Associated With Postoperative Neurological Recovery in Cervical Spondylotic Myelopathy

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Research Article

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Abstract

Purpose

Dynamic cervical motion may aggravate spinal cord compression in cervical spondylotic myelopathy (CSM), whereas conventional measurements primarily characterize compression at a single axial level. This study introduced spinal cord volume mobility (SCVM), derived from three-dimensional reconstruction of dynamic CT myelography (CTM), and investigated its association with postoperative neurological recovery.

Methods

In this prospective observational study, 23 patients with CSM underwent preoperative CTM in flexion, neutral, and extension positions and were followed for 3 years after surgery. The spinal cord at the most compressed intervertebral segment was reconstructed using Mimics. SCVM was defined as $\delta = |2 \times (V_{\text{flexion}} - V_{\text{extension}}) / (V_{\text{flexion}} + V_{\text{extension}})|$. Cross-sectional area (CSA), anteroposterior diameter, and reconstructed volume were compared across positions. Associations of imaging parameters with the 3-year Japanese Orthopaedic Association (JOA) recovery rate and postoperative JOA score were evaluated.

Results

CSA at the most compressed level decreased from $33.80 \pm 10.57 \text{ mm}^2$ in flexion and $31.43 \pm 8.88 \text{ mm}^2$ in neutral to $23.69 \pm 9.91 \text{ mm}^2$ in extension (both comparisons with extension, $P < 0.001$). Reconstructed segmental volume was lower in extension than in flexion (208.16 ± 87.99 vs $234.52 \pm 85.61 \text{ mm}^3$, $P = 0.034$). Patients with poor recovery had longer disease duration, smaller extension CSA, and greater SCVM. SCVM was negatively correlated with the 3-year JOA recovery rate ($r = -0.548$, $P = 0.0068$), whereas extension CSA was positively correlated with recovery ($r = 0.509$, $P = 0.0131$). In multivariable analysis, SCVM remained negatively associated with the 3-year postoperative JOA score ($B = -8.071$, $\beta = -0.336$, $P = 0.010$).

Conclusion

Three-dimensional SCVM quantifies posture-related spinal cord deformation on dynamic CTM. Greater SCVM was associated with less favorable neurological recovery and may provide complementary information beyond conventional single-slice CSA assessment.

Introduction

Cervical spondylotic myelopathy (CSM) results from chronic spinal cord compression caused by degenerative changes, including disc protrusion, osteophytes, ligamentous hypertrophy, and canal stenosis. In addition to these static factors, cervical flexion and extension may alter the degree and direction of spinal cord compression. Consequently, neutral-position imaging may underestimate functional compression that becomes apparent only during cervical motion [1–6].

Dynamic magnetic resonance imaging and CT myelography (CTM) have demonstrated that spinal canal narrowing and spinal cord compression are commonly aggravated during extension, although flexion-related compression may occur in patients with kyphotic alignment, anterior slippage, or high-occupancy ossification of the posterior longitudinal ligament [1–8]. Machino et al. reported a significant reduction in spinal cord cross-sectional area (CSA) during extension, and Ito et al. found that the magnitude of flexion-extension CSA change was associated with myelopathy severity [3, 6]. These observations suggest that the variation in compression across postures may be clinically relevant in addition to the absolute compression measured in one position.

Most dynamic imaging studies have relied on two-dimensional parameters, such as CSA or anteroposterior diameter. However, spinal cord deformation within an intervertebral segment may include flattening, transverse expansion, traction, and redistribution of volume along the compressed segment. A measurement obtained at a single axial slice may therefore incompletely represent this complex change.

The study used dynamic CTM and Mimics-based three-dimensional reconstruction to quantify spinal cord volume within the compressed intervertebral segment. We defined spinal cord volume mobility (SCVM) as the relative volume difference between flexion and extension.

Materials and Methods

Study design and participants

This prospective observational study was conducted at a single institution and was reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology statement [9]. Consecutive patients diagnosed with CSM who underwent dynamic cervical CTM before surgery were screened. Patients were eligible for enrollment if they had a clinical and radiological diagnosis of cervical spondylotic myelopathy based on neurological findings and conventional cervical imaging, were scheduled to undergo cervical decompression surgery, were considered able to safely complete dynamic CT myelography in flexion, neutral, and extension positions, and provided written informed consent for study participation and 3-year follow-up.

Patients were excluded if they had previous cervical surgery, cervical trauma, tumor, infection, inflammatory disease, congenital deformity, another neurological disorder affecting functional assessment, substantial imaging artifacts, or incomplete follow-up.

The institutional ethics committee approved the study (approval no. JYKSZ 202104-25). All participants provided written informed consent.

Sample-size estimation

An a priori sample-size calculation was performed using a two-sided correlation test. Based on preliminary observations and the moderate associations between dynamic spinal cord changes and neurological status reported in previous dynamic CTM studies [3, 6], an anticipated correlation coefficient of 0.60 was used. With $\alpha = 0.05$ and 80% power, at least 20 patients were required. Allowing for approximately 10% loss to follow-up, the planned enrollment was at least 22 patients. Twenty-three patients completed the required imaging and 3-year follow-up.

Dynamic CTM

Dynamic CTM was performed using an Aquilion PRIME TSX-302A scanner. After lumbar puncture and intrathecal administration of nonionic iohexol (Omnipaque), the contrast agent was allowed to enter the cervical subarachnoid space. Patients were scanned supine in maximally tolerable flexion, neutral, and maximally tolerable extension positions without inducing or worsening neurological symptoms.

The scan range extended from C2 to T1. The principal parameters were 120 kV and 250 mA. Images were reconstructed at a slice thickness of 1.0 mm and an interval of 0.8 mm and were reformatted in the sagittal and coronal planes.

Three-dimensional reconstruction and SCVM

CTM data were imported into Mimics software (Materialise, Leuven, Belgium). The contrast-filled subarachnoid space allowed the spinal cord contour to be identified on consecutive axial images and reconstructed three-dimensionally.

The intervertebral disc motion segment was used as the anatomical measurement unit. On the sagittal image, the midpoint of the posterior superior margin of the lower vertebral body was selected as a landmark. Two cutting planes, oriented according to the adjacent vertebral endplates, were placed tangent to the inferior endplate of the upper vertebral body and the superior endplate of the lower vertebral body. These planes isolated the reconstructed spinal cord within the target motion segment.

The same anatomical rule was applied independently to flexion and extension images. Segmental spinal cord volumes in flexion (V_{flexion}) and extension ($V_{\text{extension}}$) were recorded. SCVM was calculated as:

$$\delta = |2 \times (V_{\text{flexion}} - V_{\text{extension}}) / (V_{\text{flexion}} + V_{\text{extension}})|.$$

A larger δ represents a greater relative change in segmental spinal cord volume between flexion and extension.

(a, b) Sagittal CT myelography images obtained in flexion and extension, respectively. Colored markers indicate the disc-level landmarks used to define the segmental boundaries for spinal cord reconstruction.

(c, d) Three-dimensional reconstructions of the overall cervical spinal cord in flexion and extension.

(e, f) Three-dimensional reconstructions of the spinal cord at the target segment showing morphological differences between flexion and extension. In extension, the reconstructed segment appears more narrowed and elongated, indicating aggravated dynamic compression.

(g, h) Segment-by-segment reconstructed spinal cord models corresponding to the disc-level segmentation in flexion and extension. These images illustrate the method used for segmental volumetric quantification and demonstrate the positional and morphological changes of the spinal cord across dynamic postures.

Two observers, blinded to clinical outcome, independently performed segmentation and measurement twice. The interobserver and intraobserver intraclass correlation coefficients were 0.91 and 0.92, respectively.

Imaging and clinical assessment

At the most compressed level, spinal cord CSA, anteroposterior diameter, and transverse width were measured in flexion, neutral, and extension. The most compressed level was defined as the disc level with the most pronounced compression or smallest CSA on CTM, with MRI used for confirmation. C2–C7 range of motion and intramedullary high signal intensity (IHSI) grade on T2-weighted MRI were also recorded. IHSI was classified according to the previously described grading method [10].

Neurological function was assessed using the Japanese Orthopaedic Association (JOA) score. The recovery rate was calculated using the Hirabayashi formula [11]:

JOA recovery rate = (postoperative JOA – preoperative JOA)/(17 – preoperative JOA) × 100%.

The primary outcome was the JOA recovery rate at 3 years. A recovery rate > 50% was categorized as good recovery and a rate ≤ 50% as poor recovery.

Statistical analysis

Continuous variables are presented as mean ± standard deviation and categorical variables as number and percentage. Repeated positional measurements were compared using the Friedman test, followed by paired comparisons. Good and poor recovery groups were compared using Welch's t-test, the Mann–Whitney U test, or Fisher's exact test, as appropriate.

Pearson correlation analysis evaluated associations between the 3-year JOA recovery rate and SCVM, disease duration, and positional CSA. Multivariable linear regression was performed with the 3-year postoperative JOA score as the dependent variable and preoperative JOA score, C2–C7 range of motion, IHSI, and SCVM as explanatory variables. Variance inflation factors below 5 indicated no substantial multicollinearity. An exploratory logistic regression analysis of good recovery was performed as a supplementary analysis. Tests were two-sided, with $P < 0.05$ considered statistically significant.

Results

Patient characteristics

A total of 25 patients were enrolled; 2 were lost to follow-up, leaving 23 patients for the final analysis, including 12 men and 11 women. Mean age was 57.1 ± 14.0 years, and mean disease duration was 10.7 ± 4.7 months. Mean preoperative and 3-year postoperative JOA scores were 12.3 ± 2.3 and 14.5 ± 1.8 , respectively. The mean 3-year JOA recovery rate was $50.4\% \pm 24.0\%$; 12 patients had good recovery and 11 had poor recovery. Baseline characteristics are summarized in Table 1.

Table 1
Baseline characteristics and overall radiological parameters

Characteristic	Overall (n = 23)
Age, years	57.1 ± 14.0
Sex, n (%)	
Male	12 (52.2)
Female	11 (47.8)
Disease duration, months	10.7 ± 4.7
C2–C7 ROM, °	46.9 ± 8.4
IHSI grade	1.0 ± 0.7
IHSI grade, n (%)	
Grade 0	5 (21.7)
Grade 1	12 (52.2)
Grade 2	6 (26.1)
Preoperative JOA score	12.3 ± 2.3
3-year postoperative JOA score	14.5 ± 1.8
3-year JOA recovery rate, %	50.4 ± 24.0
Spinal cord volume mobility (δ)	0.113 ± 0.074
Surgical procedure, n (%)	
ACDF	13 (56.5)
Other anterior procedure	2 (8.7)
SLAC	4 (17.4)
Posterior laminectomy/decompression	4 (17.3)
<i>Data are presented as mean ± SD or n (%). JOA recovery rate was calculated as (postoperative JOA – preoperative JOA)/(17 – preoperative JOA) × 100%.</i>	
<i>IHSI = intramedullary high signal intensity; JOA = Japanese Orthopaedic Association; ROM = range of motion; spinal cord volume mobility $\delta = 2 \times (V_{flexion} - V_{extension}) / (V_{flexion} + V_{extension})$. SLAC = Longitudinal Spinous-Splitting Laminoplasty with Coral Bone</i>	

The most compressed level was C3–C4 in 4 patients, C4–C5 in 9, C5–C6 in 9, and C6–C7 in 1. SCVM did not differ significantly among compression levels ($P > 0.05$).

Dynamic spinal cord morphology

CSA at the most compressed level differed significantly across positions. Mean CSA was $33.80 \pm 10.57 \text{ mm}^2$ in flexion, $31.43 \pm 8.88 \text{ mm}^2$ in neutral, and $23.69 \pm 9.91 \text{ mm}^2$ in extension. Extension CSA was smaller than flexion and neutral CSA (both $P < 0.001$), whereas the flexion-neutral difference approached significance ($P = 0.052$).

The anteroposterior diameter decreased from $4.09 \pm 1.53 \text{ mm}$ in flexion to $3.31 \pm 1.12 \text{ mm}$ in neutral and $2.90 \pm 1.00 \text{ mm}$ in extension (flexion vs extension, $P < 0.001$). Transverse width did not differ significantly across positions.

Reconstructed segmental volume was lower in extension than in flexion (208.16 ± 87.99 vs $234.52 \pm 85.61 \text{ mm}^3$, $P = 0.034$). Dynamic morphological measurements are shown in Table 2 and Fig. 2.

Table 2
Dynamic changes in spinal cord morphology at the most compressed level on dynamic CTM

Parameter	Flexion	Neutral	Extension	Overall P	P Flexion vs Neutral	P Neutral vs Extension	P Flexion vs Extension
Spinal cord CSA (mm^2)	33.80 ± 10.57	31.43 ± 8.88	23.69 ± 9.91	< 0.001	0.052	< 0.001	< 0.001
Spinal cord width (mm)	12.48 ± 2.84	12.62 ± 3.23	12.76 ± 3.50	0.163	0.856	0.876	0.577
Anteroposterior diameter (mm)	4.09 ± 1.53	3.31 ± 1.12	2.90 ± 1.00	< 0.001	0.005	0.100	< 0.001
Reconstructed segmental volume (mm^3)	234.52 ± 85.61	—	208.16 ± 87.99	—	—	—	0.034
<i>Values are mean $\pm$ SD. Overall P values for CSA, width, and anteroposterior diameter were calculated using the Friedman test. Pairwise P values were calculated using paired t-tests. Reconstructed segmental volume was available only in flexion and extension; its P value refers to the paired comparison between flexion and extension.</i>							

1. (A) At the most compressed level, the cross-sectional area (CSA) was greatest in flexion ($33.80 \pm 10.57 \text{ mm}^2$), intermediate in neutral ($31.43 \pm 8.88 \text{ mm}^2$), and smallest in extension ($23.69 \pm 9.91 \text{ mm}^2$). CSA was significantly smaller in extension than in flexion or neutral (both $P < 0.001$), whereas the difference between flexion and neutral approached significance ($P = 0.052$). The minimum CSA occurred in extension in 18 patients, in flexion in 2, and in neutral in 3; overall, dynamic compression was more severe in extension in 20 patients and in flexion in 3.
2. (B) The anteroposterior diameter showed a similar pattern, decreasing from $4.09 \pm 1.53 \text{ mm}$ in flexion to $3.31 \pm 1.12 \text{ mm}$ in neutral and $2.90 \pm 1.00 \text{ mm}$ in extension; the value in extension was significantly smaller than that in flexion ($P < 0.001$).
3. (C) Mimics-based three-dimensional reconstruction demonstrated a lower segmental spinal cord volume in extension than in flexion ($208.16 \pm 87.99 \text{ mm}^3$ vs $234.52 \pm 85.61 \text{ mm}^3$, $P = 0.034$).

Because the absolute reconstructed volume depends on segment length and anatomical extent, spinal cord volume mobility (δ) was used as the principal parameter for dynamic volumetric change.

Table 3
Comparison of clinical and radiological parameters between good and poor recovery groups

Variable	Good recovery (n = 12)	Poor recovery (n = 11)	P value
Age, years	55.8 ± 13.0	58.6 ± 15.5	0.636
Male sex, n (%)	5 (41.7)	7 (63.6)	0.414
Disease duration, months	8.7 ± 4.4	13.0 ± 4.0	0.022
C2–C7 ROM, °	47.5 ± 7.8	46.2 ± 9.3	0.706
IHSI grade	1.08 ± 0.79	1.00 ± 0.63	0.787
Preoperative JOA score	12.8 ± 2.1	11.7 ± 2.6	0.312
3-year postoperative JOA score	15.6 ± 0.8	13.4 ± 1.8	0.002
CSA in flexion, mm ²	37.55 ± 10.36	29.72 ± 9.63	0.074
CSA in neutral, mm ²	35.09 ± 8.80	27.44 ± 7.40	0.034
CSA in extension, mm ²	28.69 ± 9.10	18.23 ± 7.89	0.008
Spinal cord width in flexion, mm	13.79 ± 1.98	11.05 ± 3.03	0.021
Spinal cord width in neutral, mm	13.39 ± 4.05	11.79 ± 1.87	0.235
Spinal cord width in extension, mm	14.72 ± 2.10	10.62 ± 3.51	0.004
Anteroposterior diameter in flexion, mm	4.00 ± 1.42	4.19 ± 1.70	0.780
Anteroposterior diameter in neutral, mm	3.24 ± 1.20	3.39 ± 1.07	0.754
Anteroposterior diameter in extension, mm	2.98 ± 0.92	2.83 ± 1.12	0.727
Reconstructed volume in flexion, mm ³	260.40 ± 81.68	206.30 ± 84.29	0.134
Reconstructed volume in extension, mm ³	229.24 ± 82.12	185.17 ± 92.20	0.242
Spinal cord volume mobility, δ	0.083 ± 0.082	0.147 ± 0.049	0.035
Values are presented as mean ± standard deviation or n (%).			
Good recovery was defined as a 3-year JOA recovery rate > 50%; poor recovery was defined as ≤ 50%.			
P values were calculated using Welch's t-test for continuous variables, Mann–Whitney U test for IHSI grade, and Fisher's exact test for sex.			
CSA, cross-sectional area; ROM, range of motion; IHSI, intramedullary high signal intensity; JOA, Japanese Orthopaedic Association score.			

Association with postoperative recovery

Compared with patients with good recovery, those with poor recovery had longer disease duration (13.0 ± 4.0 vs 8.7 ± 4.4 months, $P = 0.022$), smaller extension CSA (18.23 ± 7.89 vs 28.69 ± 9.10 mm², $P = 0.008$), and greater SCVM (0.147 ± 0.049 vs 0.083 ± 0.082 , $P = 0.035$). Age, preoperative JOA score, C2–C7 range of motion, and IHSI grade did not differ significantly between groups (Table 3) SCVM was negatively correlated with the 3-year JOA recovery rate ($r = -0.548$, $P = 0.0068$). Disease duration was also negatively correlated with recovery ($r = -0.453$, $P = 0.0300$), whereas extension CSA was positively correlated with recovery ($r = 0.509$, $P = 0.0131$). Correlation plots are shown in Fig. 3.

1. **(A)** Spinal cord volume mobility (**δ**) was significantly and negatively correlated with the JOA recovery rate at 3 years ($r = -0.548$, $P = 0.0068$), indicating that greater dynamic volumetric change was associated with poorer neurological recovery.
2. **(B)** The cross-sectional area (**CSA**) of the spinal cord in extension was significantly and positively correlated with the JOA recovery rate at 3 years ($r = 0.509$, $P = 0.0131$), suggesting that more severe spinal cord compression in extension was associated with less favorable postoperative recovery. The shaded areas indicate the 95% confidence intervals of the fitted regression line

In multivariable linear regression, preoperative JOA score was positively associated with the 3-year postoperative JOA score ($B = 0.649$, $\beta = 0.848$, $P < 0.001$). SCVM remained negatively associated with the postoperative JOA score after adjustment for preoperative JOA score, C2–C7 range of motion, and IHSI ($B = -8.071$, $\beta = -0.336$, $P = 0.010$). No substantial multicollinearity was detected (Table 4)

Table 4
Multivariable linear regression analysis for the 3-year postoperative JOA score

Dependent variable: 3-year postoperative JOA score; n = 23.							
Variable	B	SE	Standardized β	t	P value	95% CI	VIF
Preoperative JOA score	0.649	0.087	0.848	7.449	< 0.005	0.466–0.832	1.140
C2–C7 ROM (°)	–0.002	0.026	–0.008	–0.069	0.946	–0.057–0.054	1.340
IHSI grade	0.049	0.296	0.019	0.166	0.870	–0.572–0.670	1.196
Spinal cord volume mobility, δ	–8.071	2.783	–0.336	–2.900	0.010	–13.918––2.224	1.178
Model statistics	Value						
R ²	0.795						
Adjusted R ²	0.750						
F(4,18)	17.477						
Model P value	< 0.005						
Note: B values are unstandardized regression coefficients. VIF < 5 indicates no obvious multicollinearity. JOA, Japanese Orthopaedic Association; ROM, range of motion; IHSI, intramedullary high signal intensity; CI, confidence interval; VIF, variance inflation factor.							

The exploratory logistic model showed a consistent negative association between SCVM and good recovery, although the individual association did not reach significance (OR = 0.162 per 0.1 increase, 95% CI 0.016–1.642; P = 0.123;).

Discussion

This prospective study introduced SCVM as a three-dimensional parameter of dynamic spinal cord deformation. Three main findings were observed. First, extension was associated with substantial reductions in CSA, anteroposterior diameter, and reconstructed segmental volume. Second, patients with poor recovery had greater SCVM and smaller extension CSA. Third, SCVM remained negatively associated with the 3-year postoperative JOA score after adjustment for preoperative neurological status, cervical motion, and IHSI.

Previous dynamic imaging studies have shown that spinal cord compression often increases during cervical extension. Machino et al. demonstrated a reduction in spinal cord CSA on extension CTM, particularly at middle cervical levels [6]. Ito et al. subsequently reported that the magnitude of positional

CSA change and disease duration were related to neurological severity in cervical OPLL [3]. Other studies have shown that flexion-related compression may occur in selected patients with kyphosis, anterior translation, or large OPLL lesions [7, 8]. Consistent with these observations, most patients in the present cohort showed their smallest CSA in extension, although a minority had greater compression in flexion.

SCVM differs conceptually from a single-slice CSA measurement. CSA characterizes local flattening at one selected axial level, whereas segmental volume incorporates morphological change across the intervertebral motion segment. During cervical movement, the spinal cord may undergo simultaneous shortening or elongation, local flattening, transverse widening, and redistribution along the compressed segment. A relative volume-change parameter may therefore capture dynamic deformation that is not fully represented by one axial measurement.

The observed negative relationship between SCVM and neurological recovery may reflect repetitive mechanical loading. A segment showing substantial morphological fluctuation between flexion and extension may repeatedly experience compression, traction, or shear during daily neck movement. These mechanical changes may impair microcirculation, reduce the cerebrospinal fluid buffering space, and increase vulnerability of neural tissue [12, 13]. Biomechanical studies similarly suggest that spinal cord stress and strain can increase in dynamic positions despite less conspicuous abnormalities on neutral imaging. SCVM should therefore be interpreted as a marker of dynamic deformation amplitude rather than as a direct measurement of tissue injury.

From a clinical perspective, SCVM may complement conventional CSA when static imaging and neurological outcome appear discordant. A relatively preserved neutral CSA does not exclude marked dynamic deformation. Conversely, SCVM should not replace established clinical and imaging factors. Postoperative recovery remains influenced by preoperative neurological function, symptom duration, intramedullary signal change, surgical technique, and rehabilitation. The present results support SCVM as an additional imaging parameter rather than a standalone prognostic model.

This study has limitations. The cohort was small and derived from a single institution, limiting precision and subgroup analysis. The multivariable models included few outcome events and should be considered exploratory. Although measurement reliability was high, manual segmentation and posture-specific definition of the segment boundaries may introduce error. CTM is invasive and involves radiation exposure, which limits routine application. Finally, the findings require external validation before a clinical threshold for SCVM can be established.

Conclusion

Dynamic CTM-based three-dimensional reconstruction demonstrated measurable spinal cord deformation between flexion and extension. Greater SCVM was independently associated with a lower 3-year postoperative JOA score and provided information complementary to extension CSA. SCVM may be useful for characterizing dynamic spinal cord compression in patients with CSM.

Declarations

Ethics approval:

Approved by the institutional ethics committee (approval no. JYKSZ 202104-25).

Consent to participate:

Written informed consent was obtained from all participants.

Conflict of interest:

The authors declare no competing interests.

Author Contribution

Author Contributions Jiuhe Li contributed to the study conception and design, data collection, image processing, three-dimensional reconstruction, statistical analysis, figure and table preparation, interpretation of results, and drafting of the manuscript. Jinchao Wang contributed to patient enrollment, clinical data collection, surgical management, postoperative follow-up, and critical revision of the manuscript. Chao Wang contributed to clinical assessment, imaging data acquisition, interpretation of radiological findings, and manuscript revision. Ning Zhang contributed to data collection, postoperative follow-up, neurological functional assessment, and manuscript revision. Yuetao Zhu contributed to CT myelography data organization, imaging measurements, quality control of radiological data, and manuscript revision. Qingpeng Song contributed to clinical data curation, statistical review, interpretation of clinical outcomes, and manuscript revision. Xiaohan Zhao contributed to Mimics-based image segmentation, three-dimensional reconstruction, figure preparation, and manuscript revision. Yuqing Yang contributed to patient follow-up, database management, literature review, and manuscript revision. Zhichen Jiang contributed to Mimics-based image segmentation, three-dimensional reconstruction, figure preparation, and manuscript revision. Xiao Han contributed to the study conception and design, supervision of the project, surgical strategy, interpretation of findings, critical revision of the manuscript, and final approval of the version to be submitted. All authors read and approved the final manuscript.

Data availability:

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request, subject to institutional approval and applicable patient-privacy restrictions.

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Figures

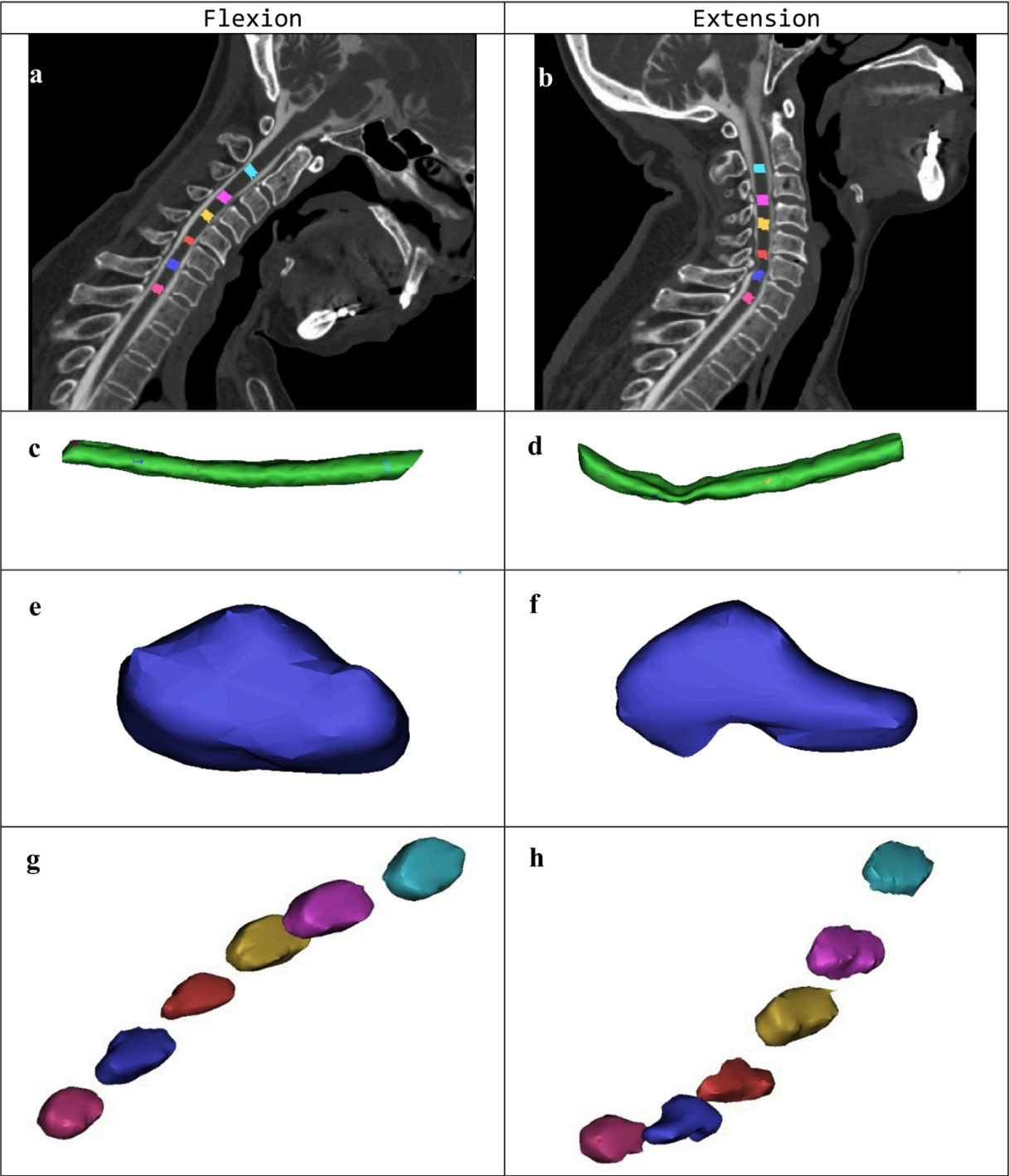


Figure 1

Representative dynamic CT myelography images and three-dimensional spinal cord reconstructions in flexion and extension.

(a, b) Sagittal CT myelography images obtained in flexion and extension, respectively. Colored markers indicate the disc-level landmarks used to define the segmental boundaries for spinal cord reconstruction.

(c, d) Three-dimensional reconstructions of the overall cervical spinal cord in flexion and extension.

(e, f) Three-dimensional reconstructions of the spinal cord at the target segment showing morphological differences between flexion and extension. In extension, the reconstructed segment appears more narrowed and elongated, indicating aggravated dynamic compression.

(g, h) Segment-by-segment reconstructed spinal cord models corresponding to the disc-level segmentation in flexion and extension. These images illustrate the method used for segmental volumetric quantification and demonstrate the positional and morphological changes of the spinal cord across dynamic postures.

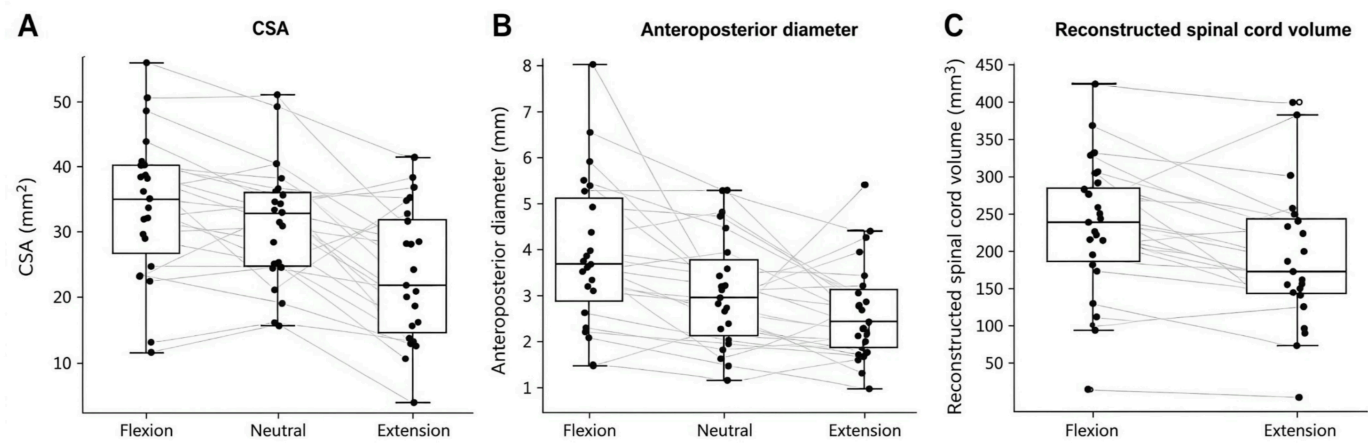


Figure 2

Dynamic changes in spinal cord morphology on dynamic CT myelography.

(A) At the most compressed level, the cross-sectional area (CSA) was greatest in flexion (33.80 ± 10.57 mm²), intermediate in neutral (31.43 ± 8.88 mm²), and smallest in extension (23.69 ± 9.91 mm²). CSA was significantly smaller in extension than in flexion or neutral (both $P < 0.001$), whereas the difference between flexion and neutral approached significance ($P = 0.052$). The minimum CSA occurred in extension in 18 patients, in flexion in 2, and in neutral in 3; overall, dynamic compression was more severe in extension in 20 patients and in flexion in 3.

(B) The anteroposterior diameter showed a similar pattern, decreasing from 4.09 ± 1.53 mm in flexion to 3.31 ± 1.12 mm in neutral and 2.90 ± 1.00 mm in extension; the value in extension was significantly smaller than that in flexion ($P < 0.001$).

(C) Mimics-based three-dimensional reconstruction demonstrated a lower segmental spinal cord volume

in extension than in flexion ($208.16 \pm 87.99 \text{ mm}^3$ vs $234.52 \pm 85.61 \text{ mm}^3$, $P = 0.034$). Because the absolute reconstructed volume depends on segment length and anatomical extent, spinal cord volume mobility (δ) was used as the principal parameter for dynamic volumetric change.

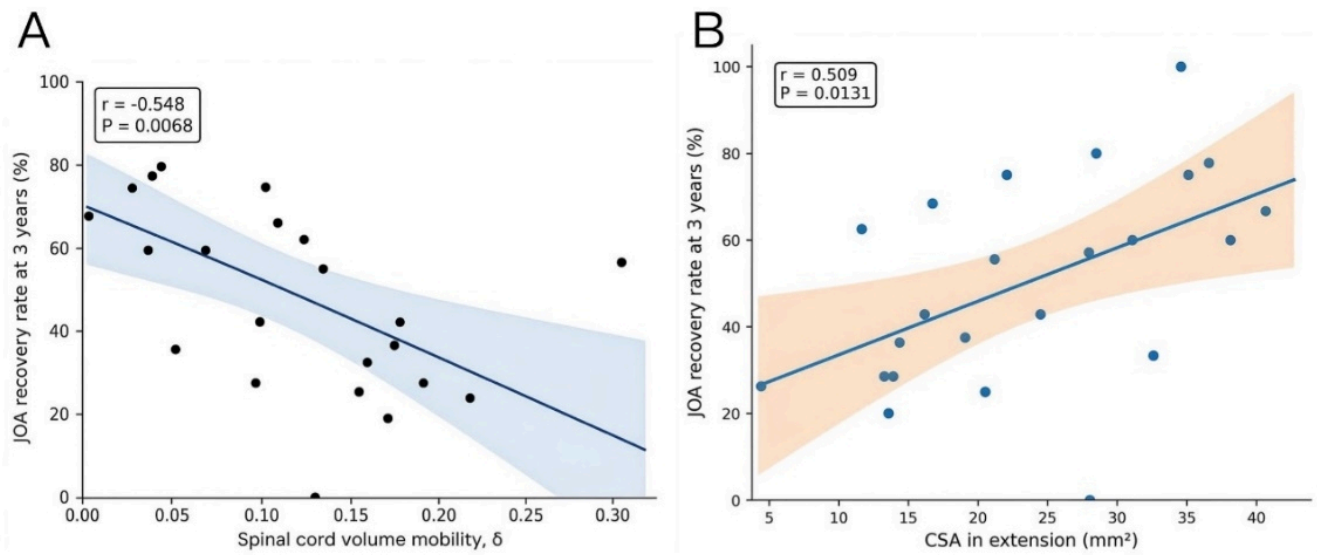


Figure 3

Correlations between dynamic spinal cord parameters and postoperative neurological recovery.

(A) Spinal cord volume mobility (δ) was significantly and negatively correlated with the JOA recovery rate at 3 years ($r = -0.548$, $P = 0.0068$), indicating that greater dynamic volumetric change was associated with poorer neurological recovery.

(B) The cross-sectional area (CSA) of the spinal cord in extension was significantly and positively correlated with the JOA recovery rate at 3 years ($r = 0.509$, $P = 0.0131$), suggesting that more severe spinal cord compression in extension was associated with less favorable postoperative recovery. The shaded areas indicate the 95% confidence intervals of the fitted regression line