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Research Article

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Individualized Surgical Treatment of Cervical Spondylotic Myelopathy Guided by Dynamic Cervical MRI: A Retrospective Cohort Study

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Abstract：

Background: Conventional neutral-position MRI frequently misses dynamic occult spinal cord compression, contributing to insufficient decompression and inferior postoperative outcomes. While dynamic flexion-extension MRI can unmask these hidden lesions, the stratified clinical utility of such findings in refining surgical strategy has not been rigorously quantified in cervical spondylotic myelopathy.

Methods: A retrospective cohort of 200 surgical CSM patients (2020–2025) was enrolled. One hundred patients underwent flexion-extension dynamic MRI (observation group), and 100 received standard neutral MRI (control group). The observation group was subsequently stratified by surgical revision. Primary outcomes were 6- and 12-month mJOA and recovery rate; secondary outcomes included VAS, NDI, complications, and reoperation. Predictors and prognosis were analyzed using LASSO and multivariable regression.

Results: Dynamic extension MRI revealed spinal cord compression not visible on neutral MRI, leading to surgical revision in 33 patients. At 6 and 12 months, the observation group showed higher mJOA and lower VAS and NDI than controls (all $P<0.05$); both its revised and unrevised subgroups outperformed controls. Preoperative mJOA ($\beta=0.27$, $P<0.001$) and the imaging-surgical composite independently predicted 12-month mJOA. Revised patients gained 0.60 points ($P=0.015$), whereas controls scored 0.78 points lower than the unrevised subgroup ($P=0.001$). Only the extension-flexion difference in compressed segments predicted surgical revision (OR=2.669, $P=0.001$). Complication rates were comparable (9.0% vs 7.0%, $P>0.05$), with lower reoperation in the observation group (1.0% vs 5.0%).

Conclusion: Dynamic MRI detects occult spinal cord compression overlooked by neutral-position scans. Individualized decompression based on dynamic imaging improves neurological outcomes without increasing complications and is recommended for CSM patients with multilevel degeneration and ambiguous symptomatic segments.

Clinical Trial Registration：Chinese Clinical Trial Registry (http://www.chictr.org.cn/), Registration number: ChiCTR2600122088, Registration date: 2026-04-09

Keywords：Cervical spondylotic myelopathy; Dynamic MRI; Anterior cervical discectomy and fusion; Myelopathy severity; Patient-reported outcome measures

Introduction

Cervical spondylotic myelopathy (CSM) is the most prevalent non-traumatic spinal cord dysfunction in the middle-aged and elderly population. Although it predominantly affects individuals aged over 60 years, a notable trend toward younger onset has been observed in recent years[1]. Alongside population aging and lifestyle changes, advances in diagnostic and therapeutic techniques have contributed to a steady rise in the global prevalence and surgical rates of CSM[2]. This disease exhibits distinct racial and geographical disparities in its distribution. East Asian populations have a higher incidence of developmental cervical spinal stenosis and a greater prevalence of ossification of the posterior longitudinal ligament, which collectively result in a markedly higher overall morbidity and clinical manifestation rate of CSM compared with Caucasian populations in Europe and the United States[3].The clinical course of CSM is generally characterized by stepwise and progressive deterioration, with highly variable and unpredictable disease progression among individual patients[4]. Given that the natural history of CSM tends to involve irreversible neurological decline, early surgical intervention is critically important. To date, surgical treatment remains the only effective approach to halt neurological deterioration and facilitate functional recovery, with the majority of patients achieving varying degrees of postoperative neurological improvement[5]. Clinically, surgical strategies are selected according to the location of spinal cord compression, the number of involved segments, and the morphological features of the spinal canal. Anterior decompression and fusion is the preferred procedure for single- or two-level anterior compression. Posterior cervical laminoplasty is primarily indicated for multilevel posterior compression and spinal stenosis, while combined anterior-posterior surgery is reserved for complex cases[6]. Nevertheless, a notable subset of patients still experience persistent axial neck pain, incomplete neurological recovery, or recurrent/progressive neurological deficits following surgery[7]. Such suboptimal postoperative outcomes largely stem from the inherent limitations of

conventional radiographic assessment, which frequently results in insufficient spinal cord decompression. The cervical spine exhibits extensive mobility, and spinal canal dimensions as well as the severity of cord compression change dynamically with positional variation. Conventional magnetic resonance imaging (MRI) is acquired exclusively in the neutral posture and therefore cannot visualize position-dependent spinal cord compression. This often leads to misjudgment of symptomatic responsible segments and inappropriate decompression ranges, ultimately impairing postoperative functional recovery and triggering residual or recurrent myelopathic symptoms[8].

Dynamic cervical MRI evaluates spinal cord morphology and compressive alterations during active cervical flexion and extension, thereby unmasking pathological lesions that are invisible on neutral-position sequences. This modality enables comprehensive evaluation of the severity and distribution of compressive segments, thereby guiding individualized surgical planning. In a cohort of 369 patients with CSM, Narvekar et al.[9] performed dynamic cervical MRI and reported that 32.52% of patients exhibited at least one additional compressive segment in extension compared with neutral positioning, while new intramedullary hyperintensity emerged in 4.28% of subjects. Among 1,845 intervertebral segments, 35.39% demonstrated aggravated stenosis on extension scans. Shin et al.[10] Conducted a prospective study enrolling 191 CSM patients with a minimum postoperative follow-up of 24 months. Their data revealed that extension MRI identified extra compressive segments relative to neutral MRI in 122 participants. Subgroup patients who received modified surgical decompression based on dynamic imaging achieved marked improvements in postoperative neurological function. Collectively, dynamic assessment of positional cord compression via cervical dynamic MRI facilitates detection of stenotic segments concealed by static neutral-position imaging. This technique allows accurate localization of symptomatic segments and targeted decompression, overcoming the limitations of conventional static radiological evaluation, improving decompression precision, and lowering the risk of residual postoperative compressive lesions.

This study aimed to compare surgical outcomes between dynamic MRI and conventional MRI protocols; evaluate the clinical value of dynamic MRI in improving neurological function and identifying symptomatic segments in patients with multilevel degenerative CSM; explore factors influencing postoperative neurological prognosis; and provide evidence to support precise clinical decision-making in spinal surgery.

Methods

Ethical approval

This study was approved by the Ethics Committee of the First Affiliated Hospital of Guangxi University of Chinese Medicine (approval number: 2025-080-KY-01) and registered with the Chinese Clinical Trial Registry (http://www.chictr.org.cn, registration number: ChiCTR2600122088, registration date: 2026-04-09). This study was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants for the use of their clinical data. All data were de-identified before analysis.

Study design

This retrospective cohort study included consecutive CSM surgical patients at our institution from January 2020 to January 2025. Patients were assessed in chronological order of surgery dates, with predefined inclusion/exclusion criteria applied sequentially. Only those with complete ≥12-month follow-up were eligible. Inclusion continued independently per group until 100 eligible cases were accumulated. Data were extracted from electronic medical records and imaging archives. Patients were grouped according to the preoperative cervical MRI protocol received: dynamic cervical MRI (n=100) or conventional neutral-position MRI (n=100). Post-hoc power analysis (primary endpoint: postoperative mJOA change; $\sigma=3.5$, $\delta=2.0$, $\alpha=0.05$, power=0.80) indicated 49 patients per group were needed, confirming adequate power. Clinical treatments and perioperative management were

standardized; only the preoperative MRI strategy differed between groups.

Study Population

A retrospective analysis was conducted on patients with cervical spondylotic myelopathy (CSM) who underwent surgical treatment between January 2020 and January 2025. All patients were diagnosed and treated by a team of board-certified surgeons with extensive experience in spinal surgery. All diagnoses were established in accordance with the 2017 AO Spine/CSRS clinical practice guidelines for CSM. As the most prevalent subtype of CSM, CSM is characterized by cervical spinal cord compression secondary to intervertebral disc degeneration, vertebral body osteophyte formation, and ligamentum flavum hypertrophy, with typical upper motor neuron signs[11]. All enrolled patients met the surgical indications for moderate-to-severe CSM as specified in the guidelines, with a preoperative modified Japanese Orthopedic Association (mJOA) score ≤ 14 [12]. The patient selection flowchart is presented in Figure 1.

Inclusion criteria were as follows: (1) fulfillment of the aforementioned clinical and imaging diagnostic criteria for CSM; (2) preoperative mJOA score ≤ 14; (3) age ≥ 18 years; (4) no prior cervical spine surgery; and (5) postoperative follow-up duration ≥ 12 months[13-17].

Exclusion criteria were as follows: (1) concomitant cervical spine trauma, tumor, or infection; or (2) presence of psychiatric or other neurological disorders.

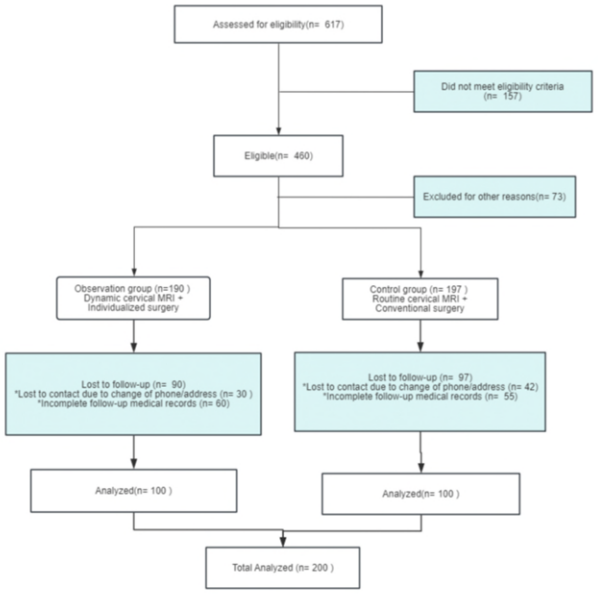


Figure 1. Flow diagram of participant enrollment and exclusion

Imaging examination protocol

1）Patient positioning and MRI protocols

All participants underwent static neutral-position cervical MRI using the same scanner with standardized imaging sequences and parameters. In addition to neutral-position imaging, patients in the observation group underwent dynamic MRI at approximately 30° of cervical flexion and 20° of extension, following the protocol proposed by Muhle et al.[14, 18] with minor angle adjustments as tolerated. Representative scanning position diagrams and corresponding sagittal MRI images are presented in Figure 2. The control group underwent neutral-position scans without additional dynamic sequences. All image assessments were performed using the hospital picture archiving and communication system (PACS).

The primary imaging outcome was the number of cervical spinal cord compressive segments under different postures. On mid-sagittal and axial images obtained at neutral, flexed, and extended positions, segments with definite spinal cord compression were identified and enumerated.

All image assessments were performed independently by two senior spine surgeons who were blinded to group allocation and clinical outcomes. Discrepancies

between the two reviewers were resolved through consensus discussion. To evaluate intra-observer reliability, each reviewer re-assessed all images after a 2-week interval. Intraclass correlation coefficients (ICC) and linear weighted Kappa statistics were used to evaluate intra- and inter-observer reliability for continuous and categorical parameters, respectively; a Kappa value > 0.80 or ICC > 0.80 was defined as excellent agreement[19].

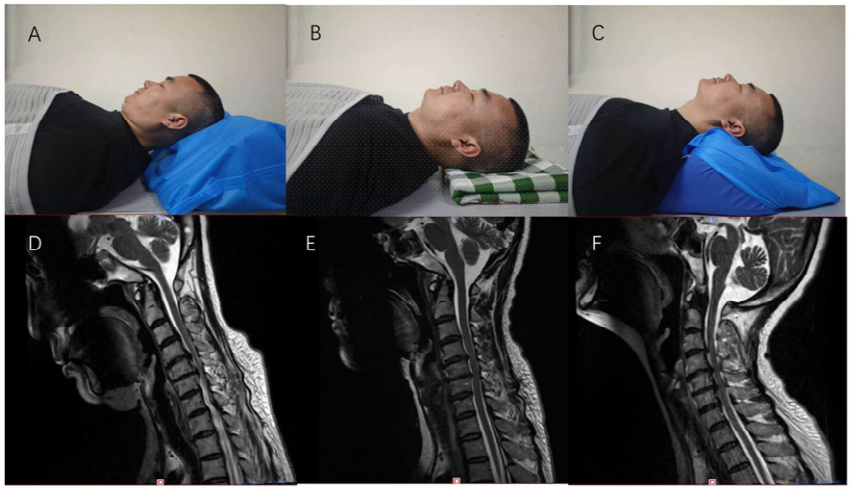


Figure 2. Photographs of supine cervical spine at flexion, neutral and hyperextension positions, and matched sagittal dynamic MRI scans acquired under each posture

2）Cervical spinal stenosis grading

A modified 4-tier MRI grading system was used to assess cervical canal stenosis severity at the most severely compressed segment on dynamic MRI images. Schizas et al. originally proposed a qualitative morphological grading system for lumbar spinal stenosis in 2010[20]. Given the anatomical differences between cervical and lumbar spinal canals and the poor reproducibility of purely qualitative assessment, we adapted the tiered concept of the Schizas system and developed a novel quantitative grading scheme based on sagittal cerebrospinal fluid (CSF) space width measured at three cervical positions. The detailed criteria were defined as follows: Grade 0, CSF space width ≥ 3 mm; Grade 1, ≥ 1 mm and < 3 mm; Grade 2, complete effacement of CSF space (< 1 mm); and Grade 3, spinal cord compression with morphological

deformation.

3）subgroups with modified surgical decompression strategies

Positional differences in compressive segments were defined as the numerical difference in the number of cord-compressed segments between maximal cervical flexion and maximal cervical extension. A positional difference of ≥1 segment was considered clinically significant, reflecting dynamic aggravation or alleviation of cervical spinal cord compression during physiological flexion-extension movements that may be underestimated by conventional static neutral-position MRI. Since positional changes in spinal cord compression could inform intraoperative delineation of decompression scope, selection of fusion segments, and overall surgical planning, patients in the observation group were stratified into subgroups based on dynamic MRI findings. Patients with ≥1 additional compressive segment detected on dynamic MRI that was not visible on neutral-position images, and who consequently underwent extended intraoperative decompression, were categorized into the revised-strategy subgroup. Those without additional compressive segments on dynamic sequences who underwent the originally planned surgery constituted the unchanged-strategy subgroup. This subgroup stratification was performed to evaluate the specific contribution of dynamic compressive features to preoperative surgical planning, intraoperative determination of decompression scope, and long-term postoperative neurological recovery.

Individualized surgical decision strategy

A standardized institutional protocol for CSM surgical approach was adopted: ACDF was routinely indicated for patients with <3 compressive segments, and posterior canal decompression for patients with ≥3 involved segments[21]. Surgical planning for both cohorts complied with this protocol, and all operative strategies were reviewed and confirmed by the spinal surgery team.

Surgical procedures

All surgical procedures were performed by the spinal surgery team at our institution, with routine intraoperative neuromonitoring. Anterior procedures consisted of cervical discectomy, decompression, and interbody fusion with internal fixation; posterior procedures consisted of open-door laminoplasty. Operative protocols, implant specifications, and intraoperative management standards were standardized and identical between the two groups for each respective surgical approach.

Perioperative management

The perioperative management protocol was identical between the two groups. Preoperatively, routine examinations were completed and baseline comorbidities assessed; patients with hypertension, diabetes mellitus, or other comorbidities continued their standardized medical therapy, with strict avoidance of any agents that could interfere with neurological assessment or exacerbate spinal cord injury throughout the study period. Postoperatively, all patients received standardized anti-infective therapy, neurotrophic support, and symptomatic care. Progressive cervical functional rehabilitation training was initiated on postoperative day 3 under the guidance of a specialized rehabilitation physician. Except for individualized adjustment of the decompression range in the observation group based on dynamic MRI findings, perioperative nursing, pharmacological protocols, rehabilitation regimens, and follow-up management standards were uniform between groups.

Follow-up protocol

Uniform outpatient follow-up was arranged for all patients at 6 and 12 months after surgery. Specified researchers documented mJOA scores, neck VAS scores, and NDI throughout follow-up. Follow-up schedules, measured indicators, and assessment standards were consistent between the two cohorts. Only patients with a postoperative follow-up period of at least 12 months were retained. Individuals with incomplete

follow-up data, follow-up less than 12 months, or missing clinical variables were excluded at case screening.

Outcome measures

The primary outcome was postoperative neurological recovery, assessed using the modified Japanese Orthopaedic Association (mJOA) score at 6 and 12 months postoperatively. The mJOA scale is a widely adopted standardized tool for functional evaluation of degenerative cervical myelopathy, covering four domains: (1) upper extremity motor function (0–5 points), (2) lower extremity motor function (0–4 points), (3) sensory function (0–6 points), and (4) sphincter (bladder) function (0–3 points). The total score ranges from 0 to 18, with higher scores indicating better neurological function[22].

Secondary outcomes focused on postoperative pain relief and cervical functional disability. The Visual Analog Scale (VAS), a well-established tool for subjective pain quantification, was utilized to evaluate pain intensity on a 0–10 scale (0 = no pain, 10 = unbearable severe pain). Neck pain (VAS-neck) and upper extremity radicular pain (VAS-arm) were assessed at 6 and 12 months postoperatively [23]. The Neck Disability Index (NDI), adapted from the Oswestry Disability Index, is one of the most commonly used disease-specific patient-reported outcome measures for cervical pain[24]. This scale covers 10 domains: neck pain intensity, personal care, lifting, reading, headache, concentration, work, driving, sleep, and recreation. Each item is scored from 0 to 5, yielding a total raw score of 0–50. The raw score is converted into a percentage, where 0% indicates no functional disability and 100% denotes complete disability, to quantify the impact of cervical pain on daily activities.

All outcome data were collected via standardized case report forms (CRFs) and evaluated by trained independent assessors under blinded conditions. Patient-reported outcomes (VAS and NDI) were collected through face-to-face outpatient follow-up combined with a web-based electronic data capture system to guarantee the integrity and accuracy of all recorded data.

Statistical analysis

Statistical analyses were conducted using SPSS 26.0 and R 4.2.1. Continuous variables were compared using the Mann-Whitney U test or Friedman test, and categorical variables were compared using the chi-square test. Inter-rater reliability was assessed using weighted kappa and intraclass correlation coefficient (ICC). Predictors of surgical revision were screened using LASSO logistic regression, and odds ratios were calculated using multivariable logistic regression. Multiple linear regression was used to analyze prognostic factors for 12-month mJOA. Recovery rates across subgroups were compared using the Kruskal-Wallis test followed by Bonferroni-corrected Dunn's test. A two-sided $P < 0.05$ was considered statistically significant.

Results

Baseline demographic characteristics

A total of 200 patients with CSM were enrolled, with 100 patients in the observation group and 100 in the control group. Baseline demographic, clinical, and radiographic characteristics of the two groups are shown in Table 1. Significant intergroup differences were found in preoperative neutral cervical Cobb angle and preoperative mJOA score, suggesting marginally worse baseline neurological function in the observation group. No significant between-group differences were identified for other variables, including age, body mass index (BMI), preoperative VAS, preoperative NDI, number of compressive segments at neutral position, sex, stenosis grading, and surgical approach (all $P > 0.05$). The distribution of stenosis detection rates across individual cervical segments under neutral, flexed, and extended postures is displayed in the second section of Table 1. Compared with neutral-position MRI, extension scans yielded markedly elevated stenosis detection rates at upper cervical segments (C4/5, C5/6) (all $P < 0.001$), alongside decreased detection rates at C6/7 and C7/T1. Flexion positioning was associated with generally lower detection rates at all

segments, and the total number of identified stenotic segments was reduced relative to neutral imaging. These findings demonstrated that extension sequences facilitated the identification of occult spinal cord compression, whereas flexion posture may partially mask stenotic lesions. Positional changes exerted a substantial impact on the detection of cervical spinal stenosis.

Table 1. Baseline demographic and clinical characteristics of enrolled patients

Part 1. Demographic, clinical and radiological characteristics

Variable	Total (n = 200)	Observation group (n = 100)	Control group (n = 100)	P-value
Age, yr	58.00 (49.00, 67.00)	57.00 (47.75, 66.25)	59.00 (51.00, 67.25)	0.10
BMI, kg/m²	23.88 (21.74, 26.17)	24.26 (22.28, 26.65)	23.61 (21.47, 25.77)	0.09
Sex, n (%)				1.00
Male	98 (49.00)	49 (49.00)	49 (49.00)	
Female	102 (51.00)	51 (51.00)	51 (51.00)	
Preoperative Cobb angle (neutral), °	18.00 (13.00, 21.00)	13.00 (8.00, 17.00)	21.00 (19.00, 25.00)	< 0.001
Preoperative mJOA score	12.00 (11.00, 12.00)	11.00 (9.00, 12.00)	12.00 (11.00, 14.00)	0.00
Preoperative VAS score	5.00 (4.00, 6.00)	6.00 (3.00, 6.00)	4.00 (4.00, 5.00)	0.05
Preoperative NDI score	44.00 (42.00, 46.00)	44.00 (39.00, 47.25)	44.00 (42.00, 46.00)	0.67
Compression grade, n (%)				0.06
Grade 1	66 (33.00)	26 (26.00)	40 (40.00)	
Grade 2	100 (50.00)	58 (58.00)	42 (42.00)	
Grade 3	34 (17.00)	16 (16.00)	18 (18.00)	
Surgical strategy changed, n (%)				< 0.001
Yes	33 (16.50)	33 (33.00)	0 (0.00)	
No	167 (83.50)	67 (67.00)	100 (100.00)	
Surgical approach, n (%)				0.03
Anterior	189 (94.50)	91 (91.00)	98 (98.00)	
Posterior	11 (5.50)	9 (9.00)	2 (2.00)	

Part 2. Segment-specific cervical stenosis distribution at different MRI positions

Cervical segment	Observation group (n=100)			Control group (n=100)	P-value
	Neutral	Extension	Flexion	Neutral position	
C2/3	2 (2.00%)	2 (2.00%)	4 (4.00%)	1 (1.00%)	1.00
C3/4	72 (72.00%)	37 (37.00%)	83 (83.00%)	33 (33.00%)	< 0.001
C4/5	86 (86.00%)	74 (74.00%)	92 (92.00%)	57 (57.00%)	< 0.001
C5/6	82 (82.00%)	70 (70.00%)	96 (96.00%)	62 (62.00%)	0.00
C6/7	44 (44.00%)	24 (24.00%)	28 (28.00%)	25 (25.00%)	0.00
C7/Th1	3 (3.00%)	—	4 (4.00%)	4 (4.00%)	1.00
Total	289.00	207.00	307.00	182.00	—

Notes:
Continuous variables are presented as median (Q1, Q3) and compared using the Mann-Whitney U test.
Categorical variables are presented as n (%) and compared using the Chi-square test.
*** P-values refer to between-group comparisons of neutral-position stenosis rates.**
The control group underwent only neutral-position MRI; dynamic MRI (extension and flexion) was performed exclusively in the observation group.
Abbreviations: BMI, body mass index; mJOA, modified Japanese Orthopaedic Association; VAS, visual analogue scale; NDI, neck disability index.

Preoperative imaging parameters based on dynamic MRI

Intramedullary hyperintensity grading constituted ordinal categorical data, and linear weighted Kappa statistics were adopted to assess inter-rater reliability. The inter-observer weighted Kappa between the two surgeons was 0.858 (95% CI 0.792–0.924, P < 0.001). The intra-observer weighted Kappa for surgeon A was 0.908 (95% CI 0.854–0.962), and that for surgeon B was 0.887 (95% CI 0.823–0.942). All weighted Kappa values exceeded 0.80, indicating excellent reproducibility for intramedullary hyperintensity grading.

All 100 participants in the dynamic MRI observation group completed cervical MRI scans at neutral, flexed, and extended positions, and were further divided into a revised surgical strategy subgroup (n = 33) and an unchanged surgical strategy subgroup (n = 67). The Friedman test revealed significant differences in the number

of detected compressive segments across the three postures ($P < 0.001$). At the extension position, the revised strategy subgroup showed a significantly higher number of compressive segments than the unchanged subgroup ($P = 0.001$), with a more pronounced increase from the neutral position. By contrast, fewer compressive segments were detected under flexion in both subgroups. These observations suggest that positional variation substantially alters the detection of compressive segments. Dynamic extension sequences can capture compressive lesions missed by static neutral MRI, providing radiographic evidence to guide modification of surgical plans. Changes in compressive segment counts across different dynamic MRI positions within the observation group are illustrated in Figure 3, where line graphs connect median values and error bars represent interquartile ranges (Q1–Q3).

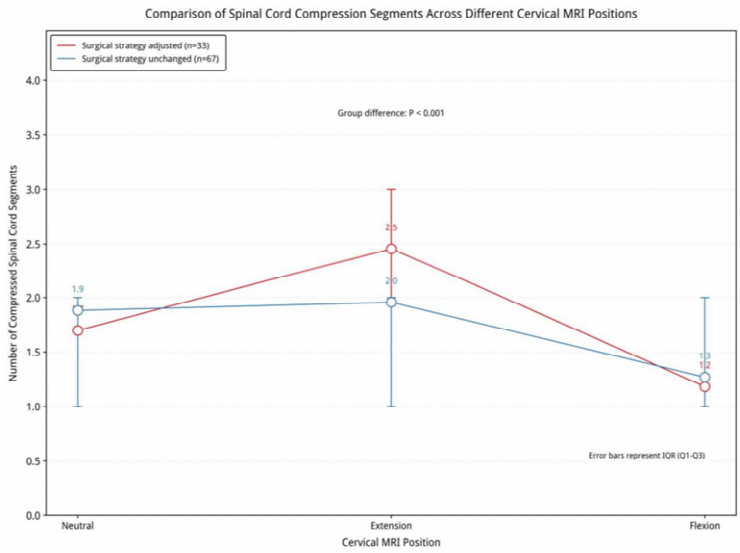


Figure 3. Variations in compressive segment counts across positions among subgroups

Subgroup baseline balance analyses are presented in Table 2. No statistically significant intergroup differences were found in age, BMI, preoperative neutral cervical Cobb angle, preoperative mJOA score, preoperative VAS score, preoperative NDI score, number of compressive segments at neutral and flexed positions, sex, stenosis grading, and surgical approach (all $P > 0.05$). Only the number of compressive segments at maximal extension differed significantly, with higher counts observed in the revised surgical strategy subgroup ($P = 0.010$).

The pattern of changes in compressive segment counts across the three scanning positions differed significantly between the two subgroups ($P < 0.001$). The revised-strategy subgroup showed a progressive increase in compressive segment counts from flexion to neutral to extension. By contrast, the unchanged-strategy subgroup showed minimal variation across all three postures (Figure 3).

These findings suggest that the key distinction prompting modification of surgical plans was primarily associated with additional compressive segments identified on extension dynamic MRI.

Table 2. Baseline and dynamic imaging comparisons of subgroups within the observation group

Variable	Total (n = 100)	Strategy modified (n = 33)	Strategy unmodified (n = 67)	P-value
Age, yr	57.00 (47.75, 66.25)	59.00 (48.00, 67.00)	55.00 (43.00, 65.50)	0.22
BMI, kg/m²	24.26 (22.28, 26.65)	24.50 (21.50, 27.38)	24.22 (22.55, 26.30)	0.78
Preoperative Cobb angle (neutral), °	13.00 (8.00, 17.00)	12.00 (8.00, 17.00)	13.00 (8.00, 15.00)	0.58
Preoperative mJOA score	11.00 (9.00, 12.00)	11.00 (9.00, 12.00)	11.00 (10.00, 12.00)	0.19
Preoperative VAS score	6.00 (3.00, 6.00)	6.00 (3.00, 6.00)	6.00 (4.00, 6.00)	0.55
Preoperative NDI score	44.00 (39.00, 47.25)	43.00 (39.00, 46.00)	44.00 (41.50, 48.00)	0.94
Number of compressed segments (neutral)	2.00 (1.00, 2.00)	2.00 (1.00, 2.00)	2.00 (1.00, 2.00)	0.51
Number of compressed segments (extension)	2.00 (1.00, 3.00)	2.00 (2.00, 3.00)	2.00 (1.00, 2.00)	0.01
Number of compressed segments (flexion)	1.00 (1.00, 2.00)	1.00 (1.00, 2.00)	1.00 (1.00, 2.00)	0.83
Sex, n (%)				0.94
Male	49 (49.00)	16 (48.48)	33 (49.25)	
Female	51 (51.00)	17 (51.52)	34 (50.75)	
Compression grade, n (%)				0.46
Grade 1	26 (26.00)	6 (18.18)	20 (29.85)	
Grade 2	58 (58.00)	21 (63.64)	37 (55.22)	
Grade 3	16 (16.00)	6 (18.18)	10 (14.93)	
Surgical approach, n (%)				0.26
Anterior	91 (91.00)	28 (84.85)	63 (94.03)	
Posterior	9 (9.00)	5 (15.15)	4 (5.97)	

Notes:
Continuous variables are presented as median (Q1, Q3) and compared using the Mann-Whitney U test.
Categorical variables are presented as n (%) and compared using the Chi-square test.
Statistically significant P-values (< 0.05) are indicated in bold in the original analysis.
Abbreviations: BMI, body mass index; mJOA, modified Japanese Orthopaedic Association; VAS, visual analogue scale; NDI, neck disability index.

Functional scores at different follow-up time points

Preoperative mJOA, VAS, and NDI scores were comparable between the two groups (Table 1). At 6 and 12 months postoperatively, all functional scores were significantly improved relative to baseline within both groups (intra-group paired tests, all $P < 0.05$), with further improvement from 6 to 12 months.

Intergroup comparisons revealed significant differences in postoperative mJOA scores. At 6 months, the median mJOA score was 15.0 (IQR, 14.0–17.0) in the observation group versus 15.5 (13.0–16.0) in the control group ($P = 0.020$). At 12

months, the median mJOA score reached 17.0 (16.0–17.0) for the observation group and 16.0 (15.0–17.0) for the control group, with a more pronounced intergroup difference ($P < 0.001$). Similar intergroup differences were observed for VAS and NDI scores at 12 months: the median VAS score was 1.0 (1.0–2.0) in the observation group versus 2.0 (1.0–2.0) in the control group ($P < 0.001$), and the median NDI score was 12.0 (9.8–15.0) versus 14.0 (11.0–18.0) ($P = 0.002$).

Subgroup analyses demonstrated balanced preoperative mJOA, VAS, and NDI values between the revised and unchanged surgical strategy subgroups (all $P > 0.05$). At 6 months, the revised-strategy subgroup presented a higher median mJOA score of 16.0 (15.0–17.0), compared with 15.0 (14.0–17.0) in the unchanged-strategy subgroup ($P = 0.004$). At 12 months, median mJOA scores were 17.0 (16.0–17.0) and 17.0 (16.0–17.0), respectively; despite identical medians, distribution differed significantly between subgroups ($P = 0.027$) with a reduced magnitude of difference. Postoperative VAS and NDI scores remained lower in the revised-strategy subgroup at both time points. Longitudinal trends of all outcome scores across follow-up are shown in Figure 4.

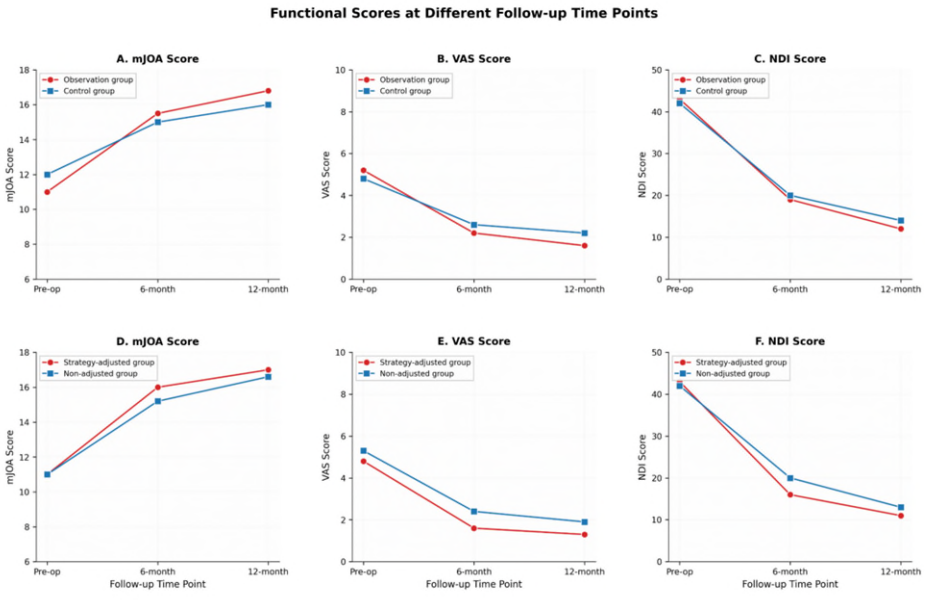


Figure 4. Comparison of dynamic trends in postoperative functional scores

To standardize the assessment of neurological recovery, the 12-month postoperative mJOA recovery rate was calculated for all participants using the

Hirabayashi formula[25]: [(12-month postoperative mJOA score − preoperative mJOA score) / (18 − preoperative mJOA score)] × 100%. The Shapiro-Wilk test confirmed the non-normal distribution of recovery rate data. The median (IQR) recovery rate was 83.3% (71.4–88.9) in the observation group versus 71.4% (55.6–75.0) in the control group, which differed significantly (Mann-Whitney U test, $P < 0.001$).

Subgroup analyses were further performed within the observation group stratified by surgical strategy revision. The median recovery rate was 85.7% (80.0–90.0) in the revised-strategy subgroup (n = 33), 80.0% (66.7–85.7) in the unchanged-strategy subgroup (n = 67), and 71.4% (55.6–75.0) in the control group (n = 100). Kruskal-Wallis test revealed significant differences among the three groups ($P < 0.001$). Post-hoc pairwise comparisons with Dunn's test adjusted by the Bonferroni method showed significant differences between the control group and both subgroups of the observation group (all adjusted $P < 0.001$). No significant difference was observed between the revised and unchanged subgroups after Bonferroni correction ($P = 0.023 > 0.0167$). Distributions of mJOA recovery rates across the three groups are illustrated in Figure 5.

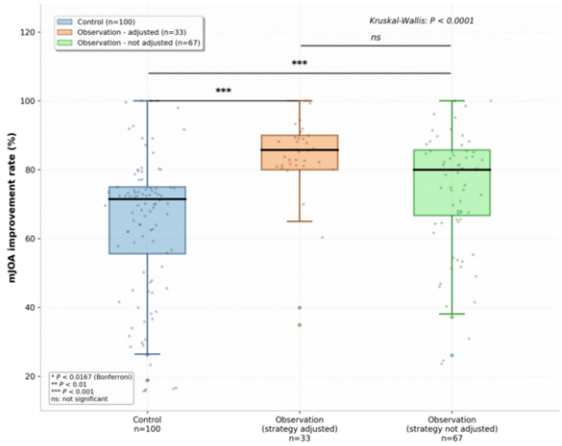


Figure 5. Comparison of 12-month postoperative mJOA recovery rate distribution among three groups

Multivariate regression results

Multiple linear regression analysis of 12-month postoperative mJOA scores in the overall cohort

A multiple linear regression model was constructed in this study to investigate the independent effects of dynamic MRI utilization, surgical plan revision, demographic indicators, radiographic parameters, preoperative functional status, and other confounding covariates on patients' 12-month postoperative mJOA scores. No patients underwent surgical plan revision in the standard MRI control group (revision rate = 0%), whereas the revision rate reached 33% in the dynamic MRI observation group. Because the cross-classification of group assignment and surgical revision status resulted in a structural zero (no patients in the standard MRI group underwent revision), directly incorporating an interaction term would yield unstable parameter estimates and inflated standard errors. To address this issue, the two variables were combined to generate a three-category composite variable: 1) standard MRI group without surgical revision, 2) dynamic MRI group without surgical revision, and 3) dynamic MRI group with surgical revision. Category 2 (dynamic MRI without surgical revision) was designated as the reference group because it represented the largest patient subset and provided the most stable comparator, and dummy variables were created for the regression analysis. The model was simultaneously adjusted for the following covariates: age, sex (female = 1, male = 0), body mass index (BMI), number of compressed segments in neutral position, preoperative Cobb angle in neutral position, surgical approach (anterior = 1, posterior = 2), preoperative mJOA score, and spinal stenosis grading (grade 1 as reference). Collinearity diagnostics revealed variance inflation factors (VIF) ranging from 1.08 to 2.35 across all independent variables, all below the critical cutoff of 5, indicating no clinically meaningful severe multicollinearity. Detailed regression coefficients are presented in Table 3.

Regression analysis identified two significant independent predictors of the 12-month postoperative mJOA score: the preoperative mJOA score and a

three-category composite variable that integrates group assignment and surgical revision status. The preoperative mJOA score exhibited a positive independent association with long-term neurological outcomes (β = 0.27, 95% CI: 0.18–0.35, P < 0.001). After adjustment for confounders, each one-point elevation in baseline mJOA corresponded to an average 0.27-point increase in the 12-month postoperative mJOA score. Statistically significant intergroup differences were detected via the composite variable. First, relative to patients in the dynamic MRI group without surgical revision, individuals receiving revised surgical plans guided by dynamic MRI achieved an average 0.60-point higher mJOA score at 12 months postoperatively (β = 0.60, 95% CI: 0.12–1.08, P = 0.015), suggesting that surgical modification based on dynamic MRI is associated with superior long-term neurological function. Second, among patients without surgical revision, those in the standard MRI control group had an average 0.78-point lower 12-month postoperative mJOA score compared with the dynamic MRI observation group (β = −0.78, 95% CI: −1.25–−0.31, P = 0.001), suggesting that dynamic MRI assessment itself is independently associated with improved postoperative functional recovery. No other covariates (age, sex, BMI, number of compressed segments in neutral position, preoperative Cobb angle in neutral position, surgical approach, or stenosis grading) showed significant independent associations with the 12-month postoperative mJOA score (all P > 0.05).

Table 3. Multivariable regression for 12-month postoperative mJOA score

Variables	B	95% CI	P value
Observation group-strategy modified (vs Observation group-no modification)	0.60	0.12, 1.08	0.015
Control group-no modification (vs Observation group-no modification)	−0.78	-1.25, -0.31	0.001
Sex (female = 1, male = 0)	−0.11	-0.43, 0.22	0.517
Age	−0.00	-0.02, 0.01	0.584
BMI	−0.03	-0.08, 0.02	0.192
Number of compressed segments in neutral position	0.13	-0.10, 0.35	0.278
Preoperative Cobb angle in neutral position	−0.00	-0.03, 0.03	0.997
Surgical approach (posterior = 2, anterior = 1)	−0.13	-1.03, 0.77	0.774
Preoperative mJOA score	0.27	0.18, 0.35	<0.001
Compression grade 2 (vs grade 1)	0.00	-0.37, 0.37	0.999
Compression grade 3 (vs grade 1)	0.41	-0.13, 0.94	0.133

LASSO regression and multivariable logistic regression analyses of dynamic MRI subgroups

Within the dynamic MRI observation group (n = 100), LASSO logistic regression was performed to identify potential predictors of surgical strategy revision. Candidate variables included age, sex, body mass index (BMI), number of compressed segments in neutral position, positional difference value (extension minus flexion), preoperative Cobb angle in neutral position, spinal stenosis grading (grades 1, 2, and 3; grade 1 as reference, with grades 2 and 3 entered as separate dummy variables), and surgical approach. Ten-fold cross-validation was used to identify the optimal penalty parameter λ based on binomial deviance, and the parsimonious model was constructed based on λ_{1se} (the largest value of λ within one standard error of the minimum cross-validation error). The coefficient shrinkage trajectory and cross-validation error curve are shown in Figure 6.

At λ_{1se}, only the positional difference value retained a non-zero coefficient following LASSO regression; the number of compressed segments in neutral position, spinal stenosis grading, preoperative Cobb angle in neutral position, surgical approach, sex, BMI, and age were all penalized to zero and excluded from the model. LASSO logistic regression was employed for variable selection. To ensure adequate adjustment for established confounders, age and preoperative mJOA score were

retained in the subsequent multivariable model regardless of LASSO selection, based on their validated prognostic significance in prior studies[26]. Multivariable logistic regression was then conducted with surgical strategy revision (yes/no) defined as the binary outcome.

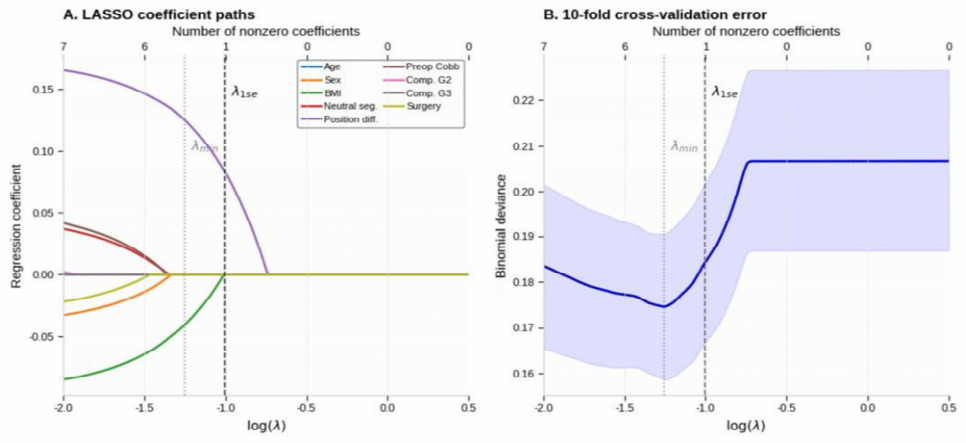


Figure 6. LASSO logistic regression for variable selection. (A) Coefficient paths; at λ1se (vertical dashed line), only positional difference value (dark blue) retained a non-zero coefficient. (B) Ten-fold cross-validation binomial deviance curve; λ1se (right dashed line) was selected by the one-standard-error rule. Shaded regions denote mean ± 1 SE.

The regression results revealed a significant positive association between positional difference value and surgical strategy revision (OR = 2.669, 95% CI: 1.460–4.878, P = 0.001). Specifically, each one-segment increase in the difference between extension and flexion compressive segments raised the odds of surgical plan modification by a factor of 2.669. Neither age (OR = 1.012, 95% CI: 0.976–1.049, P = 0.525) nor preoperative mJOA score (OR = 0.944, 95% CI: 0.733–1.215, P = 0.654) showed statistically significant independent associations with surgical strategy revision. The C-statistic of this model was 0.713, indicating moderate discriminative ability. The Hosmer-Lemeshow goodness-of-fit test yielded P = 0.306 > 0.05, which suggested no significant discrepancy between model-predicted probabilities and

observed outcomes, consistent with adequate model fit without substantial lack-of-fit. Detailed regression parameters are summarized in Table 4.

Table 4. Factors associated with surgical revision: multivariable logistic regression (dynamic MRI observation group)

Variable	B	P-value	OR	95% CI
Postural Difference	0.982	0.001	2.669	1.460, 4.878
Age	0.012	0.525	1.012	0.976, 1.049
Preoperative mJOA	-0.058	0.654	0.944	0.734, 1.215

Postoperative complications

No severe neurological complications such as acute spinal cord injury or compressive epidural hematoma were observed during follow-up. Postoperative complications occurred in 9 of 100 patients (9.0%) in the observation group and 7 of 100 patients (7.0%) in the control group, with no statistically significant between-group difference in the overall complication rate (P = 0.795). The breakdown of complications was as follows: the observation group included 4 cases of axial neck pain, 2 cases of transient C5 nerve root palsy, 2 cases of dysphagia, and 1 case of superficial wound infection; the control group included 3 cases of axial neck pain, 2 cases of transient C5 nerve root palsy, 1 case of cerebrospinal fluid leakage, and 1 case of superficial wound infection. Given the small number of events, individual complication types were not compared statistically between groups.

With respect to reoperation, 1 patient in the observation group and 5 patients in the control group underwent revision surgery, and the intergroup difference was not

statistically significant (P = 0.212).

Discussion

This retrospective cohort analysis demonstrated that individualized decompression strategies guided by preoperative dynamic MRI significantly improved postoperative neurological recovery in patients with cervical spondylotic myelopathy (CSM). Previous studies have shown that dynamic MRI efficiently identifies position-dependent spinal canal stenosis invisible on neutral-position scans, thereby shifting surgical decompression planning from indirect inference based on static imaging to precise targeting of position-related pathological compression and enhancing the adequacy of neural decompression[17, 27]. A cohort study by Dalbayrak et al[13] involving 258 CSM patients reported that the sagittal diameter of the spinal canal decreased by a mean of 0.94 mm and the severity of stenosis increased by 13.4% in cervical extension relative to neutral posture. Prost et al[28] further observed that dynamic MRI altered surgical plans in a substantial proportion of participants, and patients receiving revised operative strategies achieved substantially higher postoperative mJOA scores and neurological recovery rates. The present study produced consistent results with these prior reports while providing more precise quantitative estimates of clinical benefits. The median 12-month mJOA recovery rate reached 83.33% in the dynamic MRI observation group, a 12-percentage-point improvement compared with 71.43% in the control group ($P < 0.001$). Moreover, these functional gains were heterogeneous across subgroups: only patients in the revised-strategy subgroup (n = 33) exhibited a significantly higher median recovery rate of 85.71%, whereas no statistically significant difference was detected between the unchanged-strategy subgroup (80.00%) and the control group. These findings suggest that dynamic MRI yields prognostic benefits only when compressive lesions identified on dynamic sequences prompt responsive adjustment of surgical decompression plans; diagnostic information alone is insufficient.

Further comparisons of compressive segment counts among the three scanning

positions in the present study demonstrated that the number of spinal cord compressive segments identified at maximal extension was significantly greater than those detected at neutral and maximal flexion positions, with the C5/6 segment being the most frequently involved. Conversely, fewer compressive segments were observed in flexion compared with the neutral posture. Studies by Makhchoune et al and Shin et al have confirmed that cervical extension reduces the sagittal diameter of the spinal canal[10, 14]. Ventral intervertebral discs together with inward-buckled posterior ligamentum flavum compress the thecal sac and cervical spinal cord. These dynamic morphological alterations form the anatomical basis of position-dependent neurological symptoms in patients with CSM. Conversely, several previous studies have reported more severe spinal cord compression under cervical flexion[29]. During forward flexion, the spinal cord becomes stretched and flattened, and ventral osteophytes may produce anterior compression on the taut cord. The present findings further quantified the direction and magnitude of positional differences, extending the observations of Shin et al. Within the observation group, patients in the revised-surgery subgroup had significantly more compressive segments at maximal extension than those in the unrevised subgroup ($P = 0.010$), accompanied by pronounced variations in segment counts across the three positions. In contrast, minimal fluctuations were seen across all postures in the unrevised-strategy subgroup. This distinct pattern indicates that additional compressive lesions primarily visualized on extension MRI act as the primary imaging indicator driving modifications to surgical decompression plans.

This study revealed the unique clinical value of dynamic MRI in CSM surgery. Whole-cohort multiple linear regression identified the three-category composite variable (imaging group and surgical revision status) as an independent predictor of 12-month postoperative mJOA score: compared with the unrevised dynamic MRI subgroup, the standard MRI group had a 0.78-point lower mJOA score ($P = 0.001$), and the revised dynamic MRI subgroup had a 0.60-point higher score ($P = 0.015$). This result can be interpreted in two ways. First, for patients in whom dynamic MRI identified occult compression requiring expanded decompression, the improved

neurological prognosis resulted from detecting extension-position-specific lesions and guiding surgical revision; the revised subgroup achieved an 85.7% recovery rate. Second, for patients whose surgical plans remained unchanged, dynamic MRI served as confirmatory imaging to exclude hidden compression and prevent inadequate decompression. In contrast, the control group, which relied solely on static MRI, failed to identify occult compression requiring expanded decompression, resulting in an overall recovery rate of 71.4%. This stratification effect may explain the superior outcomes of both dynamic MRI subgroups relative to controls. Notably, no significant difference existed between the two subgroups within the observation group after Bonferroni correction for multiple comparisons ($P = 0.023 > 0.0167$). In summary, the prognostic benefits of dynamic MRI derive from optimized surgery for patients with positive dynamic findings and confirmation of adequate decompression for those with negative findings, collectively reducing the risk of incomplete decompression. However, LASSO logistic regression selected only the extension-flexion difference in compressive segment counts as a predictor of surgical revision, while all other baseline variables were shrunk to zero by the LASSO penalty. These findings indicate that standard preoperative clinical and static imaging features cannot predict whether surgical plans would be altered based on dynamic MRI findings. Therefore, dynamic MRI is recommended as a routine preoperative assessment for all CSM patients undergoing surgical planning, particularly those with multilevel degeneration, equivocal symptomatic segments, or dynamic myelopathy.

Regarding safety, despite extended decompression in 33 patients guided by dynamic MRI, the overall complication rate was comparable between groups (9.0% vs 7.0%, $P = 0.795$), and the reoperation rate was lower in the observation group (1.0% vs 5.0%). Clinically, expanded decompression is often feared to increase the risk of postoperative axial neck pain. Axial neck pain is attributed to disruption of posterior cervical muscle insertions and injury to the C7 spinous process and nuchal ligaments. Such structural damage shortens the posterior cervical moment arm and disrupts posterior tension band integrity, representing a primary mechanism of pain following extensive decompression[30, 31]. A prospective cohort study by Hosono et al[32]

reported an early axial pain rate of 50% in patients undergoing wide decompression versus 16% in those with limited decompression (P = 0.006). The incidence of intractable long-term axial neck pain decreased from 29% to 5.4% with narrower decompression ranges (P = 0.015), indicating that sparing C7 muscular attachments and limiting the number of decompressed segments substantially reduces axial pain. Nevertheless, our findings contradict this concern. Extended decompression guided by dynamic MRI is lesion-directed rather than indiscriminate, restricted to segments with occult compression identified on dynamic sequences. This strategy prevents residual symptoms and reduces reoperation attributable to insufficient decompression. Accordingly, individualized decompression guided by dynamic MRI does not increase surgical risk, offers the potential benefit of lower long-term reoperation rates, and is associated with favorable long-term safety and cost-effectiveness.

An important consideration in interpreting our findings is the baseline imbalance between groups. Patients in the dynamic MRI group exhibited lower preoperative mJOA scores and more pronounced cervical kyphosis (smaller Cobb angles) compared with the control group, suggesting more severe baseline neurological impairment and spinal deformity. We attribute this imbalance to clinical selection dynamics: patients with more severe or ambiguous symptoms—particularly those with position-dependent myelopathic signs that are poorly characterized on neutral-position imaging—are more likely to be referred for dynamic MRI evaluation. Consequently, the dynamic MRI cohort represented a higher-risk population with greater preoperative disease burden. This baseline imbalance has critical implications for the interpretation of our results. Despite worse preoperative status, the dynamic MRI group achieved significantly higher mJOA recovery rates (83.3% vs. 71.4%, P<0.001) and superior functional outcomes at 12 months. Had the two groups been perfectly balanced at baseline, the observed advantage of dynamic MRI guidance would likely have been even more pronounced. In this respect, the baseline imbalance operates as a conservative bias: it works against the study hypothesis, yet the dynamic MRI strategy still demonstrated superior outcomes. This pattern strengthens, rather than undermines, the conclusion that individualized surgical planning based on

dynamic imaging confers genuine clinical benefit.

This study has several limitations. First, its single-center retrospective design may reduce external validity. Second, follow-up was limited to 12 months. Although major neurological recovery typically occurs within 6–12 months postoperatively, long-term outcomes such as delayed adjacent segment degeneration over 5 years remain to be evaluated[33-35]. Third, the sample size of the dynamic MRI subgroup (n = 100) was relatively small for definitive subgroup analysis; therefore, multicenter prospective trials are warranted to validate our conclusions.

Conclusion

Preoperative dynamic MRI is recommended as a routine assessment for CSM patients with multilevel degeneration, ambiguous culprit segments, or position-dependent myelopathic symptoms. Because standard neutral-position MRI cannot reliably exclude dynamic occult spinal cord compression, dynamic MRI should be implemented for all CSM candidates undergoing surgical treatment to optimize decompression planning and reduce reoperation risk.

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Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Publication Consent

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

S.Y. and Y.Z. conceived and designed the study. S.Y., G.W., and H.S. collected and analyzed the data. S.Y. drafted the manuscript. Y.Z. critically revised the manuscript. All authors read and approved the final manuscript.

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