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Differential Impact of C2-7 Sagittal Vertical Axis on Postoperative Axial Symptoms in Laminoplasty vs Laminectomy With Fusion: A Propensity Score–Trimmed Retrospective Cohort Study

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Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

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Background: This study investigated the association between postoperative C2-7 sagittal vertical axis (SVA) and axial symptoms after posterior cervical surgery, and explored whether this association differed between open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF).

Material/Methods: This single-center retrospective cohort study included 64 patients with MCSM, including 33 in the LP group and 31 in the LF group, after propensity score–based trimming and covariate balance assessment. Cervical sagittal parameters, range of motion (ROM), and clinical outcomes were evaluated preoperatively and during 2 to 3 years of follow-up. Logistic regression and receiver operating characteristic (ROC) analyses were performed as exploratory analyses.

Results: The incidence of axial symptoms did not differ significantly between the LP and LF groups (21.2% vs 32.3%, $P=0.40$). Both groups showed significant improvements in visual analog scale, Japanese Orthopaedic Association, and Neck Disability Index scores. Compared with LP, LF was associated with greater postoperative changes in C2-7 SVA, C2-7 Cobb angle, C7 slope, and ROM reduction. Postoperative C2-7 SVA was associated with AS. Exploratory ROC analyses suggested optimal C2-7 SVA cutoffs of 3.46 cm in the LP group and 3.10 cm in the LF group. The group × C2-7 SVA interaction was statistically significant but based on a small number of axial symptom events.

Conclusions: Postoperative C2-7 SVA may be associated with axial symptoms, and this association appeared stronger after LF in this small cohort. All ROC-derived thresholds and interaction findings are exploratory, hypothesis-generating, and not clinically actionable, pending validation in larger prospective studies.

Keywords: **Cervical Vertebrae • Neurosurgery • Spinal Cord Compression**

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Introduction

Cervical sagittal balance has attracted increasing attention, as it plays a pivotal role in maintaining cervical lordosis and predicting clinical outcomes [1,2]. Changes in cervical sagittal balance following surgery should not be overlooked, and relevant studies have confirmed that poor cervical sagittal alignment can adversely affect prognosis [3,4]. Open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) are 2 commonly performed surgical procedures with distinct characteristics [5,6]. Although both procedures can alleviate neurological pain, postoperative complications, including axial symptoms (AS), remain a key concern. After cervical spine surgery, patients can develop chronic AS and stiffness, which can disrupt their work and daily life. The incidence of AS associated with posterior cervical approaches ranges from 5.0% to 60%, and its etiology remains unclear [7,8]. Some studies have indicated an association between AS and reduced cervical range of motion (ROM) postoperatively [9,10].

Despite existing research confirming the correlation between sagittal balance and postoperative prognosis, as well as identifying AS as a common complication, most studies have either separately explored the association between sagittal parameters and AS or merely compared the clinical outcomes of LP and LF [11,12]. Notably, Benek et al [13] recently reported comparable neurological recovery between the 2 procedures in multilevel cervical spondylotic myelopathy (MCSM) but highlighted significant differences in cervical alignment preservation and postoperative axial pain, suggesting that surgical approach may modify the relationship between sagittal parameters and clinical outcomes. However, few studies have systematically investigated this modifying effect. LP preserves segmental mobility through limited bone resection, while LF achieves rigid fixation via fusion, which may alter sagittal force distribution and reduce compensatory capacity for mild imbalance [14,15]. This biomechanical divergence could lead to differential AS risk, but this hypothesis remains untested. Therefore, we aimed to investigate whether the association between postoperative C2-7 SVA and AS differs between LP and LF in patients with MCSM.

Material and Methods

Ethics Statement

This single-center retrospective cohort study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Anhui Provincial Hospital (approval No. 2024-RE-401). Written informed consent for surgery was obtained from all patients before the operation. The requirement for additional informed consent for this retrospective analysis was waived by the ethics committee because anonymized clinical and radiographic data were used.

Sample Size Calculation

Based on preliminary data and literature, we initially planned to recruit 86 patients (43 per group [16,17]). However, due to strict inclusion and exclusion criteria and missing follow-up data, only 64 patients met the eligibility criteria for final analysis (33 in the LP group and 31 in the LF group). We acknowledge that the final sample size did not meet the a priori calculation requirements, with a post hoc statistical power of 72.3% (calculated based on the primary outcome, ie, incidence of AS, with an effect size of 0.35, alpha = 0.05, 2-tailed). Therefore, the results should be considered preliminary and require further validation in larger-sample studies. The incidence of AS in this study was 26.6% (17/64) in the total sample (21.2% in the LP group and 32.3% in the LF group), resulting in a power of 72.3%.

Patient Enrollment and Selection

A total of 145 patients with MCSM who underwent posterior cervical surgery at our institution between January 2018 and January 2022 were initially identified. Patients were excluded if they met any of the following criteria (**Figure 1**): severe cervical kyphosis with a C2-7 Cobb angle < 0° (n = 4); preoperative severe AS with a visual analog scale (VAS) score ≥ 7 (n = 5); cervical fractures, tumors, infectious spondylitis, or ossification of the posterior longitudinal ligament (n = 6); previous cervical surgery (n = 4); systemic diseases affecting pain perception or bone healing, such as rheumatoid arthritis and poorly controlled diabetes (n = 3); cognitive impairment or inability to communicate, which prevents reliable symptom reporting (n = 3); and incomplete data (follow-up < 2 years [n = 4]; missing radiographs/scores [n = 4]).

After the initial exclusions, 112 patients were eligible. An additional 36 patients were excluded because of follow-up less than 2 years (n = 18), missing radiographs or clinical scores (n = 12), or cognitive impairment/inability to communicate (n = 6), leaving a final cohort of 76 patients (37 in the LP group and 39 in the LF group). These 76 patients underwent propensity score–based trimming. Twelve patients were excluded during propensity score trimming due to extreme baseline characteristics with no acceptable matches: 4 patients in the LP group with 5 or more degenerative segments, 4 patients in the LF group with preoperative vertebral instability (slippage ≥ 3 mm), and 4 patients in the LF group with severe osteoporosis (T-score < -2.5). Final analysis included 64 patients: 33 in the LP group, and 31 in the LF group.

All surgeries were performed by the same team of spinal surgeons, with 10 or more years of cervical surgery experience, to

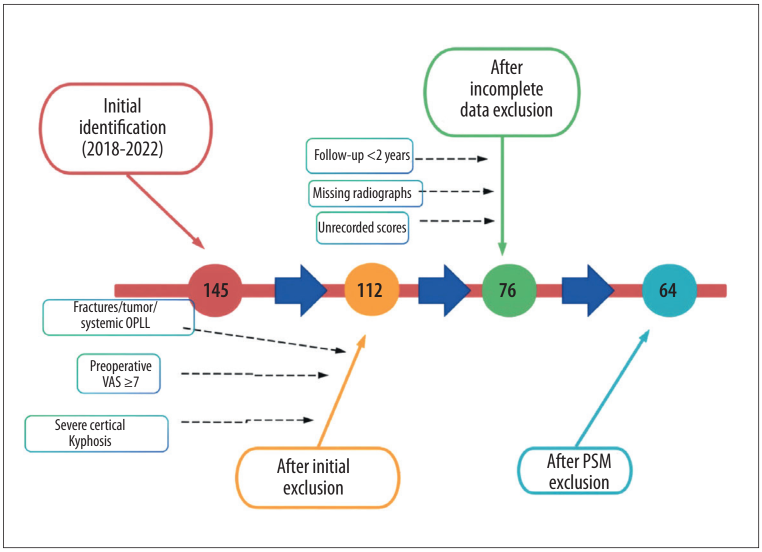


Figure 1. Flowchart of patient enrollment. Notes: Patients initially identified between 2018 and 2022 (n = 145); initial exclusions due to severe kyphosis, preoperative VAS score ≥7, ossification of the posterior longitudinal ligament (OPLL), and other exclusion criteria (n = 33); exclusions due to incomplete data, including follow-up < 2 years or missing radiographic data (n = 36); propensity score matching (PSM), with patients having extreme unmatched baseline characteristics excluded (n = 12); final study cohort included 64 patients.

minimize inter-operator bias. The surgical team composition remained consistent throughout the study period, with procedures performed or supervised by the same senior spine surgeons and assisted by surgeons from the same department, following standardized operative protocols. Somatosensory evoked potentials were used intraoperatively to prevent spinal cord injury; complications, such as dural tear and implant malposition, were recorded in real time.

Propensity Score–Based Trimming and Covariate Balance Assessment

To reduce selection bias in this retrospective cohort, we performed propensity score–based trimming followed by covariate balance assessment rather than strict 1: 1 matching. Propensity scores were estimated using a logistic regression model including age, sex, preoperative C2-7 SVA, preoperative C2-7 Cobb angle, preoperative VAS score, number of degenerative segments, and vertebral stability. Patients with extreme propensity scores and no adequate overlap between the LP and LF groups were excluded to improve comparability between groups.

Before trimming, 76 patients were eligible for analysis, including 37 patients in the LP group and 39 patients in the LF group. Twelve patients were excluded because their baseline profiles were outside the common support region: 4 LP patients with 5 or more degenerative segments, 4 LF patients with preoperative vertebral instability defined as slippage of 3 mm or greater, and 4 LF patients with severe osteoporosis, defined as a T-score below -2.5. After trimming, 64 patients remained for final analysis, including 33 in the LP group and 31 in the LF group.

Covariate balance was assessed using standardized mean differences (SMDs), with SMD < 0.20 considered acceptable. After trimming, all baseline variables achieved SMD < 0.20, indicating adequate balance between groups.

Radiological Measurement

Two spine surgeons with at least 3 years of clinical experience independently measured each parameter twice with ImageJ 1.8.0 software. The mean of these measurements was used for subsequent analysis. The test-retest reliability of 20 randomly selected X-ray images was evaluated, and the intraclass correlation coefficient for C2-7 SVA was 0.88 (95% CI, 0.76-0.94), indicating good inter-rater consistency.

C2-7 SVA was selected as the primary sagittal parameter for this study because it directly quantifies the horizontal offset between the head's center of gravity and the cervical spine base, which is the most direct determinant of paravertebral muscle load and compensatory effort. In contrast, global alignment parameters such as T1 slope are often obscured by the sternum on standard lateral cervical radiographs, leading to higher measurement variability [18,19]. Previous studies have also consistently identified C2-7 SVA as the most sensitive predictor of postoperative AS in posterior cervical surgery [13,20].

Longitudinal Data Collection

Clinical and radiological data were collected at 3 time points: preoperatively, 1 month postoperatively, and at the last follow-up (2-3 years). A flowchart was used to track data completeness (**Figure 1**).

Surgical Methods

All patients underwent general anesthesia, were placed in the prone position, and had their heads fixed on a Mayfield head

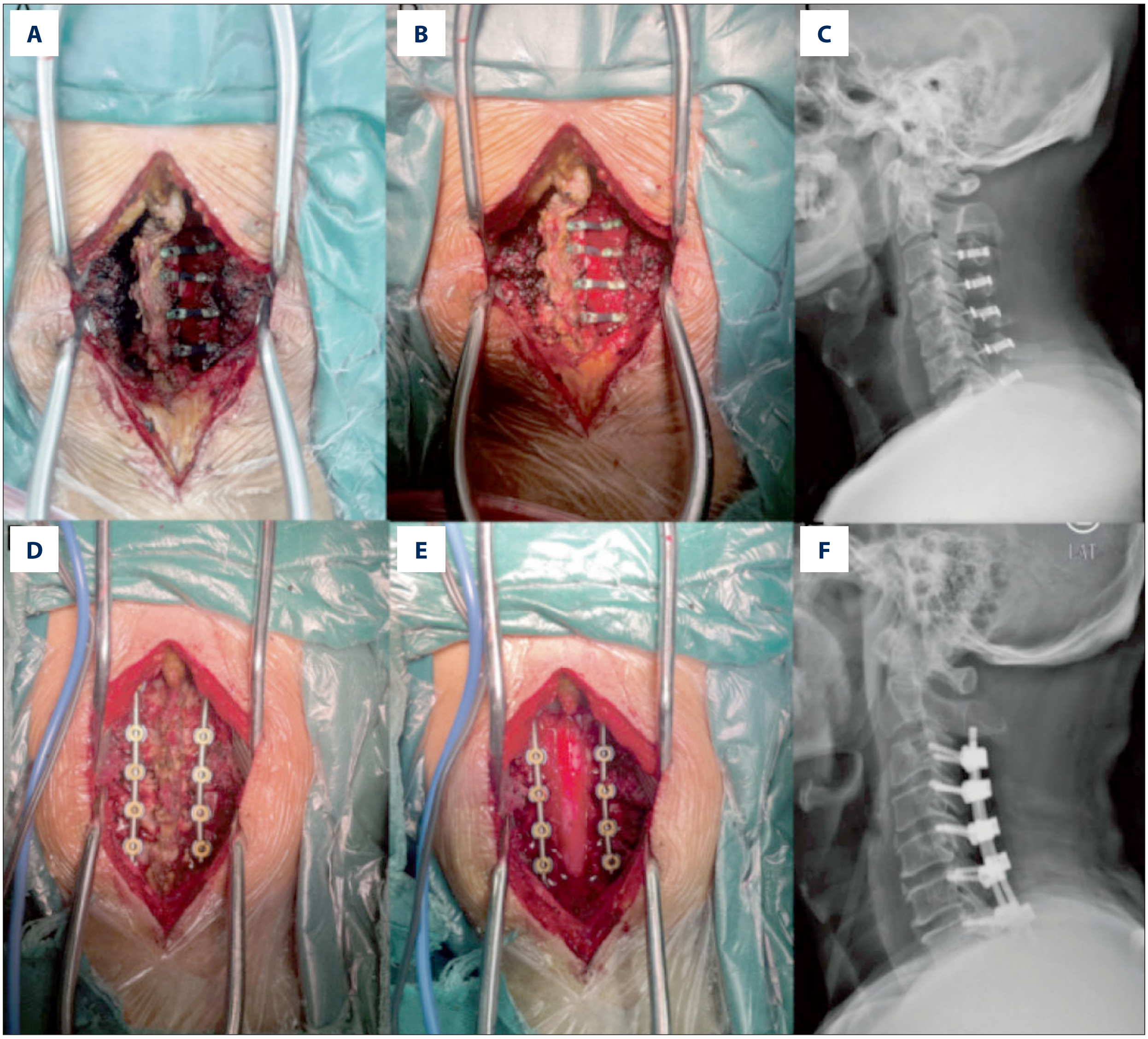


Figure 2. Intraoperative and postoperative imaging photos of the 2 procedures: open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF). (**A-C**) LP group; (**D-F**) LF group.

frame to maintain the neutral position of the cervical spine. Both surgical procedures preserved the rectus capitis posterior major and minor muscles attached to the spinous process of C2.

In the LP group (open-door expansive laminoplasty), patients were placed in the prone position. Sterilization and draping of the surgical field were performed first, followed by a midline posterior cervical incision to fully expose the surgical field. The open-door (lamina elevation) and hinge (partial cortical preservation) sides were established as follows: (1) the open-door side was created by resecting the lamina of the target segment along the inner edge of the laminofacet junction from inferior to superior using a rongeur; (2) the hinge side was prepared by creating a groove in the lateral cortical bone with a high-speed burr while preserving part of the cortex; and (3) after decompression, the ligamentum flavum was dissected and removed, the lamina was rotated toward the hinge side, and Y-shaped cervical laminoplasty plates (Fule Technology, Beijing, China) were used to maintain spinal canal expansion (**Figure 2A-2C**).

In the LF group (total laminectomy with fusion), positioning, sterilization, and draping were identical to those in the LP group. The surgical procedure consisted of the following steps: (1) the laminae and lateral masses of the preoperatively planned surgical segments (C3-6 or C3-7) were fully exposed, followed by placement of titanium alloy lateral mass screws (3.5 mm in diameter, 14-16 mm in length; Fule Technology, Beijing, China) and connecting rods (3.5 mm in diameter) to achieve rigid posterior fixation across all planned fusion segments; (2) the

Table 1. Comparison of baseline characteristics between the open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) groups before and after propensity-score-based trimming.

Variable	Before trimming				After trimming			
	LP (n = 37)	LF (n = 39)	SMD	*P*	LP (n = 33)	LF (n = 31)	SMD	*P*
Sex (n)	20/17	26/13	0.25	0.28	19/14	18/13	0.05	0.96
Age (years)	57.3 ± 8.1	56.1 ± 8.3	0.15	0.51	57.5 ± 7.5	57.1 ± 9.4	0.05	0.84
Surgical segments (n)	4/33	4/35	0.06	0.94	4/29	3/28	0.06	0.75
Disease durations (months)	17.8 ± 7.9	18.1 ± 8.3	0.04	0.87	18.2 ± 7.5	17.6 ± 8.1	0.08	0.76
Unstable/stable vertebral stability (n)	9/28	11/28	0.05	0.73	9/24	9/22	0.02	0.91
Pre-op C2-7 Cobb (°)	16.3 ± 3.0	16.9 ± 4.2	0.16	0.45	16.3 ± 3.3	16.7 ± 4.8	0.10	0.71
Pre-op C2-7 SVA (cm)	2.10 ± 1.14	2.00 ± 1.10	0.09	0.74	1.96 ± 0.98	1.89 ± 0.92	0.08	0.77
Pre-op C7 slope (°)	17.5 ± 2.8	18.4 ± 3.8	0.28	0.22	17.5 ± 2.8	18.3 ± 3.8	0.18	0.38
Pre-op ROM (°)	26.4 ± 3.2	25.8 ± 3.1	0.20	0.40	26.2 ± 3.6	25.8 ± 3.1	0.15	0.63
Pre-op VAS	5.0 ± 1.6	5.6 ± 1.4	0.40	0.07	5.2 ± 1.8	5.6 ± 1.5	0.13	0.34

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. Note: Vertebral stability definition: stable = vertebral slippage < 3 mm on cervical dynamic radiographs; unstable = vertebral slippage ≥ 3 mm. Abbreviations: SMD, standardized mean difference; SVA, sagittal vertical axis; ROM, range of motion; VAS, visual analog scale.

Table 2. The grade of axial symptoms according to visual analog scale (VAS) score.

Grade	Clinical manifestations	Functional impact & management	VAS
Excellent	No neck discomfort, tenderness, or muscle spasm	No impact on daily life; no analgesics required	0-2
Good	Mild stiffness (resolves spontaneously) after fatigue/cold	No impact on work/life; no analgesics required	0-2
Fair	Frequent symptoms; mild tenderness/spasm	Impairs daily work/life; oral analgesics (good relief)	3-6
Poor	Persistent symptoms; obvious tenderness/ severe muscle spasm	Severe impairment of daily activities; oral analgesics (poor relief)	7-10

ligamentum flavum was dissected and removed, and the laminae of the target segments were completely released with a rongeur and resected using an ultrasonic scalpel to fully expose the dural sac and achieve adequate spinal cord decompression; and (3) the connecting rods were contoured to restore the patient's preoperative cervical lordosis and secured with screw caps. Lateral mass screws were inserted perpendicular to the coronal plane of the lateral mass with a 15° to 20° cephalad trajectory (**Figure 2D-2F**).

Clinical Assessment

Preoperative baseline characteristics of the patients were collected, including age, sex, disease duration, number of surgical segments, preoperative neurological function scores, and preoperative cervical sagittal parameters (C2-7 Cobb angle, C2-7 SVA, and C7 slope). Disease duration was comparable between the 2 groups after propensity score–based trimming (LP: 18.2 ± 7.5 months vs LF: 17.6 ± 8.1 months, $P = 0.76$; full data presented in **Table 1**). Neurological function was assessed using the Japanese Orthopaedic Association (JOA) score (0-10 points, with higher scores indicating better neurological function), the Neck Disability Index (NDI; 0-100 points, with lower scores indicating less disability), and the VAS (0-10 points, with lower scores indicating less pain).

AS Grading and Assessment

AS (diffuse neck/shoulder pain) were graded according to **Table 2**, with "excellent/good" defined as no AS and "fair/poor" defined as AS. To align this grading system with the clinical definition of AS (VAS ≥ 3), corresponding VAS ranges were

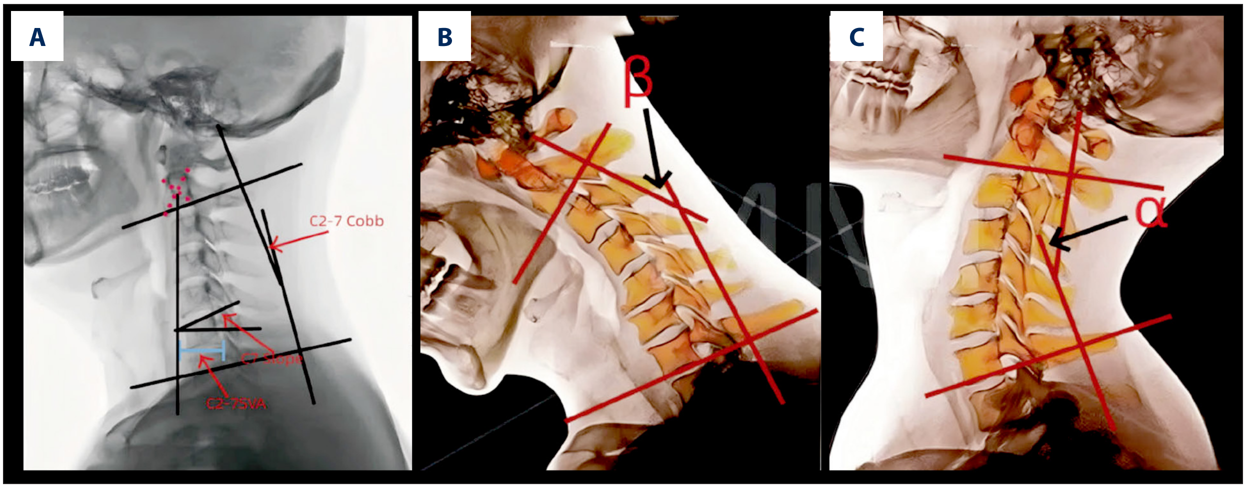


Figure 3. (**A**) Measurement of sagittal cervical parameters. C2-7 Cobb angle: the angle between the inferior endplates of C2 and C7. C2-7 sagittal vertical axis (SVA): the horizontal distance between the center of C2 and the posterior edge of the superior endplate of C7. C7 slope: the angle between the superior endplate of C7 and the horizontal line. (**B, C**) Measurement of cervical range of motion (ROM). β: C2-7 Cobb angle in the hyperflexion position. α: C2-7 Cobb angle in the hyperextension position. ROM = α + β.

specified as follows: excellent/good corresponded to VAS below 3 (no AS), fair corresponded to VAS 3 to 6 (mild-to-moderate AS), and poor corresponded to VAS 7 to 10 (severe AS). This classification consistency ensures that the grading system is directly linked to the objective pain assessment criteria used in this study [21,22].

For binary logistic regression analysis (treating AS as a dichotomous outcome: presence/absence), grouping was defined based on the above grading criteria: "excellent" (VAS 0-2 points, no neck discomfort, tenderness, or muscle spasm) and "good" (VAS 0-2 points, mild stiffness resolving spontaneously after fatigue or cold) were merged into the "asymptomatic group" (no AS); "fair" (VAS 3-6 points, frequent symptoms, mild tenderness/spasm, impaired daily work/life, responsive to oral analgesics) and "poor" (VAS 7-10 points, persistent symptoms, obvious tenderness/severe muscle spasm, severe impairment of daily activities, poor response to oral analgesics) were merged into the "symptomatic group" (with AS). This grouping method is fully consistent with the clinical standard of "VAS score ≥3 points defining AS presence" in this study, ensuring the unity of grading criteria and statistical analysis.

At the 1-month postoperative follow-up, the VAS score was used to assess the severity of AS in patients (score range: 0-10 points, with 0 points indicating no pain and 10 points indicating the most severe pain). According to commonly used clinical criteria, a VAS score of 3 or more points was defined as "presence of axial symptoms", and VAS score below 3 points was defined as "absence of axial symptoms". The assessment was completed by nurses not involved in the surgery to avoid subjective bias of the surgeons. To ensure the reliability of AS assessment, 2 independent nurses (with ≥5 years of clinical experience in pain evaluation) blindly evaluated 20 randomly selected patients' postoperative VAS scores. The intraclass correlation coefficient for inter-rater consistency was 0.92 (95% CI, 0.81-0.97).

Measurement of Cervical Sagittal Parameters and ROM

Neutral lateral cervical X-rays were taken before surgery and after surgery. The following sagittal parameters were measured using ImageJ 18.0 software: C2-7 Cobb angle, defined as the angle between the tangent line of the inferior endplate of C2 and the tangent line of the inferior endplate of C7, reflecting the overall lordosis of the cervical spine; C2-7 SVA, defined as the horizontal distance between the center of gravity of the C2 vertebra and the posterior edge of the upper endplate of the C7 vertebra, reflecting the sagittal balance of the cervical spine; and ROM, calculated as α + β, where β represents the C2-7 Cobb angle in hyperflexion and α represents the C2-7 Cobb angle in hyperextension (**Figure 3**).

Postoperative Complication Monitoring

Postoperative complications other than AS were systematically monitored and recorded to evaluate the safety of the 2 surgical procedures. Monitoring time points included intraoperatively, 1 month postoperatively, and at the last follow-up (2-3 years). Complications were defined and diagnosed based on clinical manifestations, imaging findings, and laboratory results, as follows (**Table 3**). Dural tear was defined as intraoperative observation of cerebrospinal fluid leakage from the dural sac, confirmed by the surgical team; implant malposition

Table 3. Postoperative complications other than axial symptoms in the open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) groups.

Complication type	LP group (n = 33)	LF group (n = 31)	*P* value
Dural tear	1 (3.0%)	0 (0.0%)	1.00
Implant malposition	0 (0.0%)	2 (6.5%)	0.23
Superficial infection	0 (0.0%)	1 (3.2%)	0.48
Total complications	1 (3.0%)	3 (9.7%)	0.35

Note: *P* values were calculated using the Fisher exact test.

was defined as radiological evidence of lateral mass screws or connecting rods deviating from the optimal position (eg, screw penetration of the lateral mass cortex) on postoperative cervical radiographs or CT; and superficial infection was defined as postoperative redness, swelling, warmth, or purulent discharge at the surgical incision, together with elevated white blood cell count or C-reactive protein levels, without evidence of deep tissue involvement. All complications were documented in real time by the surgical team during surgery and verified by attending physicians at each follow-up visit. The incidence of each complication was calculated for both groups, and statistical comparisons were performed using the Fisher exact test (for categorical variables with expected frequency < 5) or Pearson χ^2 test.

Statistical Analysis

All statistical analyses were performed using SPSS 26.0 statistical software and R 4.2.1 software (pROC package for receiver operating characteristic [ROC] curve analyses), with a significance level set at $\alpha = 0.05$ (2-tailed test).

Normality and homogeneity of variance were assessed using the Shapiro-Wilk test and Levene test, respectively. For continuous variables, normally distributed data with homogeneous variances are expressed as mean ± standard deviation ($\bar{\chi} \pm s$) and were compared between groups using the independent samples *t* test. Non-normally distributed data or data with unequal variances are expressed as median (interquartile range [Q1, Q3]) and were compared using the Mann-Whitney U test. Categorical variables are presented as number of cases (percentage) (n [%]) and were compared using the Pearson χ^2 test. The Fisher exact test was applied when expected cell counts were less than 5. Temporal changes in sagittal parameters were first evaluated descriptively at 3 time points: preoperatively, 1 month postoperatively, and at the last follow-up. Because the repeated-measures data did not fully satisfy the sphericity assumption and the sample size was limited, within-group temporal changes were assessed using the Friedman test. When significant within-group differences were observed, the Dunn post hoc test with Bonferroni correction was used for pairwise comparisons. Between-group differences at each time point were evaluated using independent-sample *t* tests or Mann-Whitney U tests, as appropriate. We did not perform a formal mixed-effects model or repeated-measures interaction model because of the limited sample size and incomplete longitudinal data. Therefore, comparisons of temporal trends between the LP and LF groups should be interpreted descriptively and cautiously rather than as definitive evidence of a group-by-time interaction.

For risk factor analysis for postoperative AS, multicollinearity among independent variables was evaluated separately for the LP and LF groups. For the LP group, the variance inflation factor (VIF) of all variables ranged from 1.182 to 1.487 (tolerance: 0.673-0.846); for the LF group, VIF values were between 1.159 and 1.500 (tolerance: 0.667-0.863). All VIF values were less than 2.0, indicating no significant multicollinearity and thus ensuring the reliability of the logistic regression model results. Binary logistic regression analysis was used to identify risk factors for postoperative AS. The Hosmer-Lemeshow test was used to evaluate the goodness of fit of the regression model.

Candidate variables considered for regression analyses included surgical segments, baseline VAS score, preoperative ROM, preoperative C2-7 Cobb angle, preoperative C2-7 SVA, surgical group, and postoperative C2-7 SVA. Because only 17 AS events were observed, the multivariable model was intentionally restricted to clinically relevant variables to reduce overfitting, while other variables were evaluated in univariable analyses and baseline balance assessments.

For predictive threshold determination, ROC curves were constructed to determine the optimal predictive threshold of C2-7 SVA for postoperative AS. Using the DeLong method, 95% confidence intervals (CIs) for area under the ROC curve (AUC) values were calculated. All ROC-derived thresholds are exploratory findings only, as they are based on small subgroup sample sizes.

Post hoc bootstrapping analysis with 1000 resamples was performed to assess model robustness, which demonstrated consistent directionality of effect estimates but wide confidence

Table 4. Key outcomes of the open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) groups.

Variables	LP	LF	Z/t	*P*
Operation duration, median (Q1, Q3)	75 (50, 115)	85 (60, 140)	Z = -2.75	0.001
Blood loss, median (Q1, Q3)	100 (20, 300)	100 (50, 400)	Z = -1.75	0.08
Follow-up time, mean ± SD	30.97 ± 1.98	30.13 ± 1.92	t = 1.72	0.09
Incidence of axial symptoms, n	7/33	10/31		0.40

Note: *P* value for axial symptoms incidence was calculated using the Fisher exact test.

intervals, further supporting the exploratory nature of our findings.

Limitations of the statistical analysis included multiple exploratory analyses, consisting of correlation, univariable regression, multivariable regression, subgroup analysis, and ROC analysis, performed without adjustment for multiple comparisons, increasing the risk of type I error. Additionally, the events-per-variable ratio was approximately 2.4: 1, depending on how model terms were counted, which is well below the commonly recommended threshold and raises concerns regarding overfitting. Longitudinal data were analyzed using the Friedman test due to violation of the sphericity assumption; however, mixed-effects models would have provided more robust estimates of temporal changes and group-by-time interactions. Although repeated measurements were available at multiple time points, we did not perform a formal mixed-effects model or repeated-measures interaction analysis, because of the limited sample size, small number of AS events, and incomplete longitudinal data. Therefore, the observed temporal differences between groups should be interpreted cautiously and descriptively. Future prospective studies with larger sample sizes and more complete follow-up are needed to confirm whether true group-by-time interactions exist.

Results

Comparison of Baseline Data and Surgical Data After Propensity Score Trimming

There was no significant difference between the 2 cohorts in terms of age (LP group: 57.5 ± 7.5 years vs LF group: 57.1 ± 9.4 years, *P* = 0.84), sex (male/female: 19/14 vs 18/13, *P* = 0.96), surgical segments (3/4 segments: 4/29 vs 3/28, *P* = 0.75), vertebral stability (9/24 vs 9/22), C2-7 Cobb angle preoperatively (16.3 ± 3.3 vs 16.7 ± 4.8, *P* = 0.71), C2-7 SVA preoperatively (1.96 ± 0.98 vs 1.89 ± 0.92, *P* = 0.77), or follow-up duration (LP group: 30.97 ± 1.98 months vs LF group: 30.13 ± 1.92 months, *P* = 0.09). The operation duration of the LF group was significantly longer than that of the LP group (85 [60, 140] min vs 75 [50, 115] min, *P* = 0.001). Baseline sagittal parameters and functional scores were well-balanced between the 2 groups after propensity score–based trimming, with no significant differences (**Tables 1, 4**).

Comparison of Cervical Sagittal Parameters and ROM Between LP And LF Groups

Table 5 presents inter-group comparisons of cervical sagittal parameters (C2-7 Cobb angle, C2-7 SVA, and C7 slope) and ROM at preoperative, 1-month postoperative, and last follow-up time points.

The C2-7 Cobb angles preoperatively were 16.30° ± 3.30° in the LP group and 16.71° ± 4.82° in the LF group, with no significant difference between groups (*P* = 0.71). At 1 month postoperatively, the LF group had a significantly larger C2-7 Cobb angle (21.28° ± 3.09°) than the LP group (16.44° ± 3.21°, *P* < 0.001); this difference persisted at last follow-up (LF: 22.48° ± 3.39° vs LP: 15.89° ± 3.14°, *P* < 0.001).

The C2-7 SVA measurements preoperatively were 1.96 ± 0.98 cm in the LP group and 1.89 ± 0.92 cm in the LF group (*P* = 0.77). At 1 month postoperatively, they were 1.86 (1.25, 2.87) cm in the LP group and 2.0 (1.46, 2.97) cm in the LF group (*P* = 0.56). At last follow-up, the LF group had a significantly higher C2-7 SVA (2.6 [2.1, 3.4] cm) than the LP group (2.02 [1.31, 2.9] cm, *P* = 0.01).

The preoperative C7 slope values were similar (LP: 17.55° ± 2.78°; LF: 18.28° ± 3.81°, *P* = 0.38). At 1 month postoperatively, the LF group had a larger C7 slope (21.06° ± 3.48°) than the LP group (18.47° ± 2.74°, *P* = 0.002). This gap widened at last follow-up (LF: 22.96° ± 3.11° vs LP: 18.26° ± 2.44°, *P* < 0.001).

Preoperative ROM was comparable between groups (LP: 26.22° ± 3.6°; LF: 25.81° ± 3.11°, *P* = 0.63). At 1 month postoperatively, the LP group had significantly greater ROM (22.96° ± 3.16°) than the LF group (13.91° ± 3.25°, *P* < 0.001); this difference was more pronounced at last follow-up (LP: 19.17° ± 3.07° vs LF: 10.05° ± 2.49°, *P* < 0.001).

Table 5. Comparison of cervical sagittal parameters, range of motion, and functional outcomes between the open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) groups.

	LP	LF	t/U	*P*
C2-7 Cobb (°): pre-op	16.30 ± 3.30	16.71 ± 4.82	t = -0.40	0.71
1 month post-op	16.44 ± 3.21	21.28 ± 3.09	t = -6.14	< 0.001*
Last follow-up	15.89 ± 3.14	22.48 ± 3.39	t = -8.07	< 0.001*
C2-7 SVA (cm): pre-op	1.96 ± 0.98	1.89 ± 0.92	t = -0.29	0.77
1 month post-op	1.86 (1.25, 2.87)	2 (1.46, 2.97)	U = 468	0.56
Last follow-up	2.02 (1.31, 2.9)	2.6 (2.1, 3.4)	U = 328	< 0.05*
C7 slope (°): pre-op	17.55 ± 2.78	18.28 ± 3.81	t = -0.88	0.38
1 month post-op	18.47 ± 2.74	21.06 ± 3.48	t = -3.32	0.002*
Last follow-up	18.26 ± 2.44	22.96 ± 3.11	t = -6.75	< 0.001*
ROM(°): pre-op	26.22 ± 3.6	25.81 ± 3.11	t = 0.49	0.63
1 month post-op	22.96 ± 3.16	13.91 ± 3.25	t = 11.28	< 0.001*
Last follow-up	19.17 ± 3.07	10.05 ± 2.49	t = 13.00	< 0.001*
VAS: pre-op	5.2 ± 1.8	5.6 ± 1.5	t = -0.96	0.34
Last follow-up	2 (2, 2.5)	3 (2, 4)	U = 339	0.02*
JOA: pre-op	8 (7, 10)	8 (7, 10)	U = 492	0.79
Last follow-up	14 (14, 15)	14 (13, 14)	U = 372	0.06
NDI: pre-op	28 (27, 30)	28 (26, 28)	U = 374	0.06
Last follow-up	13 (11, 15)	12 (11, 15)	U = 491	0.79

Data conforming to a normal distribution were expressed as mean ± standard deviation (SD), while non-normally distributed data were presented as median (interquartile range, IQR). For comparisons between 2 independent groups, the independent samples *t* test was applied for normally distributed data (marked as "t"), and the Mann-Whitney U test was used for non-normally distributed data (marked as "U"). * $P<0.05$; ** $P<0.01$; *** $P<0.001$. Abbreviations: SVA, sagittal vertical axis; ROM, range of motion; VAS, visual analog scale; JOA, Japanese Orthopaedic Association Scores; NDI, Neck Disability Index.

Table 6. Comparison of changes (Δ) in sagittal parameters between the open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) groups (postoperative minus preoperative values).

Indicator	Time point comparison	ΔLP [M (Q1, Q3)]	ΔLF [M (Q1, Q3)]	U	*P*
ΔC2-7 SVA	1 month post-op vs pre-op	0.20 (-0.36, 0.54)	0.11 (-1.14, 0.48)	498.5	0.86
	Last follow-up vs pre-op	0.24 (-0.40, 0.66)	0.69 (0.44, 1.05)	276	0.002**
ΔC2-7 Cobb angle	1 month postop vs pre-op	1.00 (-0.65, 1.45)	4.60 (1.90, 5.90)	141	< 0.001***
	Last follow-up vs pre-op	0.60 (-1.05, 1.40)	5.70 (3.10, 7.60)	49.5	< 0.001***
ΔC7 slope	1 month postop vs pre-op	1.10 (0.10, 2.00)	2.60 (1.60, 4.90)	245.5	< 0.001***
	Last follow-up vs pre-op	0.70 (0.30, 2.00)	4.70 (3.60, 6.70)	61.0	< 0.001***

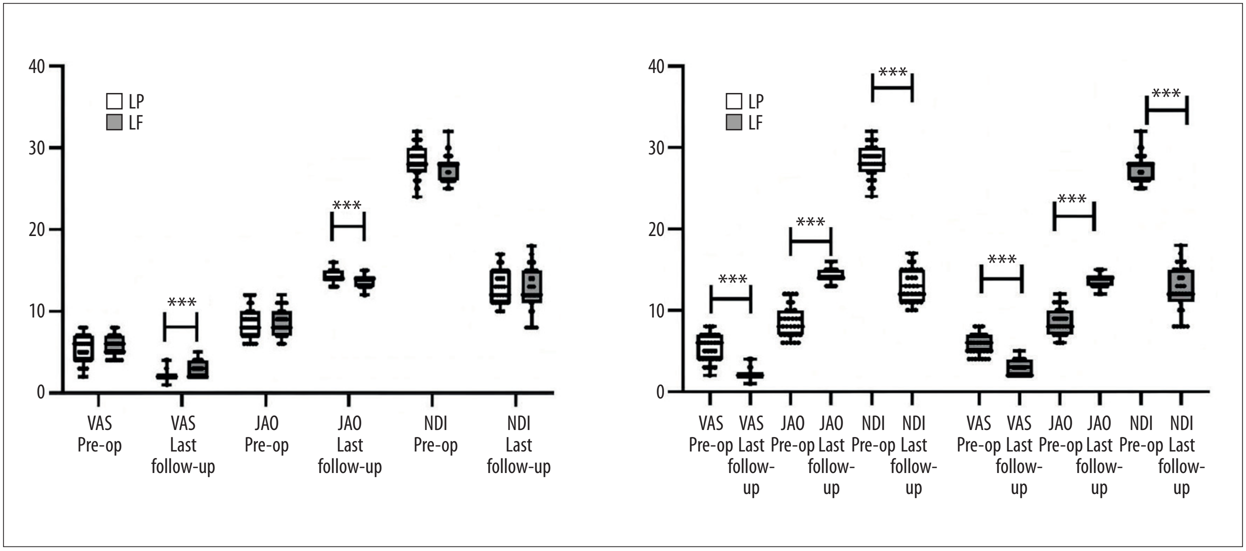


Figure 4. Comparison of clinical outcomes between LP and LF groups and according to axial symptom status. * *P*<0.05, ** *P*<0.01, *** *P*<0.001. Abbreviations: LP, open-door expansive laminoplasty; LF, total laminectomy with fusion; VAS, visual analog scale; JOA, Japanese Orthopaedic Association Scores; NDI, Neck Disability Index.

Descriptive longitudinal comparisons suggested different postoperative trajectories between the 2 groups, particularly for C2-7 Cobb angle and C7 slope at 1 month and for all 3 sagittal parameters at the last follow-up. The between-group difference in C2-7 SVA change was not significant at 1 month postoperatively but became significant at the last follow-up. Because no formal mixed-effects model was performed, these findings should be interpreted as descriptive temporal differences rather than definitive group-by-time interaction effects (**Table 6**).

Functional Outcome Comparisons (VAS, JOA, NDI)

Inter-group comparisons are presented in **Figure 4**. There were no significant inter-group differences in preoperative VAS scores (LP: 5.2±1.8 vs LF: 5.6±1.5, *P*=0.34). At last follow-up, significant differences were noted only in VAS (LP: 2 [2, 2.5] vs LF: 3 [2, 4], *P*=0.02), with the LP group showing better pain relief. No significant inter-group differences were found in JOA (*P*=0.06) or NDI (*P*=0.79). All functional outcome data are presented in **Table 5**, with intra-group changes (preoperative to last follow-up) showing significant improvements in both groups (all *P*<0.001).

Comparison of Cervical Parameters Between Pain and No-Pain Subgroups (LP vs LF Group)

Figure 5 presents the comparisons of cervical sagittal parameters and ROM between pain and no-pain subgroups within the LP and LF groups, respectively.

Subgroup Analysis in the LP Group

Within the LP group, no significant differences in age, sex, preoperative parameters (C2-7 Cobb angle, C2-7 SVA, C7 slope, and ROM), postoperative ROM (1 month and last follow-up), or C7 slope (all time points) were observed between the pain and no-pain subgroups (all *P*>0.05). Notably, C2-7 SVA showed significant differences at postoperative time points: at 1 month after surgery, the pain subgroup had a higher C2-7 SVA (3.02±1.60 cm) than the no-pain subgroup (1.88±0.79 cm, *P*=0.01), and at last follow-up, this difference had persisted (pain subgroup: 3.21±1.67 cm vs no-pain subgroup: 1.93±0.74 cm, *P*=0.005).

Subgroup Analysis in the LF Group

Within the LF group, age, sex, all preoperative parameters (C2-7 Cobb angle, C2-7 SVA, C7 slope, and ROM), postoperative ROM (1 month and last follow-up), and C7 slope (all time points) were comparable between the pain and no-pain subgroups (all *P*>0.05). Similar to the LP group, C2-7 SVA exhibited significant differences in the LF group at postoperative time points: at 1 month after surgery, the pain subgroup had a higher C2-7 SVA (2.98±1.11 cm) than the no-pain subgroup (1.84±0.62 cm, *P*=0.001), and at last follow-up, the gap remained significant (pain subgroup: 3.30±0.93 cm vs no-pain subgroup: 2.43±0.52 cm, *P*=0.002).

Univariate Logistic Regression Analysis for AS

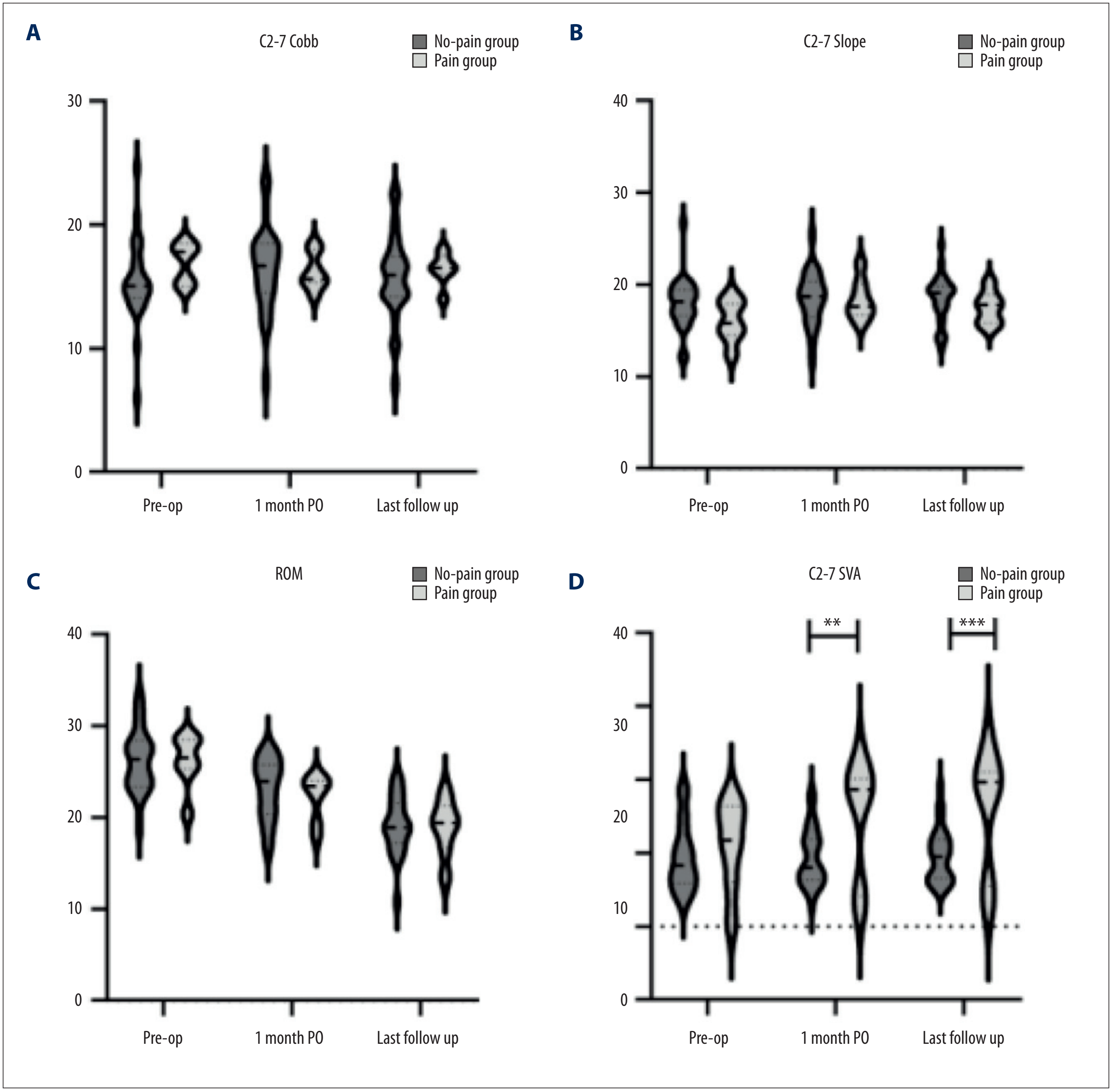
The Hosmer-Lemeshow test indicated a good fit of the logistic regression model ($\chi^2=6.23$, *P*=0.62), confirming that the model adequately explained the association between C2-7 SVA and AS. **Table 7** presents the univariate logistic regression results of factors associated with AS in the LP and LF groups. Among the variables included in the univariate logistic regression model, C2-7 SVA was the only variable associated with AS.

In the LP group, the C2-7 SVA at 1 month postoperatively (OR = 2.78, 95% CI, 1.06-7.28, *P* = 0.05) and at last follow-up (OR = 2.99, 95% CI, 1.22-7.32, *P* = 0.04) were associated with an increased risk of AS. In the LF group, the C2-7 SVA at both 1 month postoperatively (OR = 4.87, 95% CI, 1.51-13.73, *P* = 0.008) and at last follow-up (OR = 6.12, 95% CI, 1.53-24.43, *P* = 0.01) were significantly associated with a higher risk of AS. The C2-7 Cobb angle and ROM showed no significant associations with AS in either group at any time point (all *P* > 0.05).

Spearman's Rank Correlation Analysis for AS

Table 8 summarizes the Spearman correlation between AS and key variables.

For C2-7 SVA, in the LF group, significant positive correlations were observed between AS and 1-month postoperative C2-7 SVA (r = 0.494, *P* = 0.005), as well as last follow-up C2-7 SVA (r = 0.475, *P* = 0.007). In the LP group, significant positive correlations were also found between AS and 1-month postoperative C2-7 SVA (r = 0.391, *P* = 0.04) and last follow-up C2-7 SVA (r = 0.395, *P* = 0.03). ROM, age, and sex showed no significant correlations with AS in either group (all *P* > 0.05).



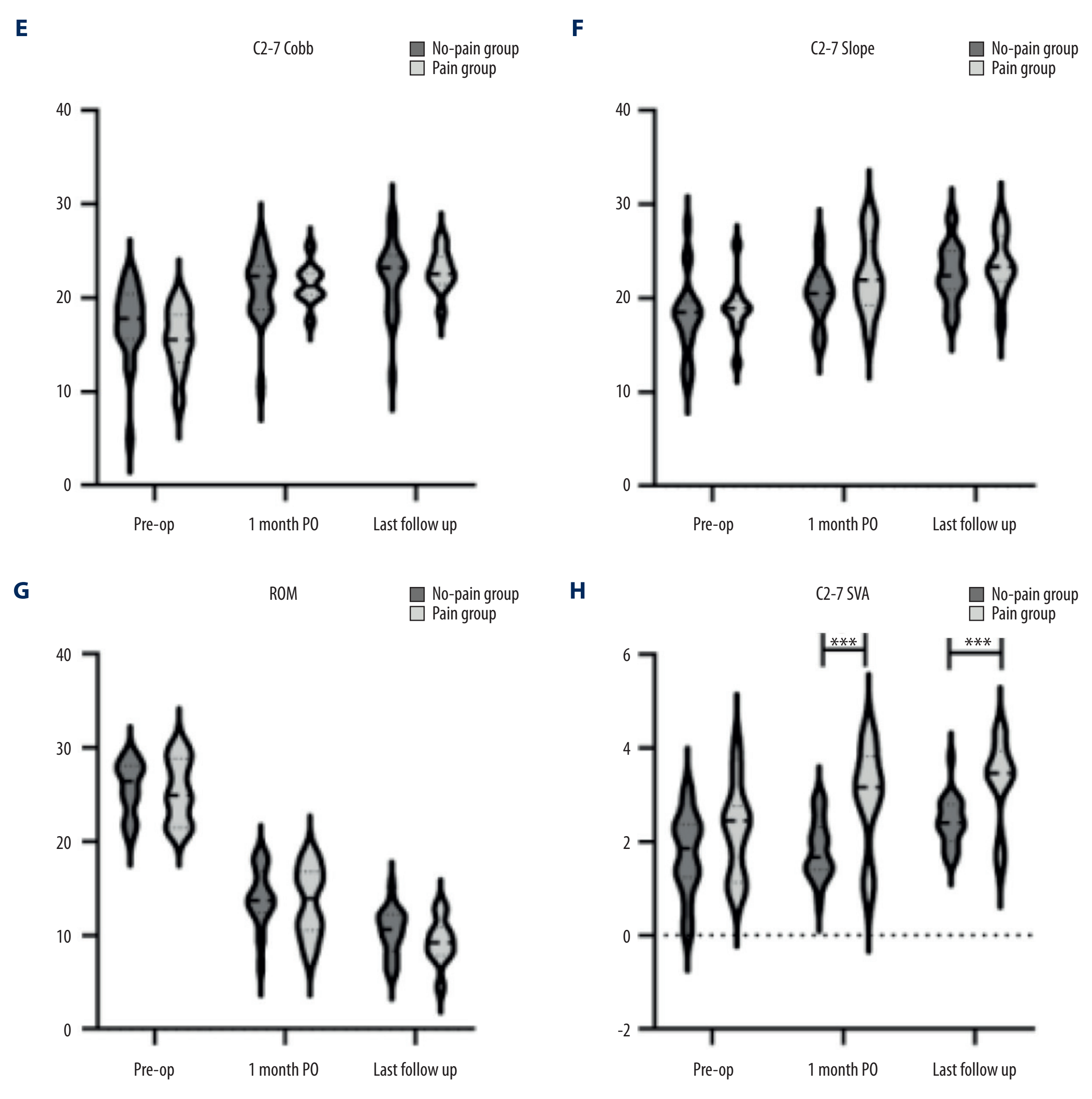


Figure 5. Comparison of sagittal parameters between the no-pain and pain subgroups. (**A-D**) LP group: (**A**) C2-7 Cobb angle, (**B**) C7 slope, (**C**) range of motion (ROM), and (**D**) C2-7 sagittal vertical axis (SVA). (**E-H**) LF group: (**E**) C2-7 Cobb angle, (**F**) C7 slope, (**G**) ROM, and (**H**) C2-7 SVA. Notes: Data are presented as median (interquartile range [IQR]). Statistical analyses were performed using the Friedman test with Bonferroni correction. $P<0.05$, $P<0.01$, $P<0.001$. Abbreviations: LP, open-door expansive laminoplasty; LF, total laminectomy with fusion; SVA, sagittal vertical axis; ROM, range of motion; PO, postoperative.

ROC Curve Threshold Analysis Assessing the Surgical Group × C2-7 SVA Interaction for AS Prediction

The ROC curves evaluated the predictive value of last follow-up C2-7 SVA for AS.

In the LP group (**Figure 6A**), the AUC was 0.723 (95% CI, 0.542-0.861), indicating moderate predictive performance in this cohort. An exploratory ROC threshold of C2-7 SVA was 3.46 cm, corresponding to a sensitivity of 0.714 and specificity of 0.962. This tentatively suggested that patients in the LP group with last-follow-up C2-7 SVA greater than 3.46 cm had an elevated risk of AS in our sample.

In the LF group (**Figure 6B**), the AUC was 0.793 (95% CI, 0.615-0.912), with an exploratory ROC threshold of 3.10 cm

Table 7. Univariate logistic regression analysis of factors associated with axial symptoms in the open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) groups.

Parameter	Time point	LP (OR, 95% CI, *P*)	LF (OR, 95% CI, *P*)
C2-7 SVA	1 month post-op	2.78 (1.06-7.28, 0.05)	4.87 (1.51-13.73, 0.008*)
	Last follow-up	2.99 (1.22-7.32, 0.04)	6.12 (1.53-24.43, 0.01*)
C2-7 Cobb	1 month post-op	0.97 (0.75-1.27, 0.83)	1.03 (0.80-1.33, 0.82)
	Last follow-up	1.08 (0.82-1.43, 0.58)	1.06 (0.84-1.34, 0.64)
ROM	1 month post-op	0.91 (0.70-1.19, 0.49)	0.95 (0.75-1.20, 0.67)
	Last follow-up	0.97 (0.74-1.27, 0.81)	0.84 (0.69-1.15, 0.27)

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. Abbreviations: SVA, sagittal vertical axis; ROM, range of motion.

Table 8. Spearman rank correlation analysis between axial symptoms and key variables in the open-door expansive laminoplasty (LP) and total laminectomy with fusion (LF) groups.

Parameter	Time point	LP (r, *P*)		LF (r, *P*)	
C2-7 SVA	1 month post-op	0.39	0.04	0.49	0.005
	Last follow-up	0.39	0.03	0.48	0.007
ROM	1 month post-op	-0.17	0.34	-0.08	0.68
	Last follow-up	-0.008	0.97	-0.19	0.31
Age		-0.28	0.12	-0.17	0.37
Sex		0.005	0.98	0.11	0.55

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. Abbreviations: SVA, sagittal vertical axis; ROM, range of motion.

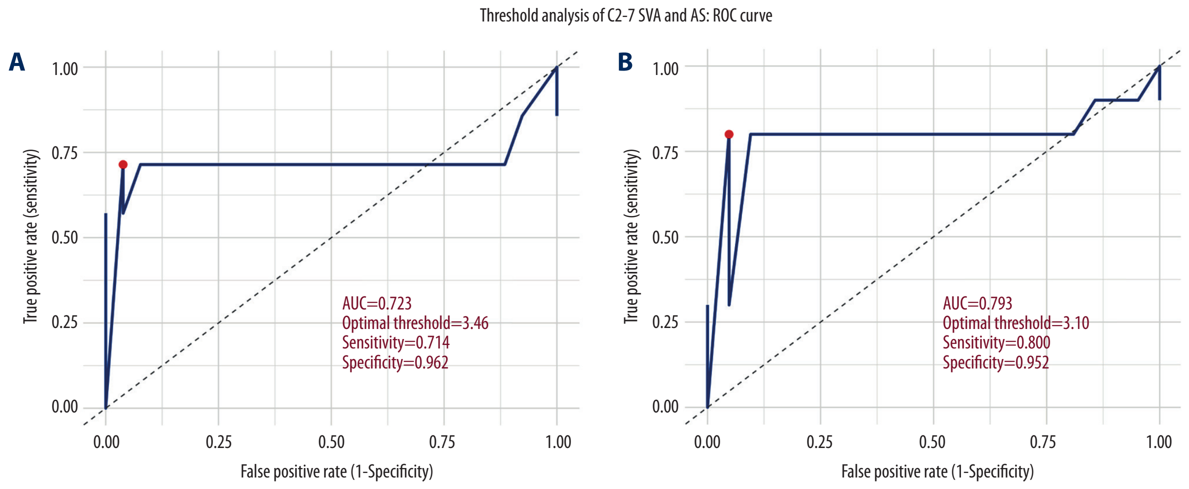


Figure 6. Threshold analysis of C2-7 sagittal vertical axis (SVA) and axial symptoms in the (**A**) open-door expansive laminoplasty (LP) group and (**B**) total laminectomy with fusion (LF) group.

Table 9. Multivariable logistic regression model for the association between surgical group, last follow-up C2-7 SVA, their interaction, and postoperative axial symptoms.

	B	SE	Wald χ^2	*P*	OR	95% CI
Age	-0.02	0.05	0.13	0.72	0.98	0.87-1.09
Sex	0.89	0.74	1.48	0.22	2.45	0.58-10.36
C2-7 SVA (pre-op)	0.31	0.18	2.94	0.08	1.36	0.96-1.86
Surgical segments	0.52	0.41	1.60	0.21	1.68	0.75-3.77
C2-7 SVA (last follow-up)	1.09	0.46	5.75	0.017	2.99	1.22-7.32
Group (LF vs LP)	1.82	0.61	8.90	0.003	6.17	1.85-20.58
Group × last follow-up C2-7 SVA	1.04	0.30	12.02	0.001	2.82	1.57-5.08
Constant	-6.75	4.04	2.79	0.09	–	–

Abbreviations: LF, total laminectomy with fusion; LP, open-door expansive laminoplasty; SVA, sagittal vertical axis.

(sensitivity = 0.8, specificity = 0.952). This tentatively indicated that patients in the LF group with last-follow-up C2-7 SVA greater than 3.10 cm had a higher risk of AS in our cohort.

Importantly, these thresholds are purely exploratory and should not be interpreted as clinically actionable values. Although the numerical difference between the LP and LF thresholds was 0.36 cm, this small difference may not be clinically meaningful given the small number of AS events, wide AUC confidence intervals, and potential variability inherent to manual radiographic measurement. Therefore, the 2 ROC-derived thresholds should be interpreted as approximate exploratory estimates rather than procedure-specific clinical cutoffs.

Multivariable Logistic Regression of Surgical Group × Last Follow-Up C2-7 SVA Interaction

In this exploratory interaction model, the group term was associated with AS (OR = 6.17; 95% CI, 1.85-20.58; *P* = 0.003). However, because the model included a group × C2-7 SVA interaction term, the main group effect should not be interpreted as an overall procedure-specific risk estimate (**Table 9**). The group × C2-7 SVA interaction was statistically significant (OR = 2.82; 95% CI, 1.57-5.08; *P* = 0.001). However, this interaction analysis is based on a small number of AS events (n = 17) and should be interpreted with extreme caution. This observation tentatively indicated that for each 1-cm increase in last follow-up C2-7 SVA, the relative risk of AS in the LF group (vs the LP group) appeared to increase by 2.82 times in our cohort—in other words, the pain risk difference between the 2 groups tended to widen as C2-7 SVA increased. This finding is hypothesis-generating and does not establish a definitive causal relationship between surgical approach, sagittal imbalance, and AS. Neither age nor sex was significantly associated with AS (both *P* > 0.05), suggesting that surgical group, C2-7 SVA, and their interaction may be relevant variables in this exploratory model.

Postoperative Complications

Postoperative complications other than AS were rare. In the LP group, 1 case (3.0%) of dural tear occurred intraoperatively and was repaired immediately; no implant malposition or infection was observed. In the LF group, 2 cases (6.5%) of implant malposition were corrected intraoperatively, and 1 case (3.2%) of superficial infection was successfully treated with antibiotics. There was no significant difference in the overall complication rate between the 2 groups (*P* = 0.35) (**Table 4**).

Discussion

The ROC-derived thresholds observed in this study differed numerically from the widely cited 4-cm threshold reported in previous literature. However, these values should be interpreted only as exploratory estimates because they were derived from small subgroup analyses with limited AS events [20,23]. This discrepancy stems from differences in research focus and patient populations between the present study and previous reports. Previous studies primarily targeted patients with severe cervical sagittal imbalance (eg, C2-7 SVA ≥ 40 mm) and focused on neurological function recovery, in which excessive sagittal displacement directly compromises spinal cord canal space and neurological integrity [24,25]. In contrast, the present study excluded patients with severe cervical kyphosis (C2-7 Cobb angle < 0°) and preoperative severe neck pain (VAS ≥ 7), with preoperative C2-7 SVA values of both groups within the normal physiological range (typically < 3 cm in healthy adults). The AS in the present study is primarily musculoskeletal pain resulting from muscle strain and compensatory loading, rather than neurological deficits.

Although the ROC analysis mathematically identified thresholds of 3.46 cm for the LP group and 3.10 cm for the LF group, these values should be interpreted with great caution. The numerical difference between the 2 thresholds was small and may not be clinically meaningful given the limited number of AS events, wide confidence intervals, and potential variability inherent to manual radiographic measurement. Therefore, these thresholds should be regarded as exploratory approximations rather than validated procedure-specific cutoffs.

The observed stronger association between C2-7 SVA and AS in the LF group may be partly related to biomechanical differences between the 2 procedures. Benek et al [13] reported comparable neurological recovery between LP and LF but noted differences in cervical alignment preservation and postoperative axial pain, which provides useful context for our findings. In the present cohort, LF involved rigid fixation of the operated segments using lateral mass screws and connecting rods, which may reduce segmental mobility and compensatory capacity [26,27]. Under these conditions, postoperative increases in C2-7 SVA may place greater mechanical demand on the upper cervical and cervicoscapular musculature. However, this explanation remains speculative. The present retrospective data demonstrate an observed association rather than a causal relationship, and this hypothesis requires validation in larger, multi-center prospective studies [28,29].

In contrast, LP preserves part of the posterior bony structure and cervical ROM, which may provide some residual capacity for segmental compensation after mild postoperative sagittal imbalance [15,30]. This could partly explain why the association between C2-7 SVA and AS appeared weaker in the LP group than in the LF group. Nevertheless, the present study does not demonstrate that LP confers superior tolerance to sagittal imbalance, nor does it prove that LF intrinsically increases susceptibility to AS. This interpretation should therefore be regarded as hypothesis-generating.

Another possible explanation is that LF may involve greater disruption of the posterior cervical ligamentous and muscular complex than does LP. Because the posterior cervical ligament complex contributes to sagittal stability, its disruption could theoretically reduce the ability of the cervical spine to compensate for postoperative sagittal imbalance [26,31]. Increased C2-7 SVA may therefore be associated with greater compensatory demand on the cervicoscapular musculature after LF [32,33]. However, ligamentous injury, cervical extensor muscle atrophy, cross-sectional area, and fatty infiltration were not directly quantified in this study [33]. Therefore, this proposed mechanism remains speculative and should be confirmed by future biomechanical studies and MRI-based assessments of cervical muscle quality.

As a well-recognized key parameter for quantifying the degree of cervical lordosis, the C2-7 Cobb angle plays a pivotal role in evaluating cervical spine alignment [34,35]. A normal cervical alignment is essential for multiple clinical functions: it sustains a horizontal line of sight during routine activities, minimizes energy consumption of the posterior cervical musculature to reduce muscular strain, and maintains the overall stability and biomechanical balance of the cervical spine [35]. Abnormal cervical alignment will indicate the changes in sagittal balance and degeneration of adjacent cervical segments [12,36]. In the present study, the preoperative physiological curvature of the cervical spine was normal in both patient groups, with no statistically significant difference observed between them.

Postoperative imaging examinations revealed a significant increase in the C2-7 Cobb angle in the LF group, whereas no obvious change was detected in the LP group. LF resulted in greater restoration of cervical lordosis compared with LP, while LP had no significant effect on the cervical physiological curvature. Studies [26,37] had demonstrated that restoring normal physiological radian will reduce the degeneration of adjacent segments and increase the posterior migration space of spinal cord to achieve outcomes. Postoperative lordotic changes were negligible in the LP cohort, mainly because this procedure involves opening only the “door” side, resulting in minimal damage to the cervical bony structure. LP does not significantly improve cervical lordosis. However, the C2-7 Cobb angle remained within a reasonable range both preoperatively and postoperatively. The open-door technique expands the spinal canal area. At the same time, it promotes posterior drift of the spinal cord. This achieves indirect decompression and alleviates clinical pain. C7 slope was significantly correlated with T1 slope. Because the T1 slope was susceptible to interference from the sternum, C7 was chosen instead. The T1 vertebra is the base of the entire cervical spine, and its shape and direction have an influence on cervical lordosis [18]. Knott et al [19] reported that it was difficult to maintain the cervical sagittal balance when the T1 slope was greater than 25° or less than 13°. In the present study, no association between C7 slope and AS was found, probably because the preoperative and postoperative C7 slope were within the normal range and had little effect on the overall cervical balance, although the increased C7 slope caused a compensatory rise in cervical lordosis, further leading to the cervical imbalance. Although the AS rate was numerically higher in the LF group, this difference was not statistically significant. Therefore, any relationship between LF, C7 slope, posterior cervical muscle demand, and AS should be interpreted cautiously and regarded as hypothesis-generating. The incidence of AS in the LP group was lower than that in LF group, mostly due to the preserved mobility of the cervical spine [38]. When cervical spine mobility is limited, the neck muscles and ligaments may be exposed to increased static loading during prolonged posture maintenance, which could contribute to muscle strain, inflammatory responses, and AS development [39]. Maintaining ROM is of great significance for improving the quality of life of patients. The optimal ROM can maximize cervical function, and the measure of cervical mobility allows for the assessment of prognosis. There was no significant difference in preoperative ROM between the 2 groups. At the last follow-up, ROM decreased in both groups, possibly due to the dissection of the posterior cervical paravertebral muscle attachment point which results in the imbalance of cervical muscle strength.

In this study, the C2-7 Cobb angle was not significantly associated with postoperative AS, which is consistent with some studies but contradicts others [40,41]. For the C2-7 Cobb angle, previous studies reporting a correlation with AS included mostly patients with preoperative cervical kyphosis (C2-7 Cobb angle $< 0°$), in which restoring lordosis improves sagittal balance and reduces muscle load [42]. However, the present study excluded patients with severe kyphosis, and the preoperative C2-7 Cobb angles of both groups were within the normal lordotic range. We speculate that within this range, the further increase in C2-7 Cobb angle observed in the LF group does not significantly optimize sagittal balance; instead, it may increase intervertebral disc pressure, offsetting potential benefits. This leads us to the view that the association between C2-7 Cobb angle and AS is dependent on preoperative cervical alignment, whereby restoring lordosis is beneficial for patients with kyphosis, but excessive lordosis within the normal range may not reduce AS risk.

For C7 slope, the lack of association with AS may be due to the fact that preoperative and postoperative C7 slopes of both groups were within the physiological range, which did not significantly affect overall cervical balance. Although the C7 slope in the LF group was significantly higher than that in the LP group, this increase was a compensatory change for cervical lordosis and did not reach the critical threshold ($> 25°$ or $< 13°$) that impairs sagittal balance, thus failing to show a significant correlation with AS.

Limitations

This study has several limitations that warrant careful consideration when interpreting the results. First, as a single-center retrospective cohort study, inherent selection bias exists due to differences in surgical indications and patient willingness, which may limit the generalizability of the findings to other centers. Second, the final sample size (64 cases) did not meet the a priori calculation requirement (86 cases), with a post hoc statistical power of only 72.3%, which is below the commonly accepted 80% threshold for robust clinical research. This insufficient statistical power increases the risk of type II error (false negative), meaning potential associations (eg, between C7 slope and AS, or subtle differences in AS incidence between the LP and LF groups) may have been missed. Regarding the overall incidence of AS, our results showed a rate of 32.3% in the LF group compared with 21.2% in the LP group. This difference did not reach statistical significance, and it should be interpreted with caution. The absolute difference of approximately 11% suggests a clinically relevant trend toward a higher risk of AS in the LF group. This lack of statistical significance may be attributed to the limited sample size. A larger cohort might be required to confirm this difference. Additionally, the reliability of the significant interaction effect between surgical group and C2-7 SVA is compromised by the small sample size, and this finding requires validation in larger studies to confirm its stability. Third, the follow-up period was limited to 2 to 3 years, which reflects only short-term correlations between sagittal parameters and AS. Cervical fusion surgery may lead to adjacent segment degeneration that becomes clinically apparent after 5 years, potentially altering C2-7 SVA and AS incidence over time. Long-term follow-up of 5 or more years is therefore needed to evaluate the durability of the observed associations. Fourth, the surgical segments were restricted to C3-6 and C3-7, excluding patients undergoing surgery on upper cervical (C1-2) or lower cervical (C7-T1) segments. The impact of different surgical segments on sagittal parameters and AS remains unclear, and future studies should expand the scope to verify the applicability of the conclusions. Fifth, we acknowledge that preoperative cervical muscle quality, specifically fatty infiltration and extensor muscle atrophy, was not quantitatively assessed using MRI. Muscle degeneration is a known confounding factor that can influence both the maintenance of sagittal alignment and the severity of AS. However, we utilized propensity score–based trimming to rigorously balance baseline characteristics including age, sex, and preoperative VAS scores. Although age and preoperative VAS were balanced between groups, this cannot fully substitute for direct MRI-based assessment of muscle quality. Future studies may benefit from automated MRI-based muscle segmentation, quantitative fat-fraction analysis, and biomechanical simulation models to better characterize paravertebral muscle degeneration and postoperative mechanical stress distribution. Sixth, several clinically relevant factors were not incorporated into the propensity-score model, including smoking status, body mass index, bone quality, comorbidities, and postoperative rehabilitation protocols. Smoking and body mass index are known independent risk factors for both postoperative axial pain and poor sagittal alignment maintenance, and their exclusion may have introduced residual confounding. Although postoperative rehabilitation protocols were standardized across our institution, individual variations in adherence could have influenced axial symptom development. Future prospective studies should prospectively collect and adjust for all these variables to obtain more robust effect estimates. Finally, multiple exploratory analyses (correlation, univariable regression, multivariable regression, subgroup analysis, and ROC analysis) were performed without adjustment for multiple comparisons, which increases the risk of type I error. However, the consistent association between C2-7 SVA and AS across all analytical approaches strengthens the credibility of this core finding.

Conclusions

The results of this preliminary, hypothesis-generating study suggest that postoperative C2-7 SVA may be associated with AS after posterior cervical surgery for MCSM. In this small cohort, this association appeared stronger after LF than after LP; however, the finding was based on a limited sample size and few AS events and should be interpreted with extreme caution. All ROC-derived thresholds and interaction estimates are exploratory and should not be regarded as clinically actionable. No definitive conclusion regarding the superiority of either procedure can be drawn. Larger prospective studies incorporating quantitative assessment of cervical muscle quality, rehabilitation adherence, and other potential confounders are needed to validate these findings.

Institutional Review Board Statement

This study was conducted in accordance with the Declaration of Helsinki, with Ethics Committee of the authors' affiliated institutions' approval (approval No. 2024-RE-401).

Informed Consent Statement

Written informed consent for surgery was obtained from all patients. The requirement for additional informed consent for this retrospective study was waived by the Ethics Committee of Anhui Provincial Hospital because anonymized clinical and radiographic data were used.

Data Availability Statement

Data analyzed in study is present in the Department of Spine of Anhui Provincial Hospital (the first affiliated hospital of USTC), Hefei. The data presented in this study are available on request from the corresponding author due to privacy/ethical restrictions.

Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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