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RESEARCH

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# T2-weighted MRI high signal in cervical spondylotic myelopathy is associated with dynamic change

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## Abstract

**Objective** The cervical spine's mobility affects the compression level of the cervical cord which varies with dynamic positioning. High signal on MRI T2-weight imaging (MRI-T2WI) of the cervical cord indicates a poorer prognosis. This study investigates the relationship between high-signal intensity on MRI-T2WI and cervical dynamic change using kinematic MRI. The objective of this study was to explore changes in the degree of cervical spinal cord compression during flexion–extension motions and identify risk factors linked to the occurrence of high signals.

**Materials and methods** We collected data on patients who underwent surgical treatment for cervical spondylotic myelopathy (CSM) in our department from 2023 to 2024. Patients were classified into two groups based on high-intensity signal presence: the high-signal group and non-high-signal group. Using kinematic MRI, the area and width of cervical cord compression in the responsible segment were measured in the axial and sagittal positions. Differences between the two groups were assessed using univariate analysis, binary logistic analysis, receiver operating characteristic (ROC) curve, and restricted cubic spline (RCS) regression model.

**Results** A total of 40 patients in the high-signal group and 30 in the non-high-signal group were included in the study. There was no significant difference in baseline characteristics between two groups. The degree of cord compression was remarkably increased in both groups with cervical ranging from flexion to extension. Additionally, the neutral position and extension compression degrees (area and width) were significantly greater in the high-signal group than in the non-high-signal group, indicating that stenosis is a risk factor for high-signal occurrence. Furthermore, the degree of dynamic compression change of kinematic MRI was significantly higher in the high-signal group compared to the non-high-signal group. Statistical analysis confirmed that cervical dynamic change was an independent risk factor for high-signal occurrence. The RCS curve demonstrated that the incidence of high signal significantly increased when the compression degree of extension/flexion exceeded 1.4.

**Conclusion** Cervical cord compression worsens with cervical dynamic change from flexion to extension. The degree of compression change is considered a risk factor for high signals on MRI-T2WI. An extension/flexion value greater than 1.4 indicates an increased likelihood of a high-signal occurrence.

**Keywords** Cervical spondylosis myelopathy, Kinematic MRI, High signal

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## Introduction

Cervical spondylotic myelopathy (CSM) is the most common cause of spinal cord dysfunction globally [1]. National databases show that the incidence of CSM-related hospitalizations is approximately 4 per 100,000 people, with the older adults and males more likely to be affected [2].

Hyperintense intramedullary lesions (HILs) are found within the cervical cord in 14.0%–61.7% of patients with CSM on MRI T2-weighted imaging (MRI-T2WI) [3, 4]. These lesions reflect a high signal change on MRI-T2WI. The presence of high signal is often associated with reduced short- and long-term efficacy, lower patient satisfaction, and reduced quality of life in patients with CSM after surgery [5–8]. Studies have shown that patients with CSM and high signal exhibit, on average, a 30% higher Neck Disability Index (NDI) score and a 15% lower Japanese Orthopaedic Association Scores (JOA) score postoperatively compared to those without high signal. However, the cause of high signals remains unclear [9]. The leading hypothesis suggests that chronic compression leads to reduced local spinal cord blood flow, which impairs spinal cord perfusion and leads to the development of spinal cord demyelination [2, 10]. Given the prognostic and clinical importance of high signal, further investigation into its etiology is essential.

The mobility of the cervical spine is an important functional characteristic, and both the spinal cord length and diameter change according to the dynamic position. Evidence from dynamic MRI indicates that the spinal canal diameter varies according to different cervical positions. With the dynamic motion of the cervical spine ranging from flexion, neutral to extension, the transverse diameter of the cervical spinal canal decreases gradually [11]. Given these positional changes and the importance of a high signal on T2-MRI, it is essential to investigate whether the cervical compression degree changes due to the different positions of the cervical spine and under what conditions a high signal appears on T2-MRI.

Therefore, we hypothesized that cervical dynamic motion leads to changes in the degree of spinal cord compression, which might result in the appearance of a high signal on MRI-T2WI. Using kinematic MRI, we analyzed the degree of cervical canal compression in different positions and sections of the cervical cord to determine and confirm the risk factor associated with the appearance of cervical high signal.

## Materials and methods

### General information

Prospectively, all CSM patients who were admitted to the Department of Spine Surgery of Qilu Hospital of Shandong University for surgical treatment were collected from 2023.01.01 to 2024.01.01. Intramedullary high signal refers to a hyperintense region within the cervical spinal cord on T2-weighted MRI images, observed in both sagittal and axial planes of the cervical spinal canal, compared to the surrounding isointense areas. Based on the presence or absence of this region in cervical MRI of patients with CSM, they are categorized into the high-signal group and the non-high-signal group.

A total of 70 people were included in the study as shown in Fig. 1. Their age, gender, BMI, JOA score, ODI score, smoking and drinking history, and chronic diseases were recorded respectively. The study was approved by the Qilu Hospital of Shandong University (Ethics No. KYLL-202310–013-2), and all study participants signed an informed consent form. The preoperative inclusion and exclusion criteria were as follows:

Inclusion criteria: (a) Typical clinical manifestations of CSM, including chronic neck pain, walking instability, chest band sensation, muscle weakness, and atrophy, as well as positive pathological findings; (b) Radiological examination revealed evidence of cervical cord compression; (c) Spinal cord compression caused by disc herniation; (d) Patients aged 18 years or older; (e) Complete clinical data available.

Exclusion criteria: (a) Spinal cord compression caused by ossification of the posterior longitudinal ligament

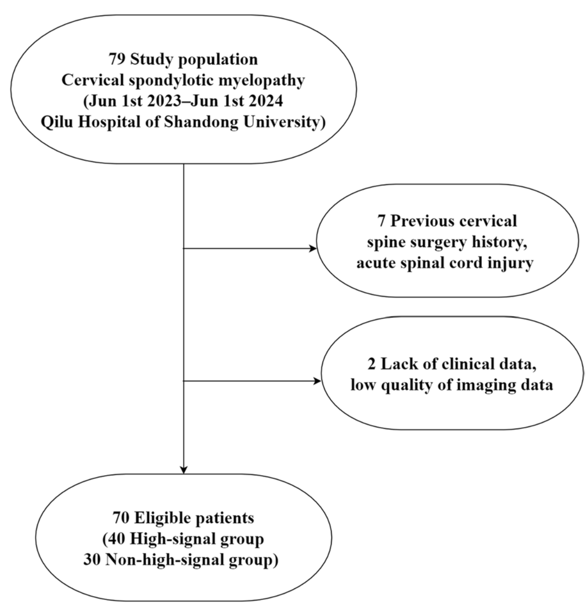


**Fig.1** Flowchart of the patient inclusion process

(OPLL); (b) Patients with other types of cervical spondylosis (e.g., radiculopathy or sympathetic type); (c) Patients with a history of previous cervical spine surgery; (d) Patients presenting with acute spinal cord injury; (e) Patients with cervical spinal tumors or infectious diseases; (f) Patients diagnosed with immune-related disorders such as amyotrophic lateral sclerosis or syringomyelia; (g) Incomplete or poor quality imaging data; (h) Follow-up data were incomplete or lost.

### Imaging examination and determination of the responsible segment

Cervical sagittal T1WI, T2WI, and axial T2WI MRI scans were performed using a 3.0 T MR Scanner (Siemens, Germany). Before the formal examination, patients underwent cervical flexion and extension postural training to ensure they completed the examination safely and comfortably. At the time of the dynamic MRI examination, each patient selected their maximum comfortable flexion and extension position, using an assistive device to secure the head position and ensure appropriate flexion and extension angles. The cervical flexion and extension angles at which dynamic MRI is performed are limited by the cervical stiffness of each patient to prevent any neurological deterioration, so the angles are different for all patients, usually 20°–30°. The relevant MRI parameters are as follows: Sagittal T2WI of the cervical spine: repetition time/echo time (TR/TE): 2500–3500 ms/80–120 ms; slice thickness: 3–4 mm; slice spacing: 0.5–1 mm; matrix: $>256\times256$ mm; number of excitations (NEX): 2–4; field of view (FOV): 20–24 cm. Axial T2WI of the cervical spine: TR/TE: 3000/100 ms; slice thickness: 3–4 mm; slice spacing: 0.5–1 mm; matrix: $>256\times256$; NEX: 2–4; FOV: 18–22 cm. Sagittal T1WI of the cervical spine: TR/TE: 400–600 ms/10–15 ms; slice thickness: 3–4 mm, slice spacing: 0.5–1 mm; matrix: $>256\times256$ mm; NEX: 2–4; FOV: 20–24 cm. The responsible segment was defined as the segment exhibiting the most considerable cervical disc herniation or cervical cord compression and the most narrowed spinal cord on sagittal cervical medullary MRI plain scan, in correlation with the patient's clinical presentation. All examinations and diagnoses were reviewed by consensus between two spine surgeons with the title of associate physician or higher. Measurements of relevant data were performed using Image-Pro Plus 6.0.

### Relevant imaging measurements and methods

#### *Measurement of cervical spinal canal compression area*

The actual cross sectional area of the vertebral canal at the level of the responsible segment and the effective spinal canal area was measured in the axial MRI of the cervical spinal cord in the cervical spinal cord kinematic MRI. The actual cross sectional area refers to the area of the spinal canal after compression, and the effective spinal canal area refers to the cross sectional area of the level after the removal of protruding tissues. The actual spinal canal area was measured at the level of the most severe compression. All values were obtained and averaged by two independent evaluators, who were blinded to the patient group and other information before measurement. The degree of canal compression (area) was calculated as (effective canal area-actual cross sectional area)/ effective canal area. The variation in dynamic cervical spinal cord compression was assessed by calculating the degree of canal compression (area) during extension and flexion (Fig. 2e).

#### *Measurement of cervical spinal compression canal width*

The actual and effective spinal canal widths of the vertebral canal at the level of the responsible segment in the sagittal cervical were measured. The actual spinal canal width refers to the width of the spinal canal after compression, while the effective spinal canal width refers to the width from the apex of the spinous process to the posterior edge of the vertebral body. All measurements of the actual spinal canal area were taken at the sagittal level where the compression was most severe. All values were obtained and averaged by two independent evaluators who were blinded to the patient group and other information before measurement. The degree of canal compression (width) was calculated using the formula: (effective canal width–actual canal width)/effective canal width. The variation in dynamic cervical spinal cord compression was assessed by calculating the degree of canal compression (width) during extension and flexion (Fig. 2b).

## Statistical methods

IBM SPSS (version 26) statistical software was used for analysis. Measurement data were expressed as $\bar{X}\pm S$. When the data were normally distributed, Student's T test and one-way ANOVA were used for comparison between groups. Neutral compression degree (sagittal and cross section) and extension/ flexion (sagittal and cross-section) were considered to be skewed in normal analysis, and the non-parametric test was used to analyze their significance. Count data were analyzed by $x^2$ test or Fisher's exact test. Differences were considered statistically significant at $P<0.05$.

To evaluate the predictive performance of meaningful variables in single factor analysis, we performed Receiver Operating Characteristic (ROC) curve analysis. First, we conducted a collinearity diagnosis to exclude adverse effects between the data and considered the data to pass the multicollinearity test with $VIF<10$. The ROC curve is

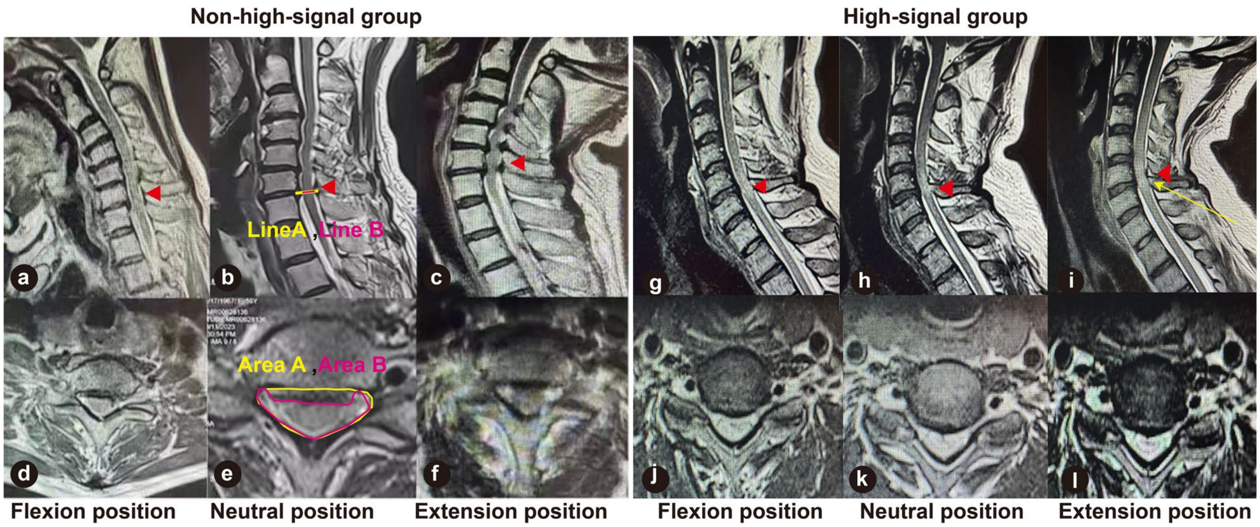


**Fig. 2** Cervical spine MRI images of patients in the high-signal and non-high-signal groups**.** **a**, **d**: Cervical cord sagittal and axial flexion position MRI images of the non-high-signal group. **b**, **e**: Cervical cord sagittal and axial neutral position MRI images of the non-high-signal group. **c**, **f**: Cervical cord sagittal and axial extension position MRI images of the non-high-signal group. **g**, **j**: Cervical cord sagittal and axial flexion position MRI images of the high-signal group. **h**, **k**: Cervical cord sagittal and axial neutral position MRI images of the high-signal group. **i**, **l**: Cervical cord sagittal and axial neutral position MRI images of the high-signal group. Red arrow: responsibility segment. Area A: Actual cross sectional area of the spinal canal. Area B: an effective spinal canal area of the spinal canal. Line A: actual spinal canal width of the spinal canal. Line B: the effective spinal canal width of the spinal canal

a graphical representation of the trade-off between sensitivity (true positive rate) and 1-specificity (false positive rate) across different cutoff values of variable A. The area under the ROC curve (AUC) was calculated to quantify the overall diagnostic accuracy of variable A. An AUC value of 0.5 indicates no predictive ability, while a value of 1.0 represents perfect discrimination. AUC values were interpreted as follows: 0.5–0.7, low predictive ability; 0.7–0.9, moderate predictive ability; and > 0.9, high predictive ability.. At the same time, to understand the risk of different factors contributing to the emergence of cervical high signals, we used the R 4.2.1 survival package to create a restricted cubic spline plot.

## Results

### Baseline characteristics of participants

70 patients with CSM (average age: 54.97 ± 10.01 years) were collected and categorized into a high-signal group (40 patients) and a non-high-signal group (30 patients) (Table 1). There was no significant difference between the two groups in terms of gender, age, BMI, responsible section, history of smoking and drinking, chronic diseases, JOA score, NDI, and VAS score ($P > 0.05$). The representative kinematic MRI image at flexion, neutral, and extension positions both in the sagittal and cross section demonstrated no intramedullary high signal appeared (Fig. 2a-f). The representative kinematic MRI image with

**Table 1** Baseline characteristics

| Characteristics | Overall (N = 70) | High-signal group (N = 40) | Non-high-signal group (N = 30) |
|---|---|---|---|
| Female (%) | 30 (42.9) | 14 (35.0) | 16 (53.3) |
| Age | 54.97 (10.01) | 55.65 (7.81) | 54.07 (12.45) |
| BMI | 26.62 (2.98) | 26.39 (2.86) | 26.92 (3.15) |
| Smoking | 20 (28.6) | 14 (35.0) | 6 (20.0) |
| Alcohol | 12 (17.1) | 8 (20.0) | 4 (13.3) |
| Chronic diseases | 27 (38.6) | 18 (45.0) | 9 (30.0) |
| Diabetes | 11 (15.7) | 7 (17.5) | 4 (13.3) |
| Hypertension | 21 (30.0) | 13 (32.5) | 8 (26.7) |
| Coronary heart disease | 5 (7.1) | 3 (7.5) | 2 (6.7) |
| Cerebrovascular disease | 7 (10.0) | 4 (10.0) | 3 (10.0) |
| *Responsible section* | | | |
| C2/3 | 1 (1.4) | 1 (2.5) | 0 (0.0) |
| C3/4 | 17 (24.3) | 12 (30.0) | 5 (16.7) |
| C4/5 | 22 (31.4) | 10 (25.0) | 12 (40.0) |
| C5/6 | 28 (40.0) | 17 (42.5) | 11 (36.7) |
| C6/7 | 2 (2.9) | 0 (0.0) | 2 (6.7) |
| JOA | 12.73 (1.90) | 12.70 (1.56) | 12.77 (2.31) |
| NDI | 0.66 (0.09) | 0.67 (0.09) | 0.65 (0.09) |
| VAS | 5.71 (0.99) | 5.60 (1.01) | 5.87 (0.97) |

a high signal appeared in the positions mentioned above, as shown in Fig. 2g-l.

### Extension position exhibited enhanced compression degree

It's reported that spinal length and width were changed according to cervical kinematic motion [12]. To determine whether compression was altered with cervical kinematic change, the relative parameters, including flexion compression degree, neutral compression degree, extension compression degree, and extension/flexion were measured in dynamic MRI images. As indicated in Fig. 3a and Supplementary Table 1, the compression degree (both sagittal and cross section) was significantly increased with cervical dynamic change from flexion to the neutral position in the high-signal group ($P < 0.05$). The same finding was also observed from neutral to extension position ($P < 0.05$). Notably, the compression degree was remarkably increased with cervical motion from flexion to extension in the high-signal group ($P < 0.05$). Similarly, as demonstrated in Fig. 3b, in the non-high-signal group. the compression degree was also significantly increased with cervical dynamic change from flexion to extension position ($P < 0.05$). However, there was no significant difference when cervical motion changed from flexion to neutral position as well as neutral to extension position in the non-high signal group ($P > 0.05$). Collectively, the compression degree was increased with the cervical motion from flexion to extension, and the cervical extension position exhibited the most enhanced degree of compression compared to the other positions in the high-signal group.

### The high-signal group exhibited an enhanced compression ratio compared to the non-high-signal group at neutral and extension positions

Given the fact that the compression degree is gradually increased with cervical dynamic change from flexion to extension in both the high-signal group and the non-high-signal group, whether the compression degree relates to high signal formation remains unclear. The degree of compression in the cross and sagittal sections (Supplementary Table 2, Fig. 4) was compared. The compression degree of the two groups exhibited no significant difference at the flexion position in both the cross and sagittal section ($P > 0.05$, Fig. 4a, e). Importantly, the high-signal group demonstrated an enhanced compression degree compared to the non-high-signal group in both cross and sagittal sections at the neutral position ($P < 0.05$, Fig. 4b, f). Similarly, the

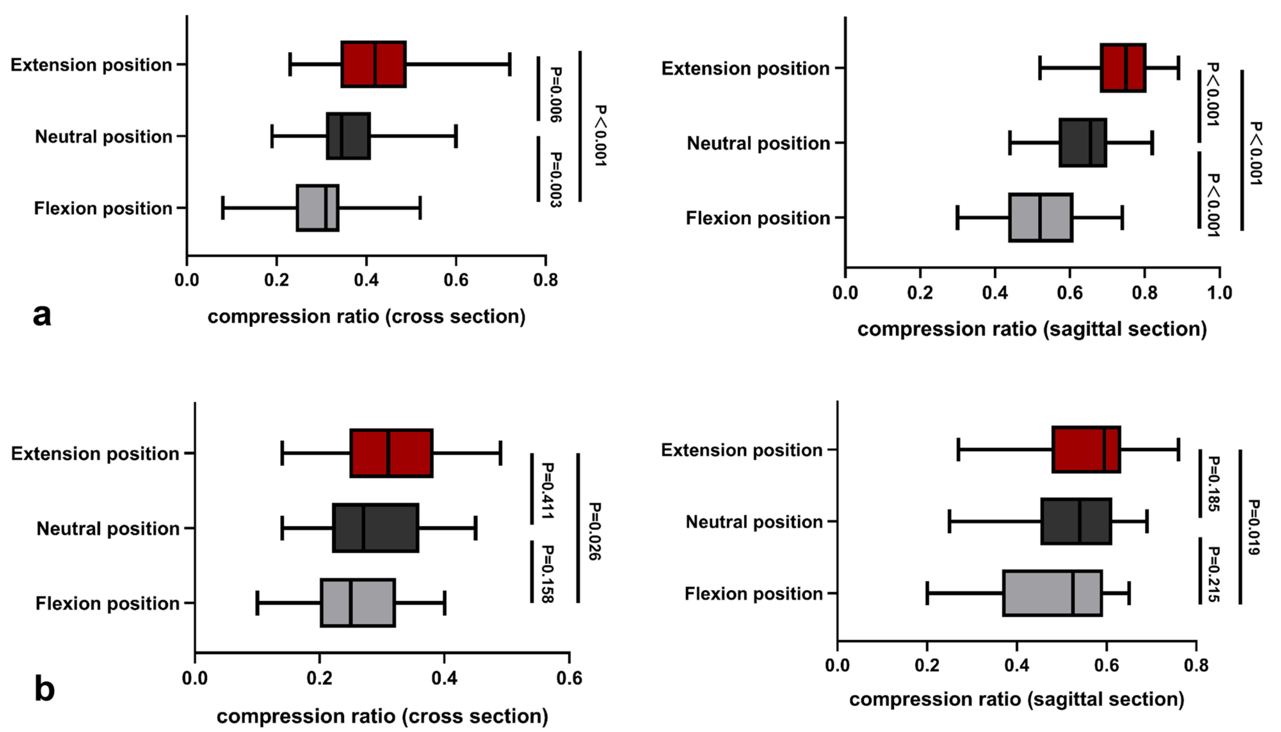


**Fig. 3** Comparison of cervical compression degree in different positions in each group. **a**. Comparison of compression degree of patients with different postures in the high-signal group, **b**. Comparison of compression degree of patients with different postures in the non-high-signal group

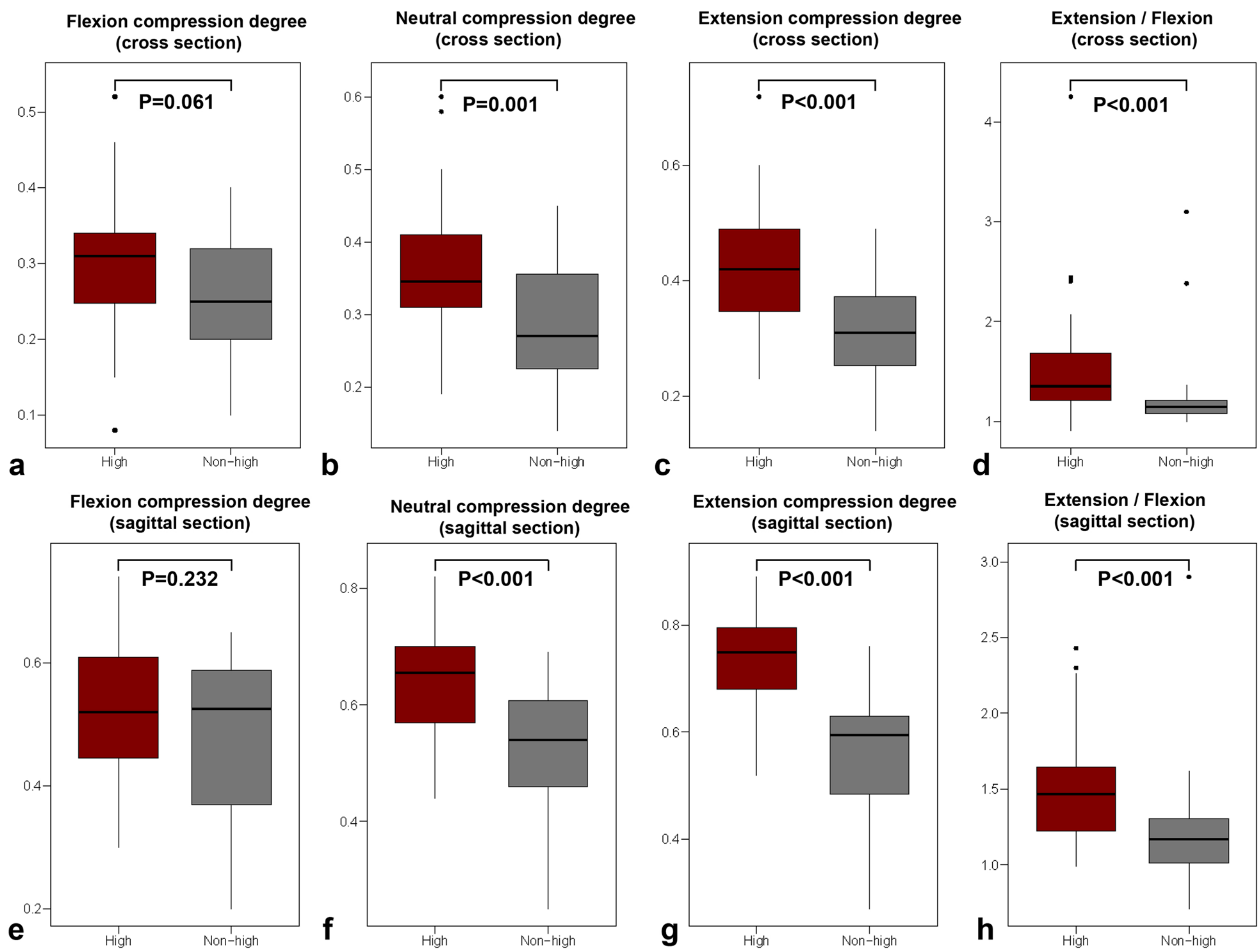


**Fig. 4** Univariate analysis of pressure degree of the high-signal group and non-high-signal group. **a**-**c**. Univariate analysis of horizontal compression area in cervical flexion, neutral, and extension positions. **d**. Univariate analysis of the ratio of extension compression area to flexion compression area. **e**–**g**. Univariate analysis of sagittal compression width in cervical flexion, neutral, and extension positions. **h**. Univariate analysis of the ratio of extension compression width to flexion compression width

high-signal group exhibited an increased compression degree compared to the non-high-signal group in both the cross and sagittal section at the extension position ($P<0.05$, Fig. 4c, g). The compression degree of extension/flexion is examined to determine whether the cervical compression degree changes the level by altering high signal formation. The high-signal group exhibited increased extension/flexion value compared to the non-high signal group in both cross and sagittal sections ($P<0.05$, Fig. 4d, h).

Collectively, the high-signal group exhibited an increased compression degree compared to the non-high-signal group at neutral and extension positions instead of flexion positions. Importantly, the compression degree change level in the high-signal group is much higher than that of the non-high-signal group.

### Predictive variables influencing high signals in CSM patients were screened based on the ROC curve.

In the univariate analysis, we found that degree of neutral position compression, degree of extension compression, and extension/flexion (both in the sagittal and cross sectional) were significant in the comparison between the two groups. VIF collinearity analysis was used to exclude adverse effects between the data. Then, The ROC curve was established to further verify the reliability of the risk factors for high signal formation. The area under the ROC curve (AUC) of the neutral position compression degree (cross section) were 0.688 (Fig. 5a). The AUC, including extension compression degree (cross section), extension/flexion (cross section), neutral compression degree (sagittal section), extension compression degree (sagittal section), or extension/flexion (sagittal section), was greater than 0.70 (Fig. 5b-f). It shows that the selected

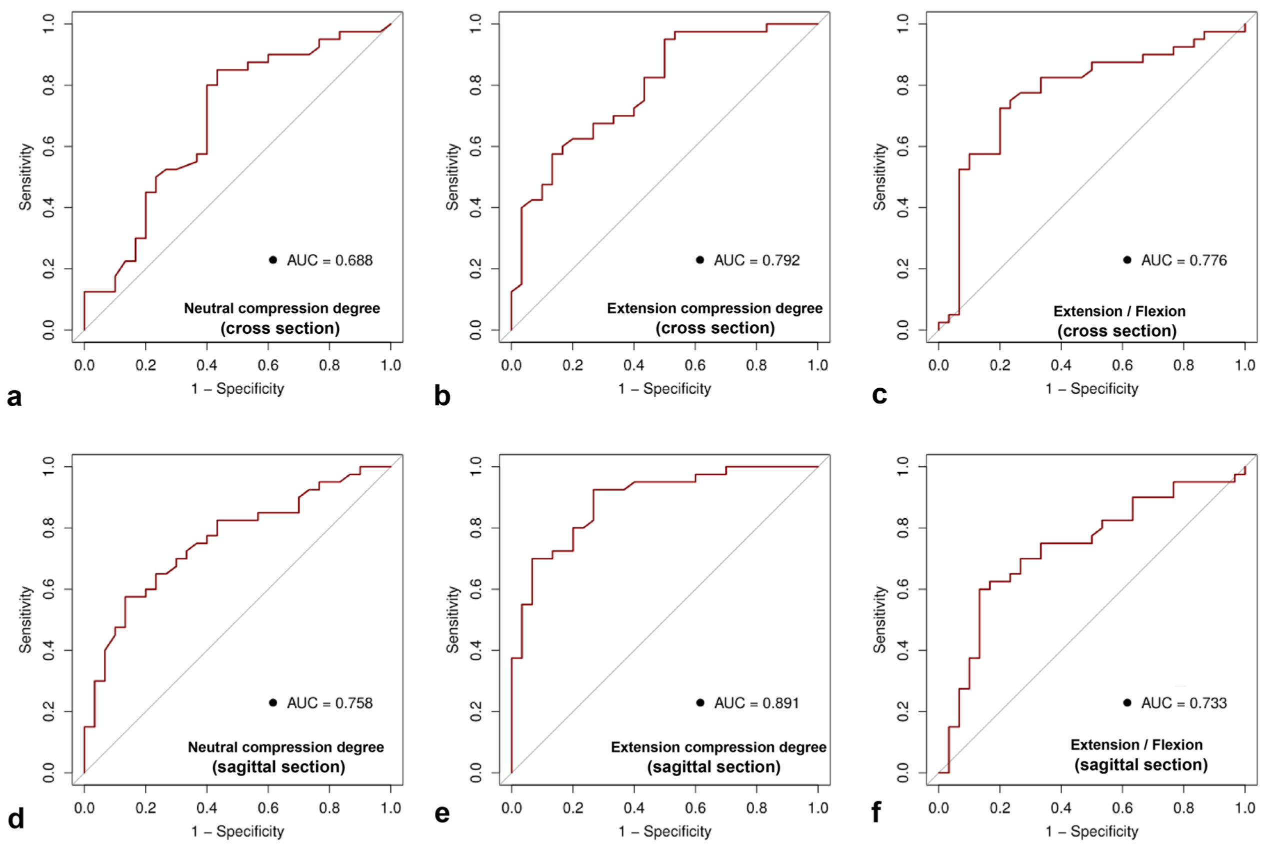


**Fig. 5** The influence of different indicators on the appearance of the cervical cord high-signal model. **a**. ROC curve of neutral compression degree (cross section). **b**. ROC curve of extension compression degree (cross section). **c**. ROC curve of extension/flexion (cross section). **d**. ROC curve of neutral compression degree (sagittal section). **e**. ROC curve of extension compression degree (sagittal section). **f**. ROC curve of extension/flexion (sagittal section)

risk factors accurately distinguished patients with high signals. The extension compression degree (sagittal section) is presented as a better risk factor.

### The value of extension/flexion at 1.4 indicates an increased likelihood of high signal formation.

We drew the RCS diagram to further determine the specific effects of these factors with a high area under the ROC curve for the high signal formation (Fig. 6). The neutral and extension position compression degree (cross and sagittal section) was in positive association with high signal formation (Fig. 6a, d, b, e). Importantly, extension/flexion reflected a cervical dynamic change degree (Fig. 6c, f), and high signal formation possibly appeared when the extension/flexion value reached 1.4 at both the cross and sagittal section.

## Discussion

Previous studies have investigated the causes and clinical significance of signal changes within the cervical cord in patients with CSM. Yasutaka described 29 patients with high signal changes within the cervical cord who underwent surgical treatment in 1980[13]. They found that signal alterations were associated with the degree of prognostic impact and hypothesized that high signals may develop due to edema, spinal cord gliosis, demyelination, or microcavities. Similarly, Morio suggested that signal changes within the cervical cord may be associated with extensive compressive myelomalacia and reflect the potential for spinal cord recovery [14]. Han further demonstrated a substantial increase in cervical cord high-signal blood flow signals in many patients with CSM, suggesting that disturbances in the movement of the cerebrospinal fluid may play a role in the formation of high signals within the cervical cord [15]. Takahashi reported increased spinal cord pressure at the intervertebral disc

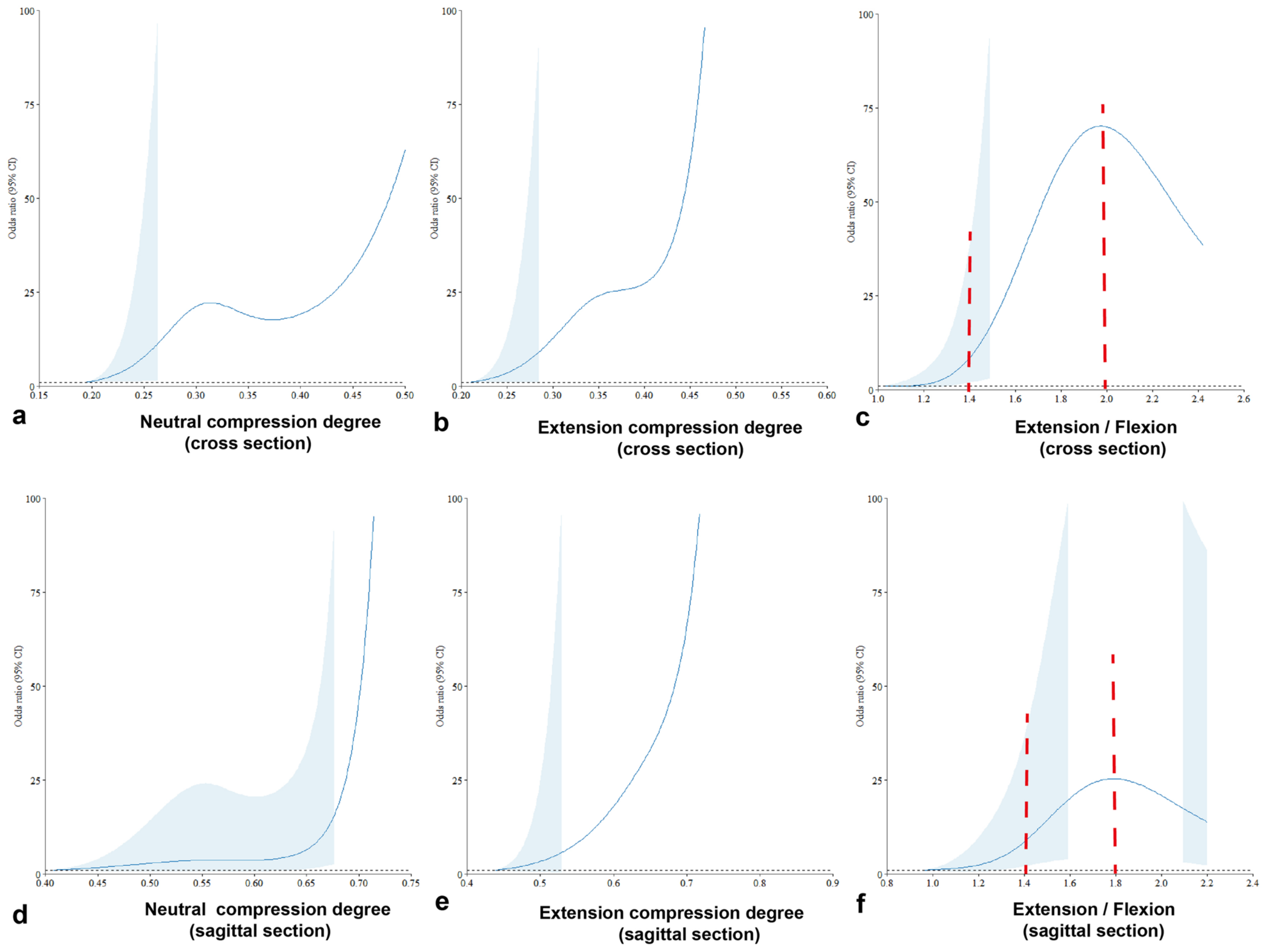


**Fig. 6** Restricted Cubic Spline Regression Model. **a**-**c**. Axial compression area of RCS Regression Model. **d**-**f**. Sagittal compression width of RCS Regression Mode. Solid lines indicate ORs, and shadow shapes indicate 95% CIs. OR, Odds Ratio; CI, Confidence Interval

level in patients with high-signal CSM, suggesting that intramedullary signal alterations in the spinal cord are closely related to intramedullary stress [16]. Our study explored the correlation between increased cervical compression and the appearance of high signals within the cervical medulla during changes in dynamic position.

Disc herniations are classified into localized and diffuse types based on their size, and orthomedial, para-orthomedial, and posterolateral herniations based on location [17, 18]. Variations in disc size and location may result in different degrees and locations of spinal cord compression. Hypertrophy and ossification of the ligamentum flavum (OLF) may also lead to dorsal encroachment [19, 20]. The spinal cord is compressed both dorsally and ventrally, as shown in Fig. 2i, this is known as the pincer effect [21]. We hypothesize that different compression modalities will produce different impingement effects on the anterior–posterior rocking motion of the cervical spine in daily life. To investigate this, we introduced a change in the degree of cervical kinematic compression in different positions. Our findings revealed that the degree of compression increased gradually with movement from cervical hyperflexion to hyperextension in patients with CSM. There was a more significant increase in cervical cord compression with the posterior extension of the cervical spine in patients in the high-signal group compared to the non-high-signal group, regardless of the sagittal or cross sectional index. This difference was pronounced in the neutral to extension position. Furthermore, flexion and extension activities of the spine can increase the maximum von Mises stress and principal strains in the spinal cord, and this effect can be further enhanced by the presence of spinal canal invasion or spinal hypermobility [22]. Alterations in the area occupied by the spinal cord during cervical flexion–extension motions may result in an imbalance in spinal tissue dynamics. Additionally, when the neck is hyperextended, a hypertrophied ligamentum flavum and other supporting ligaments may further compress the discs posteriorly, leading to the narrowing of the spinal cord and causing spinal cord compression and injury [23]. These dynamic mechanical stress alterations may lead to spinal cord dysfunction [24], which may be a new direction for investigating high-signal formation in the spinal cord.

Previous studies have highlighted the phenomenon of increased cervical spinal cord compression in the extension position, which was observed in 64.92% of patients with CSM [25, 26]. These studies also described a correlation between the appearance of high signals and increased cervical spinal cord compression. Our study demonstrated that the severity of cervical compression in the extension position poses a greater risk factor for the occurrence of high signals. Additionally, the degree of change in spinal cord compression, during cervical movement from flexion to extension position, is a risk factor for high signal generation. Severe subarachnoid space reduction may prevent cerebrospinal fluid from adequately compensating for pressure changes during cervical spine motion, leading to increased spinal tissue motion [26], and subsequent spinal cord injury and signal changes within the spinal cord on MRI-T2WI [27]. This finding underscores the important role of dynamic MRI in patients with CSM. First, the dynamic assessment of cervical spine compression using kinematic MRI can help identify patients at higher risk of developing intramedullary high signal intensity, particularly those with a high extension/flexion ratio (>1.4). This information can guide clinicians in tailoring treatment strategies—such as early surgical intervention—for patients with substantial dynamic compression changes to prevent further neurological deterioration. Second, our findings underscore the importance of avoiding excessive cervical extension and repetitive cervical flexion and extension activities in patients with CSM, as these may exacerbate spinal cord compression and increase the risk of high signal formation. Patient counseling should emphasize the potential risks of certain neck movements and the benefits of targeted physical therapy or bracing to limit harmful cervical dynamics. Finally, these findings may influence surgical decision-making, as patients with high extension/flexion ratios may benefit from posterior cervical decompression procedures. Such interventions could reduce the posterior compression caused by folding of the ligamentum flavum and reduce spinal cord impact; however, further studies are to confirm these benefits.

Our study has some limitations. First, the relatively small sample size was the main disadvantage, which may have led to bias in some of the results. Second, variations in image magnification, we could only guarantee the accuracy of the degree of cervical and spinal canal compression, but not the statistical significance of the measured cross sectional area. Consequently, we did not further analyze the cross sectional area of the cervical spinal cord. Second, while our findings suggest that neutral and extension compression degrees (both sagittal and cross section) and extension/ flexion (both sagittal and cross section) are risk factors for high signal formation, further research using multivariate analysis is needed to confirm their role as an independent risk factor. Future studies should focus on validating our findings in larger, multi-center cohorts to enhance generalizability and statistical robustness.

## Conclusion

Aggravated compression occurs with dynamic cervical changes from flexion to extension. The high-signal group exhibited an enhanced degree of compression compared to the non-high-signal group at neutral and extension positions. Furthermore, the degree of compression in the neutral and extension positions is a risk factor for the formation of an intramedullary high signal, and the risk coefficient of the extension position is greater than that of the neutral position. During movement of the cervical spine from flexion to extension, the change in the degree of compression (reflected as extension/flexion) is considered a risk factor for high-signal formation. Notably, an extension/flexion value greater than 1.4 indicates an increased likelihood of a high-signal occurrence. Kinematic cervical MRI in CSM patients has positive implications for guiding daily behavior and selecting surgical approaches.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13018-025-05715-1.

Supplementary file 1.

### Author contribution

Xiangzhen Kong: Writing-review & editing, Writing-original draft, Methodology, Formal analysis, Validation. Zhenchuan Liu: Validation, Methodology, Conceptualization. Keyu Pan: Writing-review & editing, Funding acquisition. Kangle Song: Writing-review & editing, Conceptualization. Yuanqiang Zhang: Writing-review & editing. Jianlu Wei Writing-review & editing, Data curation. Lei Cheng: Writing-review & editing, Supervision, Project administration.

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### Data availability

No datasets were generated or analysed during the current study.

## Declarations

### Ethics approval and consent to participate

This study was approved by the Research Ethics Committee of Qilu Hospital, Shandong University (KYLL-202310–013-2). Information consent was obtained from all subjects. All experiments were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

**Competing interests**
The authors declare no competing interests.

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