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Radiographic factors associated with ossification of the nuchal ligament in degenerative cervical myelopathy patients

The role of cervical paraspinal muscle fatty infiltration and C6 spinous process length

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Abstract

Background: Ossification of the nuchal ligament (ONL) is a radiographic finding frequently observed in patients with degenerative cervical myelopathy (DCM). Although its etiology remains unclear, posterior cervical anatomical factors, including paraspinal muscle degeneration and spinous process length parameters, may alter the local mechanical environment of the nuchal ligament and contribute to ONL formation. This study aimed to evaluate whether cervical paraspinal muscle fatty infiltration (FI) and C6 spinous process length are associated with ONL presence, exploratory early-stage ONL, and ONL length in patients with DCM.

Methods: This single-center retrospective cohort study included 152 patients who underwent surgery for DCM between 2022 and 2024. Patients were classified into ONL and non-ONL groups using sagittal computed tomography images. ONL length was analyzed as a continuous radiographic variable. Because no validated ONL grading system is currently available, the ONL-positive cohort was additionally divided by median ONL length into shorter- and longer-length subgroups; the shorter-length subgroup was considered an exploratory morphological surrogate for early-stage ONL rather than a validated clinical stage. Paraspinal muscle FI was assessed using the Goutallier grading system on T2-weighted magnetic resonance imaging at C4–C5, C5–C6, and C6–C7 levels. Spinous process length parameters included absolute C5, C6, and C7 spinous process lengths and C5:C6 and C6:C7 ratios. Multivariable regression, variance inflation factor analysis, and receiver operating characteristic (ROC) analysis were performed.

Results: Among 152 patients, 96 had ONL and 56 did not. Male sex and smoking status were more common in the ONL group. The ONL group showed higher C4–C5 and C5–C6 multifidus FI grades, greater absolute C5, C6, and C7 spinous process lengths, and a higher C6:C7 ratio. Multivariable logistic regression showed that the C6:C7 ratio was independently associated with ONL presence ($p = 0.012$, OR = 1.051, 95% CI = 1.011–1.092). In the exploratory early-stage ONL model, C4–C5 multifidus FI and the C6:C7 ratio were associated with shorter-length ONL. ROC analyses showed modest discriminatory performance, with area under the curve values ranging from 0.658 to 0.682. Exploratory continuous ONL length analysis showed associations with age, C4–C5 multifidus FI, and the C6:C7 ratio in the adjusted model.

Conclusions: Relative C6 spinous process length was associated with ONL presence, while C4–C5 multifidus FI and relative C6 spinous process length were associated with exploratory early-stage ONL in patients with DCM. These parameters may serve as auxiliary radiographic markers and provide a hypothesis-generating framework for understanding the anatomical, biomechanical, and mechanobiological background of ONL formation.

Abbreviations: DCM = degenerative cervical myelopathy, FI = fatty infiltration, MF = multifidus, ONL = ossification of the nuchal ligament, OPLL = ossification of the posterior longitudinal ligament, ROC = receiver operating characteristic.

Keywords: degenerative cervical myelopathy, fatty infiltration, multifidus muscle, ossification of the nuchal ligament, spinous process length

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1. Introduction

The nuchal ligament is a triangular-shaped fibrous septum that spans from the external occipital protuberance to the C7 spinous process.[1] Ossification of the nuchal ligament (ONL), an ectopic heterotopic ossification in the nuchal ligament, is a common pathological process for degenerative cervical myelopathy (DCM). While often asymptomatic in the early stages, ONL has been shown to compromise cervical stability and exacerbate osteophyte formation.[2] Along with the nuchal ligament, the paraspinal muscles constitute the "functional unit" responsible for maintaining the dynamic and static stability of the cervical spine.[3]

Cervical paraspinal muscles consist of various muscular tissues strategically located around the cervical vertebrae. The specific organization and location of cervical paraspinal muscles, cervical spine alignment, and head position maintenance are sufficiently supported.[4] Recent evidence has highlighted paraspinal muscle dysfunction—specifically sarcopenia and fatty infiltration (FI)—as key pathological drivers of cervical degeneration.[5] The relationship between paraspinal muscle FI and poor postoperative outcomes has already been well examined by several studies in patients with lumbar and cervical conditions.[6,7] Moreover, an association exists between chronic neck pain, ossification of the posterior longitudinal ligament (OPLL), and various disorders of the cervical spine with paraspinal muscle fatty degeneration.[8] Despite the well-documented deleterious effects of paraspinal muscle FI, the potential impact on DCM and ONL remains unclear.

The spinous process, a bone structure that extends from the vertebral arch of the most posterior cervical spine, serves as an anchor point for cervical paraspinal muscles and the nuchal ligament. Previous studies have proved that preserving the attachment between the paraspinal muscle and C7 spinous process could improve postoperative outcomes.[9] Variation in the length of the cervical spinous processes can affect the structure and biomechanical properties of the nuchal ligament; previous cervical anatomical research indicated that the length of the C6 spinous process influences the nuchal ligament alignment.[10] Considering the close association with the muscular–ligament complex, the spinous process plays a potential role in the onset and progression of ONL. However, the presence and progression mechanisms of ONL remain unknown, and the potential pathogenic factors include chronic overload, trauma, aging, and systemic disorders.

Therefore, we investigated the association of cervical paraspinal muscle FI and C6 spinous process length with ONL. This study aimed to determine whether posterior cervical muscle degeneration and spinous process length parameters are associated with the presence of ONL, ONL length, and exploratory early-stage ONL in patients with DCM. For the purpose of this exploratory analysis, early-stage ONL was operationally defined as median-defined shorter-length ONL. To our knowledge, this is the first study to explore the interplay between posterior cervical anatomy and ONL in this population. By identifying these anatomical associations, we seek to provide a basis for early risk recognition and propose a hypothesis-generating framework for the biomechanical and mechanobiological contributors to ONL formation.

2. Materials and methods

2.1. Study design

A single-institution retrospective cohort study was conducted from 2022 to 2024. Baseline data extraction was performed by three trained researchers, and radiological evaluations were conducted by three fellowship-trained spine surgeons. The Second Hospital of Jilin University's Institutional Review Board (IRB) approval was also obtained under IRB# 2024-525. The requirement for informed consent was waived because of the retrospective nature of the study and the use of anonymized data. This study was conducted in accordance with the Declaration of Helsinki.

2.2. Inclusion criteria and data collection

A total of 679 patients who were referred to our department with DCM between 2022 and 2024 were screened. The inclusion and exclusion criteria were as follows: no previous cervical surgery; adults aged 18 years or older who were able to provide informed consent and complete patient-reported outcome questionnaires; diagnosis of DCM without other cervical ligamentous ossification diseases, including OPLL, ossification of the ligamentum flavum (OLF), or diffuse idiopathic skeletal hyperostosis; no bone metabolic disease or concomitant cervical pathology likely to confound the analysis, including cervical trauma, tumor, or infection; and complete baseline and radiological data. Based on these criteria, 527 patients were excluded: 345 because of incomplete radiological data, 120 because of concomitant cervical ligamentous ossification, 51 because of traumatic injury, and 11 because of previous cervical surgery. Finally, 152 patients with DCM were enrolled, as shown in Figure 1. The patients were divided into a non-ONL group (without ONL; $n = 56$) and an ONL group (with ONL; $n = 96$). Because no validated clinical grading system or longitudinal staging criteria are currently available for ONL, ONL length was primarily analyzed as a continuous radiographic variable. In addition, based on the biological assumption that ONL may enlarge over time from a shorter ossified lesion to a longer ossified lesion, the ONL-positive cohort was further divided by the median ONL length into a median-defined shorter-length ONL group and a median-defined longer-length ONL group. The shorter-length ONL group was used only as an exploratory morphological surrogate for early-stage ONL, rather than as a validated clinical stage.

2.3. Demographic parameters

In this study, baseline data were collected using a standardized data collection form. Baseline data included sex,

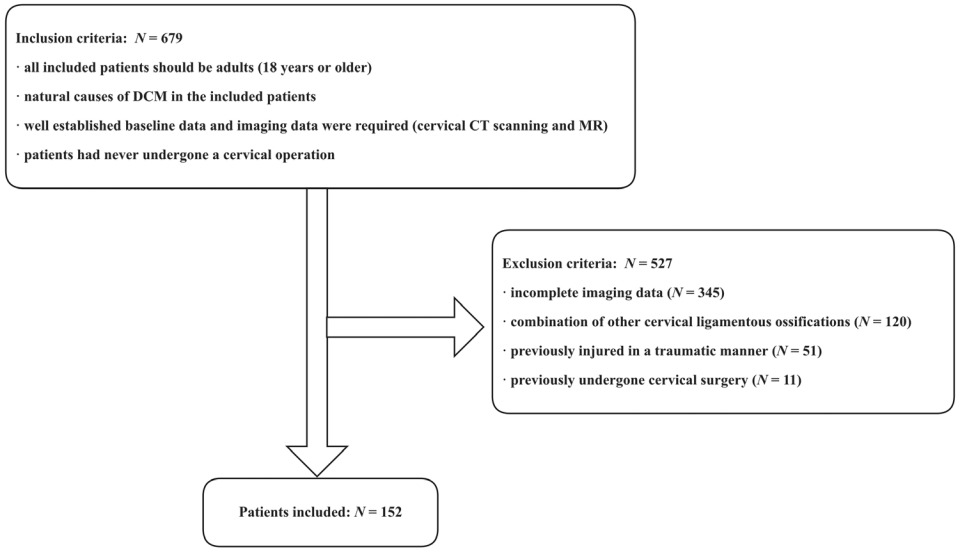


Figure 1. Strobe flow diagram for the study.

age, body mass index (BMI), smoking status (current, former, or never smoker), and diabetes status.

2.4. Radiographic parameters

ONL diagnosis was confirmed by sagittal computed tomography (CT), revealing radiopaque density in the soft tissue posterior to the cervical spinous processes. The length of ONL was measured on sagittal cervical CT images from the superior to inferior ends (Fig. S1, Supplemental Digital Content, https://links.lww.com/SPRES/A11). Paraspinal muscle FI was evaluated using the Goutallier classification for bilateral posterior cervical muscles (MF, semispinalis cervicis, and semispinalis capitis) at the C4–C5, C5–C6, and C6–C7 levels. The higher Goutallier classification between sides was recorded at each level to represent the maximum extent of muscle degeneration (Fig. S2, Supplemental Digital Content, https://links.lww.com/SPRES/A12). The Goutallier scale ranges from 0 (no fat streaks) to 4 (more fat than muscle). For muscle FI, patients were classified as mild (0–1), moderate (1.5–2.0), or severe (2.5–4.0) using the Fuchs modification (Fig. 2). Spinous process length (SL) for C5, C6, and C7 was measured from the apex to the vertebral arch on cervical CT (Fig. 3). Lines I1 and I2 defined the anterior and posterior margins of the cervical vertebra. The midpoint of I1 and the midpoint of I2 were connected and extended to the posterior cervical region. The distance between the intersection of this extension line with the corresponding spinous process base and the apex of the spinous process was defined as SL. Spinous process length parameters included absolute C5, C6, and C7 spinous process lengths and the C5:C6 and C6:C7 length ratios. In addition to the C5:C6 and C6:C7 ratios, absolute SL values of C5, C6, and C7 were recorded and reported to clarify whether differences in these ratios were primarily attributable to the elongation of the upper-level spinous process, the shortening of the lower-level spinous process, or both. Because the present magnetic resonance imaging (MRI) protocol did not include quantitative fat-fraction sequences such as T2 Dixon imaging, FI assessment remained semi-quantitative and visually graded. C5:C6 and C6:C7 ratios were calculated as follows:

$$\text{C5:C6 ratio}(\%) = \frac{\text{SLC5}(\text{mm})}{\text{SLC6}(\text{mm})} * 100\ \%$$

$$\text{C6:C7 ratio}(\%) = \frac{\text{SLC6}(\text{mm})}{\text{SLC7}(\text{mm})} * 100\ \%$$

2.5. Statistical analysis

The differences between non-ONL and ONL groups were analyzed to explore factors associated with ONL. Differences between the non-ONL group and the exploratory early-stage ONL group, defined as the median-defined shorter-length ONL group, were analyzed to explore factors associated with ONL initiation. Differences between median-defined shorter- and longer-length ONL groups were used as exploratory severity comparisons. Data distribution was assessed visually and with the Shapiro–Wilk test. Normally distributed continuous variables were presented as mean ± standard deviation, and categorical variables were presented as counts and percentages. Chi-square or Fisher exact tests were used for categorical variables, and independent-samples *t* tests or nonparametric tests were used for continuous variables, as appropriate. Multivariable logistic regression was used to determine factors independently associated with ONL presence and exploratory early-stage ONL. Available clinical covariates and radiographic parameters were evaluated together; variables were selected for the final multivariable logistic regression models based on clinical relevance, univariable group comparisons, and model stability, rather than being forced into the models solely on the basis of availability. Among ONL-positive

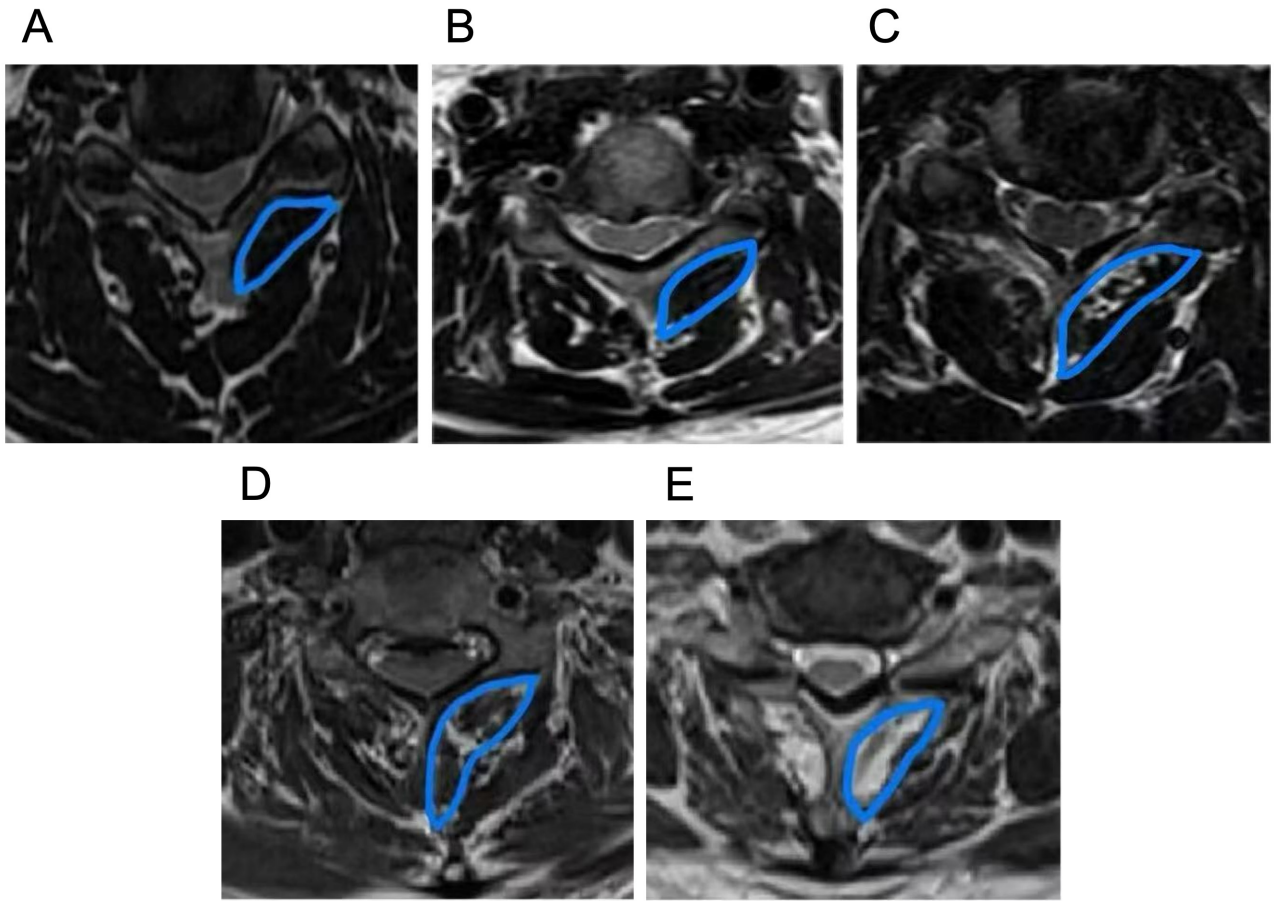


Figure 2. Assessment of FI of the cervical paraspinal muscles. Representative axial T2 MRI slices from the C4–C5 level with the left-sided MF muscle group outlined, demonstrating (A) grade 0, (B) grade 1, (C) grade 2, (D) grade 3, and (E) grade 4 (Goutallier Classification).

patients, ONL length was further analyzed as a continuous dependent variable using linear regression as a sensitivity analysis. Variance inflation factors were calculated for variables included in the multivariable models, with VIF < 5 indicating no substantial multicollinearity. Receiver operating characteristic (ROC) curves were generated to determine optimal cutoff values and discriminatory performance. Area under the curve (AUC) values between 0.6 and 0.7 were interpreted as indicating modest discriminatory ability. All analyses were performed using SPSS software (IBM SPSS Statistics for Windows, v25.0; IBM Corp., Armonk, New York). Statistical tests were two-tailed with significance set to $p < 0.05$ ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

3. Results

3.1. Demographic parameters

Table 1 summarizes the baseline data. In this study, 152 consecutive patients were enrolled, including 87 (57.2%) males and 65 (42.8%) females, with a mean age of 56.36 ± 10.36 years, ranging from 19 to 80 years, and the mean BMI was 24.35 ± 3.29 kg/m^2. All patients underwent surgery for DCM. The patient distribution included 96 individuals in the ONL group and 56 in the non-ONL group. The ONL group was further divided into median-defined shorter- and longer-length ONL groups for exploratory subgroup analysis. Because shorter ONL may represent an earlier morphological manifestation of ossification, the shorter-length ONL group was considered an exploratory surrogate for early-stage ONL. However, this classification was not intended to represent a validated clinical staging system. Age, diabetes status, and BMI did not differ significantly between the ONL and non-ONL groups ($p > 0.05$). The proportions of male patients and current smokers were more frequent in the ONL group than in the non-ONL group (male sex: 67.7% vs. 39.3%, $p < 0.001$; smoking status: $p = 0.010$). When comparing the exploratory early-stage ONL group with the non-ONL group, male sex remained more frequent (62.5% vs. 39.3%, $p = 0.018$). No significant demographic differences were found between the median-defined shorter-length and longer-length ONL subgroups (Table S1, Supplemental Digital Content, https://links.lww.com/SPRES/A13).

3.2. Radiographic parameters

Table 2 summarizes the radiographic characteristics. The Goutallier grade of C4–C5 MF and C5–C6 MF was significantly higher in the ONL group than in the non-ONL group ($p = 0.003$ and $p = 0.007$, respectively), whereas

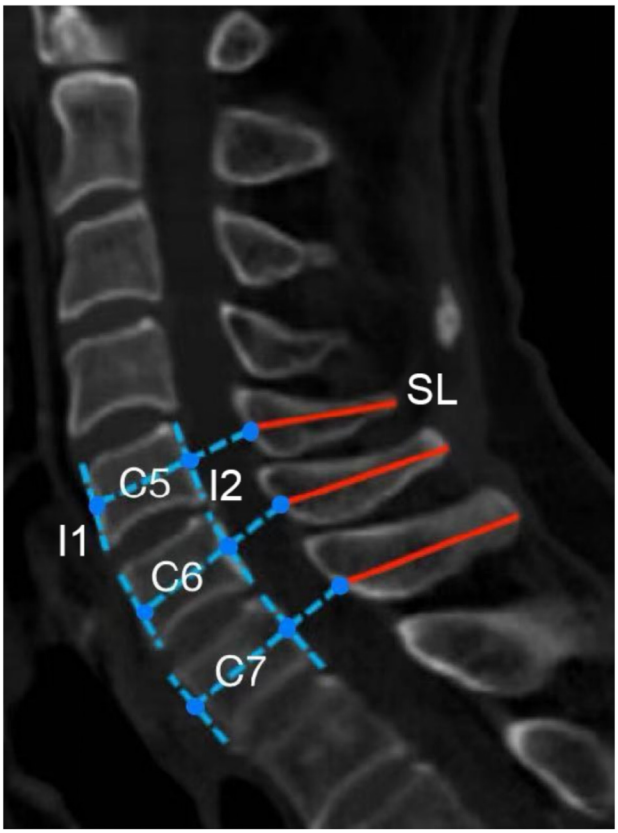


Figure 3. Measurement of cervical spinous process length (SL) on lateral CT.

no significant differences were observed for the remaining deep posterior cervical paraspinal muscles. Absolute C5, C6, and C7 SL values were significantly greater in the ONL group than in the non-ONL group (all $p < 0.001$). The C6:C7 ratio was also higher in the ONL group than in the non-ONL group (79.95% ± 10.15% vs. 75.10% ± 9.14%, $p = 0.004$), whereas the C5:C6 ratio did not differ significantly. When comparing the exploratory early-stage ONL group with the non-ONL group, the Goutallier grades of C4–C5 MF and C5–C6 MF were significantly higher in the exploratory early-stage ONL group ($p = 0.001$ and $p = 0.027$, respectively), and the C6:C7 ratio was also higher (81.01% ± 10.01% vs. 75.10% ± 9.14%, $p = 0.002$). The median-defined longer-length ONL group had a longer ONL length than the median-defined shorter-length ONL group (20.14 ± 5.57 mm vs. 9.18 ± 2.86 mm, $p < 0.001$). No other radiographic parameters differed significantly between these subgroups (Table S2, Supplemental Digital Content, https://links.lww.com/SPRES/A14).

3.3. Multivariable regression analysis

Sex, smoking status, C4–C5 MF Goutallier grade, C5–C6 MF Goutallier grade, and C6:C7 ratio were included in the multivariable regression analysis. In the model for ONL presence, the C6:C7 ratio was independently associated with ONL presence ($p = 0.012$, OR = 1.051, 95% CI = 1.011–1.092), whereas sex, smoking status, C4–C5 MF FI, and C5–C6 MF FI were not independently significant. This indicates a 5.1% increase in the odds of ONL for each 1% increase in the C6:C7 ratio. VIF values ranged from 1.073 to 1.481, indicating no substantial multicollinearity (Table 3).

For exploratory early-stage ONL, sex, C4–C5 MF Goutallier grade, C5–C6 MF Goutallier grade, and C6:C7 ratio were entered. C4–C5 MF Goutallier grade ($p = 0.011$, OR = 3.549, 95% CI = 1.342–9.387) and the C6:C7 ratio ($p = 0.005$, OR = 1.070, 95% CI = 1.021–1.121) were independently associated with exploratory early-stage ONL. These results indicate that each 1-grade increase in C4–C5 MF Goutallier grade and each 1% increase in the C6:C7 ratio were associated with higher odds of exploratory early-stage ONL. In this model, VIF values ranged from 1.062 to 1.652, indicating no substantial multicollinearity (Table 4).

3.4. ROC curve

ROC analysis was used to evaluate discriminatory performance. For ONL presence, the C6:C7 ratio showed a sensitivity of 77.1%, specificity of 48.2%, AUC of 0.658, and an optimal cutoff value of 73.82%. These results

Table 1

Patient demographic characteristics (2022–2024).

Variables	All patients (*N* = 152)	Non-ONL (*N* = 56)	ONL (*N* = 96)	*p* value	Exploratory early-stage ONL (*N* = 48)	*p* value
Age (year)	56.36 ± 10.36	54.50 ± 12.41	57.44 ± 8.85	0.120	57.02 ± 8.91	0.230
Sex						
Male	87 (57.2%)	22 (39.3%)	65 (67.7%)	< 0.001***	30 (62.5%)	0.018*
Female	65 (42.8%)	34 (60.7%)	31 (32.3%)		18 (37.5%)	
Diabetes status						
Yes	16 (10.5%)	5 (8.9%)	11 (11.5%)	0.620	6 (12.5%)	0.560
No	136 (89.5%)	51 (91.1%)	85 (88.5%)		42 (87.5%)	
Smoking status						
Current	46 (30.3%)	9 (16.1%)	37 (38.5%)	0.010**	17 (35.4%)	0.074
Former	3 (2.0%)	2 (3.6%)	1 (1.0%)		1 (2.1%)	
Never	103 (67.8%)	45 (80.4%)	58 (60.4%)		30 (62.5%)	
BMI (kg/m^2)	24.35 ± 3.29	24.02 ± 3.58	24.54 ± 3.10	0.340	23.97 ± 2.59	0.940

BMI = body mass index, non-ONL = non-ossification of the nuchal ligament, ONL = ossification of nuchal ligament.

Table 2

Patient radiographic characteristics (2022–2024).

Variables	All patients (*N* = 152)	Non-ONL (*N* = 56)	ONL (*N* = 96)	*p* value	Exploratory early-stage ONL (*N* = 48)	*p* value
SL (mm)						
C5	19.14 ± 3.18	17.53 ± 2.56	20.08 ± 3.13	< 0.001***	20.11 ± 3.14	< 0.001***
C6	26.40 ± 4.85	23.86 ± 3.45	27.88 ± 4.94	< 0.001***	27.96 ± 4.81	< 0.001***
C7	33.71 ± 3.66	31.84 ± 3.24	34.80 ± 3.46	< 0.001***	34.45 ± 3.51	< 0.001***
C5:C6 ratio (%)	73.43 ± 10.27	74.29 ± 11.21	72.92 ± 9.72	0.429	72.72 ± 8.89	0.437
C6:C7 ratio (%)	78.16 ± 10.04	75.10 ± 9.14	79.95 ± 10.15	0.004**	81.01 ± 10.01	0.002**
Goutallier grade						
C4–C5						
MF						
Mild	34	20	14	0.003**	4	0.001***
Moderate	90	31	59		32	
Severe	28	5	23		12	
SCer						
Mild	111	42	69	0.915	34	0.892
Moderate	35	12	23		12	
Severe	6	2	4		2	
SCap						
Mild	107	39	68	0.722	31	0.512
Moderate	44	17	27		16	
Severe	1	0	1		1	
C5–C6						
MF						
Mild	15	9	6	0.007**	4	0.027*
Moderate	79	34	45		21	
Severe	58	13	45		23	
SCer						
Mild	106	38	68	0.55	37	0.570
Moderate	43	16	27		10	
Severe	3	2	1		1	
SCap						
Mild	130	52	78	0.135	39	0.166
Moderate	21	4	17		8	
Severe	1	0	1		1	
C6–C7						
MF						
Mild	5	4	1	0.122	0	0.158
Moderate	53	18	35		15	
Severe	94	34	60		33	
SCer						
Mild	111	39	72	0.265	35	0.684
Moderate	37	14	23		12	
Severe	4	3	1		1	
SCap						
Mild	140	54	86	0.18	43	0.294
Moderate	10	1	9		4	
Severe	2	1	1		1	

MF = multifidus, non-ONL = non-ossification of the nuchal ligament, ONL = ossification of the nuchal ligament, SCap = semispinalis capitis, SCer = semispinalis cervicis.

Table 3

Multivariable logistic regression analysis with multicollinearity diagnostics for factors associated with ONL presence.

Variables		95% CI				
	OR	Lower	Upper	*p* value	Tolerance	VIF
Sex	0.492	0.225	1.074	0.075	0.832	1.202
Smoking	0.652	0.411	1.034	0.069	0.869	1.151
C4–C5 MF Goutallier grade	2.020	0.980	4.164	0.057	0.679	1.472
C5–C6 MF Goutallier grade	1.583	0.787	3.185	0.198	0.675	1.481
C6:C7 ratio	1.051	1.011	1.092	0.012*	0.932	1.073

C6:C7 ratio = cervical spinous process length ratio between C6 and C7, CI = confidence interval, MF = multifidus, VIF = variance inflation factor.

Table 4

Multivariable logistic regression analysis with multicollinearity diagnostics for factors associated with exploratory early-stage ONL.

Variables	OR	95% CI		*p* value	Tolerance	VIF
		Lower	Upper			
Sex	0.522	0.216	1.261	0.148	0.941	1.062
C4–C5 MF Goutallier grade	3.549	1.342	9.387	0.011*	0.614	1.630
C5–C6 MF Goutallier grade	1.007	0.433	2.338	0.988	0.605	1.652
C6:C7 ratio	1.070	1.021	1.121	0.005**	0.924	1.082

C6:C7 ratio = cervical spinous process length ratio between C6 and C7, CI = confidence interval, MF = multifidus, VIF = variance inflation factor.

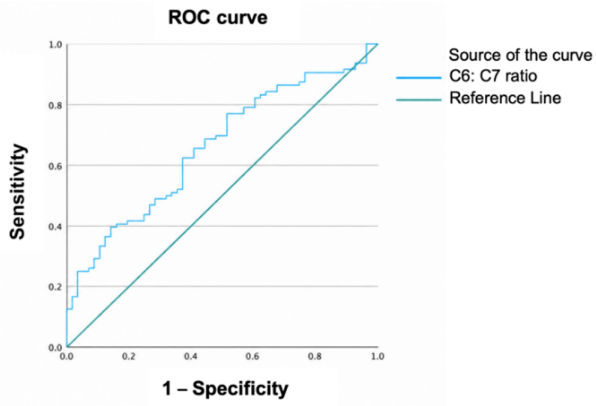
indicate that the C6:C7 ratio had modest discriminatory ability for identifying ONL presence (Fig. 4). For exploratory early-stage ONL, defined as median-defined shorter-length ONL, the C4–C5 MF Goutallier grade showed a sensitivity of 91.7%, specificity of 33.9%, AUC of 0.670, and an optimal cutoff value of 1.5. The C6:C7 ratio showed a sensitivity of 45.8%, specificity of 87.5%, AUC of 0.682, and an optimal cutoff value of 84.72%. These findings suggest that the C4–C5 MF Goutallier grade and the C6:C7 ratio may provide useful radiographic information for identifying patients who may be more susceptible to ONL formation, although their discriminatory performance remained moderate (Fig. 5).

3.5. Linear regression analysis for ONL length

To avoid the loss of information caused by dichotomizing ONL length, ONL length was analyzed as a continuous outcome among ONL-positive patients. In univariate linear regression, none of the evaluated variables was significantly associated with ONL length (Table 5). In the multivariable linear regression model adjusted for age, sex, BMI, smoking status, diabetes status, C4–C5 MF Goutallier grade, C5–C6 MF Goutallier grade, and the C6:C7 ratio, age, C4–C5 MF Goutallier grade, and the C6:C7 ratio were independently associated with ONL length (all $p < 0.05$; Table 6). VIF values ranged from 1.067 to 1.569, indicating no substantial multicollinearity. The discrepancy between univariable and multivariable findings may reflect confounding or suppression effects; therefore, these adjusted findings should be interpreted cautiously (Table S3, Supplemental Digital Content, https://links.lww.com/SPRES/A15).

4. Discussion

To our knowledge, this is the first study to examine the association between ONL and the anatomical features of the posterior cervical spine in patients with DCM. We investigated potential risk factors for ONL and provided a hypothesis-generating perspective on its pathogenesis. Among demographic parameters, male sex was more common in patients with ONL, consistent with previous studies.[11,12] Smoking was also more prevalent in the

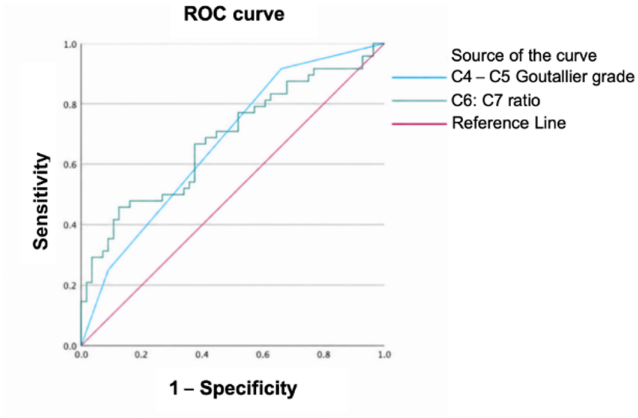


Predictor	AUC	Std	*p*	95%CI
C6: C7 ratio	0.658	0.045	0.001***	0.571–0.746

CI, confidence interval; ROC, receiver operating characteristic; AUC, area under the curve; Std, standard deviation; C6: C7 ratio, cervical spinous process length ratio between C6 and C7.

$p < 0.05$ was considered as statistically significant (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Figure 4. ROC analysis for discriminatory performance in identifying ONL presence among DCM patients (C6:C7 ratio).



Predictor	AUC	Std	*p*	95%CI
C4–C5 MF Goutallier grade	0.670	0.053	0.003**	0.567–0.773
C6: C7 ratio	0.682	0.053	0.001***	0.578–0.786

CI, confidence interval; MF, multifidus; ROC, receiver operating characteristic; AUC, area under the curve; Std, standard deviation; C6: C7 ratio, cervical spinous process length ratio between C6 and C7.

$p < 0.05$ was considered as statistically significant (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Figure 5. ROC analysis for discriminatory performance in identifying exploratory early-stage ONL among DCM patients (C4–C5 MF Goutallier grade and C6:C7 ratio).

ONL group, which is compatible with previous evidence linking smoking with spinal bone metabolic disorders.[13] However, sex and smoking were not independent predictors in the multivariable model. These findings suggest that demographic factors may be related to ONL through interactions with muscle quality, mechanical loading, or unmeasured biological factors. Age, BMI, and diabetes status were available as potential confounders.

Anatomical and mechanical features provide an additional framework for exploring potential mechanisms of ONL initiation and progression. The nuchal ligament comprises funicular (dorsal) and lamellar (ventral) portions.[14] The funicular portion extends from the occiput to the lower cervical spinous processes (C6 or C7). The lamellar portion arises from the remaining cervical spinous processes (C1–C6) and attaches to the funicular portion of the nuchal ligament.[15] Because the nuchal ligament is located in the posterior cervical region, it acts as an LMA relative to the sagittal rotation axis and helps restrict cervical flexion.[16]

The nuchal ligament was traditionally believed to attach mainly to the C7 spinous process.[17] Until 2012, a cadaveric and clinical study reported that the nuchal ligament attaches to both C6 and C7 when the C6:C7 ratio is greater than 0.8, whereas it attaches only to C7 when this ratio is lower than 0.8.[10] On this basis, the nuchal ligament can be classified into two attachment patterns. The long moment arm (LMA) pattern refers

Table 5

Univariable linear regression analysis for factors associated with ONL length among ONL-positive patients with DCM.

Variables	Unstandardized B	95% CI		*p* value
		Lower	Upper	
Age (year)	0.119	−0.067	0.257	0.249
Sex	−0.089	−4.403	1.719	0.386
BMI (kg/m^2)	0.175	−0.060	0.857	0.088
Smoking status	−0.049	−1.830	1.128	0.639
Diabetes status	0.037	−3.692	5.325	0.720
C4–C5 MF Goutallier grade	−1.502	−3.863	0.859	0.210
C5–C6 MF Goutallier grade	0.419	−1.954	2.792	0.727
C6:C7 ratio	−0.131	−0.229	0.049	0.202

CI = confidence interval; C6:C7 ratio = cervical spinous process length ratio between C6 and C7.

Table 6

Multivariable linear regression analysis with multicollinearity diagnostics for factors associated with ONL length among ONL-positive patients with DCM.

Variables	Unstandardized B	95% CI		*p* value	Tolerance	VIF
		Lower	Upper			
Age (year)	0.189	0.011	0.368	0.038	0.768	1.301
Sex	–1.882	–5.188	1.425	0.261	0.795	1.257
BMI (kg/m^2)	0.474	–0.013	0.962	0.057	0.840	1.190
Smoking status	–0.157	–1.716	1.401	0.841	0.831	1.203
Diabetes status	1.937	–2.916	6.789	0.430	0.796	1.256
C4–C5 MF Goutallier grade	–3.207	–6.070	–0.345	0.029*	0.637	1.569
C5–C6 MF Goutallier grade	1.877	–0.875	4.630	0.179	0.685	1.459
C6:C7 ratio	–0.145	–0.284	–0.006	0.041*	0.937	1.067

BMI = body mass index, C6:C7 ratio = cervical spinous process length ratio between C6 and C7, CI = confidence interval, MF = multifidus, VIF = variance inflation factor.

to nuchal ligament attachment only to the C7 spinous process, whereas the short moment arm (SMA) pattern refers to attachment to both the C6 and C7 spinous processes.

A schematic model of cervical flexion restriction for both ligament groups is provided in Figure 6. Variation in the inferior anchor points of the nuchal ligament mainly depends on the length of the C6 spinous process. A longer C6 spinous process (SMA phenotype) may move the effective lower attachment of the nuchal ligament closer to the instantaneous center of rotation, thereby shortening the functional moment arm and increasing local tensile demand during cervical flexion. Our findings—that a C6:C7 ratio > 73.82% was associated with ONL presence and a ratio > 84.72% was associated with exploratory early-stage ONL—suggest a potential relationship among relative C6 spinous process elongation, nuchal ligament attachment pattern, and ONL formation. However, the present study did not directly measure ligament strain, local stress distribution, or dynamic cervical kinematics. Therefore, the proposed influence of C6 spinous process length on the effective moment arm and loading environment of the nuchal ligament should be interpreted as an anatomical and biomechanical hypothesis rather than direct proof of causality. Future finite element analyses and dynamic kinematic MRI studies are required to determine whether different C6:C7 ratio phenotypes produce distinct stress distributions within the nuchal ligament.

Mechanical stress may also provide a biological bridge between altered tensile loading and ectopic ossification. Repetitive tensile loading may activate mechanotransduction pathways in ligamentous fibroblasts or chondrocyte-like cells, alter cellular metabolism, and promote a local microenvironment characterized by low-grade inflammation, hypoxia-related responses, neurovascular ingrowth, and osteogenic or chondrogenic differentiation.[18] In this context, pro-osteogenic signaling pathways such as BMP/TGF-beta, Wnt/beta-catenin, and RUNX2-mediated transcription may participate in the transition from soft-tissue remodeling to ectopic mineralization.[19,20] This explanation remains speculative in the absence of histological or molecular data from the nuchal ligament, but it provides a biological framework linking C6 spinous process length, altered local tensile loading, and ONL formation.

Along with the potential effect on the pathogenesis of DCM and the initiation of ONL, the C6:C7 ratio may also be clinically relevant to postoperative axial neck pain after laminoplasty. Generally, C7 spinous process preservation during laminoplasty is widely acknowledged for axial neck pain prevention.[21] Few studies have suggested that the preservation of the C6 spinous process is not superior to non-preservation for preventing postoperative axial neck pain.[22] However, these studies may ignore individual differences in C6 spinous process length parameters. Future studies should therefore investigate whether C6 preservation has differential effects in patients with SMA and LMA phenotypes.

In the present study, absolute C5, C6, and C7 SL values were higher in the ONL group than in the non-ONL group, and the C6:C7 ratio remained significantly higher. Because both C6 and C7 were longer in patients with ONL, the ratio difference does not appear to be explained by isolated C7 shortening; rather, it suggests relatively greater elongation of C6 compared with C7. The C5:C6 ratio did not differ significantly among the non-ONL, shorter-length ONL, and longer-length ONL groups. Compared with the C5 spinous process, the C7 spinous process is more directly related to the inferior attachment of the nuchal ligament, which may explain this negative result.

Cervical paraspinal muscles FI are closely related to DCM.[23] For the pathogenesis of DCM, paraspinal muscle FI has been associated with cervical disc degeneration, cervical instability, OPLL progression, and neck pain.[24,25] In clinical studies, paraspinal muscle FI has also been identified as an important predictor of functional recovery and postoperative outcomes in patients with DCM. Patients with severe FI show less improvement in neck disability and pain relief postoperatively and are more likely to report worsening PROMs following ACDF or cervical laminoplasty.[26] Furthermore, higher paraspinal muscle FI has been proven to be a risk factor for both preoperative abnormal sagittal alignment of the cervical spine and postoperative kyphosis deformities in series studies.[27]

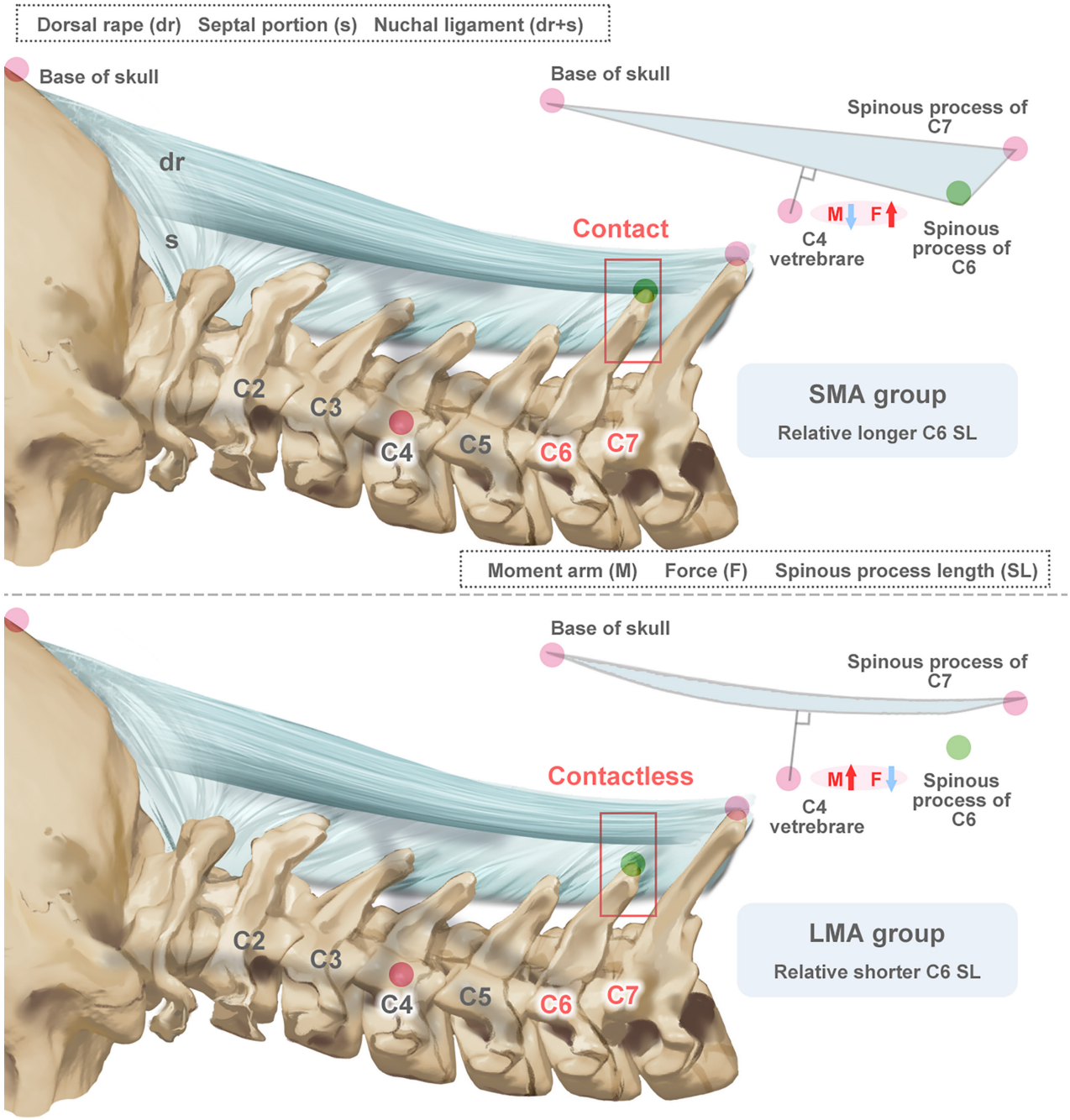


Figure 6. Schematic diagram of the SMA and LMA patterns.

Our study found an association between FI of the MF and ONL in patients with DCM. The cervical MF typically spans two to four cervical levels, while the semispinalis covers four to six levels.[28] We noted no significant relationship between semispinalis FI and ONL, possibly because the semispinalis is larger and spans more levels. The smaller MF may be more susceptible to local mechanical changes and fatigue, which can lead to injury and fatty replacement during muscle regeneration. Recent studies have also identified neurogenic atrophy and facet inflammation as potential mechanisms contributing to MF FI susceptibility.[29,30]

Our findings suggest that FI of the MF at the C4–C5 and C5–C6 levels is linked to ONL in DCM patients, with C4–C5 FI associated with exploratory early-stage ONL. One potential explanation is superficial paraspinal muscle compensation. Because a single cervical MF spans a limited number of segments, the MF plays an important role in segmental posture and stabilization.[31,32] Superficial muscles, such as the semispinalis, also contribute to maintaining cervical posture.[33,34] Once FI occurs in the MF, superficial posterior cervical muscles may compensate for the reduced stabilizing function of the deep extensor system, thereby increasing the tensile load transmitted to the

nuchal ligament. This compensatory load may contribute to microdamage, tissue repair, and eventual ossification. However, this mechanism requires confirmation using longitudinal imaging, electromyography, or biomechanical modeling.

Additionally, FI of the MF and ONL frequently occur in the same segments, particularly C4–C6, where ONL is more prevalent.[8,35] FI is notably more severe from C4 to C6 in DCM patients with chronic neck pain. Compared with the C5–C6 MF, the MF located at C4–C5 usually extends from C4 to C7 and is involved in segments with relatively large motion ranges. This may explain why FI of the C4–C5 MF was associated with exploratory early-stage ONL recognition. Clinically, these findings suggest that C4–C5 MF quality and the C6:C7 ratio may be useful auxiliary radiographic markers when evaluating posterior cervical degeneration. However, given their moderate discriminatory performance, these markers should be integrated with other clinical and radiographic parameters rather than used as stand-alone diagnostic criteria. Future studies should combine these parameters with quantitative muscle MRI, sagittal alignment, dynamic instability, and clinical symptoms to improve predictive performance.

In the present study, shorter ONL was regarded as a possible morphological surrogate for early-stage ONL based on the assumption that ONL may progress from a shorter ossified lesion to a longer ossified lesion over time. This assumption provides a clinically meaningful framework for exploring factors associated with ONL initiation. However, because this study was cross-sectional and lacked longitudinal imaging follow-up, the median-defined shorter-length ONL group should not be interpreted as a validated temporal stage, and the associations observed in the continuous ONL length analysis should not be interpreted as proof of ONL progression. Future longitudinal studies are needed to confirm whether shorter ONL lesions subsequently enlarge over time and to establish standardized ONL staging criteria.

This study has several limitations. First, this was a single-center retrospective study including only operative DCM patients, which limits causal inference and generalizability. Second, 345 patients were excluded because of incomplete radiological data, introducing a potential risk of selection bias. This accounted for 50.8% of the initially screened cohort. The included cohort may have differed from the excluded population in baseline disease severity, imaging availability, comorbidities, or treatment pathway, which may have influenced the observed associations. Third, although available covariates such as age, sex, BMI, smoking status, and diabetes status were considered in the multivariable analyses, disease duration and serum sex hormone levels were not systematically available in this retrospective cohort. Therefore, residual confounding from unmeasured variables cannot be fully excluded. Fourth, the control group consisted entirely of surgical DCM patients rather than healthy asymptomatic individuals; therefore, the findings should be interpreted as ONL-associated radiographic differences within a DCM surgical population, rather than as generalizable predictors for broader populations.

Fifth, because no validated ONL-specific clinical grading system is currently available, the median-based subgrouping of ONL length was sample-dependent and should not be considered an externally validated severity threshold. Future studies should further evaluate ONL length as a continuous radiographic outcome and develop standardized ONL grading systems. Sixth, FI was assessed using the semi-quantitative Goutallier classification. Although this approach is practical for retrospective clinical imaging studies, it remains subjective and may be less reproducible than quantitative MRI measurements, such as cross-sectional area, functional cross-sectional area, or T2 Dixon-derived fat fraction. Finally, the proposed relationship among relative C6 spinous process length, nuchal ligament attachment pattern, altered local tensile loading, and ONL formation was not directly verified by finite element analysis, dynamic kinematic MRI, electromyography, or histological evaluation of the nuchal ligament. Further prospective multicenter studies incorporating quantitative muscle imaging, biomechanical simulation, dynamic functional assessment, and molecular or histological evidence will be valuable to validate and extend these findings.

5. Conclusions

Our study demonstrated that relative C6 spinous process length was associated with ONL presence, while FI of the C4–C5 MF and relative C6 spinous process length were associated with exploratory early-stage ONL. These findings suggest that C4–C5 multifidus degeneration and relative C6 spinous process length may be involved in ONL formation by altering the local mechanical environment of the nuchal ligament and reducing deep segmental stability. Although the ROC analysis showed only moderate discriminatory performance, these parameters may provide clinically relevant auxiliary radiographic information for risk recognition and posterior cervical degeneration assessment. Future prospective studies incorporating quantitative MRI, longitudinal ONL length assessment, biomechanical modeling, and asymptomatic controls are warranted to validate these findings and refine their clinical application.

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Not applicable.

Ethical statement

This study was approved by the Institutional Review Board (IRB) of the Second Hospital of Jilin University, China (Approval No. IRB# 2024-525). The requirement for informed consent was waived by the IRB because of the retrospective nature of the study and the use of anonymized data. This study was conducted in accordance with the Declaration of Helsinki.

Conflicts of interest

The authors declare no conflicts of interest.

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Data availability statement

Relevant data can be available by contacting the corresponding author upon reasonable request.

Author contributions

ML—conceptualization
ML, QD—formal analysis.
ML—data curation.
YS, QD—visualization.
YS, QD—methodology.
JY, JM, ZQ, MW, WJ—project administration.
ML—writing – original draft.
JY, JM, ZQ, MW, WJ—writing – review and editing.
WJ—funding acquisition.

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