European Spine Journal (2023) 32:1077–1086
https://doi.org/10.1007/s00586-023-07557-z

ORIGINAL ARTICLE

Specific foraminal changes originate from degenerative spondylolisthesis on computed tomographic images

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Received: 15 September 2022 / Revised: 10 January 2023 / Accepted: 22 January 2023 / Published online: 3 February 2023

Abstract

Purpose Operative treatment for degenerative spondylolisthesis (DS) is accompanied by the high incidence of nerve injury. Foraminal structures, especially the hypertrophied facet joints, have significant impacts on the adjacent nerve. This study aims to identify the specific foraminal changes relating to DS and nerve injury.

Methods The CT images of 70 patients with DS and 50 patients without lumbar disease were collected. The length and height of the foraminal structure were measured horizontally and vertically on sagittally reconstructed images. Horizontal stenosis, meaning to pending compression to nerve root after complete reduction, was evaluated on the image located to the middle of the foramen. Chi-square test or *T*-test were carried out using SPSS 26.0.

Results The hyperplasia of the superior articular process (SAP) and articular capsule (Ac) incidence rates in DS group was significantly more common than that of the control group (9.2 vs 0.0%, 42.9 vs 2.0%). The height and width of the SAP and Ac in vertical and horizontal directions were significantly greater than those in the control group (4.95 mm vs − 0.47 mm, $P<0.0001$; 3.28 vs 0.02 mm, $P<0.0001$; 5.27 vs3.44 mm, $P<0.0001$; 2.60 vs 0.37 mm, $P<0.0001$). In the DS group, hyperplasia of the SAP and Ac accounted for 9 and 43% respectively, 85 and 45% of which were accompanied by horizontal stenosis of the intervertebral foramen.

Conclusion DS is usually characterized of excessive hyperplasia of the SAP and Ac, both of which are possible elements of nerve root injury after complete reduction in operation and should be focused on during surgery.

Keywords Degenerative spondylolisthesis · Computed tomography · Superior articular process · Articular capsule · Intervertebral foramen

Introduction

Degenerative spondylolisthesis (DS) is a common lumbar degenerative disease in the middle-aged and elderly, which commonly occurs in L4/5 level [1, 2]. The most important cause of DS is segmental sagittal instability due to morphological abnormality of posterior components in the lumbar spine [3, 4]. The facet joints play a critical role in maintaining the lumbar stability by sharing the compressive and rotational load and protecting the disc from excessive shear and rotational forces [5]. Under above both forces, the facet joints present the significant changes relating to the development of DS [5–7]. Meanwhile, studies also indicated a significant correlation between articular capsule (Ac) effusion and DS [8–10]. Both facet and Ac are important compositions of the intervertebral foramen.

The intervertebral foramen consists of the adjacent pedicle, posterior margin of the vertebral body, intervertebral disc, and posterior superior and inferior articular processes, Ac, and ligamentum flavum [11]. The geometry of the lumbar foramen in the lateral images showed different geometric shapes, such as oval, round, or inverted teardrop-shaped windows [12]. The development of DS accompanied with

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the changes of both the size of foraminal structures and the foraminal morphology, which bring a smaller area and the foraminal stenosis in patients with DS [13]. Nerve roots running through the intervertebral foramen are apt to be compressed by abnormal foraminal structure.

At present, most surgeons advocate complete reduction to restore the normal anatomical structure of the spine in the treatment of DS. During the reduction, the changes of both foraminal morphology and the resultant changed relationship between the nerve root and the foraminal structures may result in nerve injury [14, 15]. To avoid the possible nerve root injury, complete decompression is necessary, which increases the instability of the spine. So, there is great significance to reveal the foraminal morphologic changes which may injure the nerve root.

Unfortunately, there was no study focusing on the relationship between different foraminal contents in DS at the sagittal plane. This study plans to measure and analyze the size of superior articular process (SAP), Ac, and nerve root in the intervertebral foramen on CT sagittal images in patients with DS (Fig. 1), further to identify the unique changes of the SAP and Ac in DS, aiming at giving some important guidance to reduce the possible nerve root injury in the surgical treatment of DS.

Materials and methods

Patients

This study enrolled 70 patients with DS at the L4/5 level and 50 patients without lumbar disease in our hospital from January 2020 to January 2021. The study was approved by the Ethics Committee and Institutional Review Board at our hospital, and informed consent was obtained from all participants. All patients were followed up at least 12 months. The basic information and CT images of all cases were collected.

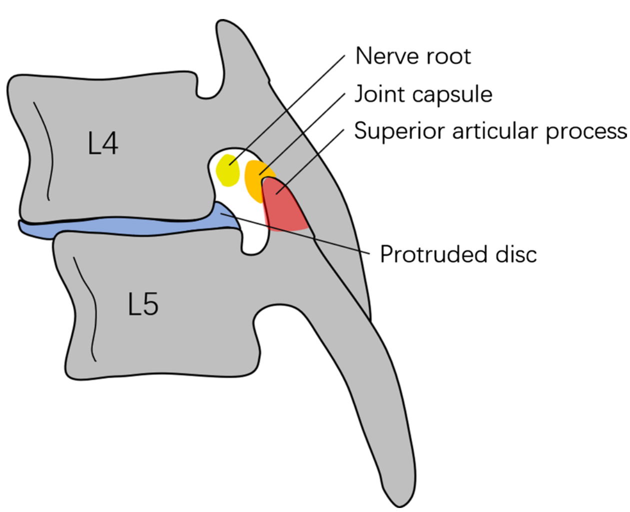

Fig. 1 Diagram of foraminal structures and their relative position on the sagittal plane

Inclusion criteria

DS was diagnosed with a 4 mm or greater slip and an associated intact neural arch on sagittal CT. The DS group only collected patients with DS at the L4/5 level. The control group included patients without lumbar disease.

Exclusion criteria

Patients with scoliosis, congenital anomalies, spinal infection, isthmic spondylolisthesis, previous lumbar surgery, or incomplete imaging or demographic information were excluded in both groups. In addition to the above conditions, patients with spondylolisthesis or instability were also ruled out of the control group.

CT scan and measurement

The CT scans were mainly acquired using a 64-row CT machine (mostly using the Somatom Sensation Cardiac, Siemens Healthineers; some using LightSpeed 64, GE) set at 120 or 150 kVp with 200–300 mAs, depending on the individual's weight and size. CT images were extracted from the radiology database of our hospital. Then the PACS software (AGFA Healthcare ICIS view 2014.1) was used to reconstruct the CT sagittal images. All measurements were performed under the guidance of a chief radiologist with more than 10 years of experience in radiology. The foraminal structures were measured on sagittal CT images positioning on the midline of the foramen. The size and distances of intervertebral foraminal structures were measured vertically and horizontally referring to the superior endplate and the posterior wall of the inferior vertebra (Fig. 2). At the same time, MRI images of patients were collected and used as reference when there were ambiguous presentation of soft tissue on CT images.

- In the vertical direction:

Height of superior articular process (A): The vertical distance from the tip of the SAP to the inferior endplate of the superior vertebra (Positive: the tip of the SAP is over the inferior endplate; Negative: the tip of the SAP is below the inferior endplate);Height of articular capsule (B): The vertical distance from the cephalic edge of Ac to the tip of the SAP;

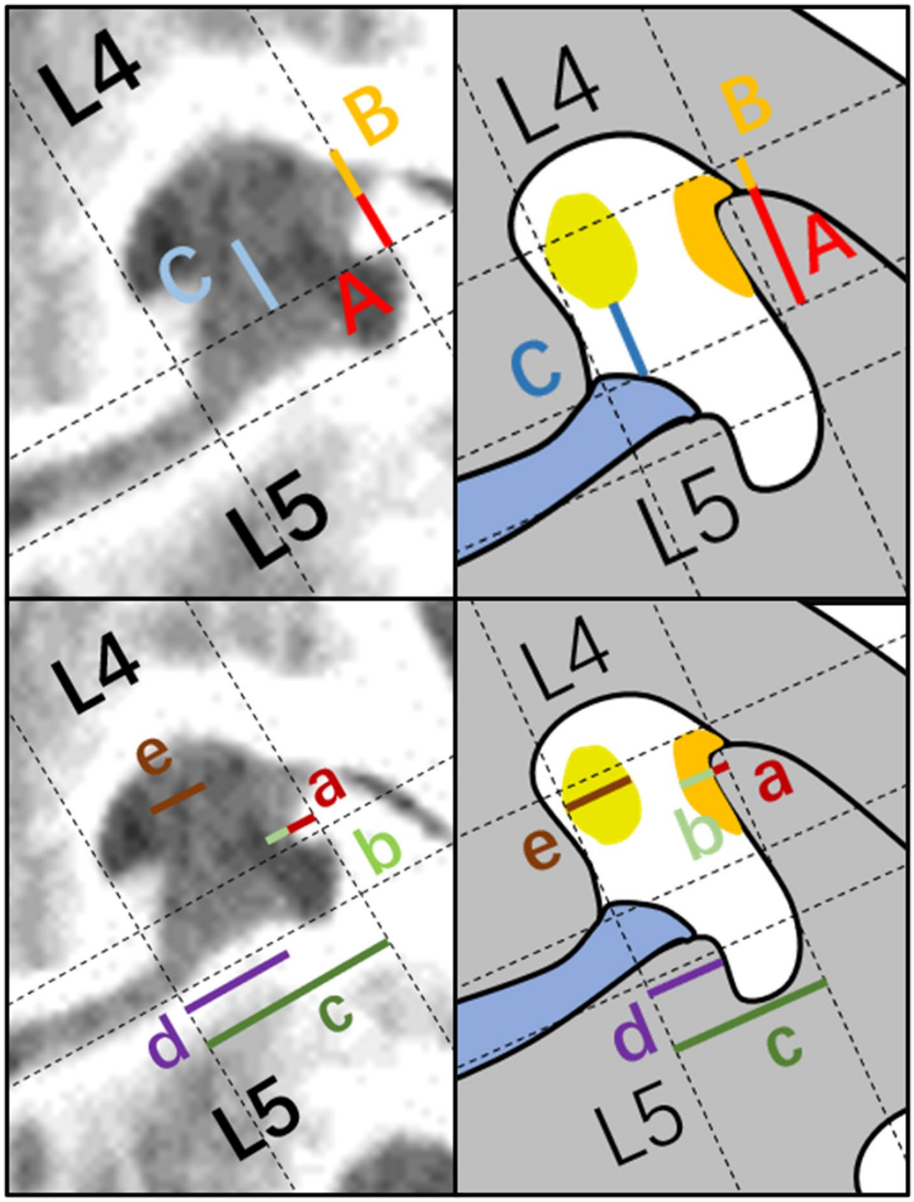

Fig. 2 Measurements of foraminal structures in vertical and horizontal direction on computed tomographic image and schematic diagram. Capital and lower-cases letters represent the vertical measurements

Height of nerve root (C): The vertical distance from the inferior edge of the nerve root to the inferior endplate of the superior vertebra.

We defined the vertical stenosis of the intervertebral foramen as the top of the SAP and the Ac higher than the inferior margin of the nerve root (A + B > C, vertical stenosis subgroup). Among them, the subgroup of the hyperplastic superior articular process refers to the hyperplastic SAP higher than the inferior margin of the nerve root (A > C, H-sap subgroup). Excluding cases of hyperplastic superior articular process from vertical stenosis cases, the obvious hyperplasia of the articular capsule (H-ac subgroup) is defined as the Ac higher and the SAP lower than the inferior margin of the nerve root (Fig. 3).

- In the horizontal direction:

Width of superior articular process (*a*): The horizontal distance from the base of SAP to the posterior notch of the pedicle of the inferior vertebra;

Width of articular capsule (*b*): The horizontal distance from the Ac to SAP;

Width of the intervertebral foramen (*c*): The horizontal distance from the posteroinferior corner of the superior vertebral body to the posterior notch of the pedicle of the inferior vertebra;

Slippage distance (*d*): The horizontal distance from the posteroinferior corner of the superior vertebra to the posterosuperior portion of the inferior vertebra;

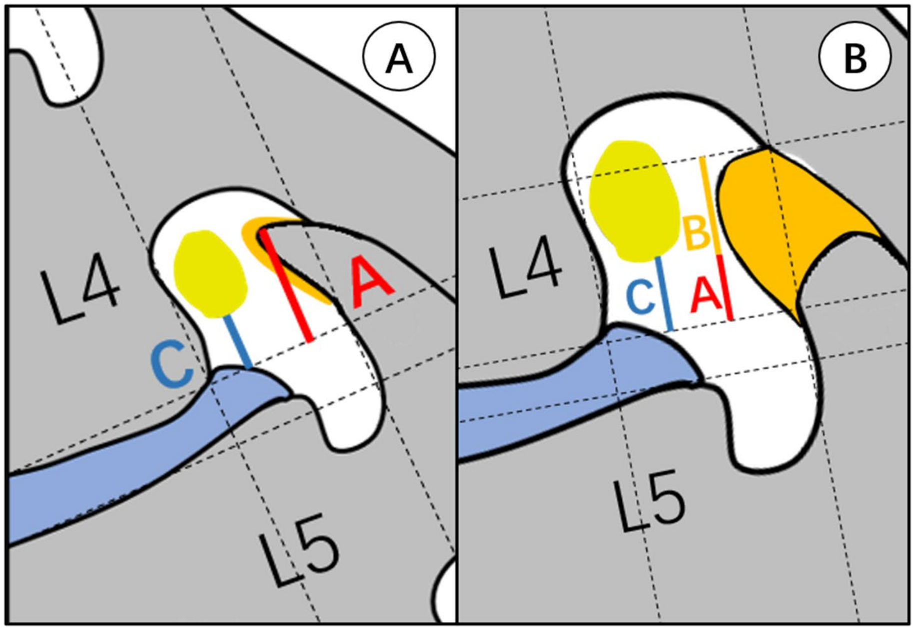

Fig. 3 Specific morphology of vertical stenosis on schematic diagram. Foraminal vertical stenosis included two specific morphologies, H-sap subgroup: A > C (**A**) and H-ac subgroup (**B**)

Width of the nerve root (*e*): The horizontal distance of the nerve root is the diameter of the nerve root in the intervertebral foramen.

We defined the horizontal stenosis as the possible horizontal compression to nerve root by other foraminal structures after complete reduction with no decompression procedure. It means the horizontal space after complete reduction less than the size of nerve root, expressing as: $c - d - (a + b) < e$.

Statistical analyses

One author blinded to the measurement performed the statistical analysis using SPSS version 26.0 (IBM Corp., Armonk, New York, USA). The Chi-square or *T*-test was used to analyze demographic and radiologic data. The statistical difference was defined as $P < 0.05$.

Results

Basic demographic and clinical data

Table 1 lists the demographic and clinical characteristics of the two groups. There was no significant difference in the demographic information between the control group and the DS group. All patients in the DS group accepted operation and experienced no permanent nerve dysfunction. 6 patients showed abnormal motor evoked potential of L4 nerve root after decompression and reduction. Further exploration was performed immediately during the operation. The secondary foraminal stenosis after reduction was identified, though incomplete decompression. Among them, 5 patients had no abnormality of lower limb movement after awakening, and 1 patient had muscular weakness compared with preoperative strength. After operation, muscular strength gradually improved under the treatment of hormone and neurotrophic drugs. No obvious weakness existed in the long-term follow-up. Compared

Table 1 Demographic and clinical data

Variable	Control group	DS group
Patients, *n*	50	70
Male	9	11
Female	41	59
Age, years	61.4 ± 9.2	61.4 ± 8.7
Neurogenic claudication, *n*		
Pre-op	–	52
Post-op	–	3
VAS (back pain)		
Pre-op	–	5.3 ± 2.0
Post-op	–	1.3 ± 0.7*
VAS (leg pain)		
Pre-op	–	5.1 ± 1.5
Post-op	–	1.5 ± 0.9*
ODI		
Pre-op	–	56.8 ± 14.5
Post-op	–	23.8 ± 12.4*

*Comparing to pre-operative data, post-operative measurements are statistically significant improvement ($P < 0.001$)

DS Degenerative Spondylolisthesis, *VAS* visual Analogue Scale, *ODI* oswestry disability index with preoperative data, there was significant improvement for the postoperative VAS and ODI scores in the DS group ($P < 0.0001$).

Vertical measurement

- Height of superior articular process (A)

The height of the superior articular process (A) in the DS group has no statistical difference compared with the control group (– 0.97 vs – 0.47 mm, $t = 1.77$, $P = 0.08$). There were 73 foramina with vertical stenosis in the DS group, including 13 cases constituting the H-sap subgroup (Table 2). The height of the SAP in the H-sap subgroup was greater than that in the control group (4.95 vs – 0.47 mm, $t = 14.09$, $P < 0.0001$). There was no statistical difference for the height of the SAP between the vertical stenosis subgroup and the control group (0.18 vs – 0.47 mm, $t = 1.16$, $P = 0.11$). Similar result was observed between the H-ac subgroup and the control group (– 0.86 vs – 0.47 mm, $t = 1.13$, $P = 0.26$) (Fig. 4a).

- Height of Articular capsule (B)

There was statistical significance for the height of the articular capsule (B) in the DS group compared with that in the control group (4.87 vs 3.44 mm, $t = 6.34$, $P < 0.0001$). There were 60 foramina with vertical stenosis resulting from the hyperplasic Ac, defined as the H-ac subgroup (Table 2). The H-ac subgroup showed greater height of the articulate capsule compared with the control group (5.27 vs 3.44 mm, $t = 6.84$, $P < 0.0001$). And the vertical stenosis subgroup also presented a greater height of the Ac than that in the control group (4.45 vs 3.44 mm, $t = 3.18$, $P = 0.002$). However, the height of the Ac was smaller in the H-sap subgroup than that in the control group (0.63 mm vs 3.44 mm, $t = 8.32$, $P < 0.0001$) (Fig. 4b).

Table 2 Measurement and calculation of foraminal structures in vertical direction

Measurement	Control group	DS group	*P*
A (mm)	−0.47 ± 1.26	− 0.97 ± 2.95	0.08
B (mm)	3.44 ± 1.13	4.87 ± 2.29	< 0.0001
C (mm)	4.13 ± 0.90	3.76 ± 1.38	0.01
A > C (*n*)	0	13	0.03
A + B > C (*n*)	2	73	< 0.0001

DS Degenerative spondylolisthesis; *A* the height of the superior articular process; *B* the height of the articular capsule; *C* the height of nerve root; *A > C* the hyperplastic superior articular process higher than the inferior margin of the nerve root; *A + B > C* the hyperplastic superior articular process and the articular capsule higher than the inferior margin of the nerve root

Horizontal measurement

- Width of superior articular process (a)
  The width of superior articular process (a) in the DS group was greater than that in the control group (0.71 vs 0.02 mm, $t = 6.16$, $P < 0.0001$) (Table 3). The SAP was wider in the H-sap subgroup than that in the control group (3.28 vs 0.02 mm, $t = 7.04$, $P < 0.0001$). The width of SAP in the vertical stenosis subgroup and in the H-ac subgroup was both greater than that in the control group, respectively (1.16 vs 0.02 mm, $t = 6.02$, $P < 0.0001$; 0.70 vs 0.02 mm, $t = 4.43$, $P < 0.0001$) (Fig. 5a).
- Width of Articular capsule (b)
  The width of articular capsule (b) in the DS group was statistically wider than that in the control group (2.59 vs 0.37 mm, $t = 13.98$, $P < 0.0001$) (Table 3). In the H-ac subgroup and the vertical stenosis subgroup, the width of Ac was 2.60 and 2.24 mm, respectively, which both

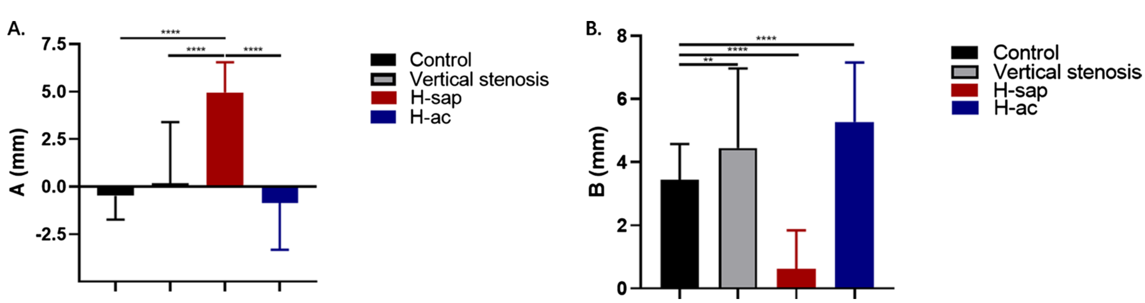

Fig. 4 Comparison of vertical measurements. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$. **A** Vertical height of superior articulate process; **B** vertical height of articular capsule (H-sap, the subgroup of hyperplastic superior articular process; H-ac, the subgroup of articular capsule)

Table 3 Measurement and calculation of foraminal structures in horizontal direction

Measurement	Control group	DS group	*P*
a (mm)	0.02 ± 0.03	0.71 ± 1.33	< 0.0001
b (mm)	0.37 ± 0.65	2.59 ± 1.70	< 0.0001
c (mm)	6.11 ± 1.14	10.33 ± 2.59	< 0.0001
d (mm)	0.00 ± 0.00	4.20 ± 2.25	< 0.0001
e (mm)	2.61 ± 0.54	2.70 ± 0.43	0.20
$c - d - (a + b) < e$ (*n*)	0	63	< 0.0001

DS Degenerative Spondylolisthesis; *a* the width of superior articular process; *b* the width of articular capsule; *c* the width of intervertebral foramen; *d* slippage distance; *e* the width of nerve root; $c - d - (a + b) < e$, the possible horizontal compression to nerve root by other foraminal structures after complete reduction procedure

was statistically different from that in the control group ($P < 0.0001$). But there was no significant difference in these subgroups ($t = 1.20$, $P = 0.23$). There was no statistical difference for the width of articular capsule between the control group and the H-sap subgroup (0.37 vs 0.62 mm, $t = 1.24$, $P = 0.22$) (Fig. 5b).

- Width of the nerve root (e)

  The control group showed no statistical significance for the width of nerve root (e) comparing with the DS group (2.61 vs 2.70 mm, $t = 1.30$, $P = 0.20$) (Table 3). The width of nerve root was 2.48, 2.72, and 2.78 mm in the H-sap subgroup, the vertical stenosis subgroup, and the H-ac subgroup, respectively. There was no statistical difference between these three subgroups ($P > 0.05$) (Fig. 5c).

Foraminal stenosis

Vertical stenosis and horizontal stenosis were observed in 73 and 63 foramina in the DS group, respectively. The control group had 2 and 0 foramina presenting with vertical stenosis and horizontal stenosis. Hyperplasia of the SAP was more common in the DS group than in the control group (9.2 vs 0.0%, OR = 21.28, $P = 0.03$). 85% of H-sap patients ($n = 11$) were accompanied with horizontal foraminal stenosis. Similarly, the DS group has more hyperplasic Ac compared with the control group (42.9 vs 2.0%, OR = 36.75, $P < 0.0001$). Meanwhile, 27 foramina showed horizontal stenosis was more common in H-ac subgroup comparing with the control group (45.0 vs 0.0%, OR = 165.00, $P < 0.0001$).

Discussion

DS is a common lumbar degenerative disease with a prevalence rate from 5 to 7%, and disabling the great population in modern society [13]. Decompression and reduction operation is the eventual treatment for patients ineffective to non-operative treatment [16, 17]. However, there is a high incidence rate of nerve injury because of the serious stenosis and the changes of anatomical position after the reduction procedure. The exiting nerve root injury is an important neurological complication [18]. As one component in the intervertebral foramen, the exiting nerve root may dysfunction due to compression from foraminal structures. Thus, this study focuses on the foraminal anatomy on sagittal CT images, aiming at identifying the specific foraminal structures and changes originating from DS.

Spondylolisthesis may occur in each lumbar vertebra. Studies reported that DS mostly occurred in the L4/5 level [1, 2]. This is consistent with our results. It can be explained by the more sagittal facet orientation at the L4/5 level in the DS patients [3]. To eliminate the influence of different levels, we only included patients with DS at the L4/5 level in this study. Because of the important function, previous studies have focused on the anatomy of facet joints in patients with DS. They considered an increased sagittal angle as a developmental predisposition to the development of DS [19–21]. Besides, the joint capsule also plays an important role in the development of DS [8–10]. Studies have been analyzing the angle and axial morphology to explore the pathogenesis of DS, but few studies systemically analyzed the sagittal foraminal morphology and its association with the development of DS and nerve injury.

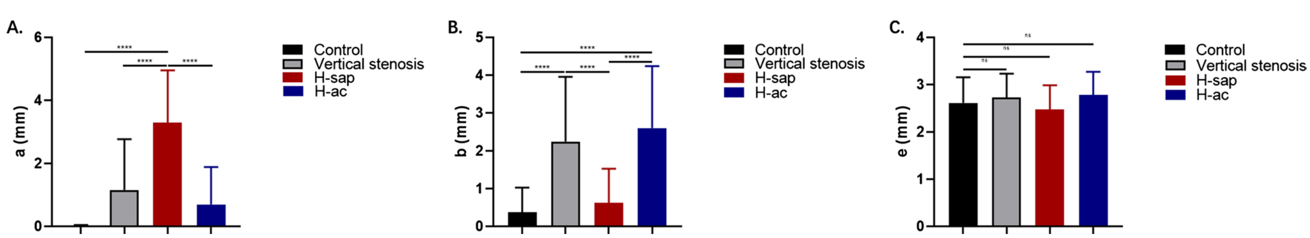

Fig. 5 Comparison of horizontal measurement data between groups. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$. **A** Horizontal width of superior articular process; **B** horizontal width of articular capsule; **C** horizontal width of nerve root (H-sap, the subgroup of hyperplastic superior articular process; H-ac, the subgroup of articular capsule)

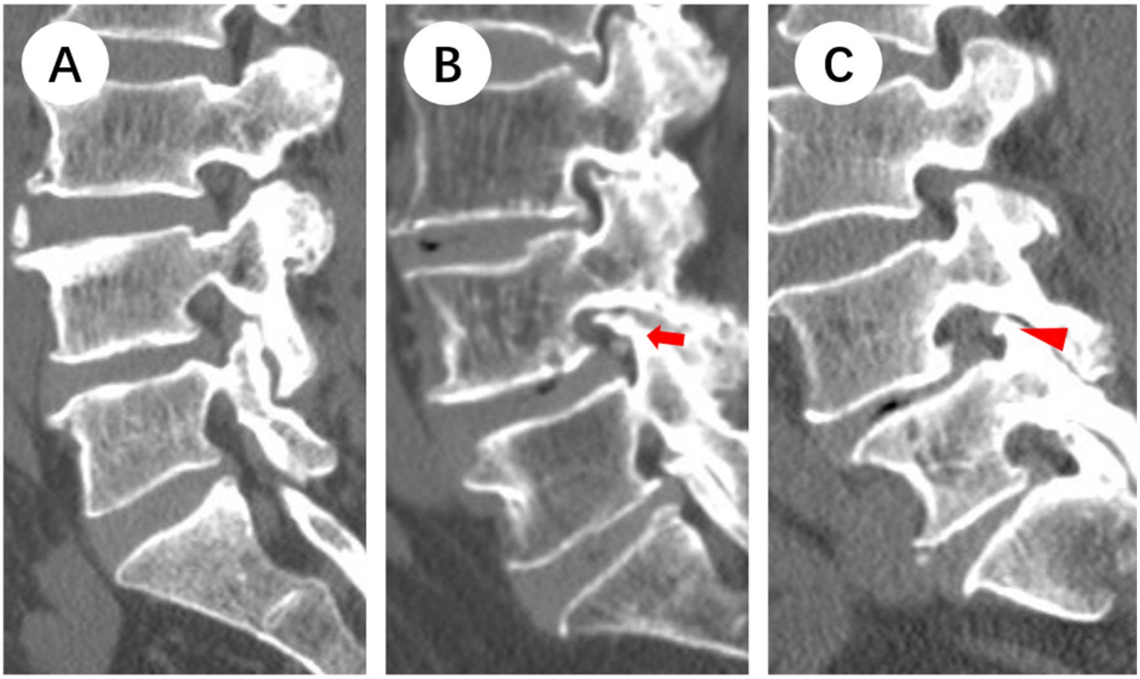

Fig. 6 Different morphologies of superior articular process on sagittal CT images. **A** Disc herniation without DS; **B** Hyperplasia of Superior facet process and the resultant vertical and horizontal foraminal stenosis (The arrow); **C** Hyperplasia of Superior facet process without horizontal foraminal stenosis (The triangle)

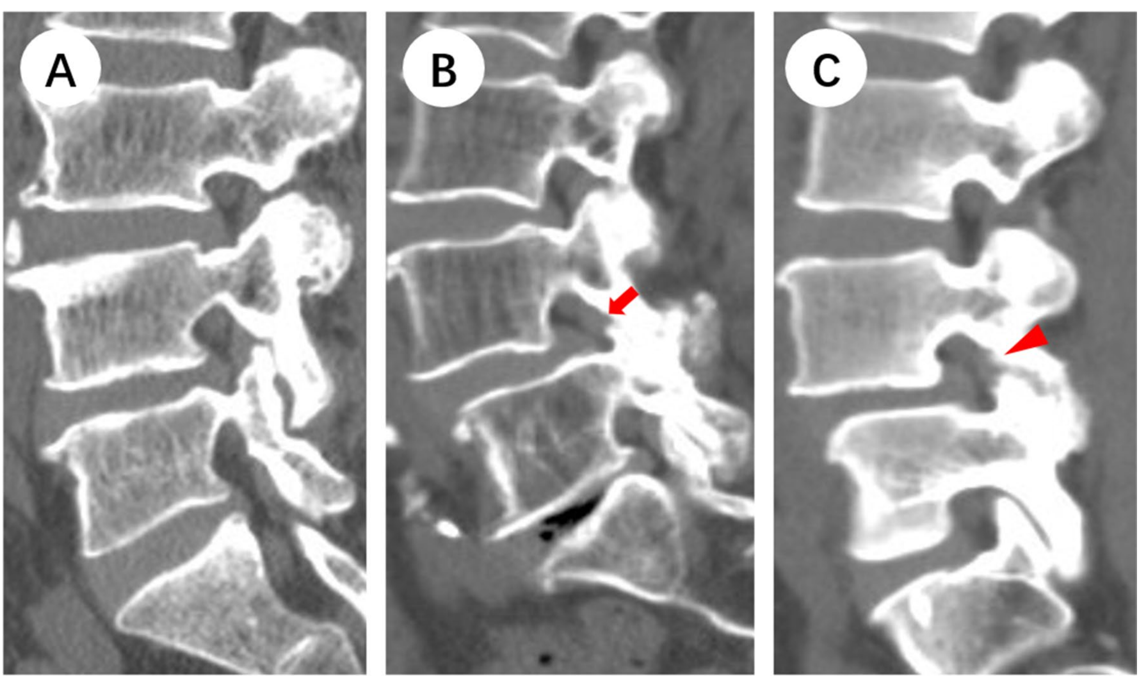

Fig. 7 The morphology of articulate capsule on sagittal CT images. **A** Disc herniation without DS; **B** vertical and horizontal foraminal stenosis mainly from the hyperplasia of articular capsule (the arrow); **C** horizontal foraminal stenosis without the hyperplasia of articular capsule (the triangle), mainly from protruded disc

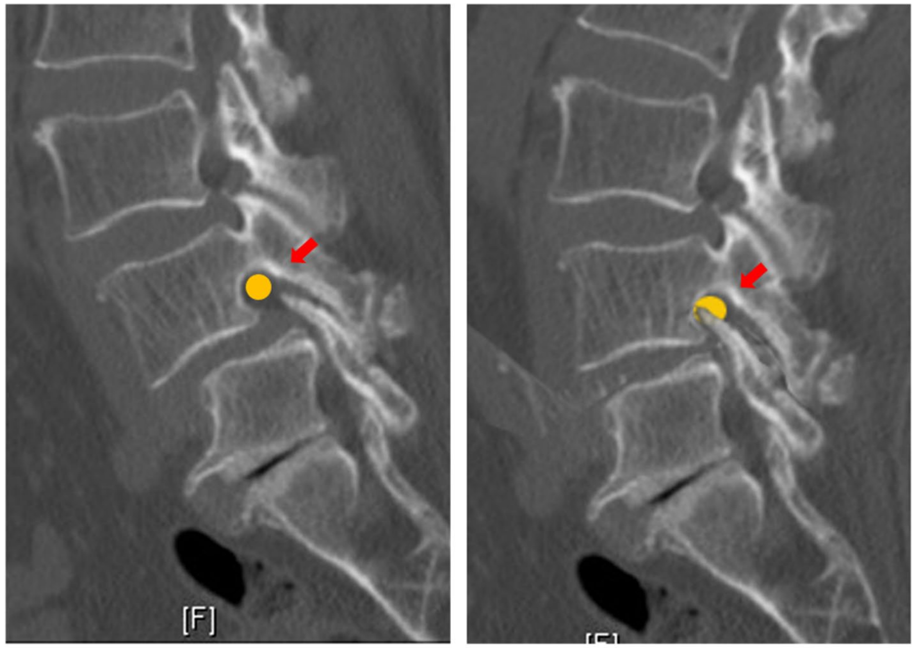

Fig. 8 Incomplete decompression of the stenosis of the foraminal leads to compression of the superior articular process on the nerve root after reduction (the arrow)

In this study, we systemically analyzed the morphology and the association of foraminal structures on sagittal CT images. The height of the SAP in the vertical height and its horizontal distance in the H-sap subgroup were both significantly greater than those in the other groups. The hyperplasic superior articulate process can compress the nerve root after reduction procedure. It indicated that the obvious hyperplasia of the SAP in the intervertebral foramen is an important cause of nerve root injury in reduction procedure [5–9]. The incidence of obvious hyperplasia of the superior articular process is 9% in patients with DS (13/140). Meanwhile, horizontal stenosis is up to 85% of these cases. We considered that bony hyperplasia of SAP is more likely to bring about an irreversible injury to nerve roots. Therefore, we believe that the hyperplasic superior articular process on the CT sagittal plane is an important indicator of foraminal decompression during operation (Fig. 6).

The incidence of joint capsule's hyperplasia is 43% in DS patients (60/140), and 45% of these cases accompanied with horizontal stenosis. The hyperplasia of the Ac is another important element exerting compressive injury to the existing nerve root in the intervertebral foramen [8–10] (Fig. 7). The vertical height of the articular capsule and its horizontal distance in vertical stenosis subgroup were significantly different from those in the control group and the H-sap subgroups. This finding was more obvious in the H-ac subgroup. Therefore, we should carefully analyze the articular capsule's morphology on sagittal plane, which is another important predisposition of nerve root injury after reduction during operation.

The present study found no significant difference in the width of nerve roots among the groups. It indicated no obvious edema and hyperplasia of the nerve root in the pathological DS. Postoperative dysfunction of the exiting nerve root possibly was caused by the foraminal compression from the hyperplasic SAP and Ac after complete reduction, especially in cases with foraminal stenosis [13] (Fig. 8). These specific morphological changes of the intervertebral foramen will have a disastrous impact on the nerve root during the operation. Meanwhile, it should not be ignored that the foraminal structures result in horizontal foraminal stenosis. Clinicians should pay more attention to these foraminal changes. Complete decompression is necessary for the operative treatment for DS patients with the vertical and horizontal stenosis caused by the hyperplasic superior articular process and articular capsule [22].

Conclusions

The hyperplasia of the superior articular process (SAP) and the articular capsule (Ac) was significant changes in patients with DS. Vertical and horizontal foraminal stenosis caused by the hyperplasic superior articulate process and articulate capsule is a predisposing factor of exiting nerve root injury after complete reduction, if no complete foraminal decompression was performed in advance.

Limitations

This study has its limitations. First, to eliminate the anatomical differences in different levels, we only included patients with DS at the L4/5 level. In the following study, we will continue to explore the morphological differences of the intervertebral foramen at different levels. Second, we analyzed only the specific changes at the sagittal plane. It is also significant to explore its morphology on other planes. We will further to analyze the three-dimensional morphology of the foraminal structures in DS and to explore its relation to neural complications.

Key Points

- The degenerative spondylolisthesis is often accompanied by severe foraminal structural changes.
- Hyperplasic superior articular process and articular capsule are important risks of nerve root injury in the surgical treatment of degenerative spondylolisthesis.
- Adequate intraoperative foraminal decompression is necessary when severe superior articular process and articular capsule hyperplasia is present on CT images.

Funding The present study was supported by the National Natural Science Foundation of China (Grant No. 82002325), the Natural Science Foundation of Shandong Province (Grant Nos. ZR2020QH075, ZR2021MH167, ZR2021LZY004 and ZR2022LZY001), Municipal Innovation Plan of Clinical Medical Science and Technology of Jinan (202134043), Shandong medical and health science and technology development plan project (Grant No. 202004071188), Practical teaching reform and research project of Binzhou Medical College (Grant No. SJJY201927), Scientific research project of Affiliated Hospital of Binzhou Medical College (Grant No. BY2020KJ74), and Shandong Province traditional Chinese medicine science and technology project (Grant No. M-2022133).

Device Status/Drug Statement The Manuscript submitted does not contain information about medical device(s)/drug(s).

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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