Qin et al. Journal of Orthopaedic Surgery and Research (2025) 20:446
https://doi.org/10.1186/s13018-025-05835-8

Journal of Orthopaedic
Surgery and Research

RESEARCH Open Access

Analyses of proximal adjacent segment degeneration and prognostic factors after lumbar fusion surgery: study based on proximal facet joint angle

Feng Qin[1†], Weiqiang Fan[1†], Lili Ren[1], Qi Chen[1], Xiaoxiao Chen[1] and Wenjun Liu[1*]

Abstract

Objective Lumbar fusion surgery is a common procedure for treating various degenerative spinal conditions. However, the incidence of proximal adjacent segment degeneration (PASD) remains a concern. This study aimed to investigate the effect of proximal facet joint angle (FJA) on PASD and then identify factors that influence prognosis after lumbar fusion surgery.

Methods In this retrospective study, the cases of 192 patients who underwent lumbar fusion surgery between January 2020 and June 2022 were analysed. Patients were classified in accordance with their baseline proximal FJA into the high (≥40°) and low (<40°) FJA groups. Prognosis was evaluated during the last follow-up by using clinical, imaging and functional recovery criteria. PASD was assessed using Weishaupt criteria, and imaging parameters were measured on postoperative computed tomography (CT) reconstructions. Statistical analyses, including univariate and multivariate logistic regression, were performed to identify prognostic factors. Receiver operating characteristic (ROC) curves were used to assess predictive value.

Results The high FJA group exhibited significantly higher rates of PASD compared with the low FJA group ($P<0.001$). No significant differences were observed in sex, age, body mass index (BMI) or follow-up duration between the two groups. Poor prognosis was associated with higher BMI, larger FJA and wider facet joint diameter. Logistic regression analysis identified BMI (odds ratio [OR] = 1.801, $P=0.001$), FJA (OR = 6.320, $P<0.001$) and facet joint sagittal (OR = 1.888, $P<0.001$) and coronal (OR = 1.462, $P<0.001$) diameters as independent predictors of poor prognosis. A smaller screw inclination angle was associated with better outcomes (OR = 0.907, $P=0.017$). Joint ROC analysis underscored the significant predictive power of these factors (area under the curve = 0.881).

Conclusion This study demonstrates that a larger proximal FJA is associated with increased PASD. It also identifies several prognostic factors that influence outcomes after lumbar fusion surgery. Patients with higher BMI, larger FJA and wider sagittal and coronal diameters are at increased risk for poor prognosis. These findings highlight the

†Feng Qin and Weiqiang Fan are co-first authors.

*Correspondence:
Wenjun Liu
0151190218@163.com

Full list of author information is available at the end of the article

importance of comprehensive preoperative assessments to optimise surgical planning and improve outcomes in lumbar fusion surgery.

Keywords Proximal facet joint angle, Lumbar fusion surgery, Proximal adjacent facet degeneration, Patient prognosis, Influencing factors

Introduction

Lumbar fusion surgery is a prevalent intervention for several degenerative spine disorders, including lumbar spondylosis, spondylolisthesis and intervertebral disc degeneration [1]. These conditions are amongst the leading causes of disability worldwide, contributing significantly to chronic back pain and impaired mobility. Epidemiological data indicate a rising trend in spinal fusion procedures, driven by an aging population and the increasing recognition of degenerative spinal conditions [2, 3]. Despite its prevalence, lumbar fusion surgery has potential complications, and one of the most significant is proximal adjacent segment degeneration (PASD). This postoperative consequence pertains to the accelerated degeneration of spinal segments that adjoin the fused area, frequently manifesting as new-onset pain or functional impairment, and occasionally necessitating additional surgical intervention [4, 5].

Although lumbar fusion effectively stabilises the targeted segment and alleviates symptoms at that level, it inadvertently alters the biomechanics of the spine. The redistribution of mechanical stresses can adversely affect adjacent segments, predisposing them towards degeneration. Significantly, the role of anatomical and mechanical parameters in influencing PASD outcomes has elicited the attention of researchers [6]. Prior studies have identified risk factors, such as age, body mass index (BMI) and original pathology [7–9]. However, understanding the extent to which facet joint morphology, particularly proximal facet joint angle (FJA), affects adjacent segment health remains an area with substantial knowledge gaps.

The existing literature underscores the significance of facet joints in spinal biomechanics, given their role in guiding and restraining spinal motion. Previous research has demonstrated a correlation between facet joint orientation and spinal stability, suggesting that the angle of these joints can influence postoperative outcomes [10, 11]. Nonetheless, proximal FJA has not been extensively studied in the context of PASD. A joint's inclination can potentially affect the load-sharing characteristics within the spinal column post-fusion, influencing the degeneration rate in segments adjacent to the surgical site [12]. Despite this theoretical basis, empirical data that delineate these relationships are sparse, highlighting an essential need for further investigation.

In addressing the unexplored facets of PASD, focusing on proximal FJA introduces an innovative angle to existing research. Recognising how FJA influences spinal biomechanics offers a novel opportunity to refine surgical approaches and improve patient outcomes. A thorough examination of these anatomical parameters can inform surgical planning, enabling healthcare professionals to better predict and mitigate risks associated with adjacent segment degeneration. Given the substantial healthcare burden and patient morbidity associated with PASD, the motivation to refine our understanding and adjust clinical practices is urgent. Advanced imaging techniques, coupled with quantitative assessments, provide a feasible method for exploring these biomechanical interactions in detail [13, 14].

Our study explores an under-investigated area by examining the relationship between proximal FJA and incidence of PASD, along with broader prognostic factors after lumbar fusion surgery. We aim to clarify the potential implications for FJA on spinal biomechanics and determine its role in postsurgical degeneration. By assessing the effect of FJA, along with other anatomical and lifestyle factors, on surgical outcomes, we seek to improve the predictive accuracy of PASD risk. This information is crucial for aiding clinicians in preoperative planning, personalising patient care and enhancing surgical outcomes by reducing the risk of PASD. This investigation aims to expand our understanding of how preexisting spinal anatomy influences postoperative degeneration, providing insights that can lead to improved patient selection, surgical techniques and postoperative management.

Materials and methods

Study design

This retrospective study included 192 patients who underwent lumbar fusion surgery at our hospital between January 2020 and June 2022, with a follow-up period of 20–25 months. Patients were included if they met the surgical indications for lumbar fusion [15], had normal cognitive function, could cooperate with various examinations and treatments and had stable vital signs. Patients were excluded if they were over 80 years old due to the potential confounding effects of age-related differences in bone quality, increased surgical risks and prolonged postoperative recovery times, which could influence outcomes and complicate the interpretation of results [16]. Other exclusion criteria included preoperative diagnoses of lumbar tumours, fractures, scoliosis or other non-degenerative lumbar spine diseases, infections or their complications (e.g. lumbar spine infection and spinal tuberculosis), a history of diabetes, rheumatological diseases, severe osteoporosis, congenital diseases, concurrent multi-segmental lumbar spine lesions, prior lumbar spine surgery and incomplete imaging or follow-up data.

Informed consent was waived given the retrospective nature of this study, which used de-identified patient data without potential harm or effect on patient care. This waiver and the study were approved by the institutional review board and ethics committee of our hospital, adhering to regulatory and ethical standards for retrospective studies.

Grouping criteria

(1) Proximal FJA Grouping: Patients were grouped in accordance with their baseline proximal FJA into the high ($n=77$) and low ($n=115$) FJA groups. The high FJA group comprised patients with FJA ≥ 40°, whilst the low FJA group included patients with FJA < 40°. This threshold was chosen based on previous biomechanical studies that suggested that angles above 40° may indicate increased mechanical stress and potential degeneration [17, 18].

(2) Prognostic Grouping: Patients were further categorised based on their prognosis during their last follow-up into the good ($n=128$) and poor ($n=62$) prognosis groups. The prognostic evaluation criteria are outlined in Table 1.

Assessment of PASD in the high and low FJA groups

To ensure accurate and reliable assessment of PASD in the high and low FJA groups, two personnel were involved in the imaging review process: an attending spinal surgeon and his assistant. They reviewed the images independently, but the final decision was made by the attending spinal surgeon to maintain consistency and reduce potential bias.

The degree of facet joint degeneration was assessed using preoperative and postoperative lumbar spine computed tomography (CT) scans during the last follow-up visit (Fig. 1). The Weishaupt criteria were applied to classify PASD into four grades [19]: Grade 0 (normal), normal joint space width (2–4 mm); Grade 1 (mild degeneration), narrowing of the joint space (< 2 mm), minor osteophytes or slight hypertrophy; Grade 2 (moderate degeneration), further narrowing of the joint space, moderate osteophytes, moderate hypertrophy or mild subchondral bone destruction; Grade 3 (severe degeneration), marked narrowing of the joint space, severe osteophytes, severe hypertrophy, severe subchondral bone destruction or subchondral bone cysts (Fig. 2).

In particular, the evaluation involved the following aspects. Imaging Modalities: Thin-slice CT 3D reconstructions were used to visualise facet joints. Thresholds: For each patient, the most clearly visible bone window layer was selected for observing and measuring facet joint dimensions in the axial, sagittal and coronal planes. Evaluator Agreement: Initial assessments were performed by the attending spinal surgeon and his assistant. Any discrepancies were resolved through discussion, with the final decision made by the attending spinal surgeon, ensuring consistent and reliable evaluations. This methodology ensures that the classification of PASD is consistent and adheres to well-established criteria, enhancing the reliability and reproducibility of the findings.

Imaging parameter measurement

Two experienced spinal surgeons measured the following imaging parameters on postoperative lumbar CT 3D reconstructions. Data were averaged from three measurements to minimise errors. For angular measurements that differed by more than 20° and linear measurements that differed by more than 1 mm, remeasurement was conducted, and the final result was determined by the senior surgeon. Measurement precision was set to 0.1 mm and 0.1°. The measurement included the following parameters [1]. FJA: The angle between the bilateral facet joints and the midline of the vertebral posterior margin on cross-sectional images at the level of the

Table 1 Prognostic evaluation criteria

Criteria	Good Prognosis	Poor Prognosis
Clinical Symptoms	-Pain relief: significant improvement or complete resolution of preoperative symptoms, such as back pain, leg pain, numbness or weakness -Activity recovery: normal daily activities, including walking and sitting without limitation or increased pain	-Inadequate or worsening pain relief: persistent or exacerbated back pain, leg pain and limitations in daily activities
Imaging Findings	-Fusion success: radiographic evidence of fusion gap closure or near-closure, good bone healing and stability of the fused segment -Stable internal fixation: no loosening or fracture of hardware (e.g. screws, plates)	-Fusion failure or incomplete fusion: visible fusion gap and poor bone healing -Unstable internal fixation: loosening or fracture of hardware
Functional Recovery	-Muscle strength recovery: good muscle strength and endurance that approach preoperative levels -Sensory recovery: normalisation of touch, pain and temperature sensation	-Poor muscle strength recovery: significantly decreased muscle strength and endurance -Poor sensory recovery: persistent or worsening sensory deficits
Complications	No severe complications, such as infection or nerve damage	Severe complications that affect prognosis and quality of life, such as infection or nerve damage

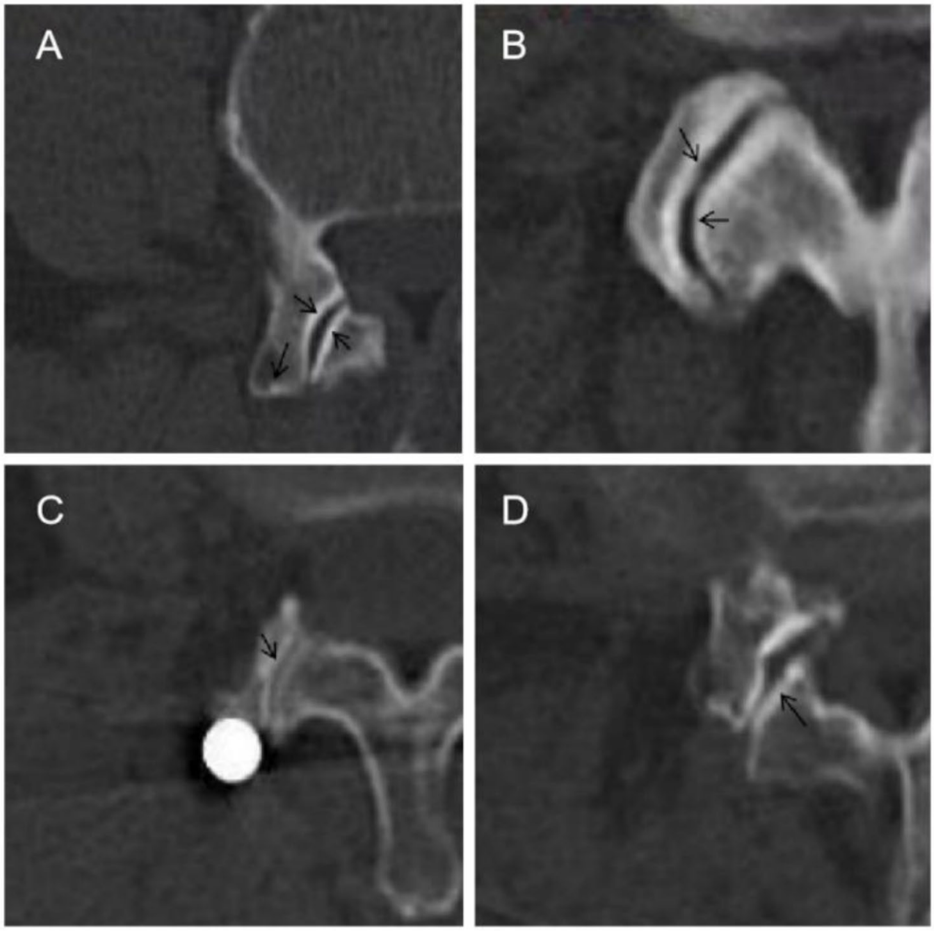

Fig. 1 Assessment of proximal adjacent segment degeneration (PASD). **A** shows from top to bottom: mild subchondral bone erosion, joint space narrowing, and subchondral cyst formation. **B** arrows indicate from top to bottom: severe subchondral erosion, joint space narrowing, and large osteophyte formation. **C** arrows show facet joint fusion. **D** shows the air sign in the facet joint

pedicles [2]. Lamina Depth: The distance from the dorsal cortex of the lamina to the skin in the sagittal plane [3]. Facet Joint Size Measurement: Using thin-slice CT 3D reconstructions, the most clearly visible bone window layer was selected for observing and measuring facet joint diameters in the axial, sagittal and coronal planes. Each diameter was measured three times and their average was obtained (Fig. 3).

Statistical analysis

Data were analysed using IBM SPSS Statistics for Windows, version 27.0 (IBM Corporation, Armonk, NY, USA). Continuous variables were tested for normality by performing the Shapiro–Wilk test. Normally distributed continuous variables were expressed as mean ± standard deviation and compared using independent samples *t*-tests. Categorical data were presented as numbers or percentages and compared via chi-squared test or Fisher's exact test when appropriate. For ordinal data related to the degree of facet joint degeneration and its association with dichotomous outcomes (e.g. presence or absence of PASD), we applied the Cochrane–Armitage test for trend to assess potential trends. Univariate and multivariate logistic regression analyses were used to identify factors that influenced patient prognosis after lumbar fusion. The predictive value of a combination of factors, including BMI, screw inclination angle, FJA, facet joint axial diameter, facet joint sagittal diameter and facet joint coronal diameter, was evaluated using joint receiver operating characteristic (ROC) curves. Additionally, to facilitate clinical decision-making, a nomogram was developed based on the results of the multivariate logistic regression analysis. The nomogram integrates significant predictors identified in our study to estimate the probability of poor prognosis. Calibration curves and decision curve analysis were used to validate the accuracy and clinical utility of the nomogram. A *P-value* of < 0.05 was considered statistically significant.

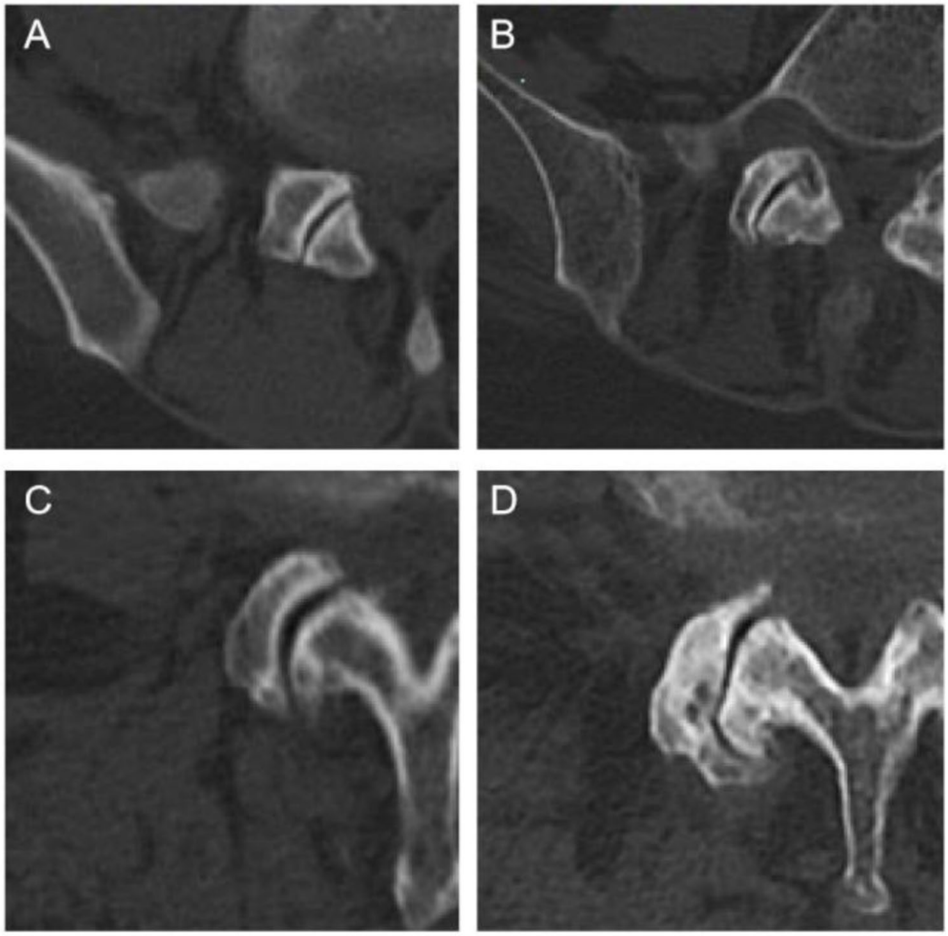

Fig. 2 Weishaupt criteria for classification of facet joint degeneration. **A**: Grade 0, normal facet joint. **B**: Grade 1, slightly narrowed joint space, small osteophytes formation, and mild hypertrophy of the small joints. **C**: Grade 2, visible joint space narrowing, moderate osteophyte formation, moderate hypertrophy of the small joints, and subchondral bone erosion. **D**: Grade 3, severe joint space narrowing, severe osteophyte formation, and severe subchondral bone erosion

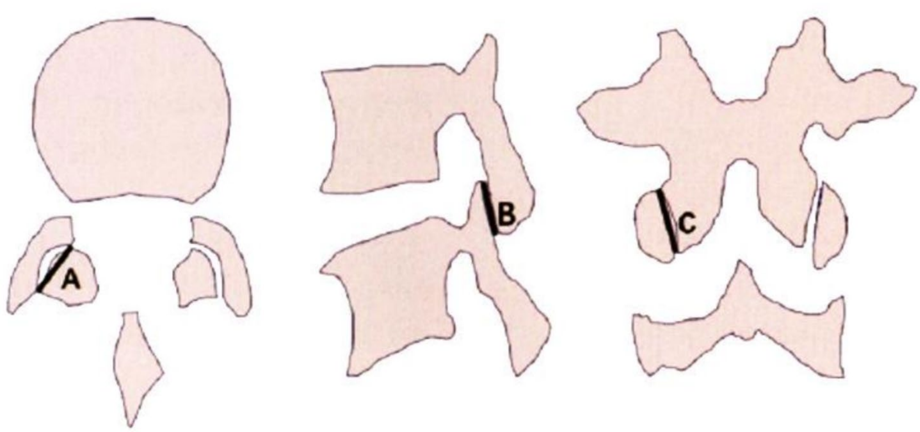

Fig. 3 Method for measuring facet joint diameters: In thin-slice CT 3D reconstructions, the most clearly visible bone window layer was selected for observing and measuring facet joint axial diameter (**A**), sagittal diameter (**B**) and coronal diameter (**C**)

Table 2 Comparison of general information between the high and low FJA group patients

Parameters	High FJA Group (n = 77)	Low FJA Group (n = 115)	t/χ^2	P-value
Sex (n, %)			0.072	0.788
- Male	51 (66.23%)	74 (64.35%)		
- Female	26 (33.77%)	41 (35.65%)		
Age (years)	56.83 ± 5.49	57.32 ± 5.41	0.613	0.541
BMI (kg/m^2)	23.17 ± 1.19	23.37 ± 1.21	1.096	0.275
Follow-up Duration (months)	22.53 ± 2.21	22.39 ± 2.23	0.428	0.669
Preoperative Diagnosis (n, %)			0.954	0.812
- Lumbar Disc Herniation	35	52		
- Lumbar Spinal Stenosis	25	37		
- Lumbar Spondylolisthesis	10	19		
- Others	7	7		

Table 3 Comparison of postoperative PASD between the high and low FAC group patients (n, %)

Degeneration Grade	Grade 0	Grade 1	Grade 2	Grade 3
High FJA group (n = 77)	7 (8.77%)	31 (40.35%)	31 (40.35%)	8 (10.53%)
Low FJA group (n = 115)	54 (46.67%)	43 (37.78%)	14 (11.85%)	4 (3.70%)
χ^2	36.672			
P	< 0.001			

Results

Effect of the proximal FJA on PASD after lumbar fusion surgery

Comparison of general information between the high and low FJA group patients

No statistically significant differences were found in sex distribution (χ^2=0.072, P = 0.788), age (56.83 ± 5.49 years versus 57.32 ± 5.41 years, t = 0.613, P = 0.541), BMI (23.17 ± 1.19 kg/m² versus 23.37 ± 1.21 kg/m², t = 1.096, P = 0.275) and follow-up duration (22.53 ± 2.21 months versus 22.39 ± 2.23 months, t = 0.428, P = 0.669) between the high (n = 77) and low (n = 115) FJA groups. Similarly, no significant differences were noted in preoperative diagnoses (χ^2=0.954, P = 0.812) (Table 2).

Comparison of postoperative PASD between the high and low FJA groups

A Cochran–Armitage trend test further confirmed a significant increasing trend in the proportion of higher degeneration grades in the high FJA group compared with in the low FJA group (χ^2=36.672, P < 0.001), as indicated in Table 3. In particular, 8.77% of the patients in the high FJA group had Grade 0 degeneration, 40.35% had Grade 1, 40.35% had Grade 2 and 10.53% had Grade 3. By contrast, 46.67% of the patients in the low FJA group had Grade 0 degeneration, 37.78% had Grade 1, 11.85% had Grade 2 and 3.70% had Grade 3.

Analysis of factors that influence prognosis after lumbar fusion surgery

Comparison of general characteristics between the good and poor prognosis groups

No statistically significant differences were found in sex distribution (χ^2=0.287, P = 0.592), age (57.67 ± 5.64 years versus 56.98 ± 5.33 years, t = 0.818, P = 0.414) and follow-up duration (22.37 ± 2.16 months versus 22.44 ± 2.19 months, t = 0.214, P = 0.83) between the good (n = 128) and poor (n = 64) prognosis groups. However, their BMI was significantly different (22.54 ± 1.15 kg/m² versus 23.34 ± 1.22 kg/m², t = 4.397, P < 0.001). No significant differences were also observed in preoperative diagnoses (χ^2=0.451, P = 0.930) (Table 4).

Comparison of perioperative parameters between the good and poor prognosis groups

No statistically significant differences were noted in intraoperative blood loss (298.54 ± 52.34 mL versus 300.54 ± 51.69 mL, t = 0.251, P = 0.802), surgical time (148.54 ± 12.64 min versus 147.67 ± 16.91 min, t = 0.367, P = 0.715) and postoperative hospital stay (5.33 ± 1.10 days versus 5.41 ± 1.23 days, t = 0.45, P = 0.653). Screw inclination angle was significantly different (17.26 ± 5.13° versus 15.14 ± 5.33°, t = 2.663, P = 0.008), whereas screw tail tilt angle (10.25° ± 3.64 versus 10.49 ± 3.29°, t = 0.443, P = 0.658), distribution of rod contour (χ^2=0.049, P = 0.825) and surgical segment (χ^2=0.407, P = 0.982) were not. No significant difference was found in screw placement (χ^2=2.069, P = 0.150) (Table 5).

Table 4 Comparison of general characteristics between the good and poor prognosis groups

Parameters	Good Prognosis Group (*n* = 128)	Poor Prognosis Group (*n* = 64)	t/χ²	*P*-value
Sex (n, %)			0.287	0.592
- Male	85 (66.41%)	40 (62.50%)		
- Female	43 (33.59%)	24 (37.50%)		
Age (years)	57.67 ± 5.64	56.98 ± 5.33	0.818	0.414
BMI (kg/m²)	22.54 ± 1.15	23.34 ± 1.22	4.397	< 0.001
Follow-up Duration (months)	22.37 ± 2.16	22.44 ± 2.19	0.214	0.83
Preoperative Diagnosis (n, %)			0.451	0.930
- Lumbar Disc Herniation	58 (45.31%)	29 (45.31%)		
- Lumbar Spinal Stenosis	42 (32.81%)	20 (31.25%)		
- Lumbar Spondylolisthesis	18 (14.06%)	11 (17.19%)		
- Others	10 (7.81%)	4 (6.25%)		

Table 5 Comparison of perioperative parameters between the good and poor prognosis groups

Parameters	Good Prognosis Group (*n* = 128)	Poor Prognosis Group (*n* = 64)	t/χ²	*P*-value
Intraoperative Blood Loss (mL)	298.54 ± 52.34	300.54 ± 51.69	0.251	0.802
Surgical Time (min)	148.54 ± 12.64	147.67 ± 16.91	0.367	0.715
Postoperative Hospital Stay (days)	5.33 ± 1.10	5.41 ± 1.23	0.45	0.653
Screw Inclination Angle (°)	17.26 5.13	15.14 ± 5.33	2.663	0.008
Screw Tail Tilt Angle (°)	10.25 ± 3.64	10.49 ± 3.29	0.443	0.658
Rod Contour (n, %)			0.049	0.825
- Bent	88 (68.75%)	45 (70.31%)		
- Straight	40 (31.25%)	19 (29.69%)		
Surgical Segment (n, %)			0.407	0.982
-L1/2	12 (9.38%)	5 (7.81%)		
-L2/3	15 (11.72%)	8 (12.50%)		
-L3/4	25 (19.53%)	11 (17.19%)		
-L4/5	40 (31.25%)	20 (31.25%)		
-L5/S1	36 (28.13%)	20 (31.25%)		
Screw Placement (n, %)			2.069	0.150
- Left	76 (%)	31 (%)		
- Right	52 (%)	33 (%)		

Table 6 Comparison of imaging parameters between the good and poor prognosis groups

Parameters	Good Prognosis Group (*n* = 128)	Poor Prognosis Group (*n* = 64)	t/χ²	*P*-value
FJA (n, %)			29.315	<0.001
- ≥40°	34 (26.56%)	43 (67.19%)		
- <40°	94 (73.44%)	21 (32.81%)		
Facet Joint Axial Diameter (mm)	12.20 ± 1.71	12.87 ± 1.26	3.075	0.002
Facet Joint Sagittal Diameter (mm)	11.72 ± 1.20	12.64 ± 1.03	5.255	<0.001
Facet Joint Coronal Diameter (mm)	11.31 ± 1.91	12.93 ± 2.01	5.442	<0.001
Lamina Depth (mm)	52.73 ± 9.41	52.54 ± 9.33	0.132	0.895

Baseline imaging parameters by prognostic grouping

The good and poor prognosis groups exhibited significant differences in several imaging parameters (Table 6). The proportion of patients with FJA ≥ 40° was significantly higher in the poor prognosis group (67.19%) compared with in the good prognosis group (26.56%, χ^2=29.315, $P < 0.001$). Facet joint axial diameter was significantly smaller in the good prognosis group (12.20 ± 1.71 mm) compared with in the poor prognosis group (12.87 ± 1.26 mm, $t = 3.075$, $P = 0.002$). Similarly, facet joint sagittal diameter (11.72 ± 1.20 mm versus 12.64 ± 1.03 mm, $t = 5.255$, $P < 0.001$) and facet joint coronal diameter (11.31 ± 1.91 mm versus 12.93 ± 2.01 mm, $t = 5.442$, $P < 0.001$) were significantly smaller in the good prognosis group. No significant difference was found in lamina depth (52.73 ± 9.41 mm versus 52.54 ± 9.33 mm, $t = 0.132$, $P = 0.895$). These results indicate that higher FJA and larger facet joint diameters are associated with poorer prognosis after lumbar fusion surgery, suggesting that these imaging parameters may serve as important predictors of surgical outcome.

Table 7 Univariate logistic regression analysis of factors that influence prognosis after lumbar fusion

Factor	β Value	SE Value	Wald Value	OR Value	95% CI	*P*-value
BMI	0.576	0.143	4.020	1.779	1.357–2.385	<0.001
Screw Inclination Angle	−0.079	0.031	2.577	0.924	0.868–0.980	0.010
FJA	1.734	0.333	5.205	5.661	2.984–11.053	<0.001
Facet Joint Axial Diameter	0.278	0.103	2.690	1.321	1.084–1.630	0.007
Facet Joint Sagittal Diameter	0.735	0.159	4.615	2.085	1.549–2.899	<0.001
Facet Joint Coronal Diameter	0.436	0.093	4.675	1.547	1.300–1.877	<0.001

Table 8 Multivariate logistic regression analysis of factors that influence prognosis after lumbar fusion

Factor	β Value	SE Value	Wald Value	OR Value	95% CI	*P*-value
BMI	0.588	0.181	3.254	1.801	1.264–2.567	0.001
Screw Inclination Angle	−0.097	0.041	−2.396	0.907	0.838–0.982	0.017
FJA	1.844	0.421	4.382	6.320	2.771–14.417	<0.001
Facet Joint Axial Diameter	0.156	0.133	1.172	1.168	0.901–1.516	0.241
Facet Joint Sagittal Diameter	0.636	0.186	3.427	1.888	1.313–2.717	<0.001
Facet Joint Coronal Diameter	0.380	0.106	3.600	1.462	1.189–1.798	<0.001

Univariate logistic regression analysis of factors that influence prognosis after lumbar fusion

Univariate logistic regression analysis identified several factors that significantly influenced prognosis after lumbar fusion surgery (Table 7). BMI was positively associated with poor prognosis (β = 0.576, standard error [SE] = 0.143, Wald = 4.020, odds ratio [OR] = 1.779, 95% confidence interval [CI] = 1.357–2.385, $P < 0.001$). Screw inclination angle was negatively associated with poor prognosis (β=–0.079, SE = 0.031, Wald = 2.577, OR=0.924, 95% CI = 0.868–0.980, $P = 0.010$). FJA was strongly associated with poor prognosis (β = 1.734, SE = 0.333, Wald = 5.205, OR=5.661, 95% CI = 2.984–11.053, $P < 0.001$). Larger facet joint axial diameter (β = 0.278, SE = 0.103, Wald = 2.690, OR=1.321, 95% CI = 1.084–1.630, $P = 0.007$), sagittal diameter (β = 0.735, SE = 0.159, Wald = 4.615, O*R* = 2.085, 95% CI = 1.549–2.899, $P < 0.001$) and coronal diameter (β = 0.436, SE = 0.093, Wald = 4.675, OR=1.547, 95% CI = 1.300–1.877, $P < 0.001$) were also associated with poor prognosis. These findings indicate that higher BMI, larger FJA and wider facet joint diameters in all three dimensions are significant risk factors for a poor prognosis after lumbar fusion surgery. In addition, a smaller screw inclination angle is associated with better prognosis. These results highlight the importance of considering these imaging parameters and patient characteristics when predicting and improving surgical outcomes.

Multivariate logistic regression analysis of factors that influence prognosis after lumbar fusion

Multivariate logistic regression analysis revealed that several factors independently influenced prognosis after lumbar fusion surgery (Table 8). BMI remained a significant predictor, with higher BMI being associated with worse prognosis (β = 0.588, SE = 0.181, Wald = 3.254, OR=1.801, 95% CI = 1.264–2.567, $P = 0.001$). Screw inclination angle was also a significant predictor, with a smaller angle associated with better prognosis (β=–0.097, SE = 0.041, Wald = – 2.396, OR=0.907, 95% CI = 0.838–0.982, $P = 0.017$). FJA was a strong predictor, with a larger angle being associated with worse prognosis (β = 1.844, SE = 0.421, Wald = 4.382, OR=6.320, 95% CI = 2.771–14.417, $P < 0.001$). Facet joint sagittal diameter was also a significant predictor, with a wider diameter associated with worse prognosis (β = 0.636, SE = 0.186, Wald = 3.427, OR=1.888, 95% CI = 1.313–2.717, $P < 0.001$). Facet joint coronal diameter was similarly a significant predictor, with a wider diameter being associated with worse prognosis (β = 0.380, SE = 0.106, Wald = 3.600, OR=1.462, 95% CI = 1.189–1.798, $P < 0.001$). Facet joint axial diameter did not exhibit a significant association with prognosis (β = 0.156, SE = 0.133, Wald = 1.172, OR=1.168, 95% CI = 0.901–1.516, $P = 0.241$). These results indicate that higher BMI, larger FJA and wider facet joint sagittal and coronal diameters are independent risk factors for poor prognosis after lumbar fusion surgery. Smaller screw inclination angle is associated with better prognosis. These findings underscore the importance of considering these factors in preoperative assessment and planning to optimise surgical outcomes.

Joint ROC analysis of factors that influence prognosis after lumbar fusion surgery

A joint ROC analysis was performed on various factors that influenced prognosis after lumbar fusion surgery. The area under the curve (AUC) value for the joint analysis of all the factors was calculated, indicating their collective predictive power for the outcome. The AUC value for the joint analysis was 0.881, suggesting that the combination of BMI, screw inclination angle, FJA, facet joint axial diameter, facet joint sagittal diameter and facet joint

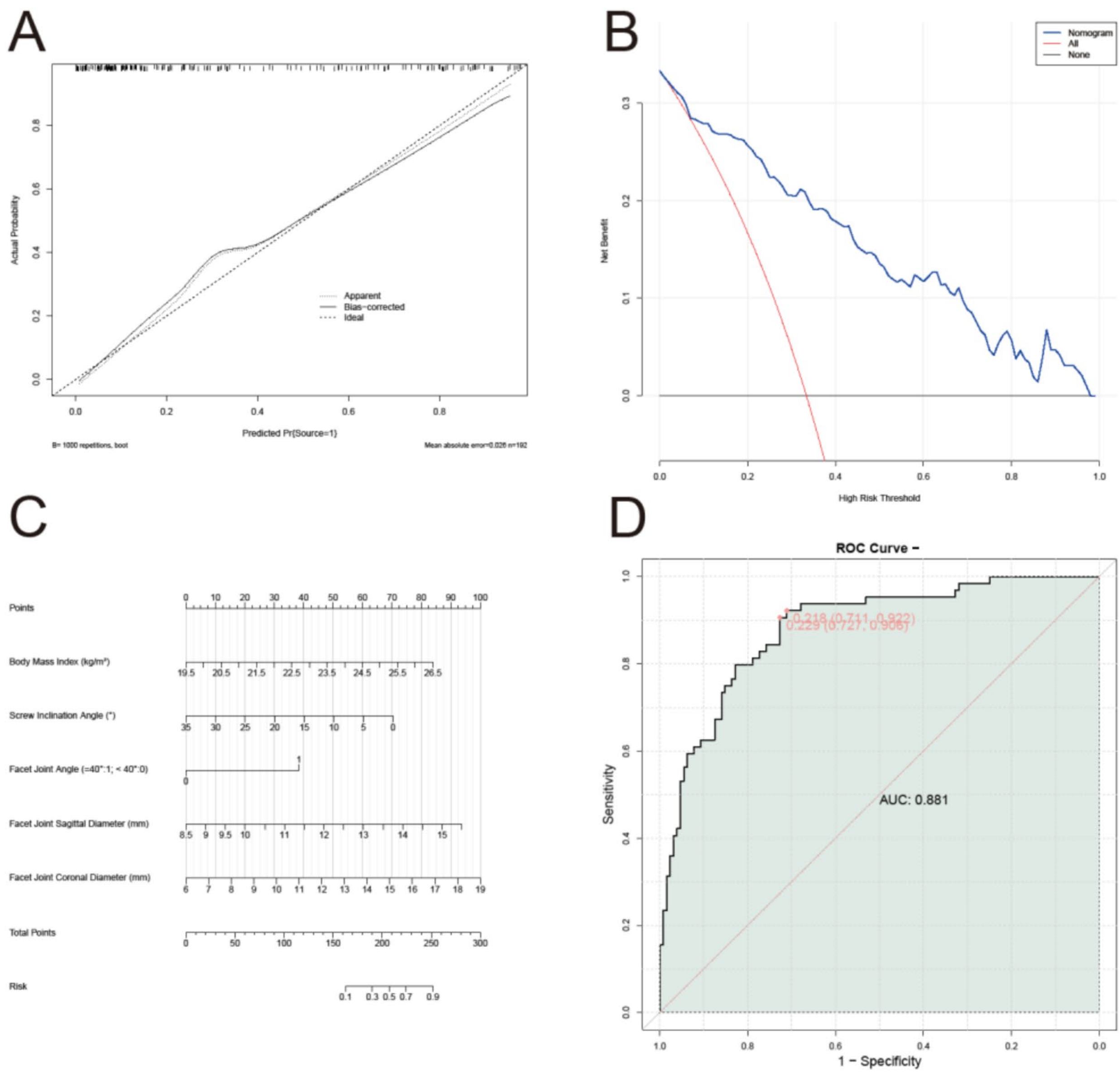

Fig. 4 Joint ROC analysis of factors that influence prognosis after lumbar fusion surgery. **A**: Calibration curve, **B**: decision curve, **C**: nomogram, **D**: combined ROC curve

coronal diameter exhibits a high discriminatory ability in predicting prognosis, as shown in Fig. 4D. To further facilitate clinical decision-making, we developed a nomogram based on the multivariate logistic regression analysis (Fig. 4C). This nomogram integrates the significant predictors identified in our study, including BMI, screw inclination angle, FJA, facet joint sagittal diameter, and coronal diameter. By assigning points to each variable according to their contribution to the outcome, the nomogram allows clinicians to visually assess the probability of poor prognosis in patients undergoing lumbar fusion surgery. Figure 4A presents the calibration curve, demonstrating a good agreement between the nomogram predictions and actual outcomes, while Fig. 4B shows the decision curve, indicating that the nomogram and combined ROC model offer clinical value by improving decision-making for patient management.

Discussion

Our study provides significant insights into the effect of proximal FJA on PASD after lumbar fusion surgery. One theory regarding the pathogenesis of PASD suggests that instrumentation-induced segmental hypo-lordosis leads to compensatory hyperlordosis in adjacent segments, exacerbating degeneration [20, 21]. Although our study did not include data on lumbar lordosis, FJA and lumbar lordosis both influence spinal biomechanics. Specifically, segmental hyperlordosis, a well-established factor contributing to PASD, shares similarities with the impact of larger FJA [22, 23]. Both mechanisms involve alterations in load distribution and mechanical forces acting on the spinal segments, leading to degenerative changes.

The association between higher FJA and increased rates of PASD can be attributed to altered load distribution and mechanical forces acting on the spinal segments. A larger FJA can result in greater shear forces across facet joints, predisposing them towards degeneration over time [24, 25]. This biomechanical imbalance can disrupt the normal range of motion in adjacent segments, leading to an accelerated degenerative process. Patients with naturally larger FJA may already possess anatomical configurations that limit their adaptability to biomechanical changes introduced by lumbar fusion, resulting in rapid degeneration when natural biomechanics are disrupted [26–28].

In comparison to segmental hyperlordosis, which primarily affects the sagittal alignment of the spine, the unique aspect of FJA is its direct impact on facet joint mechanics [29]. Larger FJAs can lead to greater shear forces specifically within the facet joints, potentially causing more localized degeneration compared to the broader effects of hyperlordosis [29]. This localized degeneration may explain why patients with larger FJAs exhibit higher rates of PASD even in the absence of significant changes in lumbar lordosis.

The prognostic implications of our findings highlight the importance of facet joint dimensions. Larger facet joints may accommodate more extensive osteophyte proliferation and hypertrophy, leading to a diminished range of motion and heightened stiffness postoperatively, adversely affecting functional outcomes. Increased facet joint sizes may also correlate with a higher prevalence of subchondral bone changes, contributing to pain and instability in the proximal segment [30, 31].

This study further underscores the significance of BMI in predicting lumbar fusion outcomes. A higher BMI was consistently correlated with poor prognosis. This association can be due to the increased mechanical burden imposed by excess body weight on the spine, which may exacerbate degenerative changes and hinder postoperative recovery. Obesity is also frequently linked with systemic inflammation, which can impede healing processes and potentiate degenerative changes in adjacent segments [32, 33]. Thus, addressing weight management preoperatively can be pivotal in improving postsurgical outcomes in lumbar fusion patients.

In addition, screw inclination angle emerged as a significant factor that deserves particular attention. A smaller screw inclination angle was associated with improved outcomes, possibly because it allows for a biomechanically favourable alignment that distributes mechanical loads more efficiently across the surgical and adjacent segments [34, 35]. This alignment minimises aberrant stress concentrations and reduces the risk of screw loosening or hardware complications, which are critical determinants of surgical success [36, 37].

One limitation of our study is its retrospective nature, which may introduce inherent biases, such as selection bias, despite the stringent inclusion and exclusion criteria used in the research. Furthermore, while CT-based measurements were used for precision, these static images may not fully capture dynamic aspects of spinal biomechanics influenced by patient movement and posture. Incorporating dynamic factors, such as patient activity levels or posture, in future studies can add depth to the findings and provide a more comprehensive understanding of the observed outcomes. In addition, although one experienced surgeon made the final decisions, future studies should include interobserver reliability assessments to validate the reproducibility of imaging parameter measurements across different evaluators and settings. Prospective studies with real-time biomechanical assessments can further elucidate these relationships. In addition, although our study identified significant factors associated with poor prognosis, the potential interplay amongst these factors, particularly in multifactorial cases, requires further exploration. Future research should focus on developing predictive models that integrate machine learning algorithms to account for complex interactions amongst numerous variables, enhancing the predictive capability for PASD and surgical outcomes.

Conclusion

In conclusion, our study reveals that proximal FJA plays a crucial role in determining the risk of PASD and overall prognosis after lumbar fusion surgery. Understanding the biomechanical and anatomical determinants of this relationship can enhance preoperative planning, patient counselling and tailored surgical interventions. In particular, larger FJA, greater facet joint dimensions and increased BMI are independent risk factors for poor prognosis. Smaller screw inclination angles are associated with better outcomes. These insights pave the way for more effective management strategies, aiming to improve patient outcomes in the evolving field of spinal surgery. Future studies should consider incorporating dynamic factors, such as patient activity levels and posture, and exploring the relationship between lumbar lordosis and FJA to provide a more holistic understanding of spinal biomechanics.

Acknowledgements
None.

Author contributions
Feng Qin and Weiqiang Fan: Conceptualization, Formal analysis, Investigation. Lili Ren: Methodology, Formal analysis, Data Curation. Qi Chen: Conceptualization, Formal analysis, Data Curation. Xiaoxiao Chen: Data Curation, Supervision. Wenjun Liu: Data Curation, Methodology, Writing - Original Draft.

Funding
None.

Data availability
The datasets used during the present study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Given the retrospective nature of this study using de-identified patient data without potential harm or impact on patient care, informed consent was waived. This waiver and the study were approved by the institutional review board and ethics committee of our hospital, adhering to regulatory and ethical standards for retrospective studies.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Spinal Surgery, Dongying Shengli Oilfield Central Hospital, Dongying, Shandong Province 257000, China

Received: 10 October 2024 / Accepted: 22 April 2025
Published online: 06 May 2025

References

1. Heemskerk JL, Akinduro OO, Clifton W, Quiñones-Hinojosa A, Abode-Iyamah KOJTSJ. Long-term clinical outcome of minimally invasive versus open single-level transforaminal lumbar interbody fusion for degenerative lumbar diseases: a meta-analysis. Spine J. 2021;21(12):2049–65.
2. Watanabe G, Palmisciano P, Conching A, Ogasawara C, Ramanathan V, Alfawares Y, et al. Degenerative spine surgery in patients with Parkinson disease: a systematic review. World Neurosurg. 2023;169:94–e1092.
3. Pheasant MS, Coulter JL, Wallace C, Kropp Lopez AK, DelSole EM, Mercuri JJ. Lumbar spine fusion and symptoms of leg length discrepancy after hip arthroplasty. J Arthroplasty. 2021;36(9):3241–e71.
4. Nessim A, Cho W, Yang XA, Applebaum A, Sekerak R, Brill S, et al. Infra-adjacent segment disease after lumbar fusion: an analysis of pelvic parameters. Spine (Phila Pa 1976). 2021;46(16):E888–92.
5. Wangsawatwong P, Sawa AGU, Pereira BA, Lehrman JN, Turner JD, Uribe JS, et al. Does the choice of spinal interbody fusion approach significantly affect adjacent segment mobility? Spine (Phila Pa 1976). 2021;46(21):E1119–24.
6. Wang Y, Shen Q, Liang C, Shen Y, Tang X, Yi P. Biomechanical analysis of adjacent segments after spinal fusion surgery using a geometrically parametric patient-specific finite element model. J Vis Exp. 2024(203).
7. Takeda K, Okada E, Shinozaki Y, Ozaki M, Kono H, Yasuda A, et al. Risk factors for early-onset radiographical adjacent segment disease in patients with spondylolytic spondylolisthesis after single-level posterior lumbar interbody fusion. Spine J. 2022;22(7):1112–8.
8. Park S, Hwang CJ, Lee DH, Kim NY, Nam HW, Kang HW, et al. Risk factors of revision operation and early revision for adjacent segment degeneration after lumbar fusion surgery: a case-control study. Spine J. 2024;24(9):1678–89.
9. Sun X, Chen Z, Sun S, Wang W, Zhang T, Kong C, et al. Dynamic stabilization adjacent to fusion versus posterior lumbar interbody fusion for the treatment of lumbar degenerative disease: a meta-analysis. Biomed Res Int. 2020;2020:9309134.
10. Musso S, Buscemi F, Bonossi L, Silven MP, Torregrossa F, Iacopino DG, et al. Lumbar facet joint stabilization for symptomatic spinal degenerative disease: a systematic review of the literature. J Craniovertebr Junction Spine. 2022;13(4):401–9.
11. Wang PT, Zhang JN, Liu TJ, Yang JS, Hao DJ. Multivariate analysis of pedicle screw invasion of the proximal facet joint after lumbar surgery. BMC Musculoskelet Disord. 2022;23(1):39.
12. Nguyen AQ, Rodriguez C, Kumar R, Gupta S, Anderson DE, Saifi C. Biomechanical analysis of complications following t10-pelvis spinal fusion: a population based computational study. J Biomech. 2024;165:111969.
13. Yin J, Liu Z, Li C, Luo S, Lai Q, Wang S, et al. Effect of facet-joint degeneration on the in vivo motion of the lower lumbar spine. J Orthop Surg Res. 2020;15(1):340.
14. Pradeep K, Pal B. Biomechanical and clinical studies on lumbar spine fusion surgery: a review. Med Biol Eng Comput. 2023;61(3):617–34.
15. Meng B, Bunch J, Burton D, Wang JJESJ. Lumbar interbody fusion: recent advances in surgical techniques and bone healing strategies. Eur Spine J. 2021;30:22–33.
16. Liu C, Guo C, Meng F, Zhu Z, Xia W, Liu H. Perioperative risk factors related to complications of lumbar spine fusion surgery in elderly patients. BMC Musculoskelet Disord. 2023;24(1):573.
17. Inoue N, Orías AAE, Segami K. Biomechanics of the lumbar facet joint. Spine Surg Relat Res. 2020;4(1):1–7.
18. Zhang RJ, Zhou LP, Zhang L, Zhang HQ, Ge P, Jia CY, et al. The rates and risk factors of intra-pedicular accuracy and proximal facet joint violation for single-level degenerative lumbar diseases: cortical bone trajectory versus traditional trajectory pedicle screw. Spine (Phila Pa 1976). 2021;46(23):E1274–82.
19. Tisot RA, Vieira JDS, Collares DDS, Tisatto DL. Pasini A, Gobetti B. Facet joint degeneration in patients with lumbar disc herniation and probable determining factors. Coluna/Columna. 2020;19:262–5.
20. Bahir AW, Daxing W, Jiayu X, Bailian L, Shao G. Comparative efficacy and fusion outcomes of unilateral bi-portal endoscopic transforaminal lumbar interbody fusion versus minimally invasive transforaminal lumbar interbody fusion in treating single-segment degenerative lumbar spondylolisthesis with lumbar spinal stenosis: a two-year retrospective study. J Orthop Surg Res. 2024;19(1):835.
21. Wang W, Cui Y, Sun X, Zhang H, Yin W, Cui X, et al. Transforaminal posterior lumbar interbody fusion microscopic safe operating area: a three-dimensional model study based on computed tomography imaging. J Orthop Surg Res. 2024;19(1):342.
22. Arunakul R, Anumas S, Pattharanitima P, Susrivaraput C, Pholsawatchai W. Unilateral biportal endoscopic versus microscopic transforaminal lumbar interbody fusion for lumbar degenerative disease: a retrospective study. J Orthop Surg Res. 2024;19(1):326.
23. Guo W, Ye J, Li T, Yu Y, Fan X. Evaluation of the learning curve and complications in unilateral biportal endoscopic transforaminal lumbar interbody fusion: cumulative sum analysis and risk-adjusted cumulative sum analysis. J Orthop Surg Res. 2024;19(1):194.
24. Nassr A, Coric D, Pinter ZW, Sebastian AS, Freedman BA, Whiting D, et al. Lumbar facet arthroplasty versus fusion for grade-i degenerative spondylolisthesis with stenosis: a prospective randomized controlled trial. J Bone Joint Surg Am. 2024;106(12):1041–53.
25. Ouchida J, Nakashima H, Kanemura T, Matsubara Y, Satake K, Muramoto A, et al. Adjacent segment degeneration after short-segment lateral lumbar interbody fusion (llif). Biomed Res Int. 2022;2022:5161503.
26. Lebedev VB, Epifanov DS, Osipov II, Esin AI, Kinzyagulov BR, Zuev AA. Revision surgery after previous spinal decompression and fusion for lumbar spinal stenosis. Zh Vopr Neirokhir Im N N Burdenko. 2023;87(1):70–6.
27. Morishita Y, Taniguchi R, Kawano O, Maeda T. Synovial facet joint cysts after lumbar posterior decompression surgery. J Neurosurg Spine. 2021;35(6):704–9.
28. Ouchida J, Nakashima H, Kanemura T, Satake K, Ito K, Tsushima M, et al. Impact of adjacent facet joint osteoarthritis on adjacent segment degeneration after short-segment lateral lumbar interbody fusion for indirect decompression: minimum 5-year follow-up. Biomed Res Int. 2022;2022:3407681.
29. Van Oosterwyck W, Vander Cruyssen P, Castille F, Van de Kelft E, Decaigny V. Lumbar facet joint disease: what, why, and when? Life (Basel). 2024;14(11).
30. Chou PH, Lin HH, Yao YC, Wang ST, Chang MC, Liu CL. Preoperative facet joint arthropathy does not impact long-term clinical outcomes after

lumbar-stability-preserving decompression and dynesys fixation. Sci Rep. 2021;11(1):11299.
31. Singhatanadgige W, Jaruprat P, Kerr SJ, Yingsakmongkol W, Kotheeranurak V, Limthongkul W. Incidence and risk factors associated with superior-segmented facet joint violation during minimal invasive lumbar interbody fusion. Spine J. 2022;22(9):1504–12.
32. Truong VT, Sunna T, Al-Shakfa F, Mc Graw M, Boubez G, Shedid D, et al. Impact of obesity on complications and surgical outcomes of adult degenerative scoliosis with long-segment spinal fusion. Neurochirurgie. 2022;68(3):289–92.
33. Iyer P, Hwang M, Ridley L, Weisman MM. Biomechanics in the onset and severity of spondyloarthritis: a force to be reckoned with. RMD Open. 2023;9(4).
34. Li Y, Chen Y, Liu Y, Hai Y, Zhang X, Guan L, et al. Changes in paraspinal muscles and facet joints after minimally invasive posterior lumbar interbody fusion using the cortical bone trajectory technique: a prospective study. Pain Res Manag. 2022;2022:2690291.
35. Zhao Y, Yuan S, Tian Y, Liu X. Risk factors related to superior facet joint violation during lumbar percutaneous pedicle screw placement in minimally invasive transforaminal lumbar interbody fusion (mis-tlif). World Neurosurg. 2020;139:e716–23.
36. Luo PJ, Tang YC, Zhou TP, Guo HZ, Guo DQ, Mo GY, et al. Risk factor analysis of the incidence of subsequent adjacent vertebral fracture after lumbar spinal fusion surgery with instrumentation. World Neurosurg. 2020;135:e87–93.
37. Chen JW, Longo M, Chanbour H, LaBarge ME, Abtahi AM, Stephens BF, et al. Cranially directed upper instrumented vertebrae screw angles are associated with proximal junctional kyphosis in adult spinal deformity surgery. Spine (Phila Pa 1976). 2023;48(10):710–9.

Publisher's note