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EDITORIAL

Dear Colleagues,

In recent years, artificial intelligence (AI) has emerged as a transformative force in the field of medicine, and spinal surgery is no exception. The integration of AI into spinal surgery promises enhanced precision, efficiency, and patient outcomes, making it an indispensable tool for surgeons navigating complex spinal pathologies. As the Journal of Turkish Spinal Surgery continues to highlight advancements in the field, it is essential to explore the profound impact AI is having on the way spinal disorders are diagnosed and treated. One of the most significant contributions of AI to spinal surgery is its ability to assist in preoperative planning. Machine learning algorithms, a subset of AI, can analyze patient data, including imaging studies such as magnetic resonance imaging and computed tomography scans, to identify subtle abnormalities and patterns that might be missed by the human eye. These algorithms not only help in diagnosing conditions like spinal stenosis, herniated discs, or deformities but also provide surgeons with detailed 3D reconstructions of the spine. This level of accuracy ensures that surgical interventions are meticulously planned, reducing the likelihood of complications and improving outcomes. Intraoperatively, AI-powered robotic systems are transforming the surgical landscape. Robotic platforms, guided by AI algorithms, allow for unparalleled precision in spinal instrumentation, particularly in pedicle screw placement. This level of accuracy minimizes the risk of nerve injury and ensures optimal spinal alignment. Furthermore, AI-driven navigation systems provide real-time feedback during surgery, enabling surgeons to make informed decisions and adapt to intraoperative challenges. This fusion of human expertise and machine efficiency is setting new benchmarks for safety and effectiveness in spinal surgery. Beyond the operating room, AI is also revolutionizing postoperative care and rehabilitation. Advanced algorithms can monitor patients' recovery through wearable devices, providing real-time data on mobility, pain levels, and other key metrics. This data-driven approach allows for personalized rehabilitation plans, ensuring that each patient receives care tailored to their specific needs. Additionally, predictive analytics powered by AI can identify patients at risk of complications, enabling early intervention and reducing hospital readmissions. Despite these remarkable advancements, the integration of AI into spinal surgery is not without challenges. Issues such as data privacy, algorithm transparency, and the need for rigorous validation must be addressed to ensure the safe and ethical use of AI. Moreover, surgeons must strike a balance between embracing technology and maintaining their clinical acumen, as the human element remains irreplaceable in patient care.In conclusion, AI is poised to redefine the field of spinal surgery. By enhancing diagnostic accuracy, surgical precision, and postoperative care, AI is empowering surgeons to achieve better outcomes for their patients. As researchers and clinicians in Türkiye and across the globe continue to explore the potential of AI, the future of spinal surgery looks brighter than ever.

The Journal of Turkish Spinal Surgery, as a leading platform for innovation and knowledge dissemination, plays a crucial role in documenting and shaping this transformative journey. Together, we can harness the power of AI to advance spinal health and improve the quality of life for countless individuals. As AI becomes more and more involved in spine surgery, we are pleased to see frequent articles related to AI in our journal.

Co-Editor-in-Chief

Ömer Erşen, M.D.,

ORIGINAL ARTICLE
98

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THORACIC ATYPICAL HEMANGIOMAS: DIAGNOSIS AND MANAGEMENT-A SINGLE CENTER EXPERIENCE

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ABSTRACT

Objective: Vertebral hemangiomas (VH) are common benign vascular tumors, often discovered incidentally. However, the clinical significance and optimal management of atypical VH, particularly in the thoracic region, remain unclear due to their variable radiological appearances and overlapping features with malignant lesions. This study aims to investigate the diagnosis, radiological characteristics, and management strategies of atypical thoracic VH.

Materials and Methods: A retrospective review was conducted on 3,175 spinal magnetic resonance imaging (MRI) reports performed at our center between January 2019 and September 2023. Patients with radiological findings suggestive of atypical thoracic VH were identified, and imaging was re-evaluated by two experienced neuroradiologists. Patients were included if radiological criteria for atypical VH were met and follow-up data were available. Demographic data, lesion characteristics, imaging findings, and clinical outcomes were recorded.

Results: A total of 41 patients (26 female, 15 male; mean age: 47.7 years) with atypical thoracic VH were included. Most lesions showed hypointensity on T1-weighted images and hyperintensity on T2-weighted and short tau inversion recovery sequences. Lesions were most commonly located at T7, and 71% were solitary. Additional imaging, including computed tomography (CT), contrast-enhanced MRI, and positron emission tomography-CT, was performed in select cases to exclude malignancy. No cases exhibited extraosseous extension or radiological progression during a mean follow-up of 49 months. Of 13 patients presenting with back pain, 69% improved with conservative management. No patients developed neurological deficits or required surgical intervention.

Conclusion: Atypical thoracic VH may present with imaging characteristics that mimic malignancy but often remain clinically silent and stable over time. Accurate radiological assessment and close follow-up are essential to avoid unnecessary interventions. Observation appears to be a safe and appropriate strategy for managing asymptomatic atypical VH.

Keywords: Atypical, spinal, thoracic, vertebral hemangioma

INTRODUCTION

Vertebral hemangiomas (VH) are incidental findings and relatively common radiological entities. As a benign vascular tumor, VH is one of the most common spinal tumors, with an estimated incidence in the general population ranging from 1% to 30%[1-4]. The male-to-female ratio varies between 1:1.2 and 1:2.25[5-7]. Multiple perspectives exist regarding the symptomatic evolution of atypical hemangiomas. While some studies suggest that atypical hemangiomas are merely a radiological diagnosis and do not exhibit aggressive features, others emphasize that the atypical form is a significant factor for progression to the aggressive type[2,5,8]. Similarly, conflicting findings are observed in terms of hormonal effects, diagnosis, treatment, symptomatic presentation, and neurological deficits[9-12]. Almost every aspect of VH reported in the literature shows widely varying rates, leading to significant uncertainty. Consequently, the management of atypical thoracic hemangiomas remains incompletely understood. In our study, we retrospectively analyzed patients diagnosed and followed up with atypical thoracic hemangiomas in our clinic. The aim of this study is to determine the diagnosis and management of thoracic hemangiomas with atypical features on magnetic resonance imaging (MRI).

MATERIALS AND METHODS

All records of spinal MRI performed at our center between January 2019 and September 2023 were retrospectively

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reviewed. A text search was conducted in the reports using the keywords "atypical hemangioma(s)" and "atypical VH(s)." All spinal MRI studies performed at our center were initially reported as part of routine clinical practice by two neuroradiologists with over 10 years of experience in neuroradiology. The images of patients suspected of having atypical VH were independently re-evaluated by the same two radiologists, and the final diagnosis was established by mutual consensus. This standardized evaluation process minimized interobserver variability and ensured that only lesions meeting the accepted radiological criteria for atypical hemangiomas were included in the study.

Inclusion criteria were: (1) availability of thoracic spinal MRI with a prospective or suspected diagnosis of atypical hemangioma; (2) confirmation of radiological features consistent with atypical hemangiomas upon expert re-evaluation; and (3) availability of follow-up imaging or clinical documentation.

Exclusion criteria included: (1) inconclusive imaging findings; (2) absence of follow-up records; and (3) contraindications to MRI or patient refusal of follow-up evaluation.

If the patients' MRIs were consistent with the radiological findings of atypical thoracic hemangiomas, further investigations, including computed tomography (CT), contrast-enhanced thoracic MRI, and positron emission tomography-CT (PET-CT), as well as clinical follow-up notes, were examined.

Demographic characteristics of the patients, lesion location and appearance, number of lesions, compression of neural elements, neurological examination findings, and follow-up results were recorded. Neurological examination findings were retrospectively obtained from electronic medical records and included in the analysis only if they were systematically documented during initial or follow-up visits. The study was approved by İstinye University Faculty of Medicine Human Research Ethics Committee (decision number: 24-213, date: 22.12.2024).

Statistical Analysis

Statistical analyses were performed using SPSS (version 22.0, IBM Corp., Armonk, NY). Descriptive statistics were presented as mean ± standard deviation or median (minimum-maximum), depending on the data distribution.

RESULTS

A text search of 3175 MRI examinations conducted at İstinye University Hospital Medical Park Gaziosmanpaşa between January 2019 and September 2023 identified 93 records with relevant keywords. Fourteen cases with lumbar and eleven with cervical atypical hemangiomas were excluded from the study. Among the remaining 68 cases, 19 were found to have thoracic metastases upon further evaluation. Six cases initially reported as atypical hemangiomas were excluded because their radiological findings did not meet the criteria for atypical hemangiomas. Two patients who did not continue follow-up after diagnosis were also excluded. A total of 41 patients met the inclusion criteria and were included in the study. The mean age of the patients was 47.68 years, ranging from 26 to 78 years. The study population included 26 (63%) female and 15 male patients (Table 1). Nineteen patients had no neurosurgical complaints, while 14 (34%) reported back pain, 5 had lower back pain, and 3 had neck pain. Lesions located at the T1 or T12 vertebrae were incidentally detected in cervical or lumbar MRI scans of 6 patients. In these cases, the adjacent thoracic vertebral levels (T1 or T12) were partially included in the imaging field, allowing for lesion identification, which was later confirmed with dedicated thoracic imaging. On T1-weighted images, 32 (78%) cases showed low signal intensity, and 9 exhibited mixed signals, while high signal intensity was observed on T2-weighted and short tau inversion recovery sequences in 39 (95%) cases (Figure 1). Upon repeated radiological evaluation, an additional atypical hemangioma was detected in 4 patients. Twenty-nine patients (71%) presented with a single lesion, while six patients had two lesions, five patients had three lesions, and one patient exhibited four atypical hemangiomas. The most frequently affected vertebra was T7, observed in 9 (22%) patients. The least affected vertebrae were T3, T5 and T9 with two cases each (Figure 2). Among patients with a single lesion, neither the T3 nor the T5 vertebra was solely affected. Additionally, 15 (37%) patients had typical hemangiomas in the thoracic region. The size of atypical hemangiomas ranged from 2 to 26 mm in maximum diameter, and in 8 (20%) cases, the lesion size exceeded 1 cm. Only 1 case showed involvement of more than 50% of the vertebral body (VB). In 39 (95%) cases, the lesions were confined to the VB. One case had a lesion in the left pedicle, and another with multiple atypical hemangiomas exhibited a lesion extending from the VB to the left pedicle. No extraosseous extension was observed in any case. To confirm the radiological diagnosis, thoracic CT was performed in 26 patients, contrast-enhanced thoracic MRI in 29 patients, and PET-CT in 2 patients. Radiological findings of atypical hemangiomas were observed in 11 patients on CT (Figure 3). On contrast-enhanced thoracic MRI, contrast enhancement was detected in 4 patients (Figure 4). PET-CT revealed cold lesions in 2 patients, ruling out metastasis. Patients with a history of cancer, symptomatic presentation, or contrast enhancement underwent their first follow-up at 6 months, which included both CT and MRI. For other patients, annual follow-ups were conducted with thoracic MRI alone. The mean follow-up duration was 49 months (17-68 months). No progression was observed in any patient. Among the 13 patients with back pain, 9 (69%) experienced pain resolution following conservative treatment. The remaining 4 reported pain unrelated to the lesion's localization. In a patient diagnosed with endometrial cancer, pathological fractures were identified in the lumbar 3, 4, and 5 VB during follow-up, leading to vertebroplasty.

Table 1. Demographic and radiological characteristics of the patients

Number of patients	**41**
Age	47.68
Female	26 (63%)
Asymptomatic	19 (46%)
Hypointense on T1-weighted MRI	32 (78%)
Hyperintense on T2-weighted MRI	39 (95%)
Single lesion	29 (71%)
Coexisting typical vertebral hemangioma	15 (37%)
Lesion larger than 1 cm	8 (20%)
Pedicle involvement	2 (5%)
Contrast enhancement	8 (28%)
Typical CT findings	11 (42%)

MRI: Magnetic resonance imaging, CT: Computed tomography

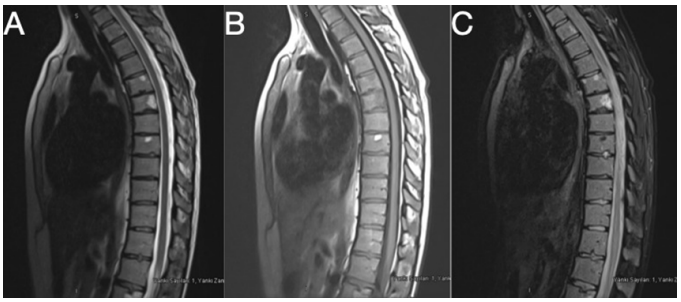

Figure 1. High signal intensity on T2-weighted imaging (A), low signal intensity on T1-weighted imaging (B), and high signal intensity on STIR sequences (C). STIR: Short tau inversion recovery

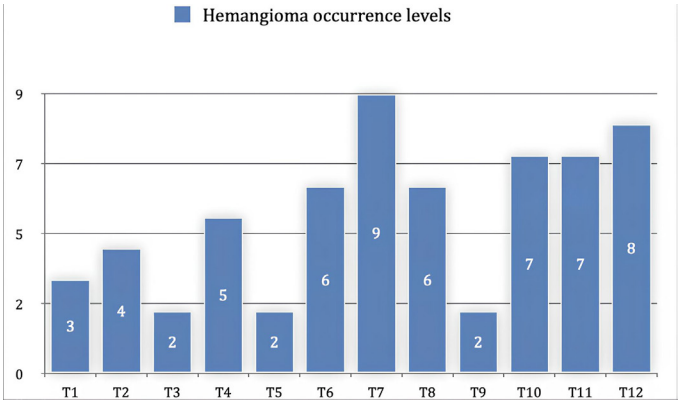

Figure 2. Frequency of vertebral hemangiomas at different vertebral levels

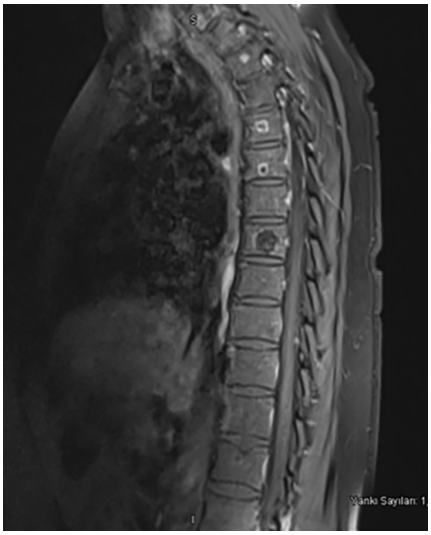

Figure 3. Thoracic CT scan illustrating an atypical hemangioma extending from the vertebral body to the left pedicle. CT: Computed tomograpy

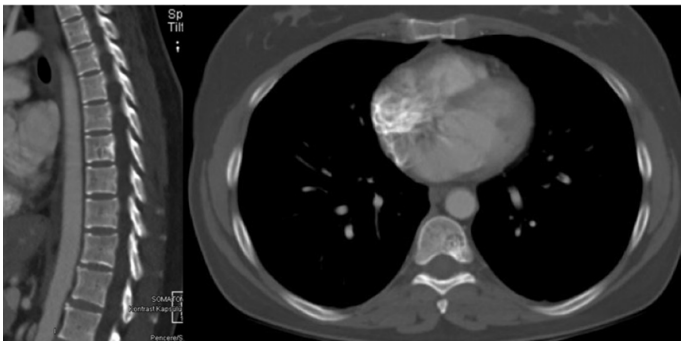

Figure 4. Demonstration of peripheral contrast enhancement in a case with both typical and atypical hemangiomas

DISCUSSION

In this retrospective single-center study, 41 cases of atypical VH were identified, corresponding to an incidence of 1.3%. Reassessment of available imaging revealed additional lesions in four patients, suggesting that smaller or less conspicuous VH may be underrecognized in routine radiological or autopsy studies. This finding supports the hypothesis that the increasing use of advanced imaging techniques contributes to higher detection rates[4,7,13,14]. Most lesions were located in the thoracic spine, followed by the lumbar and cervical regions, while no lesions were observed in the sacrum. Approximately 15% of thoracic VH located at T1 or T12 were incidentally detected on cervical or lumbar spine MRI, emphasizing the importance of thoroughly evaluating all visible vertebral levels, even when not the primary focus of imaging[11,12]. The anatomical distribution observed in this cohort is consistent with prior reports indicating a predilection for the mid-and lower thoracic segments[15,16]. The mean age of patients was

47.7 years, aligning with previous literature that describes VH as most frequently diagnosed in individuals aged 40-60 years[17]. A predominance of female patients was also noted, consistent with earlier studies suggesting a possible hormonal influence on lesion development[7,15,18,19]. However, due to the retrospective nature of the study, hormonal status could not be assessed. VH are often incidental findings and typically asymptomatic. In this cohort, no patients exhibited neurological deficits or other symptoms directly attributable to VH. Symptomatic cases, although rare, may present with localized pain or signs of neural compression[3]. In our series, 70% of patients presenting with back pain reported symptomatic relief during follow-up, and in four cases, pain localization did not correlate with the location of the VH, suggesting an incidental relationship. VH can be classified as typical, atypical, or aggressive based on radiological and clinical features[1,5,6]. Typical VH exhibit high signal intensity on both T1-and T2-weighted MRI due to their fat-rich composition, whereas atypical VH demonstrate iso- to hypointense T1 signals and markedly hyperintense T2 signals, often lacking classic imaging signs such as the "corduroy" or "polka-dot" appearance[2,6,8,11,20]. The presence of thickened vertical trabeculae remains a key diagnostic criterion, observable on both CT and MRI. CT features characteristic of atypical VH were observed in 35% of patients in this study, aligning with previous estimates indicating that atypical forms constitute approximately one-third of all VH[15]. Aggressive VH may exhibit expansion, cortical destruction, epidural or paravertebral extension, vertebral collapse, or neurological symptoms[9]. Lesions with greater vascularity tend to be more symptomatic and progressive, in contrast to asymptomatic, fat-dominant VH[2,3]. Atypical and aggressive VH may mimic malignant spinal lesions such as metastases or multiple myeloma, complicating the differential diagnosis[9,10,21]. Advanced imaging modalities, including CT, MRI, and PET-CT, are critical for accurate lesion characterization. PET-CT is particularly useful in differentiating VH from metastatic lesions based on metabolic activity[22,23]. In this study, two patients with prior oncological diagnoses underwent PET-CT scans that demonstrated metabolically inactive ("cold") lesions, and subsequent follow-up confirmed the benign nature of these findings[24-27]. The signal characteristics of symptomatic VH-low T1 and high T2 intensity-are often associated with vascular, biologically active lesions, as originally described by Laredo et al.[2] However, previous studies have shown that VH, including atypical and aggressive forms, often remain radiologically stable and asymptomatic over time[16]. Misdiagnosis of atypical VH as malignant lesions has led to unnecessary interventions and patient anxiety. Consequently, some authors have advocated replacing the term "atypical hemangioma" with "lipid-poor hemangioma" to better reflect the radiological rather than clinical behavior of these lesions[8]. In our cohort, no radiological progression or new-onset neurological deficits were observed during follow-up, even in lesions with low fat content. Management strategies for symptomatic VH include conservative measures, percutaneous interventions (e.g., vertebroplasty, sclerotherapy), surgery, radiotherapy, or combined approaches[3,28]. Surgical treatment is typically reserved for cases with neurological compromise, pathologic fractures, or intractable pain. CT-guided biopsy and PET-CT may be considered in diagnostically uncertain or atypical cases[29]. However, biopsy is infrequently performed due to limited diagnostic yield and potential risks such as bleeding or epidural hematoma[4,24]. Therefore, non-invasive imaging modalities remain the cornerstone of diagnosis.

Study Limitations

The primary limitations of this study include its retrospective design and single-center setting, which may introduce selection and observer bias and limit generalizability. Furthermore, the absence of long-term follow-up and the relatively small sample size preclude definitive conclusions regarding the natural history of atypical VH.

CONCLUSION

VH are typically asymptomatic lesions incidentally detected during routine spinal imaging. Our study demonstrates that observation-based management of asymptomatic atypical VH is a safe and appropriate approach. While atypical VH may exhibit different radiological signal characteristics, this does not always necessitate suspicion of malignancy. Proper assessment of the clinical significance of various VH types, despite the radiological diversity in signal changes, can help avoid unnecessary radiological follow-ups, invasive biopsies, and outpatient clinic visits. Moreover, this approach contributes to preventing undue anxiety and stress among patients. In conclusion, careful clinical evaluation is sufficient to prevent unnecessary interventions for asymptomatic VH.

Ethics

Ethics Committee Approval: The study was approved by İstinye University Faculty of Medicine Human Research Ethics Committee (decision number: 24-213, date: 22.12.2024).
Informed Consent: Retrospective study.

Footnotes

Authorship Contributions

Surgical and Medical Practices: H.K., Concept: B.B., H.K., Design: B.B., H.K., Data Collection or Processing: B.B., H.K., Analysis or Interpretation: B.B., Literature Search: B.B., H.K., Writing: B.B., H.K.
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BILATERAL CROSSING LAMINAR SCREW FIXATION IN LUMBAR SPONDYLOLYSIS: CT-BASED ANATOMICAL PARAMETERS

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ABSTRACT

Objective: To evaluate computed tomography (CT)-based linear and angular anatomical parameters critical for crossing laminar screws (CLS) fixation of pars interarticularis defects in spondylolysis (SPL).

Materials and Methods: Two readers independently analyzed 110 lumbar CT scans of patients with bilateral SPL using multiplanar reconstruction in Centricity software to determine the optimal CLS trajectories. The ideal CLS trajectory was defined as originating from the spinolaminar junction contralateral to the targeted pars defect, passing through the intralaminar region, pars defect, pars neck, and pedicle, and ending at the lateral or superior cortex of the pedicle, maximizing bone engagement. Linear and angular parameters required for CLS fixation were assessed along the defined screw trajectory.

Results: CLS trajectory length significantly decreased from L5 to L3 (52, 43, and 38 mm, respectively) (p>0.05). The laminar height increased significantly from L5 to L3 (7-11 mm). Laminar width was greatest at L5 (10 mm) and similar at L3 and L4 (7 mm). The spinolaminar height significantly increased from L5 to L3 (14-19 mm). Spinolaminar angle was highest at L3 (45°) and similar at L4 and L5 (40°). Coronal angle increased significantly from L5 to L3 (9°-23°). Excellent inter- and intra-reader reliabilities were observed for all measurements.

Conclusion: For the fixation of pars defects at the L3-L5 levels using CLS, a screw length of 4-5 cm and a diameter of 4.5 mm appear to be appropriate. Laminar width and height, along with the spinolaminar angle and height, are fundamental anatomical factors for ensuring safe CLS placement.

Keywords: Spondylolysis, crossing laminar screw, lumbar laminar fixation, intralaminar screw, pedicle fixation alternative

INTRODUCTION

Lumbar spondylolysis (SL) refers to a defect in the pars interarticularis. The incidence of spondylolysis (SPL) in the general population ranges from 3% to 10% and is significantly influenced by ethnicity, sex, and physical activity levels[1-8]. Factors such as supraphysiological axial loading, chronic stress accumulation in the pars, repetitive hyperextension, rotation, flexion movements, and major trauma, alone or in combination, can cause SL[9-12]. SL most frequently occurs at the L5 level, followed by L4, with decreasing frequency at other lumbar levels[5,8,13,14]. Although typically asymptomatic, approximately 80% of symptomatic patients present with bilateral defects, whereas unilateral defects which follow a more benign course occur less frequently[15]. The primary complaint is localized lower back pain at the affected segment, which intensifies with activity and diminishes with rest. Pain may also radiate to the buttocks and posterior thigh and can be provoked by extension movements. Hamstring tightness is common and may contribute to postural abnormalities. Due to hamstring stiffness, flexibility may be reduced in straight leg raise tests[7,15,16]. Neurological examination findings are usually normal because isolated SPL does not cause nerve root compression. However, in cases of bilateral pars defects progressing to spondylolisthesis, L5 radicular pain, loss of reflexes, or rarely motor weakness may be observed[10,16-18].

The disease is typically diagnosed clinically and confirmed using imaging modalities, such as radiography, computed tomography (CT), magnetic resonance imaging (MRI), and single

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photon emission CT[11,12,19]. MRI is particularly valuable for detecting bone edema and stress reactions in young patients at the pre-lysis stage, especially when fractures are not visible on CT[7,11,20,21]. In addition, MRI provides ancillary findings that can significantly aid in the diagnosing SL[11]. The goal of treatment is to achieve pars bone fusion without surgical intervention. Conservative management leads to bone fusion in approximately 90% of cases, although this rate decreases in terminal-stage defects[2,18,22,23]. Surgical options may be considered when symptomatic back pain persists despite multiple conservative treatments or when neurological deficits develop[2,18,23,24]. Although the optimal surgical procedure remains controversial, direct and indirect surgical methods involving screws, rods, hooks, wires, cables, or combinations thereof are available for pars defect fixation[22,25,26].

Intralaminar screw fixation is preferred particularly in young adults with healthy intervertebral discs and positive pars injections[5,22,27]. In 1970, Buck[28] first reported a clinical success rate of 90% in pars defect fusion using an iliac bone graft and intralaminar screws. Subsequent studies have reported significant clinical success in pars defect repair aimed at preserving vertebral segmental mobility using laminar screws with both open and percutaneous surgical approaches[2,22,27]. Intralaminar screw fixation, a low-profile technique, facilitates the restoration of posterior vertebral arch anatomical integrity while preserving the motion segment[14,22,27]. Despite advancements in minimally invasive and robotic surgical techniques, no study has evaluated the anatomical parameters of lumbar crossing laminar screws (CLS) fixation in patients with symptomatic SPL. Thus, the objective of our study was to define the optimal CLS fixation trajectory in individuals with bilateral SL using the Centricity radiological workstation software on CT scans and to comprehensively analyze the linear and angular anatomical parameters along this trajectory.

MATERIALS AND METHODS

The study was approved by the İstanbul Medipol University Non-interventional Clinical Research Ethics Committee (decision number: 688, date: 19.07.2024). Methodological amendments to the study were subsequently approved and documented by the İstanbul Medipol University Non-interventional Clinical Research Ethics Committee on May 14, 2025 (reference number: E-10840098-202.3.02-3028). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Inclusion criteria were as follows: 1) age between 18 and 80 years; 2) bilateral SPL; and 3) spondylolisthesis of 3 mm or less. The exclusion criteria were as follows: 1) postoperative patients with disrupted normal anatomical structures in the region of interest; 2) unsatisfactory image quality or metal artifacts; 3) congenital vertebral arch anomalies; 4) pedicle and/or vertebral body fractures; 5) infections; and 6) bone tumors. A total of 110 bilateral pars defects were analyzed.

The ideal CLS trajectory parameters were assessed by two independent observers using lumbar CT images obtained through oblique multiplanar reconstruction and real-time 3D axis manipulation on a radiology workstation (Centricity Universal Viewer; GE Healthcare, Chicago, IL, USA) with a slice thickness/increment of 1/1 mm (Figure 1). Observer 1 (BOG) performed all measurements twice to evaluate the intra-observer reliability.

Crossing the Laminar Screw Trajectory

For bilateral CLS trajectories, the screw entry points were selected at the lower third (1/3) and upper third (1/3) of the spinolaminar junction to avoid screw interference. The ideal CLS trajectory was defined as starting from the spinolaminar junction on the opposite side of the targeted pars defect; traversing through the intralaminar area, pars defect, pars neck, and pedicle; and terminating at the lateral or superior cortex of the pedicle (Figures 2 and 3). Additionally, the CLS technique was applied to a synthetic lumbar spine model and validated using fluoroscopic images and high-resolution 3D modeling (Figures 4 and 5).

Measured Anatomical Parameters (Figures 2 and 3)

1. Trajectory length: Maximum screw trajectory length from the spinolaminar junction opposite the defect to the pedicle cortical boundary.
2. Laminar height: Minimum laminar height along the screw trajectory in the parasagittal plane.
3. Laminar width: Bicortical width of the narrowest laminar

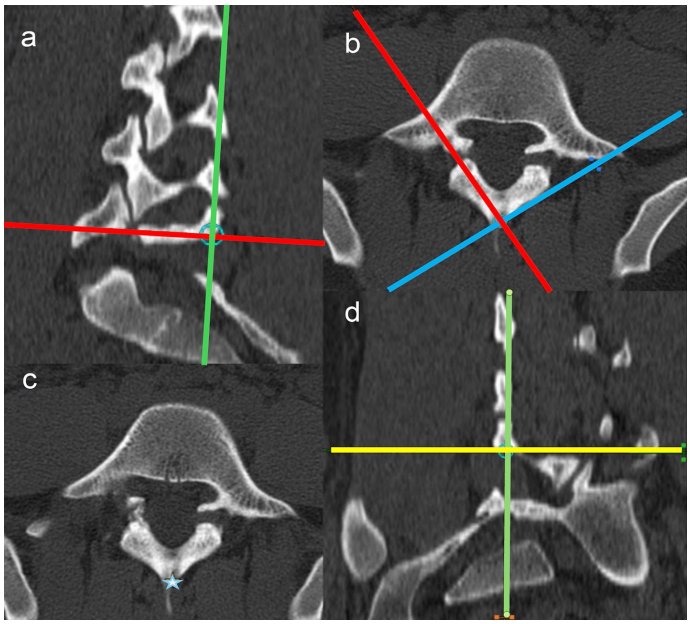

Figure 1. Three-dimensional computed tomography views in the parasagittal, axial, and coronal planes demonstrating the ideal trajectory for crossing laminar screw placement. (a) Parasagittal oblique reconstruction showing the full trajectory. (b) Axial view illustrating the screw path originating from the spinolaminar junction and passing through the laminar isthmus and pedicle. (c) Axial slice displaying the laminar entry zone. (d) Coronal plane showing the entry point of the screw

region in the axial plane.
4. Spinolaminar angle: Laminar angle of the screw trajectory from the spinolaminar entry point relative to the vertebral body.
5. Coronal angle: Angle of the screw trajectory in the coronal plane relative to the vertical axis.
6. Spinolaminar height: Maximum height measurement of the spinolaminar junction in the parasagittal plane.

Statistical Analysis

The normality of quantitative variables was assessed using the Shapiro-Wilk test and graphical methods (histogram, Q-Q plot, and box plot). The independent samples t-test was used to compare two groups of normally distributed variables, and the Mann-Whitney U test was used for non-normally distributed variables. One-way analysis of variance or Kruskal-Wallis tests were used to identify differences among the L3, L4, and L5 levels based on the variable distribution. Post-hoc analyses (Bonferroni or Dunn's tests) were performed to identify significant differences between the groups. Spearman's correlation analysis was conducted to examine the relationships between the vertebral levels and other quantitative variables, given the ordinal structure of the lumbar levels. Line graphs were created to visualize the trends.

Interobserver and intraobserver reliabilities were assessed using intraclass correlation coefficients (ICC). Interobserver reliability was assessed using a two-way random-effects model, absolute agreement, and single measures (ICC(2,1)). Intraobserver reliability was assessed using a two-way mixed-effects model, absolute agreement, and single measures (ICC(3,1)).

A distance error tolerance interval of ±0.5 mm (half of the maximum acceptable error level of 1 mm) was defined for each

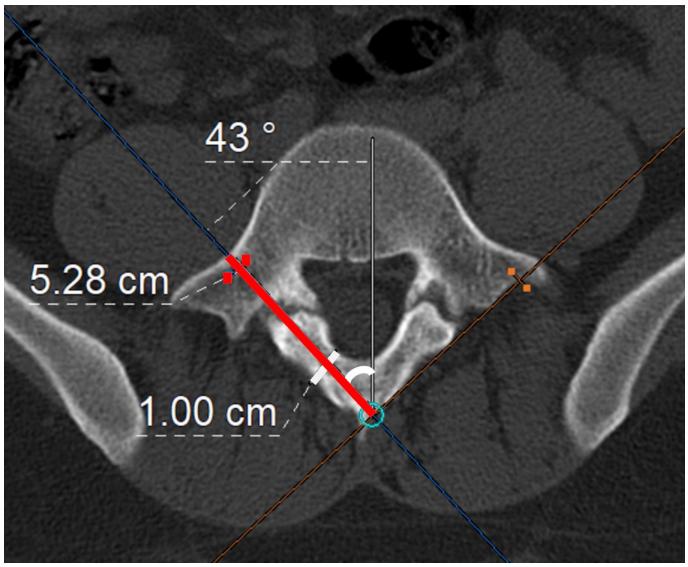

Figure 2. At the L5 level in the axial plane, the ideal trajectory length for crossing laminar screw placement was measured as 5.28 cm, with a spinolaminar angle of 43° and a laminar width of 1 cm

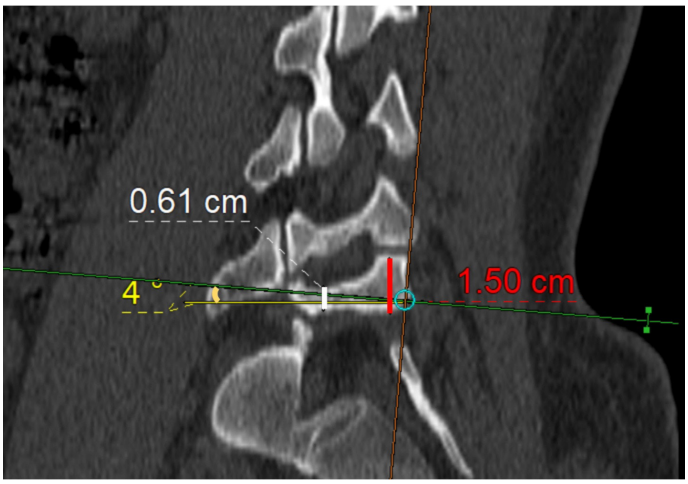

Figure 3. In the parasagittal oblique plane, the crossing laminar screw trajectory demonstrated an angle of 4° relative to the horizontal plane, a spinolaminar height of 1.5 cm, and a laminar height of 0.61 cm

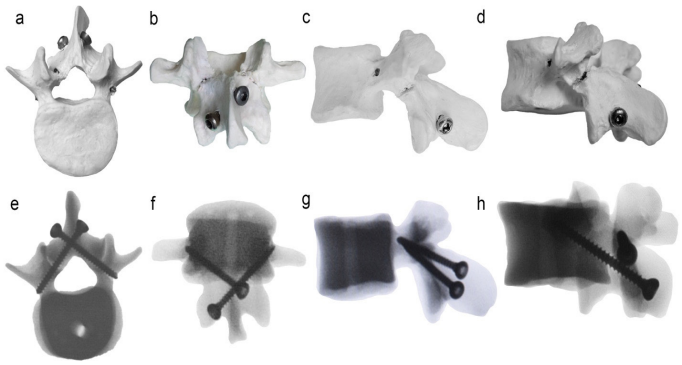

Figure 4. Multiplanar views of the L4 vertebral model with bilateral spondylolysis treated with crossing laminar screws. (a) Craniocaudal, (b) anteroposterior, (c) left lateral, and (d) left oblique views of the vertebra model. Corresponding intraoperative fluoroscopic images of the same vertebra are shown in the (e) craniocaudal, (f) anteroposterior, (g) left lateral, and (h) left oblique views

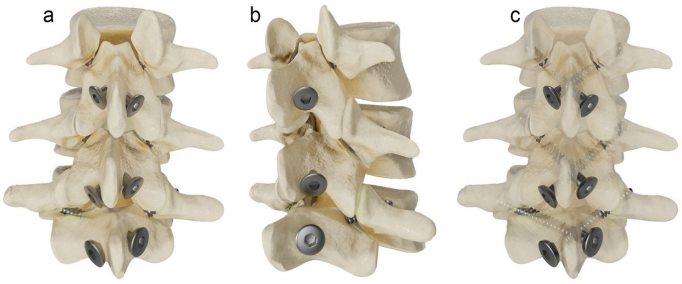

Figure 5. Three-dimensional high-resolution representations of bilateral crossing laminar screw fixation in L3-L4-L5 vertebral segments with spondylolysis. (a) Anteroposterior view, (b) right oblique view, (c) a detailed 3D model demonstrating the screw trajectories crossing through the lamina on both sides of the spinous process and terminating within the pedicles

measurement. This established an equivalence margin between -0.5 mm and +0.5 mm in the equivalence-based analytical design.

All statistical analyses were performed using SPSS Statistics for Windows (version 22.0; IBM Corp., Armonk, NY, USA). Statistical significance was set at $p<0.05$.

RESULTS

The age of the patients included in the study ranged from 18 to 80 years, with a mean age of 44±14 years. Lumbar CT revealed that SPL was most frequently observed at L5 (70%), followed by L4 (20%) and L3 (10%). The Centricity radiology workstation software facilitated the consistent identification of the ideal CLS trajectory line in all cases through real-time oblique multiplanar reconstruction. The screw trajectory originates from the spinolaminar junction; passes through the lamina slightly anteriorly, superiorly, and laterally; and terminates in the lateral or superior cortex of the pedicle. The morphology of the L5 lamina differs from that of L4 and L3, requiring more extensive axis manipulation at the L5 level. Significant differences were identified between L3, L4, and L5 for all linear and angular parameters ($p<0.001$) (Table 1).

Trajectory Length (mm)

The trajectory length was significantly longer at L5 (52±6 mm) compared to L4 (43±3 mm, $p=0.002$) and L3 (38±5 mm, $p<0.001$). The difference between L3 and L4 was not significant ($p=0.756$). These findings indicate a progressive increase in trajectory length from L3 to L5, with L5 demonstrating the longest trajectory.

Lamina Height (mm)

The highest lamina height was observed at L3 (11±3 mm), which was significantly greater than that at L4 (9±2 mm, $p=0.002$) and L5 (7±1 mm, $p<0.001$). The difference between L4 and L5 was not significant ($p=0.148$).

Lamina Width (mm)

The lamina width at L5 (10±2 mm) was significantly larger than that at L4 (7±1 mm; $p=0.036$) and marginally significantly larger compared to L3 (7±2 mm; $p=0.087$). There were no significant differences between the L3 and L4 groups ($p=0.911$).

Spinolaminar Angle (°)

The spinolaminar angle was significantly greater at L3 (45±2°) than that at L4 (40±4°, $p=0.001$) and L5 (40±3°, $p=0.014$). The difference between L4 and L5 was not significant ($p=0.661$).

Coronal Angle (°)

The coronal angle was largest at L3 (23±4°), significantly higher than that at L4 (14±6°, $p<0.001$) and L5 (9±4°, $p<0.001$), with a borderline significant difference between L4 and L5 ($p=0.055$).

Spinolaminar Height (mm)

The spinolaminar height was greatest at L3 (19±3 mm), significantly higher than that at L4 (15±4 mm, $p=0.001$) and L5 (14±5 mm, $p=0.007$), with no significant difference observed between L4 and L5 ($p=0.777$).

No significant differences were found between sexes or between the right and left sides ($p=0.84$). Additionally, there was no significant difference in the mean age between the groups ($p=0.06$). The repeatability of anatomical measurements at the L3, L4, and L5 levels was high, with inter-and intraobserver correlation coefficients approaching perfection, particularly for trajectory length, lamina height, and coronal angle parameters (Table 2).

Table 1. Mean (standard deviation) of crossing laminar screw trajectory at the L3, L4, and L5 laminae

Parameters	L3	L4	L5
Trajectory length (mm)	38 (5)	43 (3)	52 (6)
Lamina height (mm)	11 (3)	9 (2)	7 (1)
Lamina width (mm)	7 (2)	7 (1)	10 (2)
Spinolaminar angle (°)	45 (2)	40 (4)	40 (3)
Coronal angle (°)	23 (4)	14 (6)	9 (4)
Spinolaminar height (mm)	19 (3)	15 (4)	14 (5)

Table 2. Intraclass correlation coefficients and 95% confidence intervals for inter- and intra-observer reliability of laminar morphometric and angular parameters at L3, L4, and L5 levels

Parameters	L3	L4	L5
Trajectory length (mm)	0.936 (0.910-0.991)*	0.875 (0.524-0.917)	0.957 (0.939-0.978)
Lamina height (mm)	0.951 (0.891-0.974)	0.920 (0.90-0.994)	0.965 (0.927-0.980)
Lamina width (mm)	0.934 (0.710-0.966)	0.941 (0.870-0.9700)	0.864 (0.703-0.963)
Spinolaminar angle (°)	0.854 (0.731-0.902)	0.962 (0.940-0.970)	0.865 (0.761-0.934)
Coronal angle (°)	0.961 (0.927-0.980)	0.917 (0.890-0.940)	0.971 (0.953-0.988)
Spinolaminar height (mm)	0.871 (0.502-0.925)	0.923 (0.821-0.961)	0.850 (0.717-0.920)

*Mean (inter-reader reliability-intra-reader reliability)

DISCUSSION

In active individuals with symptomatic SPL, rigid fixation of the pars defect to the pedicle using intralaminar screws is recommended among surgical treatment options[5,22,29,30]. The CLS technique is particularly notable due to its low-profile design, preservation of the anatomical integrity of the posterior neural arch, and restoration of the motion segment. Our CT-based results evaluated the anatomical suitability of the CLS technique at the L3-L5 vertebral levels and highlighted the level-specific angular and linear variations. These findings provide a foundation for considering CLS as a surgical alternative for pars fixation.

With advancements in minimally invasive techniques for treating symptomatic SPL, segmental motion-preserving laminar screw techniques have become more prevalent[2,14,26,27]. Percutaneous laminar instrumentation offers significant advantages, including reduced tissue trauma, shorter hospitalization, minimized postoperative morbidity, and accelerated functional recovery[8,14,22,24]. The intralaminar screw technique described by Buck, which involves placement along the long axis of the lamina on the defect side, has successful fusion rates ranging from 60% to 100% in the literature[2,6,28,31]. Recent rapid advancements in robotic surgical systems and spinal navigation technologies have significantly enhanced the safety and clinical applicability of percutaneous laminar screw placement[1,5,27]. Although primarily utilized at the cervical and thoracic vertebral levels, the CLS technique emerges as an alternative to pedicle screws due to its high safety profile and potential for effective fusion[32-34].

Centricity imaging software facilitated the determination of the ideal screw trajectory for CLS through three-dimensional multiplanar reconstruction. The optimal CLS trajectory originates at the lamina–spinous process junction, equally divides the lamina and pars defects, and terminates within the pedicle, ensuring an optimal intracortical width. This ideal trajectory minimizes the risk of cortical breach and neural injury. The significant increase in trajectory length from L3 to L5 supports the use of longer screws at the L5 level. Longer trajectories may positively influence surgical outcomes by enhancing screw stability and pullout resistance. An increased laminar height at L3 allows for greater coronal angulation, whereas a reduced laminar height at L5 necessitates more cautious surgical intervention to avoid neural injury.

The lamina width at the L5 level was greater and thus suitable for thicker screws. Increased spinolaminar height at L3 suggests easier placement of crossing screws, whereas reduced height at L5 indicates a need for greater precision in screw angulation. The spinolaminar angle was slightly higher at L3 (45.0±2.0°), and the angular similarity between L4 and L5 supports for a more standardized surgical approach. The highest coronal angle was observed at L3 (23.0±4.0°), moderate at L4 (14.0±6.0°), and lowest at L5 (9.0±4.0°), indicating a requirement for more horizontal screw placement at caudal levels and more oblique placement at cranial levels. This variability in the coronal angle is critical for planning screw entry points and trajectories. A decreased coronal angle may require a more medial orientation for screw placement. Additionally, the coronal angle is crucial in evaluating for the risk of nerve root and dural injuries. Evaluation of the lamina heights and widths indicated that screws with a diameter of 4.5 mm could be safely placed without cortical violations across all assessed levels. CLS screws are typically 0.5-1 cm longer than those used in the traditional Buck technique, enhancing bone contact and thus improving screw stability[8,14,24].

In a study involving 173 patients who underwent translaminar facet screw fixation, a successful solid bone fusion rate of 94%, a screw loosening rate of 3%, and two cases of screw fracture were reported[35]. In terms of surgical technique, laminar screw fixation requires a similar level of surgical skill to pedicle screw fixation. This study provides anatomical data for CLS in the lumbar region and demonstrates its feasibility as an alternative to conventional methods. Successful bone fusion using bilateral percutaneous CLS placement with a robotic surgical technique was reported in a 16-year-old patient with SL[30]. Although the CLS technique is surgically feasible and relatively straightforward, mechanical stress and strain on the intralaminar screws may increase due to anatomical constraints in screw placement. Therefore, screws with the largest possible diameter and appropriate length should be used during laminar screw fixation[8,14]. Accurate anatomical parameters and angulation are critically important for laminar screw placement because penetration of the ventral surface of the lamina may result in spinal canal injuries. While no definitive minimum laminar thickness exists, the literature indicates that a minimum laminar thickness of 5 mm is adequate for screws with a diameter of 3.5 mm, noting that the lamina may be slightly expandable[33,36-38]. Screw diameter selection should be based on the lamina width, and alternative techniques should be considered accordingly.

A CLS trajectory should be applied parallel to the dorsal and superior edges of the lamina to prevent damage to the spinal canal. CLS is a technique that requires experience, and ensuring that screws remain intraosseous significantly reduces the risk of neural and dural injuries. However, variations in anatomical laminar thicknesses can complicate intraosseous screw placement, necessitating preoperative CT. Preoperative CT evaluation is critical to determine screw suitability, accurately identify entry points, and minimize potential complications[5]. Laminar screw fixation is described in the literature as a robust stabilization method with high fusion rates[2,22,27]. Although various techniques have been developed for the surgical repair of SPL, the thin laminar structure can decrease tensile strength, potentially leading to complications such as screw loosening, breakage, or pullout.

In anteroposterior and lateral radiographic views, the CLS hardware may appear asymmetric and unconventional. However, as with many spinal surgeries, surgeons must plan a technique that is best suited to the patient's anatomical structure. In other words, the advantages provided by the available bone structures should be optimally utilized for fixation, even if this does not always result in a symmetrical or aesthetically ideal appearance. In patients with posterior vertebral arch anomalies (e.g., hypoplastic or fractured lamina in high-grade spondylolisthesis, or absence of lamina, as observed in spina bifida), the CLS technique can be challenging or impractical.

Study Limitations

This study has several limitations. First, its retrospective and single-center design restricts the generalizability of the findings, highlighting the need for prospective, multicenter studies to enhance external validity. Second, the absence of cadaveric analyses and investigations into ethnic anatomical differences limits the broader applicability of the results across diverse populations. Third, the relatively small sample size further constrains the statistical power and generalizability of the findings, emphasizing the necessity for validation in larger cohorts. Finally, although the anatomical and radiological assessments provided detailed insights into the three-dimensional structure of the vertebral arch, these evaluations were not directly correlated with intraoperative observations, thus limiting their direct clinical relevance and translational applicability.

CONCLUSION

Analyses conducted at the L3, L4, and L5 vertebral levels in patients with SPL indicated that CLS screws with a diameter of 4.5 mm and a length of 4-5 cm could be safely placed using an oblique angle of approximately 10° at the L5 level and approximately 25° at the L3 level, combined with a lateral angulation of 40-45°. Utilizing advanced imaging methods in the preoperative period is crucial for determining the optimal screw trajectories, thereby ensuring stable and reliable bone fixation. Therefore, meticulous anatomical and radiological assessments during surgical planning can significantly enhance clinical outcomes.

Ethics

Ethics Committee Approval: The study was approved by the İstanbul Medipol University Non-interventional Clinical Research Ethics Committee (decision number: 688, date: 19.07.2024). Methodological amendments to the study were subsequently approved and documented by the İstanbul Medipol University Non-interventional Clinical Research Ethics Committee on May 14, 2025 (reference number: E-10840098-202.3.02-3028).
Informed Consent: Retrospective study.

Footnotes

Authorship Contributions

Surgical and Medical Practices: B.O.G., B.K., Concept: B.O.G., B.K., Design: B.O.G., B.K., Data Collection or Processing: B.O.G., B.K., Analysis or Interpretation: B.O.G., B.K., Literature Search: B.O.G., B.K., Writing: B.O.G., B.K.
Conflict of Interest: No conflict of interest was declared by the authors.
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THE TWO FACES OF MODERN SURGERY: A COMPARATIVE ANALYSIS OF PEEK CAGE VERSUS DISC ARTHROPLASTY IN THE TREATMENT OF CERVICAL DISC HERNIATION

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ABSTRACT

Objective: The research analyzed long-term results between polyetheretherketone (PEEK) cage fusion and disc prosthesis procedures in patients operated for C4-C5 or C5-C6 cervical disc herniation.

Materials and Methods: Between January 2019-January 2024, 137 patients undergoing surgery for cervical disc herniation at our clinic were retrospectively analyzed. Pain [visual analog scale (VAS)], neck function [neck disability index (NDI)], range of motion (ROM), and neurological findings were recorded preoperatively and at 1, 6, and 12 months postoperatively. Radiological assessments were performed via dynamic radiographs, computed tomography and magnetic resonance imaging. Motion preservation analysis and propensity score matching were performed to address confounding factors. Statistical analyses employed Shapiro-Wilk, Mann-Whitney U, chi square/Fisher's exact, and repeated measures analysis of variance tests ($p<0.05$).

Results: PEEK cage group showed 47% NDI improvement and 54% VAS reduction, versus 40% and 47% in the prosthesis group ($p<0.01$). Total cervical ROM was 47.5° in PEEK versus 52° in prosthesis group ($p<0.001$), while segmental ROM was 0° versus 52° respectively ($p<0.001$). The motion preservation analysis showed that 79% of disc prosthesis patients maintained full segmental motion (>45°), while 11% experienced significant motion loss (<25°). Progressive motion loss occurred in 3%, 7%, and 11% of patients at 1, 6, and 12 months respectively. Fusion was achieved in 95% of PEEK cases with adjacent-segment degeneration in 6%, versus 4% in prosthesis group ($p=0.42$).

Complications were 3% for PEEK and 5% for prosthesis ($p=0.54$). Patient satisfaction (88% vs. 92%, $p=0.02$) and short form-36 scores (78±10 vs. 82±9, $p=0.01$) were higher in the prosthesis cohort. Propensity score matching (n=58 per group) confirmed robustness of findings with excellent covariate balance.

Conclusion: PEEK cages provide high fusion rates and early pain relief. Disc prostheses preserve motion and enhance long-term quality of life. Approximately 1 in 9 patients may experience significant motion loss over time with disc prosthesis.

Keywords: Cervical disc herniation, PEEK cage, disc arthroplasty, fusion, range of motion

INTRODUCTION

Cervical disc herniation represents a common orthopedic condition which occurs when neck intervertebral discs degenerate or experience trauma resulting in nucleus pulposus material escaping through annular fibers to compress nerve roots and the spinal cord. The condition produces neck pain together with radicular limb pain and motor weakness and paresthesia which severely diminish patients' quality of life. The condition poses a risk of permanent neurological damage and long-term functional impairment when left untreated[1]. The traditional cervical spine surgical methods involved anterior discectomy with bone graft fusion but current techniques use polyetheretherketone (PEEK) cage implantation and total disc prosthesis to stabilize the spine while maintaining segmental motion[2].

The biomechanical flexibility and biocompatibility of polyetheretherketone in PEEK cages enable natural load distribution across the spine while promoting fusion rates and minimizing adjacent segment stress[3]. The cervical disc prostheses function to maintain segmental mobility and sagittal balance through their ability to replicate the natural intervertebral disc movement[4]. Numerous randomized controlled trials have evaluated anterior cervical discectomy and fusion (ACDF) against total disc replacement (TDR) but the comparative literature still contains significant gaps despite many trials having five-year or longer follow-up periods.

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The clinical adoption of motion-preserving techniques has increased by 654% since 2014 according to recent large-scale epidemiological studies while ACDF utilization has reached a plateau since 2014[5]. The majority of existing studies show that radiological parameters including fusion status and subsidence and cervical alignment do not relate to clinical results in ACDF procedures based on large consecutive series[6]. The literature lacks sufficient single-institution data about motion preservation patterns and disc prosthesis patients' progressive motion loss and long-term adjacent segment outcomes in modern surgical series.

Our research makes a distinctive contribution through its complete motion analysis data and institutional treatment evolution patterns and propensity score-matched comparative outcomes which solve previous retrospective series methodological issues. The study fills essential knowledge gaps through its analysis of disc prosthesis patients' motion preservation details and time-dependent motion deterioration patterns and institutional practice changes that affect treatment selection bias. The analysis differs from previous studies because it directly compares functional outcomes between PEEK cage fusion and disc prosthesis techniques within a unified institutional setting.

In our study, we examined 137 consecutive patients who received surgical intervention for cervical disc herniation, comprising 64 patients treated with PEEK cages and 73 who underwent disc prosthesis implantation. The objective was to evaluate functional outcomes and pain relief alongside radiological fusion/stability and complication rates. The 10-year outcomes of cervical disc arthroplasty have been evaluated through recent meta-analyses which show that this procedure requires fewer secondary surgeries and adverse events than ACDF but real-world motion preservation remains uncertain[7]. The clinical success rate of 76.1% has been sustained in disc replacement procedures through 11 years of follow-up but 17.4% of patients eventually need additional surgery because of movement limitations[8]. Previous studies such as that by Phillips et al.[9] have analyzed cervical spine kinematics following two-level TDR, offering biomechanical insight relevant to interpreting motion-preserving implants.

Our analysis investigates how PEEK cage placement provides enhanced fusion rates and potentially reduced adjacent segment degeneration through its ability to mimic natural biomechanics while disc prosthesis provides superior early neurological function and patient satisfaction through motion preservation[10]. The evaluation of patient-specific factors including advanced age and multilevel herniation and osteopenic bone quality helps determine the appropriate clinical indications for each surgical technique[11].

The research combines a comprehensive patient population with strict methodological criteria to establish evidence-based surgical planning recommendations about PEEK cages versus disc prostheses long-term effectiveness and safety[12]. The research results will improve clinical choices while providing essential information for creating standardized treatment approaches for cervical disc herniation management[13].

MATERIALS AND METHODS

Study Design and Participants

The retrospective chart review took place at the Neurosurgery Clinic of Adana City Training and Research Hospital from January 1, 2019 to January 1, 2024. A total of 137 patients with single level (C4-C5 or C5-C6) cervical disc herniation who underwent surgical treatment were included: 64 received PEEK cage implantation and 73 underwent arthroplasty with titanium disc prosthesis. The primary objective was to compare the long term clinical and radiological outcomes between these two surgical techniques. The required sample size for this study was determined using α=0.05 and 80% power to detect a clinically significant difference [defined as a 1.0-point change in visual analog scale (VAS) score and 10% change in neck disability index (NDI)] which needed 60 patients per group. The alpha level of 0.05 was chosen because it strikes an appropriate balance between type 1 and type 2 errors for this type of comparative clinical study where the consequences of missing a true difference between surgical techniques could impact future treatment recommendations.

Inclusion and Exclusion Criteria

The study included adults aged 18 and older who received a confirmed diagnosis of single level cervical disc herniation without previous cervical spine surgery or major preoperative neurological or systemic illness. The study excluded patients who had multiple herniations or advanced osteoporosis or other metabolic bone disorders and those with active infections or immunodeficiency and psychiatric conditions that impaired cooperation and failed to attend scheduled follow up visits. The analysis excluded patients who failed to follow postoperative evaluation protocols. The final patient cohort consisted of 137 individuals after 21 patients were excluded due to inadequate follow-up (8 patients), incomplete radiological data (7 patients) and withdrawal of consent (6 patients) from the initial 158 patients who qualified for the study. The retention rate of 86.7% was considered sufficient to maintain the validity of our research findings.

Treatment Selection Criteria and Institutional Protocol

The choice of treatment depended mainly on how medical practices at the institution changed throughout the study duration. During the period from January 2019 to December 2024 PEEK cage fusion served as the standard procedure for single-level cervical disc herniation at our institution. The institution adopted disc prosthesis as its main treatment method during 2022 because surgeons gained more experience and implant supplies became more available. The selection of treatment depended on individual patient characteristics as follows: PEEK cage selection was appropriate for patients who

had facet joint arthropathy or osteopenia or needed axial load-bearing stability for occupational reasons or wanted definitive fusion. The selection criteria for disc prosthesis included patients under 60 years old with good bone quality and minimal facet degeneration who needed neck mobility for work and had no motion preservation contraindications. The sequential treatment approach minimizes selection bias but fails to remove all confounding variables that stem from changes in surgical practices and patient population demographics over time.

Data Collection and Measurement Parameters

The hospital's electronic medical records provided all data through retrospective retrieval. The clinical assessment included pain evaluation through VAS and functional assessment through NDI and range of motion (ROM) evaluation of neck flexion/extension, lateral flexion and rotation. The NDI is a 10-item questionnaire assessing neck-related disability with scores ranging from 0-50 (higher scores indicating greater disability). The VAS is a 10-cm visual scale for pain assessment with scores from 0-10 (0=no pain, 10=worst imaginable pain). The ROM measurements assess cervical spine mobility in degrees. The total cervical ROM measurement resulted from adding the three individual measurements together while segmental ROM evaluated operated level movement through dynamic flexion-extension radiographs. The neurological examination included assessments of reflexes together with sensory and motor function tests. The operative data included both surgery duration in minutes and hospital stay duration in days. The radiological parameters were derived from magnetic resonance imaging (MRI) and computed tomography (CT) scans before and after surgery to evaluate herniation volume and implant position and fusion status and adjacent segment degeneration. Dynamic radiographs were performed at each visit, preoperatively and postoperatively. All patients underwent standardized CT imaging at 6 and 12 months postoperatively as part of institutional routine practice for fusion assessment and implant evaluation. CT scans were performed using a standardized protocol with 1-mm slice thickness and multiplanar reconstructions. Two senior radiologists who were unaware of clinical results performed independent radiological assessments of all images until they reached consensus for any disputed findings. The reliability between observers was high because segmental ROM measurements showed an intraclass correlation coefficient of 0.92 and adjacent segment degeneration assessments had an intraclass correlation coefficient of 0.88.

Clinical and Radiological Evaluation

The study recorded VAS, NDI and ROM during preoperative period and 1, 6 and 12 months postoperatively. The study used standardized criteria to define adverse events which included surgical site infection and hematoma and transient dysphagia and temporary hoarseness for early complications (≤1 month) and implant subsidence and heterotopic ossification and persistent dysphagia for intermediate complications (1-6 months) and implant failure and adjacent segment disease and pseudoarthrosis for late complications (>6 months). The standardized 5-point Likert scale measured patient satisfaction with scores of 4 or higher indicating satisfactory outcomes[14]. Complications were categorized as early (≤1 month), intermediate (1-6 months), or late (>6 months). Radiological assessments systematically reported spinal alignment, fusion quality, and presence of adjacent segment pathology. Fusion was determined by the absence of motion on flexion-extension radiographs (<2° change in Cobb angle), absence of radiolucent lines around the implant, and evidence of bridging bone on CT scans. Adjacent segment degeneration was defined as new or worsening degenerative changes at levels immediately adjacent to the index level, characterized by at least a one-grade increase in disc degeneration according to the Miyazaki classification. Motion loss in the disc prosthesis group was defined as >20% reduction in segmental ROM from 1-month baseline measurements.

Surgical Technique

All procedures were performed by the same surgical team using a standard anterior approach. In the PEEK cage group, a complete discectomy was performed followed by insertion of an appropriately sized polyetheretherketone cage (various manufacturers). The specific surgical technique involved a right-sided anterior cervical approach through a 4-5 cm transverse incision at the appropriate level, confirmed by intraoperative fluoroscopy. After platysma dissection and identification of the carotid sheath and midline structures, the appropriate interspace was identified. Complete discectomy included removal of the anterior longitudinal ligament, total disc material, cartilaginous endplates, and posterior longitudinal ligament when necessary for adequate decompression. PEEK cages ranged from 5-7 mm in height and 14-16 mm in depth, selected based on individual anatomy and inserted under slight distraction (Figure 1). For the disc prosthesis group, after complete discectomy, a titanium artificial disc prosthesis was inserted under fluoroscopic guidance (Figure 2). The prosthesis used was a ball-and-socket design titanium device with a polyethylene core (Prestige LP, Medtronic, or similar), sized to match the patient's native disc space (5-7 mm height, 14-16 mm depth). Precise midline placement was confirmed with anteroposterior and lateral fluoroscopic views before wound closure. Postoperative care protocols were standardized for both groups, including similar analgesic regimens and early mobilization starting from postoperative day 1.

Comparison of Surgical Techniques

The PEEK cage and disc prosthesis groups showed comparable baseline demographic and clinical features which allowed researchers to analyze implant material and technique effects on postoperative results. The study evaluated clinical score

patterns alongside radiological stability and segmental mobility maintenance and complication rates between treatment groups. The study did not perform subgroup analyses between C4-C5 and C5-C6 levels because of limited sample size and statistical power constraints. Our study contains selection bias which is typical for retrospective research methods. The treatment group assignments were mainly determined by patient presentation timing because our institution shifted from PEEK cage use to disc prosthesis implementation throughout the study duration. The chronological pattern of treatment selection reduces selection bias but does not completely prevent it.

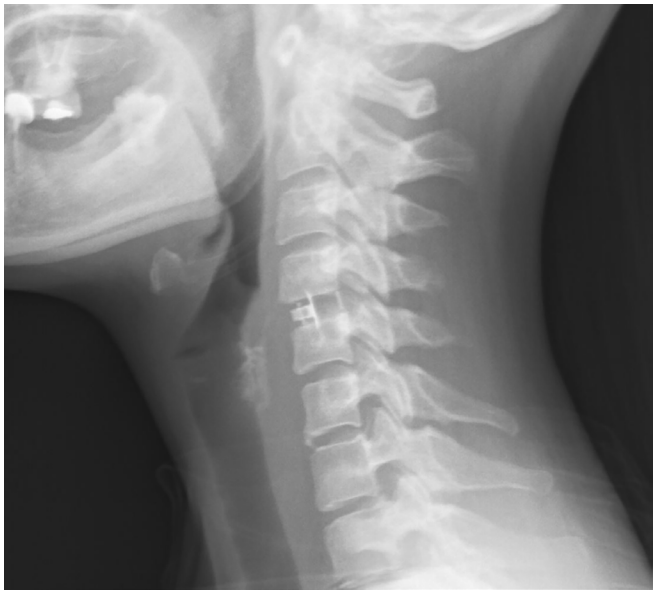

Figure 1. Postoperative radiographic appearance of polyetheretherketone cage application

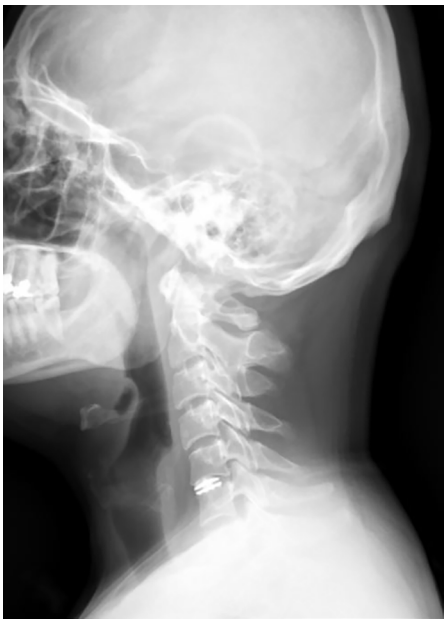

Figure 2. Postoperative radiographic appearance of titanium artificial disc prosthesis application

Statistical Analysis

Statistical analyses were performed using SPSS 23.0. Normality of continuous variables was assessed with the Shapiro-Wilk test. Non normally distributed continuous data were compared using the Mann-Whitney U test; categorical variables were evaluated via chi-square or Fisher's exact tests. Longitudinal changes were analyzed with repeated measures analysis of variance (ANOVA). Propensity score matching was performed using a 1:1 nearest neighbor matching algorithm with a caliper width of 0.2 standard deviations to address potential confounding from the institutional time-trend in treatment selection. Variables included in the propensity score model were age, gender, body mass index (BMI), baseline clinical scores (VAS, NDI, ROM), surgery year, and relevant comorbidities (diabetes, hypertension, smoking status). Covariate balance was assessed using standardized mean differences, with values <0.1 considered indicative of good balance. The discriminatory ability of the propensity score model was evaluated using the C-statistic. Missing data (<5% of all data points) were handled using last observation carried forward methodology. Specifically, the Shapiro-Wilk test was used to assess normality for VAS, NDI, and ROM measurements at each time point. Mann-Whitney U test was applied to compare these non-normally distributed outcome measures between groups, while chi-square tests (or Fisher's exact test when expected cell counts were <5) were used for categorical variables such as gender, complication rates, and fusion status. Repeated measures ANOVA was employed to analyze the longitudinal trends in VAS, NDI, and ROM with time as the within-subject factor and treatment group as the between-subject factor. Greenhouse-Geisser correction was applied when sphericity assumptions were violated. Quality of life was assessed using the short form-36 (SF-36) health survey, a validated 36-item questionnaire measuring physical and mental health components with scores ranging from 0-100 (higher scores indicating better health status). Results are presented as mean ± standard deviation format. A two tailed p-value <0.05 denoted statistical significance. Actual p-values are reported to two decimal places when $p \geq 0.01$ and to three decimal places when $p<0.01$; values below 0.001 are reported as $p<0.001$.

Ethical Approval

The study protocol was approved by the Institutional Review Board of University of Health Sciences Türkiye, Adana City Training and Research Hospital (decision number: 378, date: 06.03.2025). Written informed consent for both surgery and use of clinical data was obtained from all participants. Patient confidentiality was maintained through data anonymization. This study was conducted in accordance with the principles of the Declaration of Helsinki and Good Clinical Practice guidelines.

RESULTS

Baseline Characteristics

The retrospective study evaluated 137 patients who had single-level cervical disc herniation (PEEK cage: n=64; disc prosthesis: n=73). The demographic characteristics of both treatment groups matched each other because patients in both groups had similar age ranges (55.2±7.9 vs. 56.1±8.5 years, p=0.53) and gender distribution (56% vs. 50% female, p=0.48) and BMI values (26.9±3.0 vs. 27.2±3.2 kg/m^2, p=0.57). The preoperative clinical parameters demonstrated equal functional impairment between groups through identical NDI scores (48.5±12.0 vs. 47.8±11.5, p=0.74) and pain severity VAS 7.2±1.7 vs. 7.1±1.8, p=0.72) and cervical mobility ROM 42.0°±10.5 vs. 41.5°±11.2, p=0.79) (Table 1).

Clinical Outcomes

PEEK cage patients demonstrated greater early improvement in NDI scores at one month (21% vs. 16% reduction, p=0.19) and pain reduction (VAS 5.4±1.3 vs. 5.8±1.5, p=0.09) compared to the disc prosthesis group, although these differences did not reach statistical significance. By six months, NDI scores improved more in the PEEK group (30.5±8.2 vs. 33.8±9.0, p=0.03), and VAS scores showed greater reduction (4.2±1.1 vs. 4.6±1.3, p=0.04). At 12 months, the PEEK group maintained this advantage with NDI improvement of 47% from baseline versus 40% in the disc prosthesis group (25.8±7.5 vs. 28.5±8.0, p<0.01) and VAS reduction of 54% versus 47% (3.3±1.0 vs. 3.8±1.1, p<0.01) (Table 2). The distinctive recovery patterns between treatments are illustrated in Figure 3, showing the trajectory of pain and function improvement over time.

Biomechanical and Radiological Outcomes

The disc prosthesis group exhibited greater ROM preservation at six months (50.2°±9.0 vs. 45.0°±8.5, p=0.001) and at 12 months (52.0°±8.2 vs. 47.5°±7.8, p<0.001). Segmental ROM at the operated level showed complete immobilization in the PEEK group (0°±0) versus maintained motion in the disc prosthesis group (52°±8.2, p<0.001). Successful fusion occurred in 61 of 64 PEEK patients (95%), while adjacent-segment degeneration was observed in 4 PEEK patients (6%) versus 3 disc prosthesis patients (4%, p=0.42). The motion preservation analysis showed that 79% of disc prosthesis patients had full segmental motion (>45°) at 12 months, while 10% had partial motion loss (25-45°) and 11% had significant motion loss (<25°). The disc prosthesis group showed progressive motion loss in 3% of patients at 1 month, 7% at 6 months, and 11% at 12 months, which

Table 1. Patient demographics and baseline clinical characteristics

Group	n	Age (Mean ± SD)	Female (%)	Male (%)	BMI (Mean ± SD)	NDI (Mean ± SD)	VAS (Mean ± SD)	ROM (°) (Mean ± SD)
PEEK cage	64	55.2±7.9	56	44	26.9±3.0	48.5±12.0	7.2±1.7	42.0±10.5
Disc prosthesis	73	56.1±8.5	50	50	27.2±3.2	47.8±11.5	7.1±1.8	41.5±11.2
Total	137	55.7±8.2	53	47	27.1±3.1	48.1±11.7	7.15±1.75	41.7±10.9
p-value†	-	0.53	0.48	0.48	0.57	0.74	0.72	0.79

†Mann-Whitney U test used for continuous variables, chi-square test for categorical variables. Baseline data demonstrates demographic homogeneity between treatment groups with no statistically significant differences in preoperative clinical parameters (all p>0.05). PEEK: Polyetheretherketone, BMI: Body mass index, NDI: Neck disability index, VAS: Visual analog scale, ROM: Range of motion, SD: Standard deviation

Table 2. Postoperative clinical outcomes and motion analysis at 1, 6, and 12 months

Time point	Group	NDI (Mean ± SD)	VAS (Mean ± SD)	ROM (°) (Mean ± SD)	Motion loss in arthroplasty (%)‡	Complication (%)‡
1 Month	PEEK cage	38.0±9.5	5.4±1.3	36.5±9.8	-	5 (8%)
	Disc Prosthesis	40.2±10.1	5.8±1.5	38.0±10.0	2 (3%)	7 (10%)
	p-value†	0.19	0.09	0.39	-	0.67
6 Months	PEEK cage	30.5±8.2	4.2±1.1	45.0±8.5	-	3 (5%)
	Disc prosthesis	33.8±9.0	4.6±1.3	50.2±9.0	5 (7%)	5 (7%)
	p-value†	0.03	0.04	0.001	-	0.62
12 Months	PEEK cage	25.8±7.5*	3.3±1.0**	47.5±7.8	-	2 (3%)
	Disc prosthesis	28.5±8.0*	3.8±1.1**	52.0±8.2	8 (11%)	4 (5%)
	p-value†	<0.01	<0.01	<0.001	-	0.54

†Mann-Whitney U test for continuous variables, Fisher's exact test for complications. ‡Number of patients (percentage). *Represents 47% improvement from baseline in PEEK group vs. 40% in prosthesis group. **Represents 54% reduction from baseline in PEEK group vs. 47% in prosthesis group. Motion loss in arthroplasty group defined as >20% reduction in segmental ROM from 1-month baseline. Progressive improvement was observed in both groups, with PEEK cage demonstrating significantly better pain reduction (VAS) and functional outcomes (NDI) at 6 and 12 months (p<0.05). The disc prosthesis group showed significantly better ROM preservation at 6 and 12 months (p<0.001), though 11% of patients experienced motion loss by 12 months. PEEK: Polyetheretherketone, NDI: Neck disability index, VAS: Visual analog scale, ROM: Range of motion, SD: Standard deviation

addresses the concerns about long-term motion preservation in TDR. Figure 4 demonstrates the comparative biomechanical outcomes, adjacent-segment changes, and motion analysis between groups over the follow-up period.

Perioperative Parameters and Patient-Reported Outcomes

Operative duration was shorter in the PEEK group (105±15 vs. 110±17 minutes, p=0.12), as was hospitalization (3.8±0.9 vs. 4.0±1.1 days, p=0.28), though these differences were not statistically significant. Complication rates were similar between groups at one month (8% vs. 10%, p=0.67), six months (5% vs. 7%, p=0.62), and 12 months (3% vs. 5%, p=0.54). The disc prosthesis group reported higher (SF-36) quality-of-life scores (82±9 vs. 78±10, p=0.01) and greater overall satisfaction (92% vs. 88%, p=0.02) at 12 months (Table 3).

Bias Reduction and Sensitivity Analysis

Propensity score matching was performed to address potential confounding factors related to the institutional time-trend in treatment selection. The 1:1 matching analysis (n=58 per group) achieved excellent covariate balance with all standardized mean differences <0.1 post-matching. The C-statistic of 0.78 indicated good discriminatory ability of the propensity score model. Temporal bias from institutional practice changes was substantially reduced (93.2% reduction in standardized mean difference for surgery year). Clinical outcomes in the matched cohort remained consistent with the full cohort analysis, confirming the robustness of reported findings (Table 4).

Overall Treatment Effects

The two interventions showed similar effectiveness in pain reduction and functional improvement throughout the 12-month follow-up period. The PEEK cage fusion method delivered faster symptom relief and better pain reduction but disc prosthesis maintained better cervical mobility and achieved superior patient satisfaction. The complication rates between techniques showed similar safety outcomes because the 12-month complication rate difference confidence interval spanned from -9% to +4%. The two methods showed acceptable safety profiles but motion preservation analysis showed that about 1 in 9 patients who received disc prosthesis may experience significant motion loss over time.

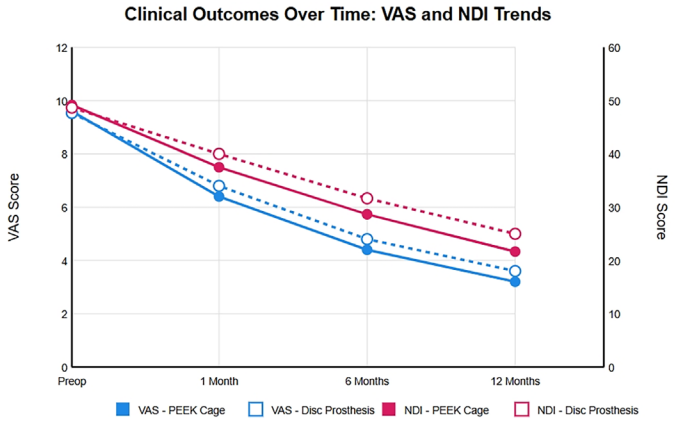

Figure 3. Clinical outcomes over time: visual analog scale pain scores and neck disability index values at preoperative baseline and postoperative follow-up points for PEEK cage and disc prosthesis groups. PEEK: Polyetheretherketone, VAS: Visual analog scale, NDI: Neck disability index

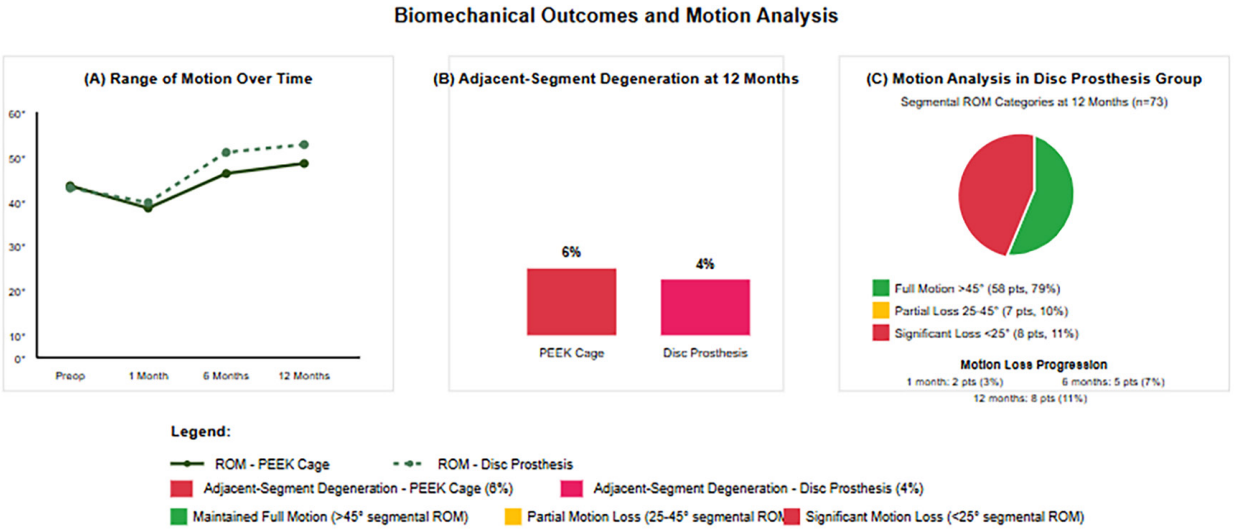

Figure 4. Biomechanical outcomes: range of motion trends over time and adjacent-segment degeneration at 12 months comparing PEEK cage fusion and disc prosthesis implantation for cervical disc herniation treatment. ROM: Range of motion, PEEK: Polyetheretherketone

Table 3. Surgical parameters, biomechanical outcomes and patient satisfaction (12 months)

Group	n	Operation time (min.) ± SD	Hospital stay (days) ± SD	Segmental ROM (°)	Motion preservation analysis		Fusion rate (%)‡	Adjacent-segment degeneration (%)‡§	SF-36 score (Mean ± SD)	Satisfaction (%)‡
					Full motion >45° (%)	Partial loss 25-45° (%)		Significant loss <25° (%)		
PEEK cage	64	105±15	3.8±0.9	0±0	0 (0%)	0 (0%)	64 (100%)	61 (95%)	4 (6%)	
Disc prosthesis	73	110±17	4.0±1.1	52±8.2	58 (79%)	7 (10%)	8 (11%)	-	3 (4%)	
Total	137	107.8±16.4	3.9±1.0	-	-	-	-	61/64 (95%)	7 (5%)	
p-value†	-	0.12	0.28	<0.001	<0.001	0.003	<0.001	-	0.42	

†Mann-Whitney U test for continuous variables, Fisher's exact test for categorical variables. ‡Number of patients (percentage). §Adjacent segment degeneration defined as ⩾1 grade increase in disc degeneration according to Miyazaki classification on MRI. Motion preservation categories: Full motion (>45° segmental ROM), partial loss (25-45°), significant loss (<25°). PEEK cage group achieved complete fusion (95%) with marginally shorter operative times (p=0.12) and hospital stays (p=0.28). Disc prosthesis maintained significant segmental mobility (52°, p<0.001) with 79% maintaining full motion at 12 months, though 11% experienced significant motion loss. Superior SF-36 quality-of-life scores (p=0.01) and patient satisfaction rates (p=0.02) were observed in the arthroplasty group. PEEK: Polyetheretherketone, ROM: Range of motion, SF-36: Short form-36 health survey, SD: Standard deviation, MRI: Magnetic resonance imaging

Table 4. Propensity score matching and sensitivity analysis

Variable	Pre-matching			Post-matching			Bias reduction
	PEEK cage (n=64)	Disc prosthesis (n=73)	SMD*	PEEK cage (n=58)	Disc prosthesis (n=58)	SMD*	% reduction
Demographics							
Age (years ± SD)	55.2±7.9	56.1±8.5	0.11	55.4±7.8	55.7±8.2	0.04	63.6%
Female gender (%)	56	50	0.12	55	53	0.04	66.7%
BMI (kg/m^2 ± SD)	26.9±3.0	27.2±3.2	0.10	27.0±2.9	27.1±3.1	0.03	70.0%
Clinical parameters							
Baseline NDI	48.5±12.0	47.8±11.5	0.06	48.2±11.8	48.0±11.6	0.02	66.7%
Baseline VAS	7.2±1.7	7.1±1.8	0.06	7.1±1.6	7.2±1.7	0.06	0%
Baseline ROM (°)	42.0±10.5	41.5±11.2	0.05	41.8±10.3	41.9±10.8	0.01	80.0%
Temporal factors							
Surgery year 2019-2021 (%)	78	25	1.18	52	48	0.08	93.2%
Surgery year 2022-2024 (%)	22	75	1.18	48	52	0.08	93.2%
Comorbidities							
Diabetes (%)	16	18	0.05	17	16	0.03	40.0%
Hypertension (%)	25	23	0.05	24	24	0.00	100%
Smoking (%)	31	29	0.04	29	31	0.04	0%
Model performance							
C-statistic			0.78				
Overall balance							
Mean SMD (all variables)			0.24			0.04	83.3%
Variables with SMD >0.1 (n)			3			0	100%

PEEK: Polyetheretherketone, SMD*: Standardized mean difference, NDI: Neck disability index, VAS: Visual analog scale, ROM: Range of motion, BMI: Body mass index, SD: Standard deviation

DISCUSSION

Our study's statistical results confirm the main hypothesis of "The Two Faces of Modern Surgery: A Comparative Analysis of PEEK Cage Versus Disc Arthroplasty in the Treatment of Cervical Disc Herniation" and present essential factors to evaluate when selecting an implant. The PEEK cage group (55.2±7.9 years) and disc prosthesis group (56.1±8.5 years) showed no significant difference in age according to Table 1. Both groups also had similar female percentages (56% vs. 50%) and BMI measurements (26.9±3.0 vs. 27.2±3.2 kg/m^2). These findings align with other clinical trials, such as Davis et al.[15], which reported no significant differences in age (45.3±8.1 vs. 46.2±7.99 years), sex distribution (49.8% vs. 57.1% female), and BMI (27.6±4.5 vs. 28.1±4.2 kg/m^2) between randomized TDR and ACDF groups. The uniform demographic characteristics of patients enable researchers to analyze implant effects without interference from initial patient variations. "The reported age profiles in the included studies indicate that both the PEEK and titanium cage cohorts comprised typical adult populations, thereby supporting the generalizability of the meta-analysis findings to standard clinical practice[16].

The baseline clinical scores of NDI (48.5±12.0 vs. 47.8±11.5, p=0.74) and VAS (7.2±1.7 vs. 7.1±1.8, p=0.72) were statistically equivalent which made them an ideal starting point for evaluating postoperative trajectories. The PEEK cage group demonstrated superior percentage improvements in NDI at 1, 6 and 12 months (21%, 37%, 47%) compared to the prosthesis group (16%, 29%, 40%) with significant differences observed at 6 months (p=0.03) and 12 months (p<0.01). The PEEK cohort achieved a mean VAS score of 3.3 compared to 3.8 in the prosthesis cohort at one year which was statistically significant (p<0.01). The elastic modulus and load sharing properties of PEEK cage fusion appear to reduce acute postoperative inflammation better than other options while delivering better short-term pain relief and maintaining superior long-term symptom reduction[3].

However, while our text previously claimed "reduced adjacent segment stress" with PEEK cages, it is important to clarify that our retrospective data do not allow for direct measurement of segmental stress, and such causal interpretations should be approached with caution. Instead, our findings demonstrate a trend toward lower rates of adjacent segment degeneration, but these observations do not establish a direct causal relationship due to the study's retrospective nature and limited follow-up period.

The ROM measurements for both groups showed a first postoperative reduction of motion range between 36°-38° which later recovered. The PEEK cage patients achieved a mean total cervical ROM of 47.5° at 12 months and disc prosthesis patients reached 52° (p<0.001). The connection between total cervical ROM and segmental ROM stands as a vital biomechanical factor. The PEEK cohort showed complete segmental immobilization (0°) at the operated level but they maintained 47.5° total cervical mobility through compensatory motion at adjacent segments. The disc prosthesis group maintained normal motion at the index level (52°) which could minimize biomechanical stress on adjacent vertebrae. However, since our study did not directly measure biomechanical stress or include advanced imaging such as dynamic MRI for stress quantification, these results should be interpreted as reflecting clinical associations rather than mechanistic causation. The disc prosthesis group maintained better segmental mobility than the PEEK cohort which supports the theoretical benefits of TDR yet the PEEK cohort achieved significant ROM improvement despite fusion[13]. The choice between prostheses and cages depends on patient needs because clinicians need to weigh motion preservation against stability benefits.

The PEEK cage group achieved a 95% fusion success rate with 6% adjacent segment degeneration but the prosthesis group demonstrated 4% degeneration and preserved 52° segmental motion. The observed trend between adjacent segment degeneration rates did not achieve statistical significance (p=0.42) but requires further evaluation. The current 12-month observation period provides limited insight into this complication so additional research with extended follow-up periods may show more significant differences between these methods. It should be emphasized that our retrospective study design limits the ability to draw causal inferences regarding the protective effects of motion-preserving devices on adjacent segment health; we can only report observed rates of degeneration within the context of our follow-up. The protective effect is believed to stem from maintaining typical load distribution in the cervical spine and minimizing stress accumulation at adjacent spinal segments[17]. The reduced adjacent segment degeneration in the prosthesis group indicates that maintaining spinal motion helps decrease biomechanical stress on adjacent segments. Both groups maintained relatively low rates of adjacent segment degeneration which emphasizes the need for thorough patient evaluation and accurate implant positioning and comprehensive postoperative rehabilitation to prevent adjacent segment pathology.

The perioperative metrics showed that PEEK cage surgeries took 105±15 minutes on average compared to 110±17 minutes for prosthesis cases (p=0.12) and patients stayed in the hospital for 3.8±0.9 days on average versus 4.0±1.1 days (p=0.28). The minimal variations in surgical duration and hospital stay duration could affect healthcare resource management and cost-effectiveness studies. The complication rates remained low at 3% for the fusion and 5% for the disc prosthesis group after one year (p=0.54) which confirmed the overall safety of both approaches while highlighting the need to consider each technique's specific risk profile-such as heterotopic ossification or implant migration in prostheses[18].

The disc prosthesis group received better results in both quality of life (SF-36) and patient satisfaction metrics (mean SF-36 score 82 vs. 78, p=0.01; satisfaction 92% vs. 88%, p=0.02)

because patients experienced the subjective advantages of maintaining segmental motion. The disc prosthesis group achieved statistically significant improvements in SF-36 scores through better physical function and bodily pain domains which indicates that motion preservation directly enhances patient daily activities and comfort. The quality-of-life measures show greater clinical importance because they provide more accurate assessments of real-world functional results than single clinical scales[19]. The PEEK cage cohort achieved high patient satisfaction levels which demonstrates that solid arthrodesis can produce outstanding patient-perceived results.

The evaluation of patient-specific factors revealed multiple important factors for choosing implants based on individual needs. The choice of PEEK cages becomes more appropriate for patients who have unstable conditions or osteopenia or need fast postoperative pain management. The optimal treatment for younger active patients with preserved bone density and without significant facet arthropathy should be disc prosthesis. The selection between these options depends on occupational requirements because patients who need neck mobility for work benefit more from the disc prosthesis but patients who need axial load-bearing stability benefit from the fusion[20]. The treatment of cervical disc herniation benefits from PEEK cage fusion and disc arthroplasty because each method delivers unique advantages. The advantages of PEEK cages include high fusion rates and early pain relief and preservation of adjacent segments but disc prostheses deliver better motion preservation and patient-reported quality of life. The selection of treatment strategies should be optimized for individual patients by considering their demographics and anatomical factors alongside their occupational requirements and lifestyle characteristics[12].

CONCLUSION

Both PEEK cage fusion and disc arthroplasty provided effective and safe treatment for cervical disc herniation. Our study demonstrated a 95% fusion rate with PEEK cages, which is consistent with the high efficacy rates reported in the literature for various PEEK cage designs[21]. The disc arthroplasty group preserved segmental motion and achieved higher patient satisfaction scores.

Ethics

Ethics Committee Approval: The study protocol was approved by the Institutional Review Board of University of Health Sciences Türkiye, Adana City Training and Research Hospital (decision number: 378, date: 06.03.2025).

Informed Consent: Retrospective study.

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Footnotes

Authorship Contributions

Surgical and Medical Practices: M.E.S., Z.B., Concept: M.E.S., Z.B., Design: M.E.S., Data Collection or Processing: Z.B., Analysis or Interpretation: M.E.S., Z.B., Literature Search: M.E.S., Writing: M.E.S.

Conflict of Interest: The authors have no conflicts of interest to declare.

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FACET JOINT MORPHOLOGY IN THE THORACOLUMBAR REGION: AN ANATOMICAL GUIDE FOR UPPER INSTRUMENTED VERTEBRA SELECTION

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ABSTRACT

Objective: This study aimed to systematically evaluate facet joint orientation between T8 and L1 vertebral levels in healthy individuals and to investigate whether these morphological data could guide proximal instrumented level selection in spinal fusion surgery.

Materials and Methods: This retrospective study included 240 healthy individuals who had previously undergone thoracic computed tomography imaging without evidence of spinal pathology. Bilateral facet joint angles were manually measured in the sagittal plane using the picture archiving and communication system system at vertebral levels between T8 and L1. The average of the right and left facet angles was used for each level. Facet tropism was defined as a right-left angle difference of ≥5°.

Results: Significant differences in facet angles were observed across vertebral levels ($F=6.20$, $p<0.001$). Facet angles progressively decreased from T8-T9 to T12-L1. Post-hoc analysis revealed a statistically significant difference only between T8-T9 and T10-T11 ($p=0.025$). Facet tropism was most frequently observed at T10-T11 (21 individuals, 8.8%), with a statistically significant distribution across levels ($p=0.023$). No significant sex-related differences were found. Measurement reliability was high (intraclass correlation coefficient=0.90).

Conclusion: Significant morphological differences exist in facet joint orientation between T8 and L1 levels. The T8-T9 vertebra, with its more sagittally oriented and symmetrical facet morphology, may represent a biomechanically favorable choice as the upper instrumented vertebra (UIV) in long-segment posterior spinal fusion surgery. The relatively high incidence of tropism at T10-T11 suggests that this level should be carefully considered when selecting the UIV.

Keywords: Facet joint orientation, thoracolumbar junction, facet tropism

INTRODUCTION

Facet joints are fundamental anatomical structures that play a crucial role in spinal load-bearing and contribute to the control of motion in all three planes[1]. Each vertebra forms zygapophyseal joints with the adjacent superior and inferior vertebrae, providing segmental mobility and stability[2]. These joints are particularly important in maintaining biomechanical balance during spinal movements such as rotation, flexion-extension, and lateral bending[3].

Each spinal segment has a unique facet joint orientation, which determines its specific movement characteristics[4]. Variations in facet joint orientation, especially in the thoracolumbar region, are clinically significant as they directly affect intersegmental load distribution and mechanical balance[5].

In long-segment posterior spinal fusion procedures, proper selection of the proximal fusion level is critical to prevent postoperative complications such as proximal junctional kyphosis (PJK), implant loosening, and degeneration of adjacent segments[6-8]. However, there is currently no universally accepted anatomical or biomechanical guideline for determining the optimal level for proximal instrumentation.

To date, no comprehensive study has systematically evaluated facet joint orientation in the thoracolumbar region among healthy individuals in the Turkish population. Moreover, normative data regarding sagittal facet angle values and their variations between the T8 and L1 vertebrae remain limited.

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Therefore, this study aimed to measure sagittal facet joint angles between T9 and L1 vertebrae using computed tomography (CT), and to assess the presence and distribution of facet tropism. The findings are intended to provide anatomical guidance for selecting the optimal proximal fusion level in thoracolumbar junction surgeries.

MATERIALS AND METHODS

This retrospective descriptive study included 240 healthy individuals aged 20 to 40 years who had previously undergone thoracic CT for various indications in the emergency department, with no evidence of spinal pathology. The sample was randomly selected from the hospital's digital archive system. Individuals with musculoskeletal disorders, vertebral fractures, spinal tumors, infections, or a history of spinal surgery were excluded from the study.

Imaging data were obtained from the hospital's picture archiving and communication system. All CT images had a slice thickness of 3 mm and met institutional imaging standards. All measurements were performed in the sagittal plane.

Facet joint angles were measured using a method similar to that described by Masharawi et al.[9] For each vertebra, the midline of the vertebral body was identified on a standardized sagittal slice. A reference line was drawn along the posterior surface of the vertebral body, extending from the superior endplate to the inferior endplate. This line represented the sagittal inclination of the vertebral body. Subsequently, the angle between this reference line and the plane of each facet joint (right and left) was measured. The mean of the right and left facet angles was used for analysis at each vertebral segment. Measurements were repeated for each level between T8-T9 and T12-L1. These measurements were performed on standardized sagittal CT slices (Figure 1). All measurements were performed independently and at different times by two experienced spine surgeons. Intraobserver and interobserver reliability were assessed using the intraclass correlation coefficient (ICC).

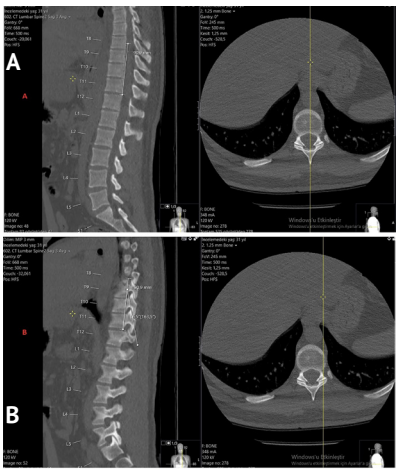

Figure 1. (A) On the sagittal slice of the T11 vertebra, a reference line was drawn from the posterior cortex. This line was fixed by the system and remained constant across all images. (B) The measurement of the facet angle was performed at the facet joint level relative to this fixed reference line

For each vertebral segment, right and left facet joint angles were measured separately, and the mean angle was used for analysis. The presence of facet tropism was also evaluated based on the absolute difference between right and left facet angles. Tropism was defined as a difference of ⩾5° between the two sides[10]. This study was approved by the Scientific Research Ethics Committee of Health Sciences University, Erzurum Faculty of Medicine (decision number: 2025/02-28, date: 12.02.2025).

Statistical Analysis

All statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). The normality of data distribution was assessed using the Shapiro-Wilk test. Normally distributed variables were presented as mean ± standard deviation, while non-normally distributed data were reported as median (minimum-maximum).

Comparisons of facet joint angles across vertebral levels were performed using repeated measures analysis of variance, followed by Tukey post-hoc test when significant differences were detected. For non-normally distributed data, the Friedman test was used. Sex-based differences were assessed using the independent samples t-test or Mann-Whitney U test, as appropriate. A p-value <0.05 was considered statistically significant in all analyses.

RESULTS

This study included a total of 240 healthy individuals aged between 20 and 40 years. The mean age of participants was 33.2±2.6 years, with 137 males (57.1%) and 103 females (42.9%).

Facet Joint Orientation

For each participant, right and left facet joint angles were measured separately at the vertebral levels between T8 and L1. The average of the right and left measurements was used for each segment in the final analysis. The measurement results are summarized below in Table 1. A statistically significant difference was found between vertebral levels ($F=6.20$, $p<0.001$) (Figure 2 and Table 2). In the post-hoc analysis, a statistically significant difference was observed only between the T8-T9 and T10-T11 levels ($p=0.025$). No significant differences were

Table 1. Facet joint angles measured at each vertebral level from T8 to L1

Vertebral level	Mean angle (°)	Standard deviation (°)
T8-T9	165.32	6.71
T9-T10	164.14	5.83
T10-T11	163.79	8.60
T11-T12	162.91	8.10
T12-L1	161.18	8.70

found between the other vertebral level pairs (p>0.05). The angular trend is illustrated in the figure below and detailed in Table 3.

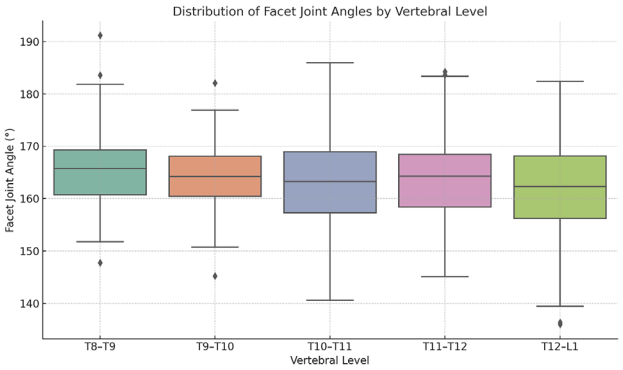

Figure 2. Distribution of sagittal facet joint angles across vertebral levels from T8-T9 to T12-L1

Table 2. Repeated measures results for facet joint angles across vertebral levels

Source of variation	SS	df	MS	F	p-value
Between levels	482.1	4	120.5	6.20	<0.001
Within subjects (error)	9237.6	476	19.4		
Total	9719.7	599			

SS: Sum of squares, df: Degrees of freedom, MS: Mean square

Facet Tropism

Facet tropism was defined as a side-to-side difference of ≥5° between the right and left facet joint angles at the same vertebral level. Tropism frequency differed significantly across vertebral levels (chi-square test, p=0.023), with the highest incidence observed at the T10-T11 level. The distribution of tropism is shown below in Table 4.

Although the tropism rate at the T10-T11 level was statistically significant, the absolute difference was relatively small and should be interpreted with caution in terms of clinical effect size.

Sex-Based Comparison and Measurement Reliability

No statistically significant differences were observed between males and females in facet joint angle measurements across all vertebral levels (p>0.05).

All measurements were independently performed by two experienced spine surgeons. Measurement reliability was assessed using the ICC:

- Intraobserver agreement: ICC=0.90
- Interobserver agreement: ICC=0.90

These values indicate a high level of measurement reliability.

DISCUSSION

The present study highlights the distinct anatomical characteristics of the thoracolumbar facet joints, revealing that the T8-T9 level possesses a more sagittally oriented and symmetrical facet morphology compared to lower levels. This finding suggests that T8-T9 may offer biomechanical advantages as a transition point during long-segment posterior spinal fusion. The presence of sagittal and symmetrical facets at this level may facilitate more stable load distribution and smoother transition between fused and mobile segments of the spine. These features are clinically relevant when determining the optimal level for the upper instrumented vertebra (UIV), as they may contribute to reducing the mechanical stress that can lead to junctional failure, such as PJK. Thus, understanding facet joint orientation patterns could inform more anatomically sound surgical strategies in spinal deformity correction.

The aim of this study was to provide anatomical reference data to guide the selection of the proximal instrumentation level in long-segment posterior spinal fusion. Incorrect selection of the UIV has been associated with a higher risk of PJK. Although sagittal alignment, pelvic parameters, and local kyphosis angles are commonly used in decision-making, the role of facet joint orientation has not been adequately studied[6,7,11]. Facet joints are key anatomical structures in load-bearing and motion control, and their orientation in the sagittal plane may directly affect segmental stability and load transfer[10,12].

Facet tropism, defined as a side-to-side asymmetry in facet joint orientation exceeding 5°, has been associated with altered load distribution and increased shear forces at the affected segment. Although the 5° threshold is widely accepted in the literature[10], its biomechanical relevance lies in its potential to disrupt symmetrical motion patterns and predispose to adjacent segment degeneration or postoperative complications such as PJK[13,14]. In our study, the highest incidence of tropism was observed at the T10-T11 level, which may reflect a transitional zone prone to biomechanical stress. From a surgical perspective, selecting a UIV level with pronounced facet asymmetry could potentially compromise construct stability or accelerate adjacent segment deterioration. Therefore, the presence of facet tropism should be considered during preoperative planning, particularly in long-segment fusions where junctional integrity is critical.

Although prior cadaveric studies by Masharawi et al.[9] and Boden et al.[12] demonstrated variation in facet orientation across vertebral levels[9,12], these investigations were limited by small sample sizes and lacked systematic sagittal plane evaluations in large populations. Our findings confirm the progressive transition from sagittal to more coronally oriented facets toward the lower thoracic spine, consistent with these earlier studies. Additionally, the high incidence of facet tropism at the T10-T11 level may indicate a region of biomechanical vulnerability due to asymmetric load transfer. Importantly, this study provides normative reference data specific to the Turkish population and offers directly applicable anatomical insights for spinal surgical planning.

Table 3. Tukey post-hoc analysis of pairwise comparisons between vertebral levels

Comparison	Mean difference (°)	p-value	95% CI	Statistical significance
T10-T11 vs. T8-T9	+2.06	0.025	(0.17, 3.96)	Significant
T10-T11 vs. T9-T10	+1.10	0.503	(-0.79, 3.00)	Not significant
T10-T11 vs. T11-T12	+0.66	0.875	(-1.23, 2.56)	Not significant
T10-T11 vs. T12-L1	-1.20	0.416	(-3.09, 0.70)	Not significant
T11-T12 vs. T12-L1	-1.86	0.057	(-3.76, 0.03)	Trend toward significance (optional)

CI: Confidence interval

Table 4. Tropism frequency by vertebral level (T8-T9 to T12-L1)

Vertebral level	Tropism present (n)	Tropism frequency (%)	Chi-square (χ^2)	p-value
T8-T9	6	2.5%		
T9-T10	9	3.8%		
T10-T11	21	8.8%		
T11-T12	14	5.8%		
T12-L1	11	4.6%		
Total	-	-	11.31	0.023

Although small angular differences may not appear statistically significant, they can have clinically meaningful consequences, especially in spinal surgical planning. Even deviations of 3-5 degrees in facet joint orientation may lead to asymmetrical load transmission and affect segmental mobility, potentially influencing the mechanical stress at adjacent levels and the risk of junctional pathology[15]. This is particularly relevant when selecting the UIV, as inappropriate alignment can predispose patients to PJK or adjacent segment disease. Masharawi et al.[9] demonstrated that even subtle morphological asymmetries in the thoracic spine can contribute to mechanical imbalances. Therefore, these minor angular differences should not be overlooked and must be integrated into the surgical decision-making process. Our findings highlight the importance of considering such parameters in preoperative planning.

Although this study provides valuable normative data on thoracolumbar facet morphology in healthy adults aged 20-40 years, it does not fully represent the typical surgical population. Long-segment posterior spinal instrumentation is most frequently performed in older adults with degenerative spinal pathologies, whose facet joint anatomy may differ significantly due to age-related structural changes. Therefore, caution is warranted when generalizing these results to elderly surgical cohorts. Nevertheless, posterior instrumentation is also commonly applied in younger patients, particularly in cases of adolescent idiopathic scoliosis. In this context, our findings may still offer partial guidance for selecting upper instrumentation levels in adolescent deformity surgery. Future studies incorporating a broader age range and pathological cases would enhance the generalizability and clinical relevance of these anatomical observations.

The study has several limitations. Measurements were performed manually using retrospective CT images. However, the high ICC value supports the reliability of the findings. Additionally, the analysis was limited to the sagittal plane; this unidimensional approach may overlook complex 3D joint morphology, such as axial rotation or coronal tilt. Future studies incorporating three-dimensional imaging modalities (e.g., 3D CT or magnetic resonance imaging) may yield more comprehensive and clinically applicable anatomical insights.

CONCLUSION

This study systematically evaluated facet joint orientation between T8 and L1 in healthy adults aged 20-40 years. Significant anatomical differences in facet angle were observed across vertebral levels, with angles becoming progressively more horizontal in caudal levels. Facet tropism was significantly more frequent at the T10-T11 level compared to other levels.

These findings suggest that T11 should be carefully evaluated before being selected as the UIV. Furthermore, the study highlights that facet joint morphology, in addition to sagittal alignment and pelvic parameters, may be an important factor when determining the proximal fusion level.

The results offer anatomical and biomechanical guidance for surgical planning in posterior spinal instrumentation. Further studies in diverse populations and clinical cohorts are needed to validate these findings and enhance their generalizability.

Ethics

Ethics Committee Approval: This study was approved by the Scientific Research Ethics Committee of Health Sciences University, Erzurum Faculty of Medicine (decision number: 2025/02-28, date: 12.02.2025).

Informed Consent: Retrospective study.

Footnotes

Authorship Contributions

Surgical and Medical Practices: B.P., M.D., Concept: B.P., Design: B.P., Data Collection or Processing: M.D., Analysis or Interpretation: M.D., Literature Search: B.P., M.D., Writing: B.P.

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A COMPARATIVE STUDY OF ORTHOPEDIC SURGEONS AND AI MODELS IN THE CLINICAL EVALUATION OF SPINAL SURGERY

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ABSTRACT

Objective: Spinal surgery (SS) is an area characterized by high intra-operative challenges and higher complication rates compared to several other surgical specialties. The purpose of this study is to evaluate the effectiveness of artificial intelligence (AI) instruments-Chat Generative Pre-trained Transformer (ChatGPT)-4o, DeepSeek-V3, and Gemini Pro-in patient assessment and the clinical decision-making process compared with specialists of orthopedic surgery on a series of case-based and knowledge-based questions relevant to SS.

Materials and Methods: By two experienced orthopedic surgeons, a set of 50 questions has been created, including 25 requiring clinical judgement through the use of a case presentation format and 25 to test theoretical understanding. The test was given to two groups: Group 1 included three AI software programs (ChatGPT-4.0, DeepSeek-V3, Gemini Pro) and Group 2 included ten experienced orthopedic surgeons. The answers given were scored independently by the two expert surgeons.

Results: Group 2 performed significantly better than Group 1 in the case-based questions. There was a significant difference between the groups in one section (p=0.025), while there was no significant difference for the knowledge-based questions section (p=1.000). On the assessment of total correct responses, Group 2's performance was significantly better (p=0.036).

Conclusion: AI technologies have proved their utility for knowledge-based tasks but are dramatically inferior to clinicians for areas requiring clinical judgement and case analysis. Even if AI algorithms can become auxiliary tools, they should not take the clinician's place as the decision-maker.

Keywords: Artificial intelligence, spinal surgery, large language model

INTRODUCTION

In today's modern age, the need for instant and accessible information has increased exponentially across all areas, including the healthcare. This need encompasses not only the patient but also the healthcare professionals who, even with extensive training and higher-level expertise, often require up-to-date information to support clinical decision-making.

One of the most complex and risky fields in the realm of medicine is represented by spinal surgery (SS), being an area to which such technological support would be beneficial given the complexity of its clinical problems and the high risk of complications.

SS is marked by its application in anatomically critical regions, long operation times, complex postoperative care, increased morbidity and mortality, and the risk of extensive rehabilitation if there are complications-factors serving to significantly increase medicolegal risk. Therefore, SS requires support at the logistical level. Under such circumstances, the use of artificial intelligence (AI)-based tools through healthcare settings has emerged as an attractive strategy for the improvement of decision support and the enhancement of patient safety.

Navigation systems, computer programs for pedicle screw insertion, advanced radiological evaluation devices, and neurological monitoring systems, are now being used intraoperatively during spinal surgical procedures, helping to reduce surgical risks[1]. It has also been proposed that AI systems may provide benefits in diagnostic processes, prognostic analyses, and treatment planning[2,3]. Beyond their present uses during surgery, AI also has the potential to improve preoperative risk evaluations as well as standard and complicated postoperative management.

AI is a set of technologies that mimic the cognitive processes of humans, such as thought processes, learning, and problem-solving. One subset of AI, large language models, is designed specifically to understand natural language and absorb information from varied sources like scientific papers, books,

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research journals, and online data. Chat Generative Pre-trained Transformer (ChatGPT) is a well-known application of large language model technology. Due to its multimodal architecture, ChatGPT-4o can perform case-based analysis in the medical field and demonstrates remarkable expertise in critical thinking, literature synthesis, and clinical evaluation. Its use is particularly relevant in SS, due to its strengths in analyzing clinical cases, appraising patient trends, making academic evaluations, and interpreting images[1]. However, the use of this application is by subscription[4].

DeepSeek is another widely used AI model that is open-source; however, it does not have the function of processing image input[5]. It is claimed that this model is superior to ChatGPT in analyzing long medical papers, patient histories, and clinical studies[6]. It is also suggested that DeepSeek better follows the advancements in medical literature more dynamically and flexible[6,7]. The latest version, DeepSeek-V3, also offers offline functionality, thus enhancing data confidentiality[6]. On the other hand Bhattacharya et al.[8] reported that ChatGPT is superior in aspects of literature synthesis, clinical reasoning, medical education, and patient communication, DeepSeek is stronger in areas of surgical education, skill acquisition, patient teaching, and preoperative planning. Therefore, these two models play complementary roles.

In December 2023, the release of Google's Gemini model arrived with claims of improved reasoning capabilities as well as increased ability to handle complex tasks; however, their use in clinical settings remained somewhat constrained[9]. Nevertheless, Gemini has been suggested to be used as an adjunct to clinical decision-making processes[10-12]. With the growing debate over the use of AI to replace humans, it is important to consider the efficiency with which the models can read academic literature, understand it, and derive accurate conclusions in the field of medicine. This study compares the performances of orthopedic surgeons with three AI models-ChatGPT-4o, DeepSeek-V3, and Gemini Pro-in their accuracy for clinical decision-making scenarios and their theoretical knowledge capacity. The main focus is to examine the efficacy of AI systems within the context of preoperative patient evaluation and identify their reliability and efficiency compared to their human clinician counterparts across clinical decision-making scenarios.

MATERIALS AND METHODS

As the differences between the AI models carried less significance in the purview of this study, with the foremost aim being to identify the disparity in performance between AI and humans, ChatGPT-4o, DeepSeek-V3, and Gemini Pro were grouped as Group 1. On the other hand, ten orthopedic and traumatology surgeons with a minimum of 10 years of clinical experience were grouped as Group 2. The current study doesn't need to have authorization from an ethics committee because it doesn't involve patient interventions, procedural interventions, or the obtaining of personal health information.

In order to design the study question, two senior orthopedic surgeons formulated 50 study-type questions exclusively based on SS. Of these, 25 were case-based questions requiring clinical judgement, and the other 25 were on knowledge-based questions requiring theoretical knowledge. The question content breaks up as follows: 4 on anatomy, 12 on trauma, 4 on tumors, 4 on infections, 8 on postoperative surgical complications, 3 on physical examination, 7 on deformities, 5 on degenerative spine disease, and 3 on congenital spinal diseases. Since the DeepSeek model is unable to process images inputs, visual material or radiologic images were excluded from the questions developed for this study. The multiple choice questions were e-mailed to ten orthopedic and traumatology surgeons, instructing them to spend exactly 1 minute per question and record their answers. The answers were reviewed by the same surgeons who had formulated the questions. Concurrently, the same set of questions was administered to the three AI models, and their outputs were documented for subsequent analysis (Table 1). Statistical significance between the two groups was calculated by the Mann-Whitney U test. The correct answers rendered by AI models in the case-based and knowledge-based question sets were proportionally compared with those of the surgeons' group.

Statistical Analysis

In the current study, the evaluation results of the AI models-ChatGPT, GEM, and DeepSeek-were compared with those of ten orthopedic surgeons. The three AI models were placed in a single group, and the ten surgeons were placed in another group. The number of correct answers was taken both in absolute terms and in percentages. To compare the two groups, the Mann-Whitney U test, a non-parametric statistical method, was used. The reason for the choice of this specific test was the small sample sizes and the predicted non-normal distribution of the data, as it is an appropriate and stringent method for the comparison of two independent groups. The count of correct answers for each participant was counted separately for the clinical case-based questions (the first 25 questions), the fact-dependent knowledge-based questions (the last 25 questions), and the total of 50 questions. Independent Mann-Whitney U tests were performed for each of the above three categories. A p-value of less than 0.05 is considered statistically significant. All the analysis steps were performed using the SciPy package in the Python programming language.

RESULTS

In the case-based questioning analysis, Group 2 performed best compared to all other groups, with an overall accuracy of 88.8%. In Group 1, DeepSeek-V3 was found to be the best-performing model with an accuracy of 44%, which is half the rate of the

Table 1. The number of correct responses generated by artificial intelligence systems for case-based and knowledge-based questions

	ChatGP-4.o (n)	DeepSeek V3 (n)	Gemini Pro (n)
Case-based questions (n=25)	10	11	7
Knowledge-based questions (n=25)	19	20	16
Total (n=50)	29	31	23

ChatGPT: Chat Generative Pre-trained Transformer

Table 2. The individual and overall average accuracy rates of artificial intelligence models (Group 1), and the average correct response rate of orthopedic surgeons (Group 2)

Group	Case-based question accuracy rate (%)	Knowledge-based question accuracy rate (%)	Overall accuracy rate (%)
ChatGPT-4o	40.0	76.0	58.0
Gemini Pro	28.0	64.0	46.0
DeepSeek-V3	44.0	80.0	62.0
Group 1	37.3	73.3	55.3
Group 2	88.8	72.0	80.4

ChatGPT: Chat Generative Pre-trained Transformer

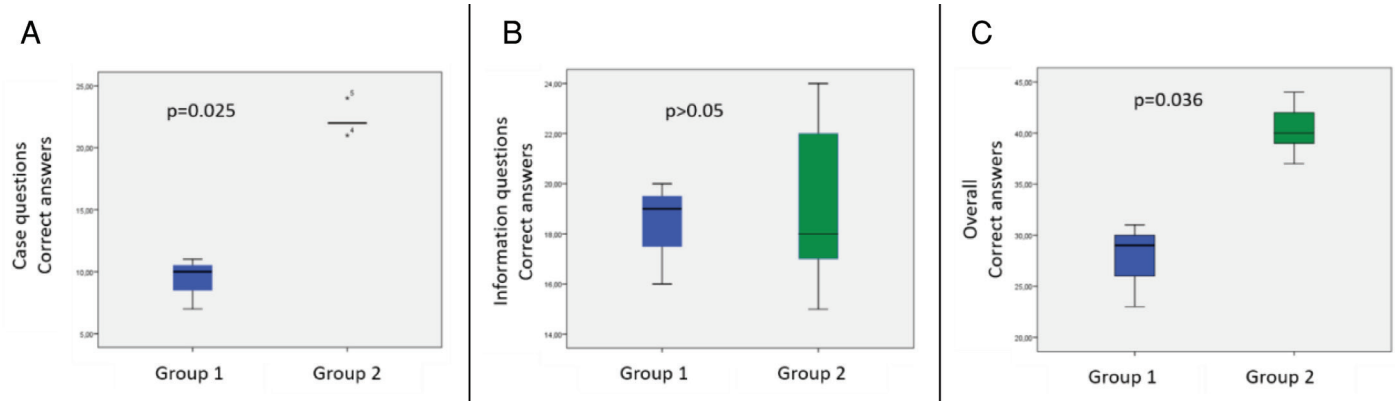

Figure 1. Comparison of correct answer numbers of (A) case-based questions, (B) knowledge-based questions and (C) overall between Group 1 (artificial intelligent) and Group 2 (orthopedic surgeons). Blue and green boxes represent Group 1 and Group 2, respectively

surgeons. ChatGPT-4o and Gemini Pro had accuracy rates of 40% and 28%, respectively (Table 2).

In the knowledge-based questions, DeepSeek-V3 had an accuracy of 80%, ChatGPT-4o demonstrated an accuracy of 76%, and Gemini Pro registered at 64%. On the other hand, Group 2 averaged 72%. As far as the overall performance is concerned, the AI models were again exceed by the Group 2 team who had an overall average score of 80.4%. Out of the AI models tested, the highest score was achieved by DeepSeek-V3 at 62.0%, followed by ChatGPT-4o with 58.0%, and then Gemini Pro with 46.0%. The overall success rate of 55.3% for Group 1 was calculated.

The Mann-Whitney U test was utilized to analyze statistically the test results from Group 1 and Group 2. The percentage of correct answers to case-based queries across Group 2 demostrated significantly higher performance compared to Group 1 (p=0.025). On the other hand, no statistical difference between the two groups was observed pertaining to knowledge-based questions (p=1.000). With respect to the total number of correct answers across the test, Group 2 revealed significantly improved performance compared to Group 1 (p=0.036) (Figure 1).

DISCUSSION

The growing use of AI models by healthcare professionals and patients has seen numerous clinical assessments on the potential applications and limitations of the technologies across the healthcare area, as seen through the numerous clinical studies[1-3,5,6,8,11,12]. The performances of ChatGPT-3.5 and ChatGPT-4o on the United States Medical Licensing Examination have been compared, indicating that the two

models passed the examinations, specifically clinical decision areas[13]. Another study, on the other hand, compared the diagnostic skill of ChatGPT to those of healthcare professionals and demonstrated that ChatGPT to have a limited understanding of examination questions[14]. Another study, on the use of wrist radiographs, tested the performances of ChatGPT-4o, Gemini 1.5, and DeepSeek-V3, with all failing to be identified as being useful clinical decision support systems[15]. A seperate study stated that diagnostic processes and systematic reviews would be aided using AI, postulating that tools such as ChatGPT and Gemini would become useful adjuncts to the clinical practice, but should not be entrusted to independently guide decision-making[12].

A comparison between ChatGPT, Gemini, and DeepSeek revealed stark differences in their performance in advanced situations requiring clinical judgement, highlighting the premise that such models should only exist as auxiliary tools and not the primary decision-maker[11]. In an orthopedic board test, AI models performed better on test items where analytical reasoning is not required[16].

This study entailed presenting 50 questions, which specific to SS, to ChatGPT-4o, Gemini Pro, DeepSeek-V3, and a group of ten experienced clinicians. The major objective was to compare the reasoning of AI models with that of human clinicians in situations requiring clinical judgement. The findings of this study stated that human clinicians perform superior than AI systems in the decision-making aspect when it comes to realistic case-based scenarios; however, AI models can perform as well as clinicians in situations entailing knowledge-based testing. These findings imply that while AI technologies can have some value in performing data-dependent tasks, they are largely insufficient to replace human expertise in clinical problem-solving and judgement on a case-by-case basis.

Although the AI system has shown proficiency in diagnostic and knowledge-related performance, it has yet to achieve the level of reliability needed for autonomous use in clinical decision-making. This study supports the current trend and emphasizes the importance of using AI technologies as supporting tools for healthcare professionals, not substitutes for them as main primary decision-makers. A wide range of clinical studies that compared various AI models have shown varied results[5,10,15]. In this analysis, overall accuracy percentages for the 50 integrated case-based and knowledge-based questions were 62% for DeepSeek-V3, 58% for ChatGPT-4o, and 46% for Gemini Pro. In a study focused on musculoskeletal radiology, ChatGPT proved to be more accurate compared to DeepSeek[17]. On the other hand, another study reported that DeepSeek provided more understandable replies compared to ChatGPT, credited to its high reasoning ability[18]. In this study, the results indicate that the DeepSeek models have higher overall accuracy, while ChatGPT-4o has similar performance for case-based and knowledge-based questions. However, the Gemini models performed generally worse.

The problems of verifiability and accountability of information created through the use of AI remain controversial topics. AI models utilize datasets limited to publicly available information up to a specified date. This constraint naturally raises the prospect of ignoring the newest literature and developments in the field of medicine. In one study analyzing different questions over time, it was noted that the accuracy of ChatGPT declined as the recency of the question improved[14]. These results suggest that the accuracy of the AI technologies may change in time and may not always match the current medical information. This finding shows that the accuracy of AI programs is time-dependent, indicating that they may not always have the most updated medical information. Because of this, our study sought to analyze the up-to-date validity of the AI programs by creating new test items and presenting them to the AI programs for preliminary testing.

An important limitation of the use of AI is the fact that the provided information often has no corroboration from credible scientific sources. Empirical research has shown that many of the references provided by ChatGPT-4o are scientifically unreliable, and DeepSeek-V3 has been shown to generate fake citations[19]. This fact makes the AI technology used in clinical decision support unreliable, thus posing great risks to patient safety[5,20]. Decisions from AI systems can lead to incorrect conclusions or late treatment, which may have great medical and legal consequences. Additionally, the lack of accountability of AI models represents a great shortcoming with regards to safety and responsibility in healthcare service provision[4,21]. For this reason, it is critical that AI systems are used only as auxiliary devices having human governance, the final decision authority resting entirely with the clinician[22,23].

Many studies on the application of AI to the field of SS havehighlighted the future potential of AI algorithms to become useful tools for preoperative planning and intraoperative assistance[22,23]. There is evidence showing ChatGPT is 68% successful at generating appropriate ideas relevant to spine surgery[23]. Additionally, it has been suggested that AI can represent an ideal asset for the development of educational resources, the simulation of complex clinical scenarios, the construction of personalized learning paths for medical students, and postoperative patient surveillance[6,22-25]. Given the relatively high complication rates of SS during intra-and postoperative periods compared to other surgical fields, this field requires strong technological support and an acceptance of new methodologies. The current study suggests further advancement of the AI technologies used in SS to position them among trustworthy auxiliary resources for healthcare professionals.

Study Limitations

A key limitation of the current study is the inability of DeepSeek to read images. Thus, radiology-and visually based assessments-that are critical to SS-cannot be examined. Additionally, the study only had 25 clinical cases, and this would limit the

generalization of the findings. The study used answers from ten expert orthopedic surgeons; inclusion of more clinicians would enhance both the reliability and the generalizability of the results. Further studies that involve more clinical involvement and large question sets are needed to obtain a more reliable evaluation.

CONCLUSION

The traditional view of medicine as an art emphasizes the role of numerous individual factors such as sociocultural context, cognitive capacity, medical history, and individual circumstances to bring the healing to fruition. Based on this model, it is technologically impossible for AI programs to fully understand the various human factors and generate context-relevant recommendations. Rather than viewing the technologies of AI as autonomous decision makers, it is more fitting to think of such applications as clinical practice-assisting instruments, tools for immediate access to relevant information, and reinforcement of decision support systems for diagnosis and therapy. These technologies should be envisioned as supportive tools to complement clinical decision-making and not to replace healthcare professionals; they are supportive factors strengthening clinical judgment. AI technologies have proved their utility for knowledge-based tasks but are dramatically inferior to clinicians for areas requiring clinical judgement and case analysis.

Ethics

Ethics Committee Approval- Informed Consent: The current study does not require ethics committee and informed consent because it does not involve patient interventions, procedural interventions, or the acquisition of personal health information.

Footnotes

Authorship Contributions

Surgical and Medical Practices: M.T.D., Y.K., Concept: M.T.D., Y.K., Design: M.T.D., Y.K., Data Collection or Processing: M.T.D., Analysis or Interpretation: M.T.D., Y.K., Literature Search: M.T.D., Y.K., Writing: M.T.D., Y.K.

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POSTERIOR APPROACH IN SPINAL TUBERCULOSIS: WITH OR WITHOUT CORPECTOMY?

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ABSTRACT

Objective: Spinal tuberculosis is a challenging condition that often requires surgical intervention. The posterior surgical approach has gained popularity due to its technical advantages, yet the necessity of vertebral body resection (corpectomy) remains debated. This study aimed to compare the clinical and radiological outcomes of posterior decompression and spinal fusion surgeries performed with and without corpectomy in patients with spinal tuberculosis.

Materials and Methods: A total of 13 patients were retrospectively analyzed. Group 1 (n=5) underwent posterior decompression and fusion with corpectomy, while Group 2 (n=8) underwent the same procedure without corpectomy. Key variables such as kyphotic angle correction, neurological recovery, operation duration, and hospital stay were compared using appropriate statistical methods.

Results: Group 1 showed significantly better kyphosis correction (33.34% vs. 18.06%, p=0.003) and slightly higher neurological improvement (60% vs. 50%, p=0.171). Operation time was significantly longer in Group 1 (10.6 vs. 4.8 hours, p=0.003). Hospital stay was longer in Group 1 but without statistical significance (19.4 vs. 15.3 days, p=0.435).

Conclusion: Corpectomy via the posterior approach provides significantly better deformity correction but is associated with longer operative time. Surgical decision-making should be tailored to individual clinical and radiological factors.

Keywords: Spinal tuberculosis, posterior approach, corpectomy

INTRODUCTION

Spinal tuberculosis is the most common form of musculoskeletal tuberculosis and predominantly affects the thoracolumbar junction. While medical treatment remains the primary modality, surgical intervention becomes necessary in cases of severe back pain, neurological deficit, progressive kyphotic deformity, spinal instability, or failure of conservative therapy[1-3].

The main objectives of surgery are neural decompression, debridement of infected tissue, correction of spinal alignment, and restoration of mechanical stability. Depending on the location and severity of the disease, surgical approaches can be anterior, posterior, or combined. Although anterior approaches allow direct access for debridement and reconstruction, they are associated with longer operative time, higher blood loss, and potential visceral injury, especially in the thoracic region[4,5]. Recently, the posterior approach has gained prominence due to its lower complication rates, shorter surgical time, effective deformity correction, and ability to achieve stable instrumentation through pedicle screws[6,7]. However, one major question remains controversial: whether decompression and fusion should be performed with or without corpectomy.

Corpectomy allows direct decompression of the spinal canal and correction of kyphosis, but it comes at the cost of longer operative time, greater blood loss, and increased surgical risk[8,9]. Posterior decompression and stabilization without corpectomy, on the other hand, offers a less invasive alternative, but may lead to insufficient deformity correction or implant failure in some cases[10].

In light of these considerations, the present study aims to compare the clinical and radiological outcomes of spinal tuberculosis patients treated via the posterior approach with and without corpectomy. Our goal is to contribute to the evolving literature by providing single-center data and clinical insight into patient selection and technique optimization.

MATERIALS AND METHODS

This study was a retrospective evaluation of 13 patients who underwent surgical treatment for spinal tuberculosis between 2016 and 2024 in our clinic. Demographic data, comorbid diseases, lesion levels, number of diseased vertebrae, pain levels, preoperative kyphosis angles, preoperative neurological function status, types of bone destruction, surgical techniques

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used, operative times, postoperative kyphosis correction rates, neurological recovery levels, intraoperative and postoperative complications, and length of hospital stay were analyzed in detail. The main aim of this study was to compare patients who underwent posterior decompression and fusion with corpectomy versus without corpectomy and to evaluate the clinical and radiological outcomes of these two surgical strategies. The study was approved by the University of Health Sciences Türkiye, Gülhane Training and Research Hospital Non-Interventional Research Ethics Committee (decision number: 2025/9, date: 16.01.2025).

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics v25.0. For non-normally distributed numerical variables, group comparisons were conducted using the Mann-Whitney U test. A p-value less than 0.05 was considered statistically significant.

Patients included in the study were those who presented with progressive back pain, radiologically confirmed vertebral destruction, and the need for posterior stabilization due to spinal instability or neurological compromise. All patients underwent detailed preoperative evaluation, including clinical history, laboratory testing, and radiological imaging [magnetic resonance imaging and computed tomography (CT)]. Microbiological confirmation was achieved through sputum acid-fast bacilli testing, polymerase chain reaction (PCR), and/or intraoperative culture and histopathology.

Pre- and postoperative neurological function was assessed using the Frankel classification and Medical Research Council muscle strength scale. Radiological parameters, including local kyphosis angle, were measured using the Cobb method, calculated between the superior endplate of T2 and the inferior endplate of T12.

Bone destruction patterns were classified as fragmentary, subperiosteal, osteolytic, or sclerotic based on CT imaging. Patients were categorized into two groups according to the surgical approach: Group 1 underwent posterior decompression and fusion with corpectomy, while Group 2 underwent posterior decompression and fusion without corpectomy. The clinical and radiological outcomes of both groups were compared.

Inclusion Criteria

Patients were included if spinal tuberculosis was confirmed microbiologically (via culture or PCR from intraoperative specimens), or if there was strong clinical and radiological evidence consistent with spinal tuberculosis in the presence of active pulmonary tuberculosis. All patients had complete medical records and a minimum follow-up duration of 12 months.

Exclusion Criteria

Patients were excluded if no microorganism could be isolated and alternative diagnoses could not be ruled out. Cases with incomplete medical records or insufficient follow-up (<12 months) were also excluded.

Surgical Procedure Without Corpectomy

The indication for this surgical intervention was instability and deformity due to vertebral destruction. As part of the procedure, bilateral transpedicular screw fixation was applied to the involved vertebral levels, and osteotomy was performed on the posterior elements. However, no corpectomy was performed, and only posterior stabilization was achieved (Figure 1).

Preoperative and postoperative radiologic measurements were performed to monitor spinal alignment and kyphotic deformity in the postoperative period. Intraoperative tissue samples were subjected to histopathologic and microbiologic examination.

Surgical Approach in Patients with Corpectomy

This surgical approach is based on the progression of neurologic dysfunction and the presence of severe vertebral deformity and instability. The thoracic spinal surgical procedure was performed with bilateral transpedicular screw fixation at the involved vertebral levels. Prior to the corpectomy procedure, osteotomy was performed on the posterior elements of the involved segment, followed by total corpectomy through a transpedicular approach. For spinal reconstruction, a titanium cage was placed in the defect area. Access was achieved by partial retraction or ligation of nerve roots at involved levels when necessary (Figure 2).

RESULTS

A total of 13 patients were evaluated in this study. Group 1, which included patients who underwent posterior decompression and fusion with corpectomy, consisted of 5 individuals (3 females, 2 males) with a mean age of 60.4 years (range: 46-73). Group 2, in which corpectomy was not performed, included 8 individuals (3 females, 5 males) with a mean age of 60.5 years (range: 44-81). Radiological evaluation revealed three main types of bone destruction across the cohort: fragmentary (n=7), osteolytic (n=3), and subperiosteal (n=3). The most commonly affected spinal levels were T6-T7 and T10-T12. Vertebral involvement most frequently spanned two vertebrae, followed by single- and four-level involvement.

The mean kyphosis correction rate was significantly higher in Group 1 (33.34%) compared to Group 2 (18.06%) (p=0.003). Neurological improvement was observed in 60% of patients in Group 1 and 50% in Group 2; however, the difference was not statistically significant (p=0.171).

The mean operation duration was significantly longer in Group 1 (10.6 hours) than in Group 2 (4.8 hours) (p=0.003). While the average length of hospital stay was greater in Group 1 (19.4 days vs. 15.3 days), this difference did not reach statistical significance (p=0.435).

Screw failure or implant-related complications were observed only in Group 2, affecting one patient (20%). No such complications were seen in Group 1.

Table 1 summarizes the demographic characteristics and patterns of spinal involvement. Table 2 presents the comparative clinical and radiological outcomes between the two surgical groups.

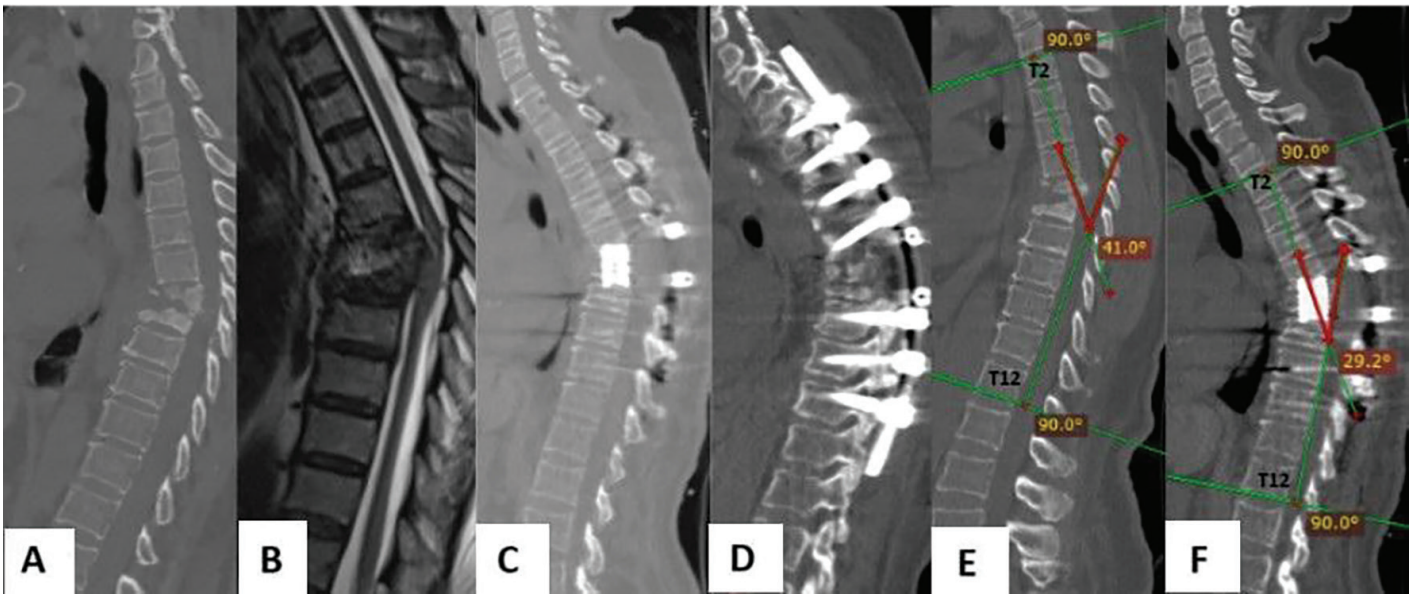

Figure 1. (A) Preoperative MRI scan shows significant spinal cord compression between the T6-T9 levels. (B) A preoperative CT scan shows significant height loss and vertebral destruction of the T6, T7, T8, and T9 vertebrae. (C) Postoperative CT image of transpedicular screw fixation applied during the surgical procedure. (D) An osteotomy procedure was performed on the posterior elements of the T6, T7, T8, and T9 vertebrae. (E) Radiological image of the kyphosis angle measured in the preoperative period. (F) A corrected version of the kyphosis angle measured in the postoperative period. MRI: Magnetic resonance imaging, CT: Computed tomography

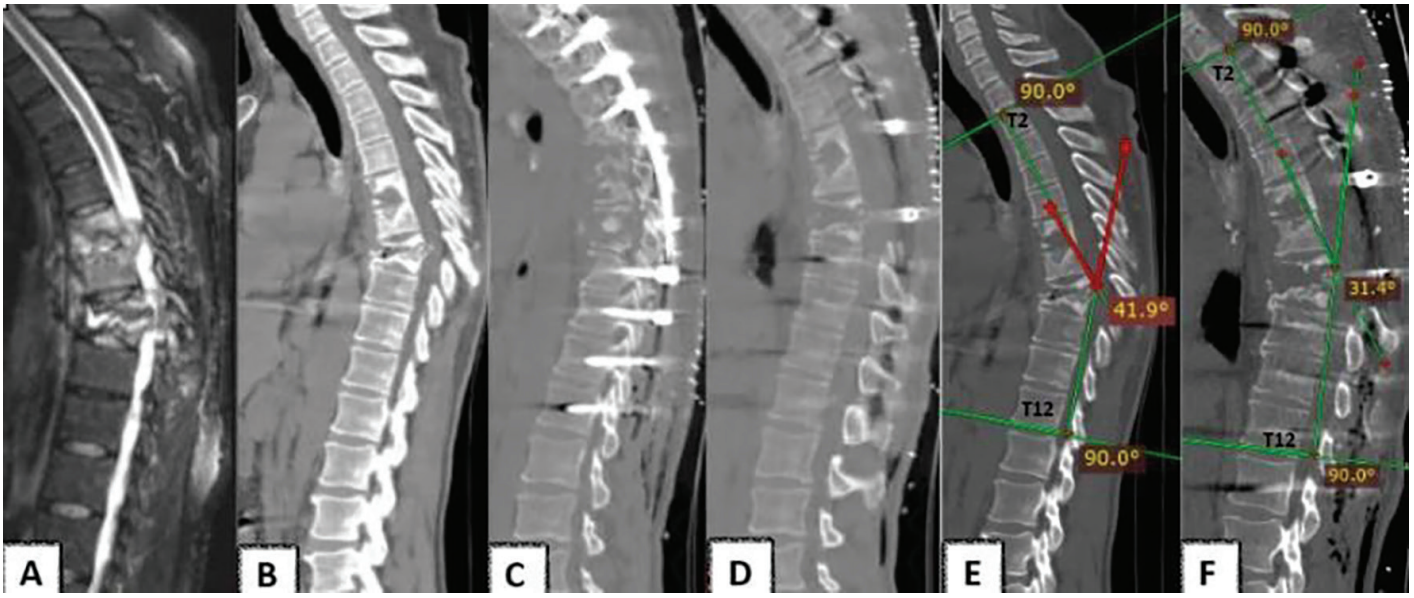

Figure 2. (A) Preoperative CT image shows loss of height and bone destruction at the T6-T7 levels. (B) The fat-suppressed MRI section shows significant spinal cord compression at the T6 level. (C) A titanium cage was placed at the T6 and T7 levels. (D) Bilateral transpedicular screw fixation was applied at the T2-T5 and T8-T10 levels for posterior stabilization. (E) The preoperative kyphosis angle shows the degree of deformity. (F) Postoperative radiologic examination shows improvement in the kyphosis angle. MRI: Magnetic resonance imaging, CT: Computed tomography

Table 1. Demographic characteristics, comorbidities and spinal involvement features of the patients

Group	Patient number	Age	Sex	Other comorbidities	Pathological region	Number of involved vertebrae	Preoperative kyphotic angle	preoperative neurological function	Operation duration (hours)	Postoperative kyphotic angle	Postoperative neurological function	Hospital stay (day)
Group 1	**Patient #1**	69	Female	Diabetes mellitus, hypertension, ovarian cancer	T6-T7	2	41	Frankel B	6	29.2	Frankel C	11
	Patient #2	56	Male	Diabetes mellitus, hypertension	T8-9	2	48.2	Frankel D	8	31.3	Frankel C	13
	Patient #3	46	Female	None	T10-T11-T12	3	52.1	Frankel A	12	37.2	Frankel A	32
	Patient #4	58	Female	Hypertension	T9-T10	2	55.2	Frankel B	13	35.7	Frankel E	24
	Patient #5	73	Male	Diabetes mellitus, hypertension	T11-T12	2	51.2	Frankel B	14	32.2	Frankel D	17
Group 2	**Patient #6**	65	Female	Asthma, hypertension, hypothyroidism	T5-T6-T7-T8	4	44.3	Frankel D	3	37.2	Frankel D	37
	Patient #7	48	Male	Silicosis	T6-T7-T8-T9	4	41.9	Frankel E	5	31.4	Frankel E	20
	Patient #8	72	Male	Hypertension	T11	1	42.2	Frankel C	5	39.2	Frankel C	19
	Patient #9	44	Male	None	T10	1	43.1	Frankel D	4	38.4	Frankel E	15
	Patient #10	63	Male	None	T10-T11	2	44.2	Frankel C	6	36.2	Frankel D	8
	Patient #11	81	Male	Diabetes mellitus, hypertension	T6-T7-T8	2	42.1	Frankel A	7	37.4	Frankel A	12
	Patient #12	42	Female	None	T10	1	46.2	Frankel D	4	31.3	Frankel E	5
	Patient #13	69	Female	Hypertension	T12	1	43.2	Frankel C	5	33.4	Frankel C	7

Table 2. Comparison of clinical and operative outcomes of two surgical approaches

	Surgical approaches		
	Group 1	Group 2	p-value
Kyphosis correction	33.34%	18.06%	0.003
Neurological improvement (Frankel Classification)	60%	50%	0.171
Mean operation duration (hour)	10.6	4.8	0.003
Mean hospital stay (day)	19.4	15.3	0.435
Screw failure or fracture	0%	20%	

DISCUSSION

Early surgical intervention has been shown to support pain control, spinal cord decompression, and functional recovery in selected patients with spinal tuberculosis, particularly when pharmacological treatment alone is insufficient. In our clinical approach, surgical decisions are made based on the severity of spinal cord compression, progressive neurological deficits, deformity, and patient-specific risk factors[11]. In this context, corpectomy with a posterior approach or only posterior decompression and stabilization are decided on a patient-specific basis.

In determining the surgical approach, the segmental extent of the disease, the number of vertebrae involved, the degree of vertebral instability, concomitant systemic diseases, and the patient's general health status are considered. In the literature, many studies are comparing anterior and posterior surgical techniques, and these studies have reported various results in terms of parameters such as intraoperative blood loss, operation time, postoperative complications, hospitalization time, effects on kyphotic deformity, neurological recovery rates, and spinal stability[2,9,12].

Since anterior approaches require a thoracotomy, especially in cases involving the thoracic region, they have been associated with postoperative respiratory complications, delayed mobilization, more extended hospital stays, and often the need for additional posterior stabilization. In contrast, the posterior approach has become a more preferred method by spine surgeons because of its advantages, such as relatively fewer surgical complications and more effective correction of the kyphotic angle[5,6,13].

Consistent with recent large-scale series, posterior-only approaches have shown efficacy comparable to anterior or combined methods in terms of deformity correction and neurological recovery[14]. In our study, Group 1 (posterior + corpectomy) achieved significantly greater kyphosis correction (33.3% vs. 18.1%, p=0.003) with a trend toward better neurological improvement (60% vs. 50%, p=0.171). These results mirror findings by Debnath et al.[15] and others, who reported excellent neurological outcomes ($p<0.0001$) following posterior corpectomy. On the other hand, an implant-related complication-specifically, screw breakage-was observed only in Group 2, which did not undergo corpectomy, and occurred in one out of five patients. Although this corresponds numerically to a 20% rate, the fact that it was observed in a single patient precludes meaningful statistical analysis. Nevertheless, the occurrence of this complication exclusively in the non-corpectomy group may suggest a potential limitation of posterior stabilization techniques when corpectomy is omitted, particularly in cases where long-term structural support is insufficient. Previous studies have reported that in spinal tuberculosis-especially in patients requiring multilevel instrumentation-complete spinal fusion may take as long as two to three years to be achieved. Therefore, longer follow-up periods are essential to more accurately reveal potential differences in outcomes between surgical approaches. Based on our clinical experience and current data, posterior decompression and stabilization without corpectomy appear to provide satisfactory clinical and radiological outcomes in cases of single-level involvement. However, in patients with three or more vertebral segments affected, the increased biomechanical load may necessitate the inclusion of corpectomy to ensure long-term spinal stability. This approach aligns with current literature advocating extended posterior stabilization in the management of multilevel spinal tuberculosis cases[14,15].

In our clinical practice, we have largely moved away from anterior approaches based on our previous experience and have made posterior surgical techniques our primary choice. We prefer the transpedicular approach during posterior surgical procedures, especially in cases requiring corpectomy[16]. During the surgical planning process, the localization of the lesion on the spinal axis, the number of vertebrae involved, the degree of vertebral destruction, the neurological status of the patient, and the accompanying systemic comorbidities are evaluated in detail.

Although human immunodeficiency virus (HIV) infection is considered an important risk factor for the development of spinal tuberculosis, HIV positivity was not detected in any of the patients evaluated in our study[17,18]. Although the literature has reported that the posterior approach gives more successful results in kyphosis correction, neurologic recovery rates are similar in the surgeries performed in our clinic. In addition, the increase in kyphosis deformity after anterior surgery and the resulting need for a second posterior surgery is one of the important factors decreasing the interest in the anterior approach[10,19,20]. In contrast, our patients who underwent corpectomy via the posterior approach did not require a second surgical intervention. In patients who underwent posterior decompression and stabilization without corpectomy, screw failure was observed at a rate described in the literature[21].

In conclusion, the literature still lacks studies examining the relationship between the number of diseased vertebrae and the need for corpectomy. This situation causes decision-making processes in clinical practice to be primarily based

on the surgeon's personal experience and center-based practice protocols. The need for large-sample, multicenter, and randomized controlled clinical trials to obtain more robust evidence continues in this context.

According to our clinical observations and current experience, in cases with single vertebral involvement, satisfactory clinical and radiological results can be achieved with posterior decompression and stabilization procedures performed in addition to anti-tuberculosis pharmacological treatment, often without corpectomy. However, when three or more vertebrae are involved in the disease process, the surgical planning process becomes more complex, resulting in longer operation time and a significantly increased risk of surgical complications.

For these reasons, the necessity of corpectomy in cases with multilevel vertebral involvement is carefully re-evaluated on a patient-by-patient basis, and posterior stabilization and decompression methods are recommended as a priority in our clinical practice to reduce surgical morbidity, optimize operation time, and support the postoperative recovery process.

Study Limitations

This study has several limitations that should be acknowledged. First, the retrospective design inherently limits the ability to control for confounding variables and may introduce selection bias. Second, the sample size was relatively small, which reduces the statistical power and limits the generalizability of the findings. Third, there was a degree of diagnostic heterogeneity among patients, as the diagnosis of spinal tuberculosis was based on a combination of microbiological, radiological, and clinical criteria, which may vary in specificity and sensitivity. In addition, the absence of a non-operative or comparative control group restricts our ability to assess the relative efficacy of surgical versus conservative treatment. Finally, the follow-up period was limited to 12 months, which may not fully capture long-term outcomes such as delayed fusion, implant stability, or recurrence. Despite these limitations, the study provides clinically relevant insights into surgical decision-making in patients with spinal tuberculosis and may serve as a basis for future prospective and multicenter research.

CONCLUSION

Corpectomy can be performed through a posterior approach in spinal tuberculosis surgery, and the clinical outcomes of this method may be more favorable compared to patients who undergo only posterior decompression and fusion surgery. Corpectomy through the posterior approach offers certain advantages but also some disadvantages. Therefore, patient selection should be meticulous, and this method should be preferred in appropriate cases. Considering the available literature, further studies are needed to increase the level of evidence in this field.

Ethics

Ethics Committee Approval: The study was approved by the University of Health Sciences Türkiye, Gülhane Training and Research Hospital Non-Interventional Research Ethics Committee (decision number: 2025/9, date: 16.01.2025).

Informed Consent: Retrospective study.

Footnotes

Authorship Contributions

Surgical and Medical Practices: S.K., M.C.E., M.O.D., Concept: S.K., Design: S.K., A.K., M.C.E., Data Collection or Processing: S.K., A.K., Analysis or Interpretation: S.K., Literature Search: S.K., A.K., Writing: S.K., A.K.

Conflict of Interest: No conflict of interest was declared by the authors.

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COMPLICATIONS IN PEDIATRIC NEUROMUSCULAR SPINAL DEFORMITY SURGERY: A COHORT STUDY OF 45 PATIENTS AND RISK FACTOR ANALYSIS

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ABSTRACT

Objective: Neuromuscular spinal deformity (NMSD) is a complex, progressive condition that affects children with disorders such as cerebral palsy, muscular dystrophy and spinal muscular atrophy. These children often experience significant functional limitations and an increased risk of surgery. This study aims to classify intraoperative and postoperative complications in pediatric NMSD surgery and identify related risk factors.

Materials and Methods: We retrospectively reviewed 45 pediatric patients who underwent surgical correction for NMSD between June 2020 and December 2024. We collected demographic, clinical, and surgical data. Complications were categorised as either intraoperative or postoperative. Logistic regression analysis was performed to identify risk factors associated with complications.

Results: Of the 45 patients (53% female; mean age: 11.7 years), 13 underwent growth-friendly procedures and 32 underwent definitive posterior spinal fusion. Intraoperative complications occurred in 37.8% of cases, primarily due to excessive bleeding (n=14). Postoperative complications were observed in 55.6% of patients, with the most frequent being infections (n=16), respiratory issues (n=12), and implant problems (n=9). The presence of a ventriculoperitoneal shunt, a history of previous spinal surgery, non-ambulatory status, pelvic fixation, and longer operative times were all significantly associated with higher complication rates.

Conclusion: Children with NMSD are at considerable risk during and after spinal surgery due to their underlying health conditions. Our findings emphasise the importance of recognising risk factors early on to improve outcomes. While surgical correction can offer substantial functional and postural advantages, a personalised, multidisciplinary care approach is essential to minimise complications and facilitate recovery in this vulnerable group.

Keywords: Neuromuscular spinal deformity, pediatric spine surgery, surgical complications, risk factors, posterior spinal fusion

INTRODUCTION

Scoliosis, defined as a three-dimensional deformity of the spine, is typically identified by a Cobb angle exceeding 10 degrees on the coronal plane[1]. Among its various forms, neuromuscular spinal deformities represent the second most frequent subtype[2]. This condition is commonly associated with underlying neuromuscular disorders, such as cerebral palsy, muscular dystrophies, or spinal muscular atrophy, which interfere with motor control and muscle tone.

In contrast to idiopathic scoliosis, curves in neuromuscular scoliosis patients tend to present earlier and often progress rapidly[3]. These deformities are usually more extensive and rigid, posing greater surgical challenges. Untreated cases can lead to deterioration in sitting balance, difficulty in mobility, and severe cases, compromise of respiratory and cardiac functions[4].

The extent of spinal curvature and its progression are closely related to the nature of the underlying neuromuscular disease. As such, surgical planning must be individualized, taking into account the patient's functional capacity, ambulatory status, and systemic health[5]. Although recent improvements in spinal instrumentation have enhanced the correction potential and overall outcomes[6], complication rates-especially in the perioperative period-remain high, necessitating a collaborative, multidisciplinary care model[7]. These complications result in longer stays in hospital and intensive care, placing a heavy burden on healthcare resources[8].

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The primary goals of surgery in this context include curve correction, enhancement of sitting and standing balance, pain reduction, and improved pulmonary function and quality of life[9]. Despite these objectives, intraoperative and postoperative complications continue to be a pressing concern. In our study, we aimed to classify these complications and analyze the risk factors for neuromuscular spinal deformity.

MATERIALS AND METHODS

The study was approved by the Clinical Research Ethics Committee of the University of Health Sciences Türkiye, Başakşehir Çam and Sakura City Hospital (decision number: 213, date: 27.03.2024), and was conducted in accordance with the principles outlined in the Declaration of Helsinki. Written informed consent was obtained from all participating patients and their legal guardians before data collection.

Pediatric patients diagnosed with neuromuscular spinal deformity who underwent surgical correction between June 2020 and December 2024 were retrospectively reviewed. Inclusion criteria consisted of complete documentation across preoperative, intraoperative, and postoperative phases, along with a minimum of six months of follow-up following surgery.

Collected demographic variables included age, sex, and ambulatory status. The underlying etiologies were categorized as central nervous system (CNS), peripheral nervous system, muscular, or mixed in origin. Operative data covered the surgical approach (posterior or anterior), type of instrumentation-either growth-friendly surgery (GFS) or posterior spinal fusion (PSF)-and additional interventions such as pelvic fixation or spinal osteotomies. Comorbidities were also recorded, including the presence of ventriculoperitoneal (VP) shunts and previous spinal surgery history related to spinal anomalies (e.g., tethered cord release, diastematomyelia surgery, or myelomeningocele repair). Intraoperative data included surgical duration, estimated blood loss, dural injury, and neurological events.

All patients were treated under a standardized surgical protocol. This included the administration of intravenous tranexamic acid (TXA) at induction, the use of prophylactic topical vancomycin, and the application of autograft material before wound closure. Surgical strategies were individualized based on curve characteristics, patient age, and progression rate. Growth-friendly techniques employed included Magnetic Expansion Control (MAGEC) rods, Shilla guidance systems, traditional growing rods, and other expandable constructs. For fusion cases, posterior spinal arthrodesis was the standard technique, supplemented with osteotomies where necessary. Pelvic fixation was performed when required. This was based on the status of the patient and the severity of the Cobb curvature and pelvic obliquity degree. Intraoperative neuromonitoring (motor-evoked potential, somatosensory evoked potentials, and electromyography) was routinely utilized.

Complications were stratified into intraoperative and postoperative events. Intraoperative complications were defined as excessive blood loss (≥30% of estimated blood volume), dural tears, and neurologic injury. Postoperative complications were further divided into early (within six weeks) and late (beyond six weeks) and categorized into three subtypes: infectious (superficial or deep SSI), respiratory (e.g., pneumonia, prolonged intubation, atelectasis, pneumothorax), and implant-related issues (e.g., screw loosening, breakage, rod migration, skin erosion).

Statistical Analysis

Statistical analysis was performed using SPSS version 27.0. The normality of data was evaluated with both Kolmogorov-Smirnov and Shapiro-Wilk tests. Normally distributed continuous variables were analyzed using the independent-samples t-test, while non-normally distributed data were evaluated with the Mann-Whitney U test. Categorical data were assessed via chi-squared or Fisher's exact tests as appropriate. Multivariate logistic regression was applied to identify factors independently associated with complication risk. A p-value of less than 0.05 was considered statistically significant.

RESULTS

A total of 45 pediatric patients underwent surgical correction for neuromuscular spinal deformity. Among them, 24 (53%) were female and 21 (47%) were male. The average age at the time of surgery was 11.7 years (range: 8-18 years), with a mean postoperative follow-up duration of 27.5 months (range: 7-48 months).

Etiology

The distribution of underlying diagnoses was as follows:

- **CNS disorders:** Cerebral palsy (n=13), syringomyelia (n=1), Chiari malformation (n=2), hydrocephalus (n=1), autism spectrum disorder (n=1), transverse myelitis (n=1).
- **Mixed central-peripheral etiology:** Myelomeningocele (n=19).
- **Peripheral neurological disorders:** Polyneuropathy (n=2), Friedreich's ataxia (n=1), spinal muscular atrophy type I (n=1).
- **Muscular disorders:** Myopathy (n=3).

Radiological and Surgical Parameters

The mean preoperative coronal Cobb angle was 55° (range: 30°-90°). Mean thoracic kyphosis (T5-T12) was 38° (range: 15°-70°), and mean lumbar lordosis (L1-S1) was 42° (range: 10°-70°). Four patients with myelomeningocele with lumbar kyphosis underwent kyphectomy, while the remaining 41 cases underwent scoliosis correction. Following surgery, the average Cobb angle improved to 10° (range: 0°-15°), with thoracic kyphosis reduced to 35° (range: 15°-50°) and lumbar lordosis to 40° (range: 10°-70°).

A posterior-only surgical approach was used in 44 out of 45 cases (97.7%), with a single myelomeningocele patient, who underwent anterior surgery. GFS were applied in 13 patients and included: MAGEC rods (n=7), Shilla rods (n=2), traditional growing rods (n=2), and sliding systems (n=2). PSF was performed in 32 cases. Among these, 18 patients underwent spinal osteotomy, and 21 required pelvic fixation using iliosacral or sacral alar-iliac screw instrumentation.

Complications

Overall complications were observed in 25 patients (55.6%). Intraoperative events occurred in 17 cases (37.8%) and included excessive bleeding (n=14), dural tears (n=2), and one transient neurological deficit. A total of 40 postoperative complications were recorded: surgical site infections (SSI) in 16 patients, respiratory issues in 12, and implant-related complications in nine. Rare complications included VP shunt dysfunction (one patient), gastrointestinal ileus (one patient), and cardiac arrest resulting in death (one patient).

The management of SSI involved treating five patients with intravenous antibiotics and wound care on the ward, eight patients with both treatment and surgical debridements in the operating room, and three patients were transferred to the intensive care unit (ICU) due to wound site-related sepsis. Respiratory complications included pneumonia (n=5), prolonged intubation (n=4), pneumothorax (n=2), and atelectasis (n=1). Implant-related problems were screw loosening or breakage (n=4), rod fracture (n=1), and soft-tissue erosion/skin breakdown (n=4). Some individuals experienced multiple complications (Figure 1).

Risk Factor Analysis

Patients with intraoperative complications were, on average, significantly older than those without (13.3 vs. 10.8 years, p=0.033). No association was found between complications and sex or deformity magnitude in either the coronal or sagittal plane (p>0.05). PSF procedures were linked with a significantly higher intraoperative complication rate compared to GFS (p=0.008).

Longer operative time was associated with both intraoperative (p=0.049) and postoperative complications (p=0.003). Higher intraoperative bleeding also correlated with increased complication rates (p<0.001 intraoperative; p=0.034 postoperative). These patients also required more transfusions (p=0.003 intraoperative; p=0.030 postoperative). Postoperative complications led to extended hospitalization (p<0.001) and prolonged ICU stays (p=0.036).

Pelvic fixation was found to significantly increase the likelihood of postoperative complications [odds ratio (OR): 3.2, p=0.009]. Other independent predictors were non-ambulatory status (OR: 2.9, p=0.033), the presence of a VP shunt (OR: 4.5, p=0.007) and previous spinal surgery (OR: 2.6, p=0.045).

DISCUSSION

Neuromuscular spinal deformities present significant challenges to surgical correction due to their complex interplay with musculoskeletal deformities and systemic comorbidities[10]. Neuromuscular patients frequently exhibit multi-organ involvement, thereby increasing perioperative risk[7]. It is imperative that these vulnerabilities are recognised and addressed in order to facilitate safe surgical planning, intraoperative management, and postoperative care. Surgical correction of neuromuscular scoliosis has been shown to be associated with a high complication rate, ranging from 17 to 74%[11].

The study found that 55.6% of patients experienced surgical complications. The most common intraoperative event was excessive bleeding, followed by dural tears and neurological injuries. Postoperatively, 40 complications were documented, primarily involving SSIs, respiratory problems, and implant-related issues. Infections ranged from superficial to deep SSIs and sepsis. Respiratory complications included pneumonia, atelectasis, prolonged intubation, and pneumothorax. Implant-related issues included rod fractures, pedicle screw loosening or breakage, and skin irritation due to hardware prominence.

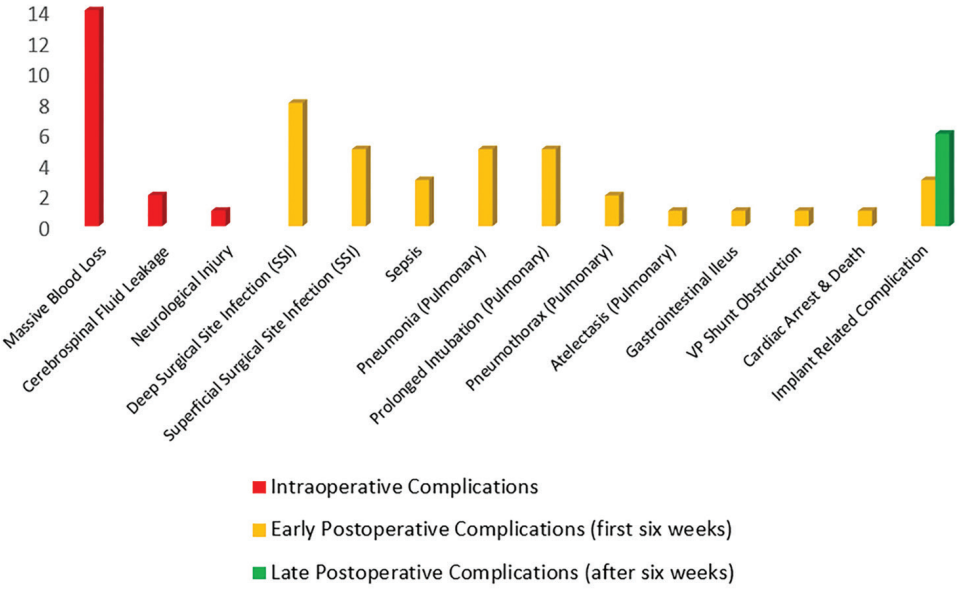

Figure 1. This illustrates the number of patients who experienced intraoperative and postoperative complications

Less common but clinically significant complications included VP shunt obstruction, gastrointestinal ileus and cardiac arrest/death. Several patients experienced multiple complications.

The study identifies risk factors associated with complications, including non-ambulatory status, VP shunt presence, previous spinal surgery history, and pelvic fixation use. Older age also correlates with increased intraoperative complications. The findings emphasize the need for comprehensive preoperative risk stratification for preventive measures. Complications in patients with prolonged surgeries, higher intraoperative bleeding, and blood transfusions result in longer ICU and hospital stays, highlighting the need for comprehensive risk stratification.

Previous studies have linked severe spinal deformities (e.g., Cobb ⩾50°, hyperlordosis, thoracolumbar kyphosis) with higher complication rates[12-14], but our data did not show a significant correlation between coronal or sagittal deformity and overall complications.

Although there was a difference in age at the initial surgery, PSF may be more effective than GFS at managing deformity. Although GFS patients experience greater spinal growth, they also encounter more complications and require additional surgeries[15]. However, GFS has several benefits, including improved lung health, better correction of deformities and an enhanced quality of life[16]. Furthermore, GFS has been associated with less blood loss, shorter surgeries, and faster recovery times[17]. Our research shows that GFS reduces bleeding during surgery much more effectively than PSF. However, GFS did not reduce the rate of complications after surgery compared to PSF.

Patients with neuromuscular disease are at high risk of extensive blood loss due to factors such as older age, increased fusion length, prolonged procedures and reduced bone mineral density[18-20]. Coagulopathies, often caused by antiepileptic drugs or an underlying condition, can also increase the risk of bleeding[21]. Bleeding often necessitates blood transfusions and extended hospital stays[22]. Perioperative blood transfusions also increase the risk of wound infection[23]. Topical and systemic TXA, hemostatic matrixes, and fibrin glues have been reported to effectively reduce bleeding[24,25]. In addition, a dual-surgeon approach has been demonstrated to reduce operative time, blood loss, complication rates and hospital stays[26]. In our study, excessive bleeding was associated with longer operative times, higher transfusion requirements, and longer stays in the ICU and hospital. Our data also showed that older patients experienced a higher amount of intraoperative bleeding. Postoperative complications were significantly associated with longer operative times and higher blood loss.

Patients who have undergone spinal surgery or intrathecal procedures are at a higher risk due to the presence of dural adhesions, altered anatomy, and compromised tissue planes[27]. Dural tears can lead to cerebrospinal fluid leakage, pseudomeningoceles, arachnoiditis, and wound infection[28]. Two patients with myelomeningocele in our cohort recovered without complications after their dural tears were repaired during surgery.

Preoperative computed tomography and magnetic resonance imaging imaging of the entire spine, as well as intraoperative neuromonitoring, are essential for ensuring neurological protection[29,30]. In our cohort, one non-ambulatory patient with myelomeningocele experienced transient hip flexor weakness which resolved within three months after surgery.

Malnutrition is common among neuromuscular patients due to feeding difficulties, gastrointestinal dysmotility, and increased metabolic requirements[31]. Low serum albumin and prealbumin levels can hinder wound healing and increase the risk of infection[32]. Poor nutritional status can also exacerbate respiratory muscle weakness and delay healing[33]. Percutaneous endoscopic gastrostomy tube feeding is often necessary to meet these patients' caloric requirements and prevent aspiration[34].

Patients with neuromuscular conditions are at a higher risk of infection following spinal fusion. Reported rates are 6-15% for patients with cerebral palsy and 8-42% for those with myelodysplasia. SSIs result in increased patient morbidity, the need for multiple operations, prolonged hospital stays and significant financial costs[35]. A study found that wound infection in children treated surgically for neuromuscular spinal deformity was associated with increased body weight after surgery, residual lumbar lordosis, pulmonary comorbidity, a history of myelomeningocele repair, seizures and previous operations[36]. The presence of a VP shunt prior to corrective surgery significantly increases the likelihood of a wound infection[37]. Our cohort confirms this, with a high incidence of postoperative complications in VP shunt patients. One case also required surgical shunt revision in the early postoperative period. The management of SSI involved treating five patients with intravenous antibiotics and wound care on the ward, eight patients with both treatment and surgical debridements in the operating room, and three patients were transferred to the ICU due to wound site-related sepsis.

Respiratory complications are particularly prevalent in this population due to weakened musculature and impaired thoracic mechanics[38]. These complications can include pneumonia, pneumothorax, atelectasis and pleural effusion, as well as the need for prolonged mechanical ventilation[39]. Patients with conditions such as Duchenne muscular dystrophy and spinal muscular atrophy are particularly susceptible to respiratory problems following surgery for spinal deformity[40,41]. Our findings were consistent with those reported in the literature, with pneumonia, prolonged intubation, atelectasis and pneumothorax being the most common postoperative respiratory issues. Although perioperative pulmonary rehabilitation has been shown to reduce the risk of respiratory complications[42], limited cooperation may hinder recovery and increase the risk of complications.

Patients with non-ambulatory status are more susceptible to implant-related issues, such as rod fractures, screw loosening and implant migration, partly due to poor bone quality[43]. Furthermore, non-ambulatory patients often have pelvic obliquity and hip dislocation, which impair sitting balance

and quality of life[44,45]. Of the 45 patients in our study, 23 had hip dislocation; all of these patients had an underlying neuromuscular condition, primarily myelomeningocele or cerebral palsy. Although pelvic fixation can improve alignment and function, it increases surgical complexity and the risk of complications[46,47]. Our data confirmed higher postoperative complication rates in non-ambulatory patients and in those requiring pelvic fixation. Several patients required revision surgery due to rod or screw breakage or loosening, as well as soft tissue irritation and skin breakdown. Figure 2 shows the postoperative complications related to the implant in a non-ambulatory patient with myelomeningocele and a VP shunt, who underwent lumbar kyphectomy and pelvic fixation. The patient is still being followed up and treated.

Although less common, gastrointestinal complications can arise from the use of narcotic analgesics and reduced motility[48]. One patient developed postoperative paralytic ileus, which was managed conservatively.

Cardiac complications are also a concern, particularly in patients with muscular dystrophy[49,50]. One patient in our cohort with type 4 collagen myopathy experienced cardiac arrest after surgery and subsequently died from multi-organ failure in the ICU. This case emphasises the importance of thorough cardiac evaluation prior to surgery.

Study Limitations

This study has several limitations. Its retrospective design and relatively small sample size limit the generalisability of our findings. Additionally, variability in follow-up duration and the lack of consistent data on nutritional status and pulmonary function further limit the ability to assess specific risk factors.

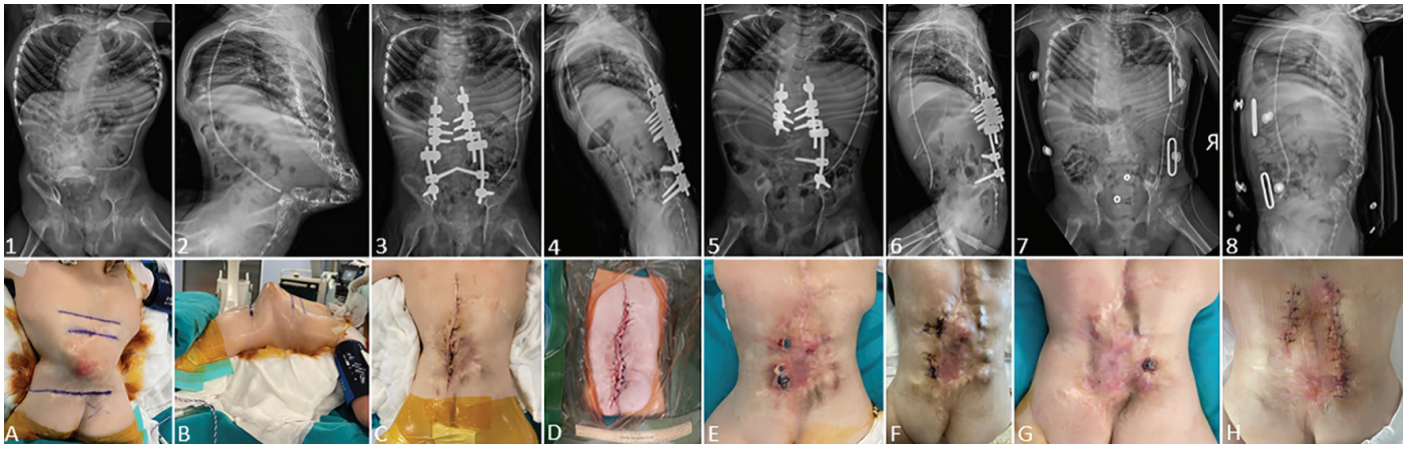

Figure 2. (1) and (2) show X-ray images of a patient with myelomeningocele taken before deformity surgery. (3) and (4) show X-ray images taken after the first surgical debridement. (5) and (6) show the results of the second surgical debridement, which involved implant removal due to exposure. (7) and (8) show the X-rays taken after the third surgical debridement, when all the implants were removed due to exposure. (A) and (B) show photographs of the patient's skin before the initial deformity surgery. (C) and (D) are photographs of the patient's skin before (C) and after (D) the first surgical debridement at 3 weeks after index surgery. (E) and (F) are photographs of the patient's skin before (E) and after (F) the second surgical debridement at 4 months after index surgery. (G) and (H) are photographs of the patient's skin before (G) and after (H) third surgical debridement at 6 months after index surgery

CONCLUSION

This study highlights the complex and multifactorial nature of surgical complications in neuromuscular scoliosis. Non-ambulatory status, pelvic fixation, VP shunts, and previous spinal surgery significantly increase the risk of postoperative complications. Comprehensive preoperative assessment, multidisciplinary management, and careful surgical planning are critical in reducing morbidity and improving outcomes in this vulnerable population. Future prospective studies are needed to validate these findings and refine perioperative risk models.

Ethics

Ethics Committee Approval: The study was approved by the Clinical Research Ethics Committee of the University of Health Sciences Türkiye, Başakşehir Çam and Sakura City Hospital (decision number: 213, date: 27.03.2024).

Informed Consent: Written informed consent was obtained from all participating patients and their legal guardians before data collection.

Footnotes

Authorship Contributions

Surgical and Medical Practices: Y.Ö., K.A., A.V.Ö., M.B.B., Concept: M.B.B., Design: Y.Ö., Data Collection or Processing: Y.Ö., Analysis or Interpretation: K.A., Literature Search: Y.Ö., A.V.Ö., Writing: Y.Ö.

Conflict of Interest: No conflict of interest was declared by the authors.

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