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ORIGINAL RESEARCH

Efficacy of Modified Transforaminal Lumbar Interbody Fusion in Three-Planar Correction for Severe Adult Spinal Deformity: Radiographic and Clinical Outcomes

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Background: Adult spinal deformity (ASD) significantly impacts quality of life in geriatric populations due to severe sagittal imbalance, degenerative scoliosis, and associated neurological compression that usually requires surgery when conservative treatment fails.

Objective: To evaluate the clinical and radiological outcome of a modified transforaminal lumbar interbody fusion (TLIF) technique in the three-planar correction of severe adult spinal deformity (ASD).

Methods: This was a single-center case series study. We recruited 72 ASD patients (mean age 64.5 years) with at least one of the following criteria met (SRS-Schwab sagittal modifier ++; Cobb angle >30°; Coronal vertical axis >3cm) operated between January 2020 and May 2025. The surgical protocol involved four modifications: (1) bilateral facetectomy and posterior column resection; (2) a concave-side approach to the disc space; (3) anterior positioning of the PEEK cage; and (4) supplemental bone grafting posterior to the cage. Clinical and radiological outcomes were evaluated at a mean follow-up of 2.3 years.

Results: Significant improvements were observed in SRS-22 (2.6 to 3.7) and NCOS (43 to 74.5) scores ($p < 0.05$). After surgery, both PI-LL mismatch and the Cobb angle have been markedly improved (35° down to 17° and 21.5° down to 5°, respectively). The fusion rate was 90% at 1 year. Univariate analysis identified osteoporosis (OR = 13.4, $p<0.05$), "pear-shaped" disc morphology (OR = 14, $p<0.05$), and PI > 65° (OR = 13.7, $p<0.05$) as significant risk factors for unchanged sagittal modifier after surgery. Early complications included infection (2.7%) and pneumonia (2.7%) whereas the main mid-term adverse event was PJK (15%).

Conclusion: Modified TLIF is associated with improvement of mid-term radiographic and clinical outcomes and an acceptable complication rate. Additional research involving larger cohorts and extended follow-up, preferably with a control group, is required to reach more definitive conclusions.

Keywords: modified transforaminal lumbar interbody fusion, sagittal imbalance, degenerative scoliosis, coronal malalignment, lumbar spinal stenosis

Background

Adult spinal deformity (ASD) encompasses malalignments in both the sagittal and coronal planes, typically manifesting as sagittal imbalance and degenerative scoliosis, and is commonly observed in the geriatric population. In addition to low back pain being the chief complaint in most cases, symptoms of neurological compression due to spinal stenosis or degenerative spondylolisthesis are also major negative factors affecting the patient's quality of life. Corrective surgery is usually indicated for severe ASD cases when conservative treatment fails with the following two main goals: (1) restoring both coronal and sagittal balance and (2) neurological decompression.[1] Severe spinal deformity was defined when at least one of the following

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radiographic findings occured: (1) severe sagittal imbalance (sagittal modifier ++), (2) severe coronal imbalance (CVA >3cm) or (3) severe degenerative scoliosis (Cobb angle of the main lumbar curve ≥30°).

With the progress in technology and surgical techniques, different MIS techniques (OLIF, ALIF, and MIS-TLIF) are becoming increasingly popular for patients with ASD.[2] In developing countries with limited resources, multilevel transforaminal lumbar interbody fusion (TLIF) remains one of the most popular options, as financial barriers could reduce the accessibility of novel techniques.[3] In Vietnam, MIS-TLIF is primarily reserved for one- or two-level pathologies, while the application of multi-level OLIF and ALIF remains in the experimental phase. Conversely, extensive procedures such as three-column osteotomy are often considered too invasive for elderly patients with ASD. Those are the reasons why TLIF operation still remains one of the most popular options for surgeons. The drawbacks of conventional TLIF comprise limited ability of lordosis restoration[4] and the risk of cage subsidence[5] that can lead to non-union. To resolve these problems, we applied four major modifications: additional posterior column osteotomy, approaching the disc space from the concave side for PEEK case insertion, pushing the PEEK cage to the anterior half of the disc space to promote segmental lordosis correction, and additional bone grafting behind the cage to enhance bone fusion (Figure 1). These modifications were separately proposed in various domestic and international articles and researches and have been proven to be superior than conventional TLIF. However, most of studies focused on one or two pathology levels (lumbar spinal stenosis, spondylolisthesis) and not on severe ASD patients. Furthermore, to the best of our knowledge, this study is among the few to implement all modifications simultaneously, with the objective of optimizing both corrective power and fusion rates. To this end, we performed a prospective pilot study evaluating the efficacy of the modified TLIF technique.

Patients and Methods

Design of Study

A case series study was conducted to assess the radiological and clinical outcomes of modified TLIF. Patients with ASD who satisfied the inclusion and exclusion criteria and underwent the modified TLIF technique between January 2020 and May 2025 were recruited. Informed consent was obtained from all participants and the study was approved by the Research Ethics Board of Hospital for Traumatology and Orthopedics, Ho Chi Minh city, Vietnam; number of ethics document: 03/HDDD-BVCTCH and our study complies with the declaration of Helsinki.

Patient Selection

The inclusion criteria were as follows: age >50 years; severe spinal deformity with at least one of the following radiographic findings: (1) severe sagittal imbalance (sagittal modifier ++), (2) severe coronal imbalance (type B or

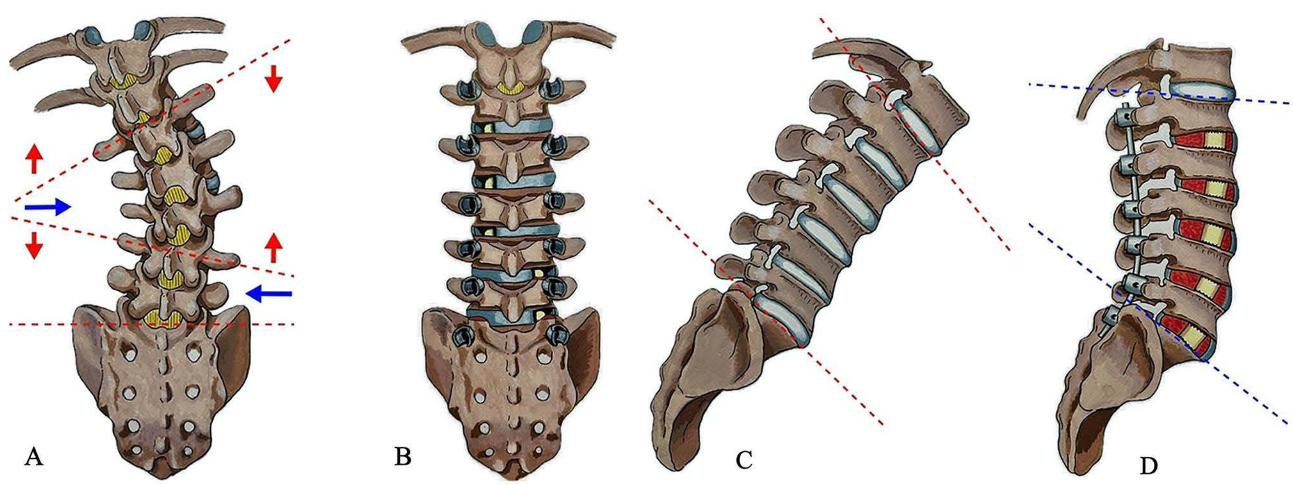

Figure 1 Modified TLIF protocol illustration. Degenerative scoliosis (**A**) often presents with coexisting main lumbar and lumbosacral fractional curves in opposite concave directions (red dotted lines). To straighten the spine (**B**), the surgeon distracts the concave sides and compresses the convex sides (red arrows) via PEEK cage insertion from the concave aspect of the curves (blue arrows). Preoperative kyphosis (**C**) and postoperative lordosis (**D**) restoration are shown (red and blue dotted lines, respectively). Cages are placed in the anterior disc space with supplemental bone graft positioned posteriorly.

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C according to Bao classification) or (3) severe degenerative scoliosis (Cobb angle of the main lumbar curve ≥30°) and back and/or leg pain refractory to conservative treatment.

The exclusion criteria included uncontrolled comorbidities (hypertension, diabetes mellitus, and Parkinson's disease) and acute or subacute infections (skin infection, pneumonia, tuberculosis, and spondylodiscitis).

Surgical Planning

All patients were indicated to have a digital full spine X-ray, and the measurement and evaluation were performed using Surgimap software, which has been proven reliable in surgical planning and projection of radiological outcome after correction.[6–10] This software also simulates the surgical tools, allowing surgeons to identify the optimal screw length, PEEK cage size, and position at each level. In addition to virtual assessment and planning, we used a 3D printed spinal model for each patient as a practical tool. The 3D model was based on the cortical bone density obtained from the CT scan of the spine, and therefore provided a tubular structure of the real pedicles, which in turn served as a realistic sawbone for preoperative practice. The ability to handle the model, study it from different angles, and even place pedicle screws provide profound and realistic insight to surgeons.

Surgical Technique

The patient was placed in the prone position on the surgical frame under general anesthesia. The pathological spinal portion was exposed using a conventional midline incision, followed by subperiosteal dissection, and pedicle screws were placed at predetermined levels using the freehand technique. Neurological decompression was performed at the symptomatic level by full laminectomy or posterior column resection with flavectomy, depending on the severity of spinal stenosis. In either way of decompression, full facetectomy was performed bilaterally in order to obtain adequate foraminal decompression and lordosis restoration. TLIF was performed at designated levels, and the approach to the disc space was always from the concave side to open up the disc height, resulting in adequate foraminal decompression and segmental coronal correction. The PEEK cage was inserted into the disc space to the ideal depth calculated from the preoperative surgical plan, ensuring that its center was located in front of the center of the disc space to maximize the fulcrum effect for the subsequent correction steps. A morselized bone graft (obtained from the removed lamina and facet joints) was then placed in the disc space behind the cage to enhance the fusion rate. The annular cut hole was sealed with Gelfoam to prevent the bone graft from protruding into the spinal canal. The first rod was measured, cut, contoured, and inserted on the convex side. The rod derotation maneuver was then performed to correct the scoliotic and rotational deformities of the lumbar spine. The other rod is placed on the concave side. The head screws were then compressed from bottom to top, focusing on the convex side to correct both sagittal and coronal deformities. An intraoperative C-arm check was performed to ensure that the correction met the planned threshold.

Outcome Assessment

The radiographic assessment and measurement were done independently by another radiologist and proper blinding procedure was employed throughout the study. The radiological outcomes were evaluated separately in the coronal and sagittal planes. Spinal parameters in the sagittal plane included the sagittal vertical axis (SVA), pelvic tilt (PT), sacral slope (SS), lumbar lordosis (LL), and thoracic kyphosis (TK), while those in the coronal plane included the Cobb angle (CA) and coronal vertical axis (CVA). In the sagittal plane, a good outcome was defined as a postoperative decrease in the severity of all SRS-Schwab sagittal modifiers. In the coronal plane, a good outcome was defined as a final Bao classification of type A (CVA <3 cm). All patients underwent a CT scan at one-year postop in order to evaluate bone fusion. The criteria for fusion were based on the Bridwell classification. We also evaluated the effect of correction in the axial plane by measuring the axis angle of the apical vertebra on axial CT scans before and after the operation. This evaluation was limited to a subgroup of patients with severe apical vertebral rotation (Nash–Moe grade ++ or above) that required rotational correction.

Clinical outcome evaluation was based on the two main chief complaints of the patients: back pain and neurological claudication. Back pain and its effect on quality of life were assessed using the SRS22 scoring system. A good outcome was defined when the improvement in SRS22 score at the final follow-up was equal to or superior to the minimal clinically important difference (MCID), which is 0.77 according to Carreon.[11] Neurological claudication was evaluated

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using a neurological claudication outcome score (NCOS) system. The NCOS system scored the neurological status of patients from 0/100 (extremely poor) to 100/100 (perfectly healthy), and a good outcome was defined as a final NCOS score of 60 points and above.

Statistical Analysis

All data were analyzed using non-parametric methods. Clinical and radiological outcomes were assessed preoperatively, three months postoperatively, and at the final follow-up and compared with each other using the Wilcoxon signed-rank test. Univariate logistic regression was used to identify relationships between binary variables. All results were considered statistically significant at $P<0.05$. Statistical analyses were performed using the STATA 18.0 BE software package.

Results

Patient Demographics

Seventy-two patients were recruited in our study (12 men and 60 women), with a mean age of 64.5 (61.8–69.8) years and a mean follow-up time of 2.3 (1.6–2.8) years. All patients presented with severe back pain (preop SRS22 of 2.6 (2.2–2.7)), 62 patients (86%) presented with radiculopathy, and 10 patients (14%) presented with neurological deficit (drop foot). The most common comorbidities included hypertension (56/72), diabetes mellitus (18/72) and Cushing syndrome 13/72). Fifty patients (70%) had two or more comorbidities.

The highest UIV was T9, whereas in the majority of cases, the UIV was L1 or L2 (52/72), as we attempted to minimize the instrumentation as much as possible. The LIV was S1 in all patients, and additional iliac screws were used in 15 patients. The average number of fusion levels was 5 (4–6), the average operative time was 210 (200–240) min, the average blood loss was 700 (562–800) mL, the average time from the operation to getting out of bed was 2.2 (2–3) days, and the average postoperative hospital stay was 8.5 (7–14) days.

Clinical and Radiological Outcome Evaluation (Table 1)

Both back pain (presented by SRS22 score) and neurological status (presented by NCOS score) improved remarkably over time, when their values at preop, 3 month-postoperative and final follow-up (FU) assessments were significantly different ($P<0.05$).

In terms of radiographic outcomes, the efficacy of sagittal balance restoration was demonstrated when all sagittal parameters (SVA, PT, PI-LL, and TK) improved significantly after surgery ($P<0.05$). When comparing these parameters at 3 months postoperatively and at the final FU assessments, there was no difference ($P>0.05$), demonstrating the ability of preserving the correction of the instrument (with only three cases (4%) having correction loss over time). The same results were observed in the coronal plane when both the CA and CVA could be corrected to ideal values after surgery, with only one case (1%) showing coronal correction loss. Although the rate of correction loss in both planes was relatively low, it remains a concern for surgeons when managing elderly patients with poor bone quality.

When evaluating the power of rotational correction of modified TLIF on the axial plane, we only focused on cases with severe apical vertebral rotation (AVR) presented on plain radiography with Nash–Moe grade classified as ++ or above. Seventeen (24%) patients had severe AVR, and the effect of rotational correction of modified TLIF was verified when significant improvement in vertebral rotation was noticed after surgery, specifically at 17.5° and 7°, before and after surgery, respectively. The fusion rate was 90% based on the CT scan evaluation at the one-year postoperative follow-up.

Complications

Early complications included two (2.7%) cases of infection, two (2.7%) cases of pneumonia, and no surgery-related fatalities have been noticed. The main late complication in our study was proximal junctional kyphosis (PJK), which occurred in 11 patients (15%) with mild-to-no clinical effect, and all PJK cases were stable over time. No implant failure or cage protrusion was observed during the final follow-up.

Table 1 Comparison of Clinical Status and Radiographic Parameters at Different Times: Preoperative, Three-Month Postoperative and Final Follow-Up

Parameters	Preop	Postop	Final FU	*p* (Preop and 3m Postop)	*p* (3m Postop and Final FU)	*p* (Preop and Final FU)
Clinical outcome (n = 72)*						
SRS22	2.6 (2.2–2.7)	3.3 (3.1–3.5)	3.7 (3.6–3.8)	< 0.0001	<0.0001	<0.0001
Good outcome			82%			
NCOS	43 (32–47)	67.5 (60–69)	74.5 (72–79)	< 0.0001	<0.0001	<0.0001
Good outcome			90%			
Sagittal plane (n = 72)*						
SVA (cm)	52 (30–76)	35,5. (12.5–55.8)	40 (23.3–54.8)	<0.0001	0.113	0.0059
PT (°)	30 (21.3–34)	19 (24–28)	22 (19.3–26)	< 0.0001	0.486	<0.0001
LL (°)	15,5 (6.5–25)	32 (26–38)	35 (21.5–37)	<0.0001	0.064	<0.0001
PI-LL (°)	35 (26.3–43)	17 (12–20)	18 (13.3–24)	<0.0001	0.0875	<0.05
TK (°)	19 (15–20)	29 (25–31)	31 (28–32)	<0.0001	0.207	<0.0001
Good outcome		61 (85%)	58 (81,2%)			
Coronal plane (n = 72)*						
CVA (cm)	16 (12–23)	10 (5–13.9)	8 (5–10)	<0.0001	0.176	<0.0001
Cobb angle (°)	21.5 (16.5–31)	5 (3–9)	7 (4–8)	<0.0001	0.202	<0.0001
Good outcome		67 (93%)	66 (92%)			
Axial plane (n = 17)*						
Vertebral rotation (°)	17.5 (11–21.5)	8 (3–10.5)	7 (3.5–9.5)	<0.0001	0.185	<0.0001
Fusion rate (n = 72)			90%			

Note: *Wilcoxon sign-rank test.

Regression Analysis

Univariate analysis was performed to identify risk factors for poor outcomes in terms of postoperative back pain, poor neurological recovery, and poor radiographic outcomes in both sagittal and coronal planes. In terms of back pain, risk factors for poor outcome included SRS-Schwab sagittal modifiers that remained unchanged after surgery (OR = 42, (9.11–219.17)) and non-union (OR = 6.1, (1.29–28.93)), while other factors, including age (>70 years), sex, obesity, permanent coronal malalignment (CVA >3 cm), and PJK, did not affect the final clinical outcome.

When analyzing the risk factors for poor neurological recovery, we found that preoperative NCOS < 40/100 (OR=11.72 (1.32–101.58)) and foot drop (OR=6.21, 1.14–33.27) were risk factors, implying that existing severe nerve root damage due to chronic compression would impede neurological recovery despite thorough decompression. Other factors such as age, sex, and MRI-based severity of spinal stenosis did not have any effect on neurological recovery.

In terms of sagittal balance restoration, osteoporosis (OR = 13.4, (3.13–88.77)), pear-shape disc (OR = 14, (2.36–-72.96)) and high PI (>65°) (OR = 13.7, (2.65–69.43)) were risk factors of poor radiographic outcome on sagittal plane (sagittal modifier unchanged). In the coronal plane, the risk factor for poor radiographic outcome (CVA >3 cm) was preoperative type C (OR = 16.8, (2.59–104.85)), while the preoperative Cobb angle and amount of scoliosis correction did not affect the final radiographic outcome in the coronal plane.

Discussion

Goals of Correction in Coronal and Sagittal Planes

The keystone in corrective surgery for ASD is determining the required amount of correction in both the coronal and sagittal planes to restore adequate global balance. In the coronal plane, we utilized the Bao classification, according to which types B and C (CVA exceeding 3 cm) were corrected to type A (CVA < 3 cm).[12] The greatest challenge lies in determining the optimal postoperative lumbar lordosis (LL). Although numerous methods and classifications have been proposed to assess sagittal balance, the SRS-Schwab classification remains the most popular consensus-based protocol for managing sagittal imbalance.[13] According to the "cone of economy" principle of Dubousset, the body achieves the optimal state in terms of

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energy (where paraspinal muscle activity and energy expenditure are minimized) in the upright posture when the spine is well-balanced.[14] Specifically, all sagittal balance modifiers were classified as "level 0", with PI-LL <10°, PT <20° and SVA <45 mm. However, in elderly populations, correcting the spine to this perfectly balanced state might not yield significant clinical benefits; conversely, it could increase the risk of complications, such as instrument failure, proximal junctional kyphosis (PJK), and adjacent segment degeneration.[15] Several age-adjusted sagittal balance concepts[16,17] have been proposed. However, in reality, the application of these recommendations could be complicated because a specific value of LL, PT, or SVA is difficult to achieve. Passias argued that correcting a deformed spine precisely as planned is clinically challenging, and that a margin of error would be more realistic and feasible in clinical practice.[18] The authors concluded that for severe lumbar spinal deformity cases with SRS-Schwab sagittal imbalance modifiers ++, correcting for mild imbalance (modifiers +) is sufficient to achieve a good clinical outcome. From a surgical standpoint, decreasing the PI and LL mismatch within the range of 10° to 20° in elderly patients with ASD was adequate for clinical improvement, which was the principle of sagittal correction in our study (Figure 2). Our study focused on the lumbar spine because this is the main origin of all spinal pathologies, from neurological deficits to spinal disability. Thoracic deformities in our cohort did not require rigorous correction as all curves were mild and secondary to the primary lumbar curvature. Therefore, in all the patients in our study, the highest UIV was T9.

Surgical Technique

While MIS-TLIF,[2] OLIF,[19] LLIF[20] and ALIF[21] are increasingly popular worldwide, open TLIF, with a familiar approach and no special instrumental requirement, remains an popular option in developing countries.[22] However, to correct severe deformities in elderly patients, major drawbacks of conventional TLIF (limited segmental lordotic correction ability,[4] cage subsidence[5] and posterior migration[23]) require thorough modifications. Based on the results of biomechanical and clinical studies, we propose a modified TLIF method comprising four main modifications. First, we performed posterior column resection to restore the segmental lumbar lordosis. The "from pedicle to pedicle decompression", facilitated by bilateral facetectomy, was highly suitable for ASD patients with severe central and bilateral foraminal spinal stenosis, represented by high rate of good neurological outcome at final FU in our study (90%). Second, we chose the side of the discectomy and PEEK cage insertion based on the concave side of the lumbar curve and not on the more symptomatic side of the patient (conventional TLIF). Third, the PEEK cage was positioned more to the front of the disc space compared to conventional TLIF. Specifically, a PEEK cage was considered optimally positioned when its center remained in front of the center of the disc space (Figure 3), as proposed by Vialle.[24] Anterior placement of the cage would enhance the fulcrum effect, resulting in more efficient restoration of segmental lumbar lordosis. The cortical bone

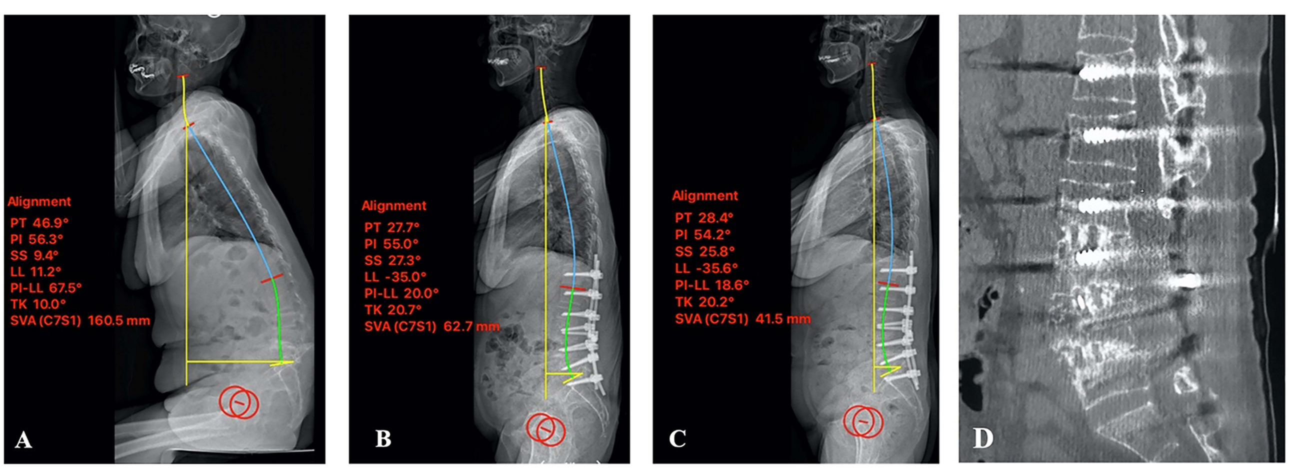

Figure 2 Full spine Xray of a 60-year-old female patient with true kyphosis of the thoracolumbar spine (**A**), resulting in severe sagittal imbalance that impeded normal standing and walking. Radiographic evaluations at 3-month (**B**) and 2-year postoperative assessment (**C**) showed excellent sagittal balance restoration with no correction loss and no PJK. One-year postop CT scan showed solid fusion at L2/3, L3/4 and L4/5 levels (**D**). The L5 vertebra was partially sacrolized and therefore no interbody fusion was required at that level.

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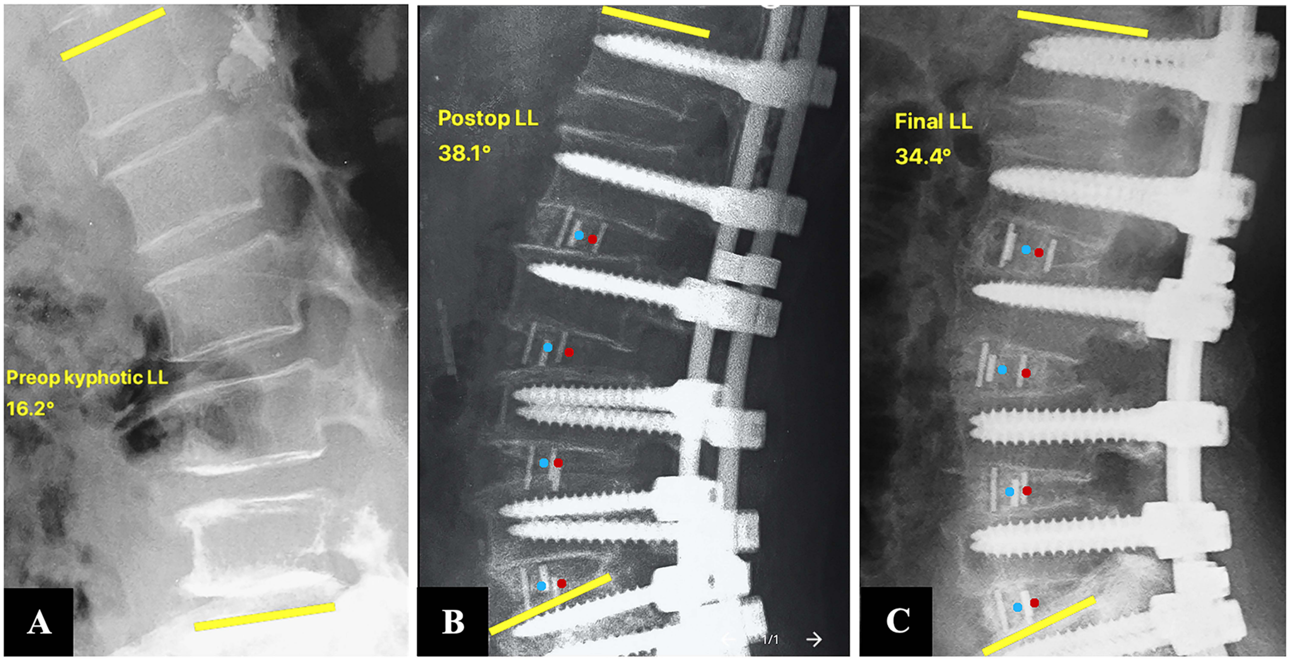

Figure 3 Illustration of a kyphotic deformity case (**A**) adequately corrected with the modified TLIF surgery. Optimal cage position according to the modified TLIF: the center of the cage (blue dot) should be anterior to the center of the disc (red dot) in order to create an effective fulcrum for segmental lordosis restoration. Good sagittal correction at three-month postoperative evaluation (**B**) with no correction loss until fusion (**C**). Lumbar kyphotic and lordotic angles were measured and shown by the yellow lines.

of the anterior half of the endplate was thicker than that of the posterior half,[25] thus an anteriorly placed cage would have a lower risk of cage subsidence, not to mention the benefit of reducing the risk of cage protrusion into the spinal canal. Fourth, placing the cage in the front enlarges the behind-cage space, designated for supplemental bone grafting. This modification has been demonstrated to be safe with a very low risk of bone protrusion into the spinal canal.[26] Furthermore, studies have proven that during disc preparation for TLIF, the posterior third of the endplate had a better fusion rate than the anterior third,[27] and additional grafting should be focused on this area to promote the fusion.

Contributing Factors to the Ability of Correction

Our analysis of the factors contributing to LL correction revealed that osteoporosis (OR = 13.4, (3.13–88.77)), "pear-shaped" disc (OR = 14, (2.36–72.96)), and PI greater than 65° (OR = 13.7, (2.65–69.43)) were risk factors for unchanged sagittal modifier after surgery. In osteoporotic patients, the vertebral endplates are prone to fracture during disc space preparation and cage subsidence could occur during the operation, preventing the "trapped" cage from moving anteriorly (Figure 4). A similar situation could be found in pear-shaped disc patients, when inserting the cage anteriorly became challenging as the cage was usually stuck at the "belly of the pear" (posterior half of the disc space) (Figure 4). The mismatch between the cage and endplate interfaces results in poor contact area and a high risk of cage subsidence.[28] Early subsidence and posterior position of the peek cage would limit the power of segmental lordosis restoration, and the final consequence was under-correction of LL. Finally, according to our analysis, a large PI (>65°) was a risk factor for insufficient sagittal restoration. A similar finding was reported in a study by Le Huec, which showed that a PI angle greater than 65° is a risk factor for insufficient LL correction to improve sagittal balance.[29] When correcting sagittal imbalance in patients with a large PI, three-column osteotomy may be considered.[30] However, as this approach is significantly more invasive and carries higher risks than TLIF,[31] surgeons should carefully consider the risk-benefit ratio during decision-making.

In the coronal plane, our study showed that the risk factor for poor radiographic outcome (CVA at the final follow-up >3 cm) was preoperative type C (Bao classification) (OR = 16.8, (2.59–104.85)). This finding was in line with those of other studies, emphasizing the importance of identifying and correcting the lumbosacral fractional curve in type

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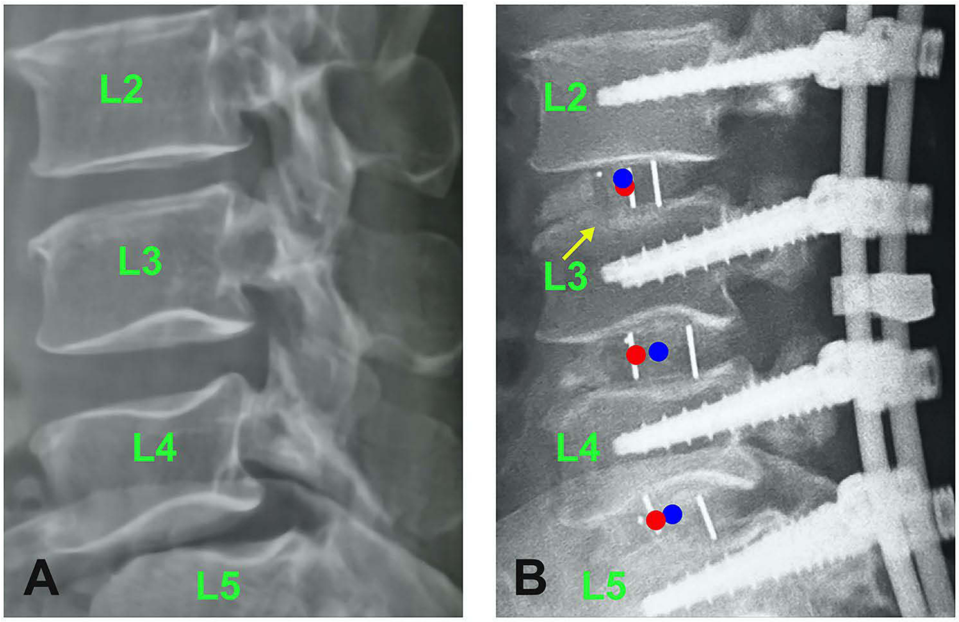

Figure 4 Illustration of potential causes for suboptimal PEEK cage positioning. Preoperative (**A**) and immediate postoperative radiographs (**B**) were shown. Note that the cages at all three levels demonstrate suboptimal placement, with cage centers (blue dots) were not positioned anteriorly relative to the disc centers (red dots). At the L2–3 level, the L3 superior endplate was inadvertently fractured during disc preparation (yellow arrow); subsequent cage subsidence prevented further anterior migration. At the L3–L4 and L4–L5 levels, the cages became sequestered within the central "belly" of the "pear-shaped" disc spaces, resulting in relatively posterior positioning.

C patients to prevent permanent postoperative malalignment[32,33] (Figure 5). Reducing the lumbosacral curve could be challenging as the formation of bridging osteophytes on the concave side usually complicates the restoration of intervertebral disc height at the L4-L5 and L5-S1 levels. In such cases, the surgical strategy involves discectomy and disc preparation from the convex side. Sequential disc space dilation and mobilization were performed from the convex to the concave side with caution, and the dilator size was incrementally increased until the concave disc space was sufficiently enlarged to achieve the required foraminal decompression and realignment of the deformity. Finally, the interbody cage was inserted from the concave side to correct segmental scoliosis.

Vertebral rotational deformity in ASD patients is usually mild, and cases with pronounced rotated apical vertebrae are usually accompanied by neglected idiopathic scoliosis during adolescence.[34] In our study, only 17 patients had severe rotation deformity of the apical vertebrae, and all of them were efficiently corrected in the axial plane, with the preop and final apical axis angles of 17.5° and 7°, respectively ($P<0.05$). Few studies have focused on the benefit of vertebral derotation in adult degenerative scoliosis; however, we believe that by correcting the axial deformity in ASD patients with severe apical vertebral rotation, we could improve their sagittal imbalance and cosmetic outcome.

Clinical Correlations and Patient Outcomes

Our univariate analysis showed that failure to improve the SRS-Schwab sagittal modifiers postoperatively (due to insufficient LL correction) and the presence of non-union were risk factors for poor clinical outcomes. These results were consistent with the study by Passias,[18] demonstrating that improving the SRS-Schwab sagittal modifiers by at least one level significantly correlates with reduced back pain and improved quality of life after surgery. Conversely, factors such as age, sex, obesity, and PJK did not significantly affect final clinical outcomes. Interestingly, our results did not find any correlation between postoperative coronal malalignment and clinical outcomes, which differed from the data of other studies, indicating a strong correlation between final coronal malalignment and clinical outcome.[32,35] This contrast might be explained by the small number of cases with persistent coronal malalignment (only six cases) in our study. Finally, non-union was proven to be a risk factor for poor clinical outcome, which is in line with other studies,[36,37] emphasizing the importance of promoting fusion rate, especially in elderly patients with poor bone quality.

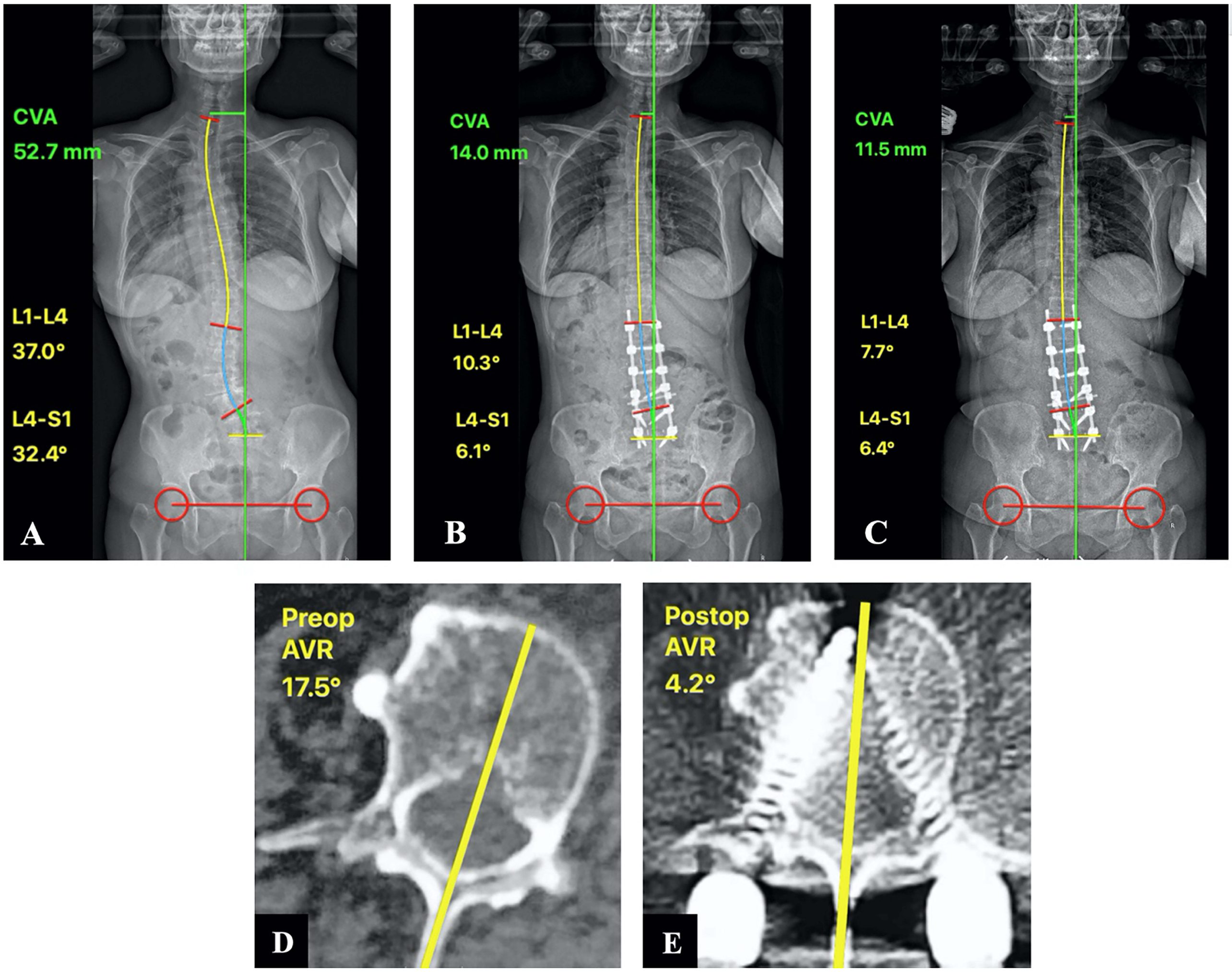

Figure 5 Full spine Xray of a 62-year-old female patient with severe degenerative scoliosis and type C coronal malalignment before surgery (**A**), at three-month (**B**) and two-year postoperative assessment (**C**). Note the significant correction of both coronal malalignment (**A** and **C**) and rotational deformity (**D** and **E**), with no loss of correction observed over the study period.

Study Limitations

Despite the clinical significance of our findings, this study is subject to several limitations that must be considered when interpreting the results. The cohort size was relatively small, which limited the overall statistical power of the study. Due to the small sample size, our statistical analysis was primarily restricted to univariate comparisons. The lack of a robust multivariate regression model means we were unable to adjust for potential confounding variables—such as age, body mass index (BMI), or baseline bone mineral density—that might independently influence surgical outcomes. As a case series pilot study, the absence of a randomized control group makes it difficult to definitively compare the efficacy of this modified TLIF technique against standard procedures or alternative interbody fusion approaches. These findings should be viewed as preliminary evidence supporting the feasibility and safety of the modified method. While the one-year follow-up period provided essential data on early fusion rates and initial clinical improvements, it may not be sufficient to capture long-term outcomes. Extended follow-up is necessary to evaluate the maintenance of sagittal balance over time, the incidence of adjacent segment disease, or late-stage implant-related complications. The study was conducted at a single institution in Vietnam and this may limit the generalizability of our findings to different healthcare systems or populations with different baseline characteristics. In summary, while these limitations exist, this study provides a vital proof-of-concept for the modified TLIF in treating complex spinal deformities. Future research involving larger, multicenter cohorts and randomized designs is required to confirm these preliminary findings and establish long-term clinical efficacy.

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Conclusion

Surgical intervention for severe ASD cases is a complex spinal surgery that requires not only technical proficiency, but also comprehensive preoperative planning and patient selection. Among the currently available techniques, modified TLIF is associated with improvement of mid-term radiographic and clinical outcomes with an acceptable complication rate. High PI (OR = 13.7, (2.65–69.43)), osteoporosis (OR = 13.4, (3.13–88.77)) and "pear-shaped" disc (OR = 14, (2.36–72.96)) increase the risk of sagittal suboptimal restoration, which in turns can negatively affect the final clinical outcome. Additional research involving larger cohorts and extended follow-up, preferably with a control group, is required to reach more definitive conclusions.

Ethics Approval and Consent to Participate

All procedures in this study were approved by the Review Board of Hospital for Traumatology and Orthopedics, Ho Chi Minh city, Vietnam, and our study complies with the Declaration of Helsinki.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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The authors report no potential conflicts of interest relevant to this article.

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