

Review

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Review

Minimally Invasive Surgery for Adult Spinal Deformity Using Lateral Lumbar Interbody Fusion

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Abstract: Minimally invasive surgery for adult spinal deformities (MIS deformity surgery) utilizes MIS lumbar interbody fusion and percutaneous pedicle screw fixation (PPSF) without posterior corrective osteotomy. While MIS reduces issues associated with open deformity surgery, it has limitations in correcting sagittal imbalance. This review discusses the limitations and solutions of lateral lumbar interbody fusion (LLIF) and introduces our experience in addressing marked sagittal deformities. We reviewed the literature and incorporated our clinical experience to evaluate the efficacy of recent MIS techniques, particularly focusing on oblique lumbar interbody fusion (OLIF) at L1-5 and L5-S1. The use of higher profile and greater angle cages and the application of PPSF with curved rods and percutaneous rod compression were discussed. Advances in MIS techniques, such as OLIF, have enabled significant improvements in increasing disc height and angle. Combining these new techniques and concepts, we successfully corrected marked sagittal deformities using MIS deformity surgery. Early onset of proximal junctional kyphosis was identified as a notable complication. Although recent advancements in MIS deformity surgery have shown promise in correcting sagittal deformities, further clinical experience and data are necessary to enhance outcomes and mitigate complications such as proximal junctional kyphosis.

Keywords: adult spinal deformity; minimally invasive surgery; lateral lumbar interbody fusion; percutaneous pedicle screw fixation; marked sagittal deformity

1. Introduction

Minimally invasive surgery (MIS) for the spine began in 1991 with laparoscopic lumbar discectomy, a simple and low-risk surgery [1]. Currently, MIS can successfully replace nearly all types of spinal surgeries except those for spinal deformities, which require fusion and fixation across multiple spinal levels and represent the last challenge for MIS [2,3]. Since the first report of MIS surgery for adult spinal deformity (ASD) in 2008 [4], numerous studies have documented the outcomes of MIS surgery for degenerative spinal deformity [5–10].

There are three types of deformity surgeries: open deformity surgery using classical open techniques, hybrid deformity surgery combining MIS and open techniques, and MIS deformity surgery employing only MIS techniques [6]. Circumferential MIS (cMIS) deformity surgery involves MIS procedures on both the anterior and posterior sides, aligning with the definition of MIS deformity surgery [11], which combines MIS interbody fusion and posterior percutaneous screw fixation (PPSF) without corrective osteotomies or posterior bone fusion [4].

Open deformity surgery, the standard approach, has limitations [12], particularly for older patients with multiple comorbidities, leading to higher perioperative complication and mortality rates [12–15]. Studies indicate that MIS deformity surgery mitigates many issues associated with open surgery [4,5,13,16], making it a favorable option for ASD [17]. However, MIS deformity surgery still faces challenges in correcting rigid adult deformities [18,19] and sagittal imbalance in ASD [9,16,20].

This review examines the limitations of MIS deformity surgery, recent advancements in MIS techniques for deformity correction, solutions to overcome these limitations, and approaches to correcting marked sagittal deformities.

2. Techniques for MIS Deformity Surgery

The MIS techniques used for deformity surgery include MIS lumbar interbody fusion and PPSF.

2.1. MIS Lumbar Interbody Fusion

MIS lumbar interbody fusion techniques include anterior lumbar interbody fusion (ALIF), MIS transforaminal lumbar interbody fusion (TLIF), and lateral lumbar interbody fusion (LLIF) [19]. All these techniques— anterior, lateral, and posterior—are effective in correcting scoliosis [20,24,26–28]. However, their effectiveness in sagittal correction varies when a posterior corrective osteotomy is not performed. ALIF without osteotomy corrects the sagittal angle by approximately 5.3°–8.3° per level, outperforming posterior lumbar interbody fusion techniques [29,30]. In contrast, TLIF is less effective, achieving only -0.1° to 2° per level [29,31,32].

LLIF is divided into direct lateral lumbar interbody fusion (DLIF) [33], extreme lateral interbody fusion (XLIF) [34], oblique lumbar interbody fusion at L1-5 (OLIF25), and OLIF at L5-S1 level (OLIF51) [35,36]. DLIF and XLIF are retroperitoneal approaches to the lateral surface of the lumbar disc [33,34]. OLIF25 uses a retroperitoneal extrapsoas approach to the anterolateral lumbar disc [35,36]. OLIF51, distinct from DLIF and OLIF25, approaches the anterolateral L5-S1 disc through a pathway between the ureter and the common iliac artery [35,36].

For DLIF, either a right- or left-sided approach is used, with the patient in the right or left lateral decubitus position and the hip flexed, facilitating access at L4-5. In OLIF25 and OLIF51, the patient is positioned in a right lateral decubitus position without hip flexion, enabling interbody fusions from L1 to S1 in a single position [35,36].

2.2. Effectiveness of LLIF in Sagittal Correction

LLIF techniques show distinctive factors in creating lordotic angles compared to other methods [37–39]. DLIF with the cage placed in the middle or posterior part of the disc space is ineffective for sagittal correction, achieving only -1.2° to 3.8° per level [40,41]. However, DLIF with the cage positioned in the anterior disc space achieves sagittal correction similar to ALIF (7.4° per level) [42]. High-angle, high-profile cages placed in the anterior disc space during LLIF create more posterior space, increasing lumbar lordotic angle by posterior shortening [37,43]. OLIF25 allows for consistent anterior disc space placement due to the exposed anterior disc margin, which serves as a reference point for cage positioning. This improves the postoperative disc angle compared to DLIF [37]. OLIF51 uses cages with lordotic angles up to 24°, effectively increasing the lordotic angle at L5-S1 [44]. Mun et al. reported that the OLIF51 could achieve disc angles significantly greater than the cage angle by posterior rod compression (mean cage angle = 11.2 ± 1.6° vs. mean postoperative disc angle = 22.6 ± 4.7°), over 10° greater than TLIF [44]. The amount of angle correction at L5-S1 depends on the fusion technique and cage angle. OLIF51 with a 12° cage produces a greater angle than TLIF, and OLIF51 with a 24° cage achieves an even greater angle than OLIF51 with a 12° cage [Figure 1].

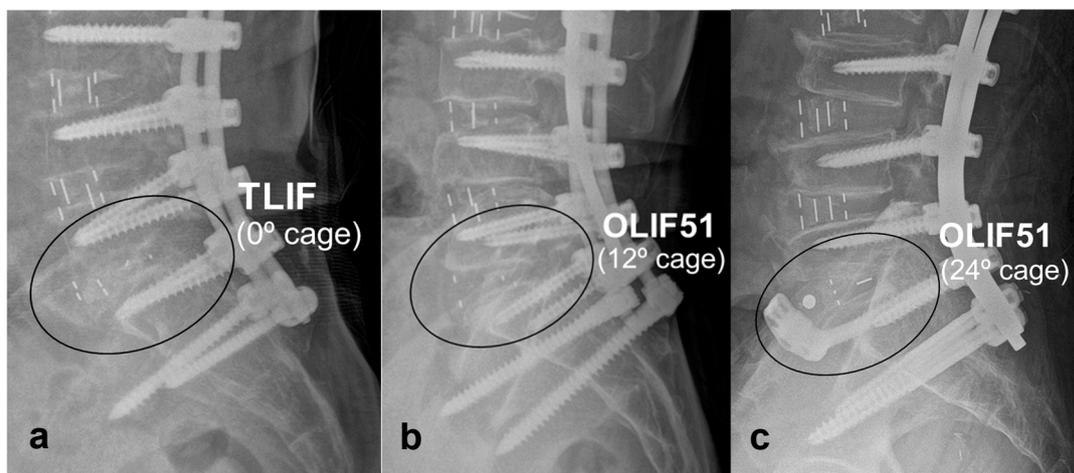


Figure 1. Differences of postoperative disc angle at L5-S1 according to the types of lumbar interbody fusion (LIF) and cage angles. (a) Transforaminal LIF (TLIF) using a bullet-shaped cage; the postoperative disc angle was 7.8°. (b) Oblique LIF at L5-S1 (OLIF51) using a 12° cage; the postoperative disc angle was 18.9°. (c) OLIF51 using a 24° cage; the postoperative disc angle at L5-S1 was 24.5°. We performed posterior rod compression for posterior shortening without corrective osteotomy in all three cases.

2.3. Percutaneous Pedicle Screw Fixation

PPSF is an essential technique in MIS deformity surgery for minimally invasive spinal stabilization. Compared to open pedicle screw fixation, PPSF offers several advantages, including higher accuracy, fewer injuries to spinal muscles and the medial branch of the dorsal ramus, less blood loss, shorter operation time, and reduced hospital stays [45–51]. Multilevel PPSF is effective for deformity correction, with rods bent to match the sagittal angle and rod compression resulting in greater lordotic angles [4]. The rods are then inserted into the iliac screws. The screw extender must have a large slot to pass the bent rod, as its curve elevates the rod tip at the thoracolumbar junction. Extender reduction starts from the caudal levels and continues proximally, similar to the cantilever maneuver in open deformity surgery [4,52]. Minimally invasive iliac screws or subcrestal iliac screws, when connected to the long-level thoracolumbar PPSF, provide strong mechanical support and protect the L5-S1 joint [13,52–54]. An illustrative case demonstrates the successful connection of a subcrestal iliac screw to the PPSF, as shown in Figure 2.

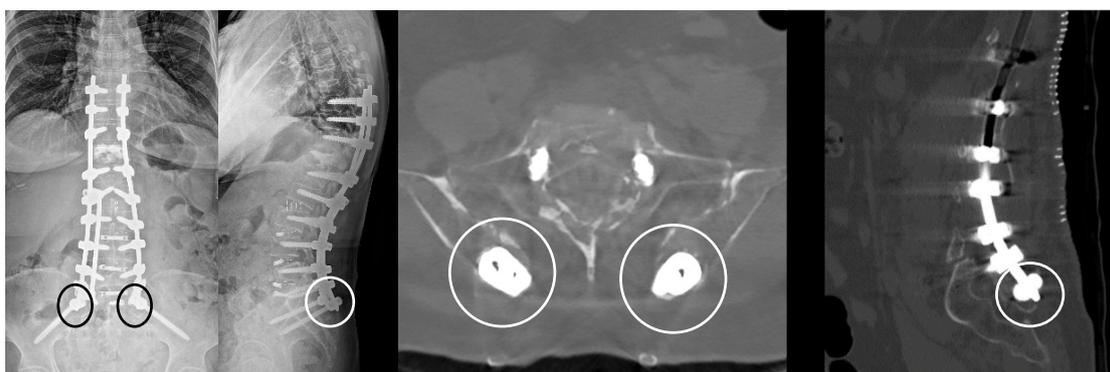


Figure 2. A case of MIS deformity surgery with a long-level posterior percutaneous pedicle screw fixation connection to the subcrestal iliac screws (circles).

2.4. Avoiding Posterior Corrective Osteotomy

Corrective osteotomy techniques, such as Smith–Petersen osteotomy (SPO) for 10° – 20° /level [55,56], pedicle subtraction osteotomy (PSO) for 30° – 40° /level [57,58], and vertebral column resection (VCR) for $>40^{\circ}$ /level [59,60], can create additional lordotic angles. However, these osteotomies are associated with complications, including vascular [61,62], neural [60,63–65], increased intraoperative bleeding [66], and pseudoarthrosis [67,68]. Therefore, MIS deformity surgery should avoid corrective osteotomy whenever possible. Posterior corrective osteotomy can be avoided if the preoperative estimated angle correction via MIS deformity surgery is sufficient for successful sagittal correction.

Before surgery, it is essential to calculate the correctable lumbar angle using MIS techniques. Maximum lordotic angles can be achieved with LLIF and PPSF without corrective osteotomy by using higher-profile, greater lordotic angle cages inserted at the anterior disc space, allowing for additional rod compression for posterior shortening [Figure 3] [37,43]. A case illustrated in Figure 4 demonstrates the preoperative estimation of sagittal correction. The patient's preoperative spinopelvic parameters were: SVA = 95.8 mm, PI = 54.2° ; LL = $+9.6^{\circ}$; and PI-LL = 63.8° . These parameters suggested that the patient should undergo open deformity surgery with posterior corrective osteotomies as recommended previously [7]. Setting the target LL between the PI and PI + 10° according to the SRS-Schwab criteria [69], the target LL would be $\geq 54.2^{\circ}$.

Angle correction must consider pre-existing angle losses due to kyphotic vertebral bodies or previous fusion operations. In this case, the total pre-existing angle loss was $+7.5^{\circ}$, calculated from the kyphotic vertebra bodies of L1 ($+17.9^{\circ}$) and L2 ($+1.9^{\circ}$) with compensated lordotic angles at L3 body (-2.3°) and Cobb angle of L4-5 level (-10.0°). Thus, the minimum required angle correction was $54.2^{\circ} + 7.5^{\circ} = 61.7^{\circ}$. Postoperative disc angles can be estimated using cage angles, as data shows the postoperative disc angle is greater than the cage angle after LLIF and PPSF [37,43,44,52].

There were four lumbosacral disc levels (L1-2, L2-3, L3-4, and L5-S1) where OLIF and PPSF could produce lordotic angles. The estimated disc angles were $\geq 36^{\circ}$ at the L1-2-3-4 levels using three 12° cages and $\geq 24^{\circ}$ at the L5-S1 level using a 24° cage. The total estimated angle correction was $\geq 60^{\circ}$, and the corrected LL was $\geq 52.5^{\circ}$ (60° – 7.5°). According to the SRS-Schwab criteria or global alignment and proportion (GAP) score [67,68], this estimated LL was acceptable, allowing us to avoid posterior corrective osteotomy. The final postoperative lumbar angles were 62.3° and 56.5° , better than the preoperative estimates. Postoperative sagittal balance was satisfactory, with SVA = 25.3 mm and PI-LL = 2.3° [Figure 4].

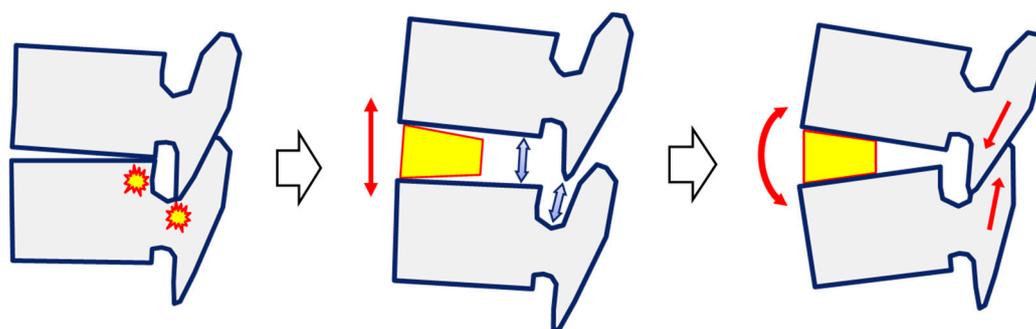


Figure 3. A high-angle and high-profile cage, placed at the anterior disc space, can make more space posteriorly, providing an increased allowance for making lumbar angle by posterior shortening.

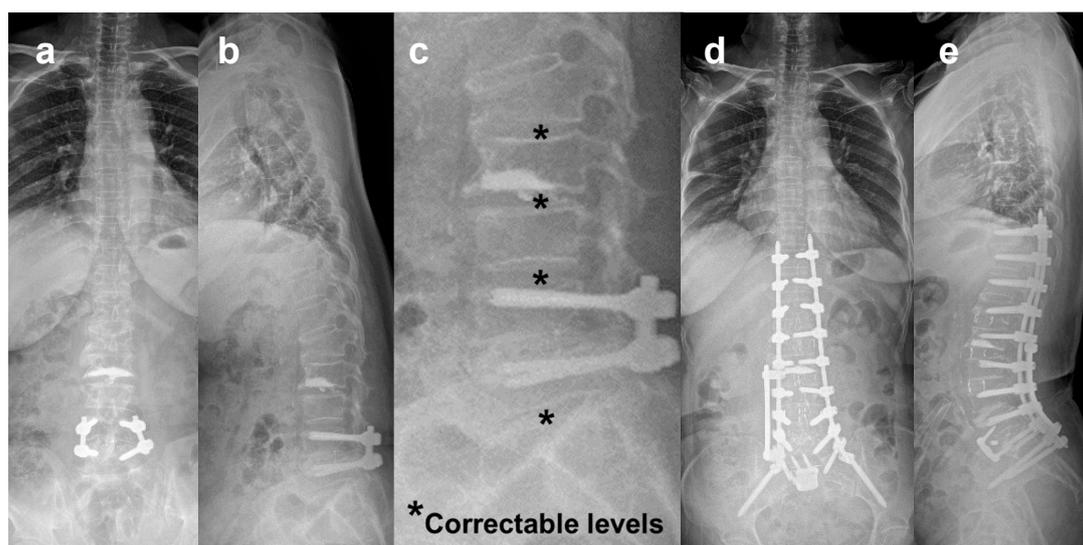


Figure 4. An illustrative case of MIS deformity surgery showing how to calculate lumbar angle correction preoperatively. **(a, b)** Preoperative radiographs; SVA = 95.8 mm, PI = 54.2°, LL = +9.6°, and PI-LL = 63.8°. If we set the minimum target LL as \geq PI [69], the target LL would be \geq 54.2°. A pre-existing angle loss was +7.5°: by summation of +17.9° (kyphotic L1 body), +1.9° (kyphotic L2 body), -2.3° (lordotic L3 body), and -10.0° (Cobb angle of L4-5). The minimum required angle correction was calculated as $54.2^\circ + 7.5^\circ = 61.7^\circ$. **(c)** Based on the data that the lateral lumbar interbody fusion could make disc angle greater than or equal to the cage angle [37,43,44,52], the estimated disc angle correction would be $\geq 36^\circ$ at L1-2-3-4 with three 12° cages and $\geq 24^\circ$ at L5-S1 with a 24° cage. Finally, the estimated angle correction and the estimated postoperative LL were $\geq 60^\circ$ ($36^\circ + 24^\circ$) and $\geq 52.5^\circ$, respectively. According to the SRS-Schwab criteria or GAP score [66,81], the estimated LL was acceptable, and we could avoid the corrective osteotomy. **(d, e)** The final postoperative radiographs; lumbar angle correction = 62.3° and corrected lumbar angle = 56.5°, better than the preoperative estimations. Postoperative sagittal balance was satisfactory with SVA = 25.3 mm and PI-LL = 2.3°.

3. Discussion

3.1. Limitations of MIS Deformity Surgery

Several studies have reported various limitations of MIS for deformity surgery in patients with ASD. While MIS deformity surgery is satisfactory for coronal correction, it is deficient in sagittal correction [20,21]. Patients with ASD often require multiple anterior and posterior releases due to their rigid deformities, unlike adolescent idiopathic scoliosis [18,22]. Severe fixed ASD must be corrected using open posterior surgery rather than MIS techniques [19,23]. The MIS approach to the L4-5 level in patients with a high iliac crest involves a long operation time and shows a high complication rate [24]. Mummaneni et al. suggested that open deformity surgery with posterior corrective osteotomies is needed for patients with preoperative SVA ≥ 60 mm and PI-LL ≥ 30 [7]. Wang et al. reported a maximum corrected lumbar lordosis (LL) of only 47.5° [16] and a ceiling effect of 23° for sagittal curve correction and 34° for coronal correction [23]. Yen et al. concluded that MIS deformity surgery remains in its early stages [8].

Combining the results of previous studies, the major concerns are twofold. First, MIS deformity surgery is effective only for coronal correction, not for sagittal correction, due to technical limitations. Second, MIS deformity surgery is suitable only for mild sagittal imbalance because of the limited sagittal angle correction. Since restoring sagittal balance is more critical than coronal balance [25], MIS deformity surgery presents significant challenges in managing ASD, with sagittal imbalance being the main issue.

To overcome these limitations, solutions must address technical constraints and achieve satisfactory correction of marked sagittal imbalance. Solutions include the effective use of LLIF and

PPSF to increase disc angles and avoid posterior corrective osteotomies. The key lies in the optimal combination and application of MIS techniques for maximum angle correction.

3.2. Correction of Marked Sagittal Deformity

When deformity surgery is insufficient for correcting high-grade sagittal imbalance, it may not be considered an appropriate surgical option for ASD. Most patients requiring surgery for ASD exhibit marked sagittal deformity, necessitating effective correction through MIS. Marked sagittal deformity is defined as having two or more significant sagittal modifiers: SVA >9.5 cm, PI-LL $>20^\circ$, and PT $>30^\circ$ [69,70]. Unfortunately, no studies have focused on correcting marked sagittal deformities using MIS.

Based on our previous report [52], ASD patients with marked sagittal deformity underwent MIS deformity surgery with LLIF and PPSF and were followed for over 2 years post-surgery. The patients were divided into the OLIF51 and TLIF51 groups, with all patients undergoing LLIF at the lumbar level. The OLIF51 group underwent OLIF51, and the TLIF51 group underwent TLIF at L5-S1. Blood loss was significantly lower in the OLIF51 group compared to the TLIF51 group (260.7 ± 83.5 ml vs. 423.0 ± 59.3 ml). Preoperative SVA and PI-LL were 125.9 ± 21.3 mm and $36.5 \pm 8.5^\circ$ in the OLIF51 group, and 125.5 ± 22.1 mm and $34.1 \pm 10.6^\circ$ in the TLIF51 group. Postoperative SVA and PI-LL improved to 27.1 ± 11.4 mm and $3.6 \pm 3.0^\circ$ in the OLIF51 group, and 32.7 ± 18.4 mm and $7.5 \pm 3.2^\circ$ in the TLIF51 group. The corrected LL and LL corrections were $55.5 \pm 2.8^\circ$ and $38.7 \pm 10.2^\circ$ in the OLIF51 group, and $46.9 \pm 5.2^\circ$ and $26.6 \pm 9.8^\circ$ in the TLIF51 group, outperforming previous MIS deformity surgery reports with LL corrections up to 47.5° and 23° [16,23]. The OLIF51 group achieved better sagittal correction due to the greater corrected disc angle at L5-S1, with mean postoperative L5-S1 disc angles of $18.4 \pm 3.7^\circ$ and $6.9 \pm 2.8^\circ$, respectively. An illustrative case of ASD with marked sagittal imbalance demonstrated successful sagittal correction after MIS deformity surgery [Figure 5].

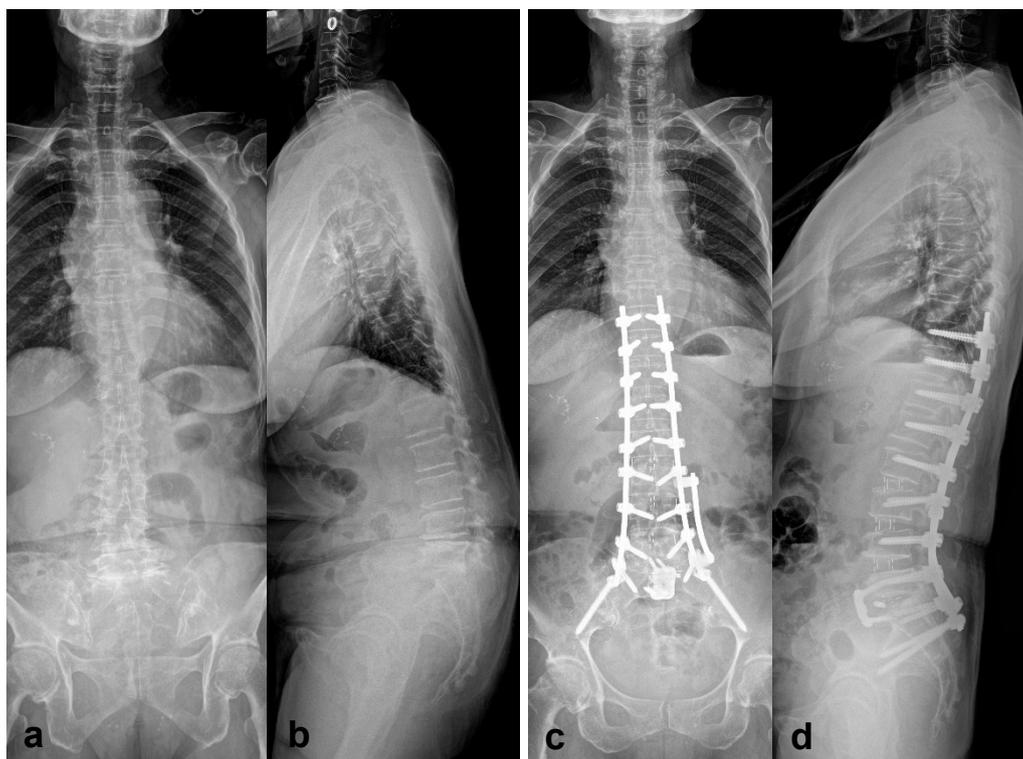


Figure 5. Correction of marked sagittal imbalance by MIS deformity surgery using lateral lumbar interbody fusion at L2-3-4-5-S1 and posterior percutaneous pedicle screw fixation without corrective osteotomy. (a, b) Preoperative radiographs; PI = 50.7° . SVA = 147 mm, LL = $+7.8^\circ$, PI-LL = 58.5° , and PT = 44.2° . (c, d) Postoperative radiographs; the SVA = -27.0 mm, LL = -53.9° , PI-LL = 3.1° , and PT = 23.9° .

3.3. Concerns of MIS Deformity Surgery

Our previous study indicated that MIS deformity surgery can result in various complications such as psoas symptoms, ileus, vascular injury, and proximal junctional kyphosis (PJK) [52]. No major complications were observed. The incidence of PJK (30–31%) was similar to other reports of open deformity surgeries (26–41%) [71–74]. However, the onset of PJK in the OLIF51 group was significantly earlier (8.6 ± 1.9 months post-surgery) than in the TLIF51 group (26.3 ± 4.7 months) and previous studies (18.6–34.8 months) [75,76]. The earliest onset of PJK in the OLIF51 group was 7 months post-surgery [Figure 6].

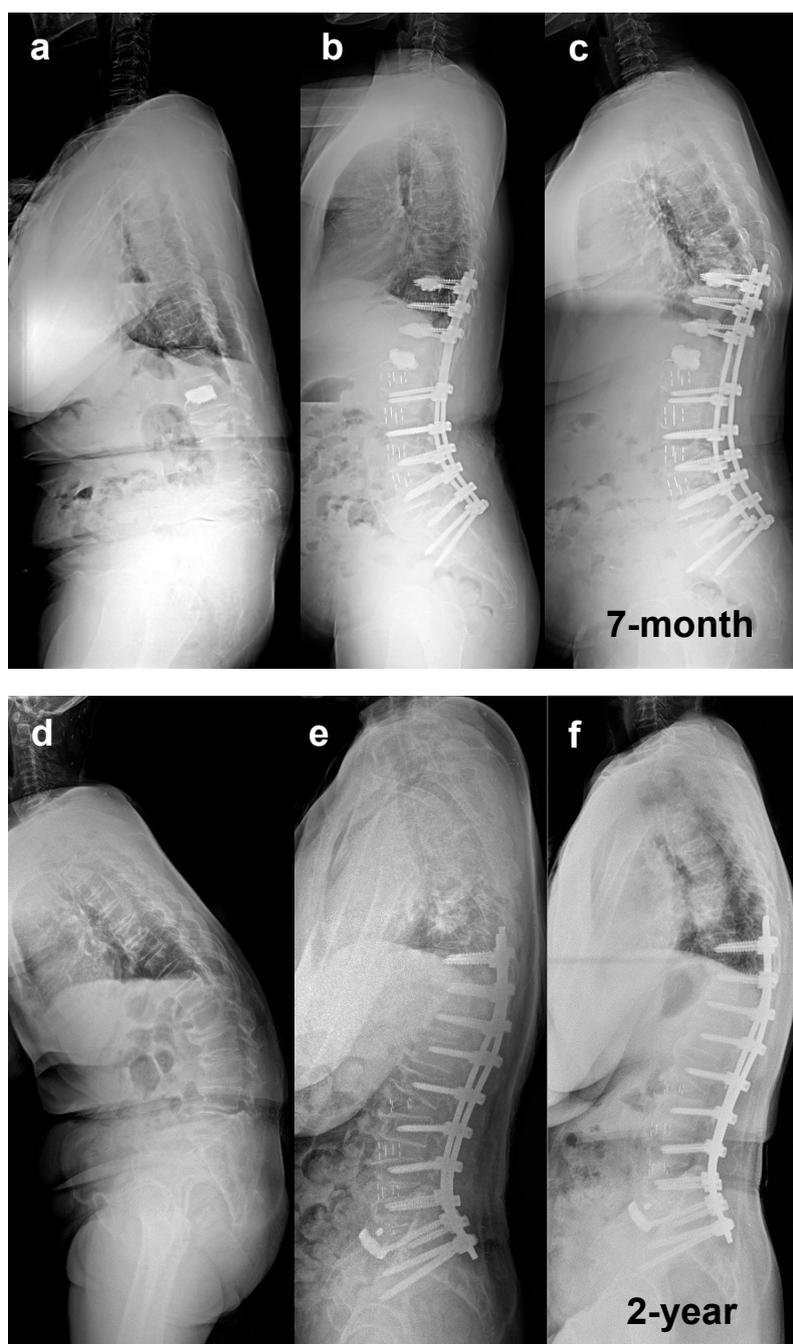


Figure 6. Two cases underwent MIS deformity surgery with postoperative follow-up radiographs. Case 1 (a, b, and c): Preoperative (a), immediate postoperative (b), and postoperative 7 months (c) radiographs. Early PJK started 7 months after surgery due to exaggerated upper lumbar lordosis with a decreased lower lumbar lordosis (LLL) proportion (38.7%) caused by the lordotic rod curve at the thoracolumbar junction. Case 2 (d, e, and f): Preoperative (d), immediate postoperative (e), and

postoperative 2 years (f) radiographs. The patient showed a well-preserved proximal junctional level 2 years after surgery. Compared to Case 1, the kyphotic rod angle at the thoracolumbar junction reduced upper lumbar lordosis and increased the LLL proportion (71.5%).

Several risk factors for PJK have been suggested, including age, bone quality, higher lumbar angle correction, higher PI, and smaller PI-LL [71,74,77,78]. Among these factors, we focused on achieving a harmonious lumbar curve with greater lower lumbar lordosis (LLL) at L4-5-S1 [79–81]. An exaggerated upper lumbar angle, indicating a smaller LLL proportion, increases stress at the proximal junction, leading to junctional failure [80]. The ideal LLL proportion is proposed to be 50–80% of the total LL [82–84]. We suspect that the persistent lordotic rod angle at the lower thoracic and thoracolumbar junction levels, along with a greater angle correction in the OLIF51 group, contributed to early PJK. Therefore, a solution is needed to decrease upper lumbar lordosis and increase LLL proportion to prevent early PJK after MIS deformity surgery.

Rigid lumbar joints, associated with degenerated stiff facet joints, can hinder the release of disc space without posterior corrective osteotomy [4,7,10,18,19,85]. In our experience, we encountered only one lumbar disc level that failed to release via LLIF due to rigid facet joints; however, almost all lumbar disc levels were successfully released during MIS deformity surgery (data not presented). A solution for releasing severely rigid joints without an osteotomy has yet to be established.

While OLIF51 is effective in achieving higher LL and LLL for sagittal correction, it has a relatively high complication rate (7.2–15.5%) [36,86], predominantly involving vascular injuries and ileus [87,88]. Additionally, OLIF51 has a steep learning curve compared to posterior approaches [89,90].

4. Conclusions

MIS has proven effective in correcting ASD using LLIF, including the correction of marked sagittal deformities. Among the techniques studied, oblique lumbar interbody fusion at the L5-S1 level (OLIF51) demonstrated superior angle correction compared to TLIF. Percutaneous fixation is crucial for achieving the desired lumbar angle through posterior shortening with rod compression. However, early onset of PJK remains a notable complication, potentially linked to exaggerated upper lumbar lordosis and a decreased proportion of LLL. The findings underscore the potential of MIS techniques in managing ASD effectively, yet also highlight the need for strategies to mitigate complications such as early PJK.

5. Future Directions

Future studies should explore optimized surgical protocols to enhance sagittal balance correction and investigate long-term outcomes to validate the sustainability of MIS benefits. Additionally, developing techniques to improve LLL proportion and reduce the incidence of PJK will be critical in advancing MIS deformity surgery.

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