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RESEARCH

Proximal and distal junctional failures after a short-segment minimally invasive surgery combination that incorporates anterior column realignment (ACR) for adult spinal deformity

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Abstract

Purpose To examine the incidences and risk factors for proximal/distal junctional kyphosis (PJK/DJK) and failure (PJF/DJF) after a short-segment (≤4 levels) minimally invasive surgery (MIS) combination involving anterior column realignment (ACR), lateral lumbar interbody fusion (LLIF), and percutaneous pedicle screw (PPS) fixation for adult spinal deformity (ASD).

Methods Ninety-five elderly ASD patients (mean age, 73.1 years) with pelvic incidence (PI)-lumbar lordosis (LL) mismatch > 10° underwent single-stage short-segment MIS (mean, 3.1 [range 2–4] segments) extending to L4 or L5. Exclusion criteria included: thoracic scoliosis as main deformity; thoracolumbar junction kyphosis > 25°; ankylosed facet joints; L5-S1 instability; and prior spinal fusion.

Results Operative time averaged 158 min; blood loss, 98 mL. At ≥2-year follow up, PJK occurred in 11.6%, PJF in 7.4%, DJK in 0%, and DJF in 2.1%. In the non-PJK/P(D)JF group, PI-LL mismatch improved from 30.5 ± 1.3° to 12.6 ± 1.3° ($p < 0.0001$), whereas loss of correction compromised gain in PJK/PJF groups. Compared with non-PJK/P(D)JF group, PJK patients showed significantly lower bone mineral density ($p = 0.0323$), and PJF patients exhibited significantly greater postoperative increase in upper arc of lordosis (ΔUAL: 5.7 ± 0.7° vs. 11.3 ± 2.3°; $p = 0.0200$), without significant difference in L1-S1 lordosis (ΔLL). DJK/DJF rates remained markedly lower than those reported in recent literature.

Conclusions This MIS approach minimized access-related morbidity, operative time, and blood loss, while achieving PJK/PJF rates comparable to or lower than those from long-segment open or MIS techniques. Greater ΔUAL–but not ΔLL–in the PJF group implies that restoring lordosis in more physiological locations may protect against PJF.

Keywords Adult spinal deformity (ASD) · Minimally invasive surgery (MIS) · Short-segment fusion · Lateral lumbar interbody fusion (LLIF) · Anterior column realignment (ACR) · Percutaneous pedicle screw (PPS) fixation · Proximal/Distal junctional kyphosis (PJK/DJK) · Proximal/Distal junctional failure (PJF/DJF) · Upper arc of lordosis (UAL) · Lower arc of lordosis (LAL)

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Introduction

A widely-used long-segment fusion with open surgery from the lower thoracic spine to the sacrum or pelvis for adult spinal deformity (ASD) involves the following drawbacks: prolonged operative time with increased blood loss; a high prevalence of proximal junctional kyphosis and failure (PJK/PJF), which undermines surgically restored sagittal alignment, partly because of a long lever arm of the construct [1–3]; a loss of spinopelvic mobility, which tends to lower the patient's daily activities [4]; and an increase in rod fracture risk.

A minimally invasive surgery (MIS) combination consisting of anterior column realignment (ACR) with anterior longitudinal ligament (ALL) release, lateral lumbar interbody fusion (LLIF), and percutaneous pedicle screw (PPS) fixation for selected ASD patients helps shorten the fusion length without compromising clinical and radiographic outcomes [5]. A powerful enhancement of segmental lordosis by ACR plays an important role in restoring lumbar lordosis (LL). ACR also enlarges the central spinal canal, lateral recess, and foraminal space through indirect neural decompression mechanisms [6]. As compared with long-segment procedures, our short-segment (≤4 levels) MIS has the advantage of reducing PJK/PJF owing to a shorter construct with smaller forces acting on the adjacent segments and preservation of important stabilizers including paraspinal musculature, posterior ligamentous complex, and facet joint [7]. Preserving a greater number of motion segments also minimizes the adverse effects on patients' postoperative daily activities.

Table 1 Patient-related and demographic factors and operative details

Parameter	Value
No. of patients	95
Mean age, yrs (range)	73.1 (52–87)
Female sex, n (%)	64 (67.4)
Mean hip BMD, g/cm2 (range)†	0.81 (0.41–1.19)
T-score	-0.89 (-4.4–1.9)
Medical comorbidities, n	92
Hypertension	42
Heart disease	19
Diabetes	17
Cerebral infarction	8
Rheumatoid arthritis	6
Mean no. of levels treated (range)	3.1 (2–4)
ACR level, n (%)	
L2-3	4 (4.2)
L3-4	91 (95.8)
UIV, n (%)	
T12	4 (4.2)
L1	15 (15.8)
L2	62 (65.3)
L3	14 (14.7)
LIV, n (%)	
L4	2 (2.1)
L5	93 (97.8)
Mean op time, mins (range)	157.6 (85–284)
Mean EBL, mL (range)	98.2 (8-520)
Mean FU, mos (range)	38.7 (24–72)

BMD = bone mineral density; ACR = anterior column realignment; UIV = uppermost instrumented vertebra; LIV = lowest instrumented vertebra; EBL = estimated blood loss; FU = follow-up

†Measured using dual-energy x-ray absorptiometry of the hip

However, fusions ending on L4 or L5 preserve distal lumbosacral motion, which may reduce the risk of PJK/PJF [8, 9], but also carry a risk of distal junctional kyphosis and/or failure (DJK/DJF) below the "floating" fusion [9]. In addition, although controversial [2, 11], combined anterior-posterior (AP) fusion—as opposed to a posterior-only arthrodesis—may increase the risk of PJK/PJF [10]. The risk is thought to stem from the greater construct rigidity, which causes a more abrupt transition in stiffness between the instrumented and adjacent uninstrumented mobile segments [12].

Despite these concerns, we postulated that the benefits of short-segment MIS combination might outweigh its negatives. To examine this hypothesis, we have analyzed 95 ASD patients treated by short-segment MIS with ≥2-year follow-up.

Materials and methods

Patients

The IRB-approved study included 95 ASD patients (31 men) with a pelvic incidence (PI)-LL > 10°, who underwent the short-segment (≤4 levels) MIS down to L4 or L5, provided that the adjacent distal disc(s) remained stable. All had a single-stage operation at a mean age of 73.1 (range, 52–87) years from 2018 to 2022 at our institution with ≥2 years (38.7 ± 12.1 months [mean ± SD]) follow-up. Elderly women with low bone mineral density (BMD) accounted for many of the patients, reflecting rapidly aging society (Table 1). Presurgical symptoms included low back pain (LBP) in all patients with radicular buttock/thigh/leg symptoms (44) or neurogenic claudication (19) or both (12). We excluded patients with the following conditions: thoracic scoliosis as the main deformity; thoracolumbar junction kyphosis > 25°; ankylosed facet joints; L5-S1 instability; and previous spinal fusion.

Radiological assessment as a primary endpoint

(1) Spinopelvic Parameters.

All patients underwent coronal and sagittal full-length digital radiographic studies in the free-standing clavicle position at a minimum of 4 different time points: preoperatively; early postoperatively; 1 year postoperatively or immediately before revision operation; and at the latest follow-up. Measurements of sagittal spinopelvic parameters included PI, L1-S1 LL, pelvic tilt (PT), T5-T12 thoracic kyphosis (TK), sagittal vertical axis (SVA), segmental disc angle at ACR level (SDA), proximal/distal junctional angle (PJA/DJA). As previously defined, PJA was measured between the uppermost instrumented vertebra (UIV) and the vertebra 2 level above (UIV+2) [1], and DJA between the lowest instrumented vertebra (LIV) and the adjacent distal vertebra (Lowe et al., 2006). In agreement with Martin et al. [3], we defined PJK/DJK as a kyphotic PJA/DJA≥10° and an increase by ≥10° during follow-up compared with the immediately postoperative baseline, rather than the preoperative value. According to their findings, surgical restoration of LL may induce reciprocal changes above and below the construct, potentially leading to overestimation of the kyphotic change with using preoperative baseline. Proximal and distal junctional failures (PJF/DJF) represent the complications requiring surgical revision around the construct's proximal/distal levels. As commonly used in ASD literature, all angular parameters (LL/TK/SDA/PJA/DJA) were

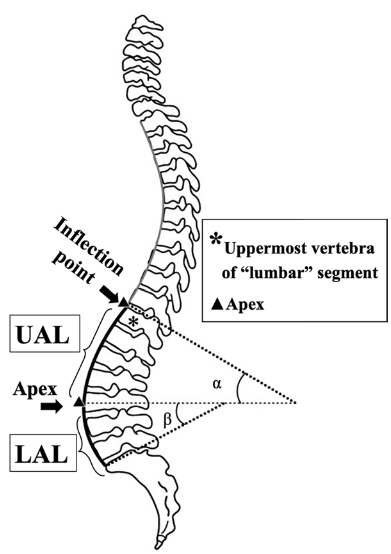

Fig. 1 Schematic drawing of the sagittal spinal alignment with an inflection point, where thoracic kyphosis turns into lordosis [13]. The symbols "*" and "▲" respectively indicate the uppermost vertebra and the apex of the "lumbar" segment. The upper arc of lordosis (UAL) extends from the inflection point to the apex and the lower arc of lordosis (LAL) from the apex to S1 [14]

expressed as positive values, regardless of their kyphotic or lordotic orientation. Accordingly, LL, SDA, and DJA represent lordosis, while TK and PJA represent kyphosis—all expressed as positive values.

(2) Additional Assessment.

As originally described by Roussouly et al. [13], lumbar lordosis begins, not necessarily at L1, but at an inflection point, where thoracic kyphosis turns into lordosis. Subsequently, Chevillotte et al. [14] divided lumbar lordosis into the upper arc of lordosis (UAL) extending from the inflection point to the lordosis apex and the lower arc of lordosis (LAL) from the apex to S1, defining the spinal lordosis ratio (SLR) as SLR=UAL/LAL (Fig. 1). In this light, we located the inflection point and measured UAL and LAL preoperatively and early postoperatively.

Surgical procedure

We used previously described techniques for transpsoas ACR and LLIF, involving threshold-based electromyography monitoring of the lower-limb muscles for safe introduction of the dilators followed by opening the retractor blades through the psoas [5, 6]. It may deserve mention that, contrary to common practice, we placed the patient in the true lateral position, right side up [5, 6]. This right-sided approach provides direct visualization of the more friable vena cava when placing the blunt retractors anterior to the ALL and posterior to the great vessels/sympathetic plexus. Closing the wound for the ACR and LLIF, we repositioned the patient from lateral to prone. Again, nerve root monitoring with PPS stimulation facilitated safe PPS placement [15].

Clinical assessment as a secondary endpoint

We collected Oswestry Disability Index (ODI) scores preoperatively, 1 year postoperatively or immediately before revision for PJF/DJF, and at the latest follow-up.

Statistical analysis

For statistical analysis, we used the chi-square test to analyze categorical data and the paired t-test and Mann-Whitney U-test to compare continuous data of the two groups, and repeated-measures ANOVA followed by the Tukey-Kramer honestly significant difference (HSD) test to examine 3 or more groups of related data, with $p<0.05$ considered significant. Mean values±SE are reported unless indicated otherwise. For all these analyses, we used SAS JMP software

(SAS Institute Inc.) including JMP Pro version 18.0.2 for post-hoc power analyses.

Results

Operative details and complications

The fusion length averaged 3.1 segments (range, 2–4). The UIV was most commonly located at L2 (65%), and the LIV at L5 (98%). All patients underwent a single-level ACR either at L3–4 (96%) or L2–3 (4%). The operative time and the estimated blood loss (EBL) averaged 158 min and 98 mL, respectively (Table 1). No patients had potentially serious surgical complications, such as neurologic injury and ACR- or LLIF-related vascular/visceral/ureteral injury requiring surgical repair. However, mostly transient transpsoas approach-related complications included anterior/groin compromise in 12 patients, resolving within 6 months in all but 2 patients with persistent numbness at the latest follow-up, and hip flexor weakness in 8 patients, with all recovering to near-normal levels within 3 months.

Radiographic and ODI changes

Of the 95 patients, 75 (78.9%) fell into the non-PJK/P(D)JF group, 11 (11.6%) into PJK, 7 (7.4%) into PJF, 0 (0%; none) into DJK, and 2 (2.1%) into DJF.

As shown in Table 2, all patients preoperatively had lumbar hypolordosis (PI-LL mismatch > 10°), and the majority showed increased pelvic retroversion (PT > 20°) and impaired global sagittal balance (SVA > 40 mm). The non-PJK/P(D)JF group showed that LL more than doubled from 16.5 ± 1.7° preoperatively to 34.8 ± 1.5° at the latest follow-up. PI-LL reduced to less than half from 30.5 ± 1.3° to 12.6 ± 1.3° (both $p < 0.0001$). This correction of PI-LL mismatch accompanied a significant improvement in PT and SVA at ≥2 years follow-up (Fig. 2). In contrast, the other 3 groups initially showed a significant postoperative improvement in LL and/or PI-LL, but the subsequent loss of correction resulted in no significant change from preoperative to the latest follow-up, except for SDA with persistent improvements across all groups, reflecting an advantage of LLIF against cage subsidence with the use of the cage that spanned lateral borders of the apophyseal ring bilaterally [5, 6]. PJA significantly worsened from early postoperative to the latest follow-up in the PJK group (Table 2; Fig. 3), but DJA showed no significant changes at any postoperative time point across all groups.

Clinically, the ODI significantly improved at the latest follow-up, not only in the non-PJK/P(D)JF, but also in the PJK group. However, the scores did not significantly improve in the PJF/DJF groups (Table 2).

Risk-factor analyses of PJK/PJF

Of the patient demographic factors, only BMD, but not T-score, showed significantly lower values ($p = 0.0323$) in the PJK than in the non-PJK/PJF group. No operative factors–including fusion length, ACR level, and UIV/LIV locations showed significant intergroup differences (Table 3). Two patients with L4-LIV belonged to non-PJK/P(D)JF group.

None of the typically-measured radiographic parameters—PI/PI-LL/PT/SVA, etc.—showed significant intergroup differences preoperatively, early postoperatively, and their changes (Table 4). However, the magnitude of changes in UAL, an angle not commonly measured, showed significantly greater values ($p = 0.0200$) in the PJF than in the non-PJK/PJF group (Table 4; Figs. 4 and 5). Postoperatively, an inflection point significantly shifted rostrally in the non-PJK/PJF ($p = 0.0001$), PJK ($p = 0.0405$), PJF ($p = 0.0433$), and non-DJF ($p = 0.0001$) groups, but not in the DJF group ($p = 0.3679$).

Discussion

In this series of 95 ASD patients with PI-LL mismatch > 10°, a short-segment (≤4 levels; average, 3.1) MIS combination with LLIFs, a single-level ACR, and PPS fixations resulted in PJK, PJF, DJK, and DJF rates of 11.6%, 7.4%, 0%, and 2.1%, respectively, with ≥2 years follow-up. The non-PJK/P(D)JF group showed an LL more than doubled with a reduced PI-LL to less than half at the latest follow-up (both $p < 0.0001$), but in the other groups, the subsequent loss of correction lowered or even eliminated the initial improvements.

Published PJK/PJF rates after ASD surgery vary widely depending on fusion length, the procedure, and patient demographics. One large single-institution study [16] of open long fusions (> 5 levels) reported 39.5% (144/364) for PJK. A multicenter study [17] of open long fusions (mean: 9.8 levels) showed 5.6% (68/1218) of acute PJF (<28 weeks) compared to 3.2% (3/95) in our series. A systematic review [18] reported PJK/PJF rates of 5–46%/13–55%, respectively, suggesting these complications frequently follow long-segment ASD corrections.

Following the advent of LLIF and ACR, Gandhi et al. [19] reported 20.5% PJK and 11% PJF in long-construct ACR with ≥1 year follow-up. Rates rose with surgical

Table 2 Preoperative to postoperative changes in sagittal spinopelvic alignment parameters and ODI scores for non-PJK/P(D)JF, PJK, PJF, and DJF groups

Parameter	Non-PJK/P(D) JF group (n=75)				PJK group (n=11)				PJF group (n=7)			DJF group (n=2)		
	Preop Mean [SE] (power)§	4wks postop Mean [SE] (power)§	1yr postop Mean [SE] (power)§	≥2 yrs postop Mean [SE] (power)§	Preop Mean [SE] (power)§	4wks postop Mean [SE] (power)§	1yr postop Mean [SE] (power)§	≥2 yrs postop Mean [SE] (power)§	Preop Mean [SE] (power)§	4wks postop Mean [SE] (power)§	Just before revision Mean [SE] (power)§	Preop Mean [SE] (power)§	4wks postop Mean [SE] (power)§	Just before revision Mean [SE] (power)§
PI, °	47.0 [1.2]	47.3 [1.2]	47.0 [1.2]	47.4 [1.2]	42.8 [2.7]	42.3 [2.8]	42.4 [2.9]	43.1 [2.6]	48.0 [3.6]	47.2 [3.8]	47.3 [3.3]	47.8 [19.8]	47.8 [18.2]	48.4 [18.3]
LL, °	16.5 [1.7]	37.9††† [1.2] (1.000)	36.3††† [1.3] (1.000)	34.8††† [1.5] (1.000)	12.6 [3.1]	34.0† [3.1] (0.996)	24.6 [4.1]	18.0 [4.5]	20.8 [5.3]	38.2* [4.5] (0.634)	23.8 [5.5]	9.6 [3.1]	33.1** [0.8] (0.938)	25.5** [3.4] (0.478)
PI – LL°	30.5 [1.3]	9.6††† [0.8] (1.000)	10.7††† [1.0] (1.000)	12.6††† [1.3] (1.000)	30.1 [3.5]	8.4†† [2.5] (0.997)	17.8** [3.6] (0.650)	25.1 [4.0]	27.3 [2.9]	9.0†† [1.1] (0.999)	23.5 [3.3]	38.3 [16.8]	14.8 [19.0]	22.9 [14.9]
PT, °	28.8 [0.9]	21.8††† [0.7] (1.000)	22.4††† [0.8] (0.999)	23.1††† [0.9] (0.995)	27.5 [2.3]	21.4 [1.5]	23.7 [1.9]	26.1 [2.4]	27.5 [2.0]	20.3* [1.9] (0.663)	25.2 [1.8]	40.3 [6.8]	28.5 [8.4]	34.7 [11.5]
TK, °	22.6 [1.4]	27.5* [1.3] (0.741)	28.7** [1.4] (0.871)	29.3*** [1.5] (0.996)	19.1 [2.5]	25.2 [3.3]	25.5 [3.3]	24.9 [2.8]	54.4 [15.1]	7.3 [10.0]	66.0 [27.3]	17.7 [10.3]	27.5 [10.2]	22.7 [12.1]
SVA, mm	74.8 [6.4]	28.8††† [4.3] (1.000)	35.7††† [5.3] (0.996)	50.9** [5.8] (0.785)	64.9 [14.3]	15.6 [15.4]	62.8 [17.0]	86.9 [20.3]	54.4 [15.1]	7.3 [10.0]	66.0 [27.3]	47.4 [39.6]	14.9 [63.4]	24.7 [17.8]
SDA	2.0 [0.3]	19.3††† [0.3] (1.000)	19.0††† [0.3] (1.000)	18.6††† [0.3] (1.000)	1.7 [0.4]	20.6††† [0.4] (1.000)	19.6††† [0.4] (1.000)	19.1††† [0.4] (1.000)	2.3 [1.5]	19.6††† [0.6] (1.000)	19.5††† [0.2] (1.000)	1.6 [0.1]	18.5*** [1.4] (0.999)	18.4*** [1.5] (0.997)
PJA, °	6.8 [1.3]	9.1 [1.4]	10.3 [1.4]	10.7 [1.5]	11.1 [2.9]	11.6 [2.2]	19.8 [2.9]	27.1ϕϕϕ [3.5] (0.9444)	6.4 [2.6]	7.2 [4.2]	20.1 [4.8]	15.2 [13.4]	12.5 [7.7]	13.7 [7.6]
DJA, °	8.7 [0.7]	7.6 [0.6]	7.5 [0.7]	7.0 [0.7]	10.2 [1.7]	8.9 (1.4)	8.5 [0.9]	7.6 [1.3]	9.2 [2.4]	8.7 [2.1]	7.7 [2.4]	7.4 [3.1]	2.9 [4.8]	0.9 [4.1]
ODI Score	41.4 [1.8]	NA	20.1††† [1.6] (1.000)	19.6††† [1.5] (1.000)	44.9 (3.1)	NA	25.3*** [5.0] (0.885)	26.5** [4.1] (0.925)	48.3 [8.3]	NA	57.4 [5.8]	42.0 [12.0]	NA	49.0 [19.0]

Values are presented as mean (SE) unless indicated otherwise

PJK = proximal junctional kyphosis; PJF = proximal junctional failure; DJF = distal junctional failure; PI = pelvic incidence; LL = lumbar lordosis measured between L1 and S1; PT = pelvic tilt; TK = thoracic kyphosis measured between T5 and T12; SVA = sagittal vertical axis; SDA = segmental disc angle at the ACR level PJA = proximal junctional angle measured between the inferior endplate of the uppermost instrumented vertebra (UIV) and superior end plate of the vertebra 2 level proximal to the UIV (UIV + 2); DJA = Distal junctional angle measured between the superior endplate of the lowest instrumented vertebra (LIV) and the adjacent distal vertebra; FU = follow-up; ODI = Oswestry disability index

§: Statistical power obtained by post-hoc power analysis using JMP® Pro version 18.0.2 software

†††: $p<0.0001$ compared to Preop

††: $p<0.0005$ (vs. Preop); †: $p<0.001$ (vs. Preop); ***: $p<0.005$ (vs. Preop); **: $p<0.01$ (vs. Preop); *: $p<0.05$ (vs. Preop)

ϕϕϕ: $p<0.005$ (vs. Early postop)

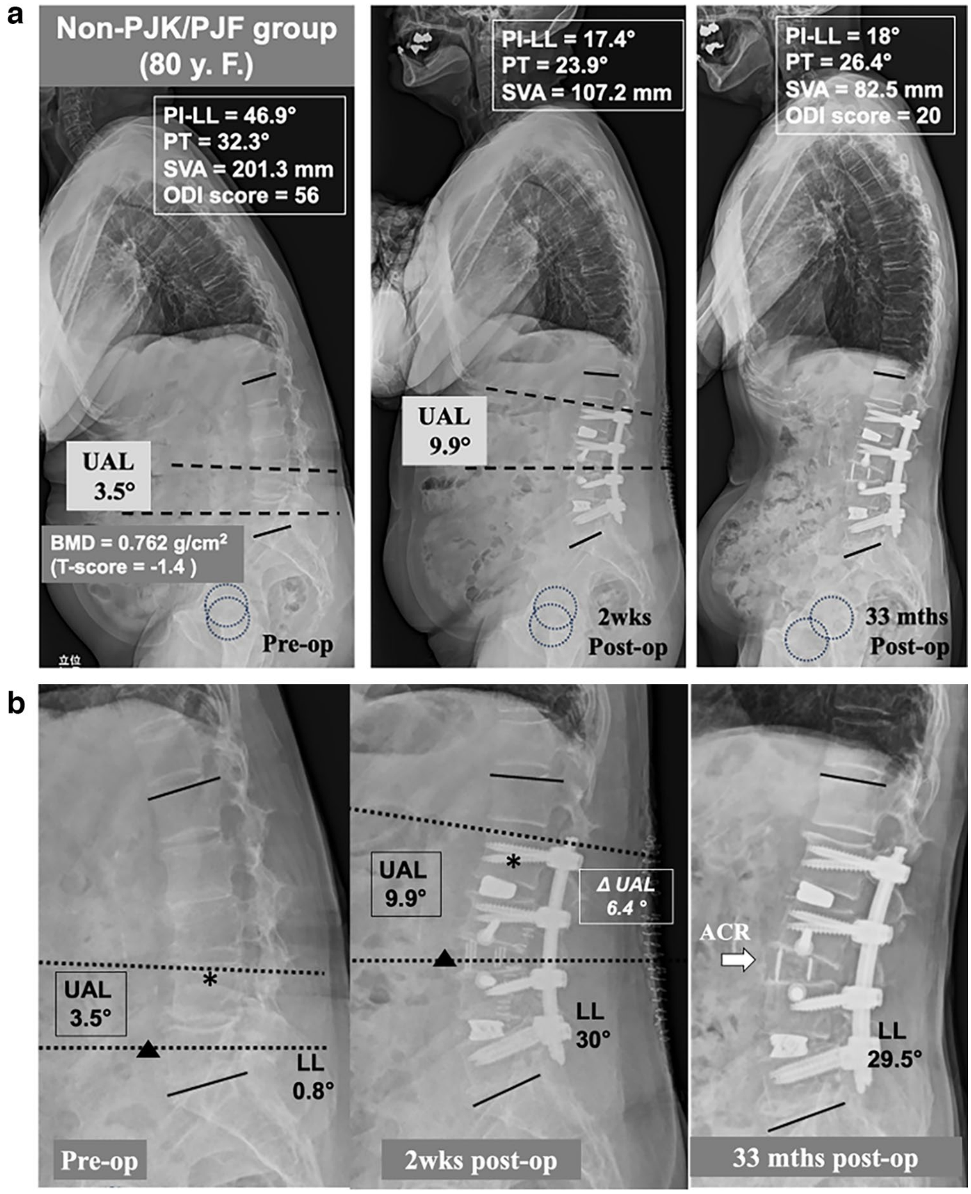

Fig. 2 Full-length (**a**) and close-up (**b**) plain radiographs, respectively showing the global balance and regional alignment in an 80-year-old woman from the non-PJK/PJF group. An inflection point shifted rostrally from L4 preoperatively to L2 postoperatively with an increase in UAL angle by 6.4°

extensiveness: 0% PJK/0% PJF with LLIF alone, 30%/11% with LLIF + ACR, and 42.9%/40% with LLIF + ACR+*PCO (*posterior column osteotomy*)*. A more recent multicenter database study [2] on 641 patients with long constructs (≥ 9 levels to pelvis) reported 47.9% PJK and 12.9% PJF at 2 years. The 10-year trend revealed a slight decline, correlating with fewer three-column osteotomies and increased ACR use.

Our data from short-segment MIS constructs, while subject to inherent selection bias and differences in patient populations, showed PJK/PJF rates comparable to—or even lower than—those reported for long-segment open or MIS techniques, while also reducing access-related morbidity, operative time, and EBL.

Previous reports identified older age [16, 19, 20] and low BMD [21] as risk factors for PJK/PJF, and such findings abound. Consistent with those observations, BMD—unlike T-score or other patient demographics—showed significantly lower values ($p = 0.0323$) in the PJK than in the non-PJK/PJF group (Table 3). No operative factors—including fusion length, ACR level, and vertebral locations of UIV/LIV—showed significant group-wise differences in our series. This series offered no basis to link PJK/PJF to

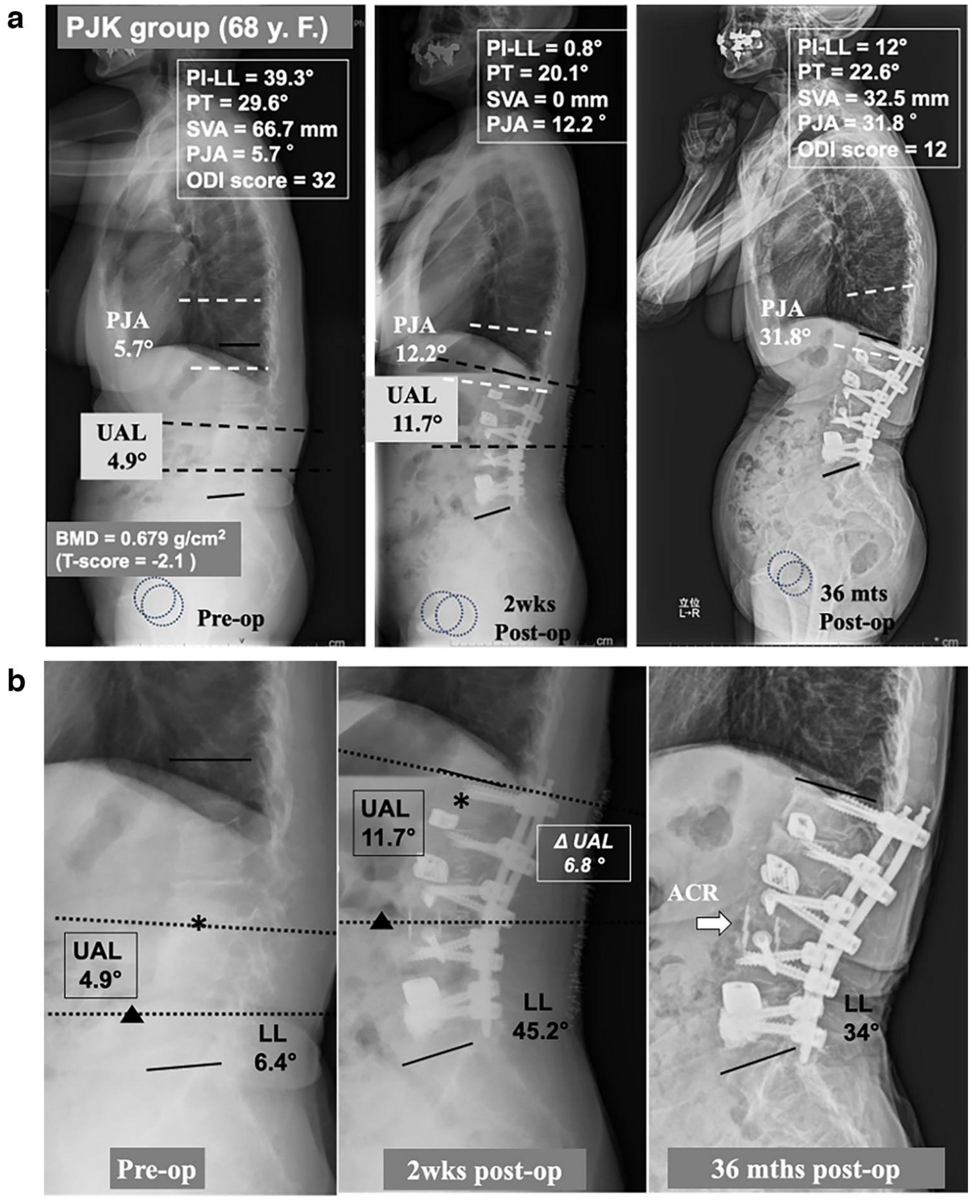

Fig. 3 Full-length (**a**) and close-up (**b**) plain radiographs, respectively showing global balance and regional alignment in a 68-year-old woman from the PJK group. An inflection point shifted rostrally from L3 preoperatively to L1 postoperatively with an increase in UAL angle by 6.8°. Despite an increase in PJA by 19.6° during follow-up (PJK), the ODI score improved at the latest follow-up

either preoperative sagittal imbalance severity or its insufficient restoration. In fact, none of the standard radiographic parameters (e.g., PL-LL/PT/SVA) yielded significant intergroup differences preoperatively, early postoperatively, and their deltas (Table 4).

Why, then, does the initially improved sagittal spinopelvic alignment deteriorate in PJK/PJF groups, while maintained in the non-PJK/PJF group throughout follow-up? Across groups, our short-segment MIS construct produced longer lordosis with an upward shift of the inflection point, where lumbar lordosis transitions to thoracic kyphosis. This mirrors a prior study [22] of 468 asymptomatic volunteers showing proximal migration of the lordosis apex with greater proximal lordosis (UAL). Increased UAL requires more lordotic vertebrae, thus shifting the inflection point upward. Notably, ΔUAL— but not ΔLL—showed significantly greater angles in the PJF than in the non-PJK/PJF group (11.3 ± 2.3° vs. 5.7 ± 0.7°; $p = 0.0200$; Table 4/Fig. 5). This finding, consistent with the view of Lafage et al. (2019) [20], indicates that restoring lordosis in more physiological locations (i.e. L4–S1) may protect against PJK. Adding excessive lordosis to the upper arc may trigger unfavorable reciprocal changes in the proximal junctional segments, potentially precipitating PJF. Counterintuitively, all 7 PJF patients underwent ACR not at the more proximal L2-3—supposedly riskier under this reasoning—but at L3-4 instead. It remains unclear why all PJF cases involved ACR at L3-4 rather than L2-3. Notably, neither BMD nor postoperative sagittal spinopelvic parameters showed significant differences between PJF and non-PJK/PJF groups (Tables 2,

Table 3 Analysis of demographic and operative risk factors for PJK/PJF/DJF

Parameter	Non-PJK/PJF group ($n=77$)	PJK group ($n=11$)	PJF group ($n=7$)	p Value (Power)§		Non-DJF group ($n=93$)	DJF group ($n=2$)	p Value DJF vs. Non-DJF
				PJK vs. Non-PJK/PJF	PJF vs. Non-PJK/PJFP			
Demographics								
Mean age [SE], yrs	73.2 [1.0]	72.2 [2.9]	74.0 [2.6]	NS	NS	73.3 [0.9]	67.0 [10.0]	NS
Females, n (%)	53 (68.8)	8 (72.7)	3 (42.9)	NS	NS	62 (66.7)	2 (100)	NS
Men BMD [SE], g/cm2	0.82 [0.03]	0.57 [0.2]	0.85 [0.1]	0.0323* (0.5097)	NS	0.79 [0.04]	0.67 [0.06]	NS
Mean T-score [SE]	-0.85 [0.2]	-1.16 [0.4]	-0.81 (0.5)	NS	NS	-0.85 [0.2]	-2.20 [0.5]	NS
Operative factors								
Mean number of levels fused [SE]	3.1 [0.1]	3.1 [0.1]	3.1 [0.1]	NS	NS	3.1 [0.1]	3.0 [0]	NS
ACRlevel, n (%)								
L2-3	4 (5.2)	0 (0)	0 (0)	NS	NS	4 (4)	0 (0)	NS
L3-4	73 (94.8)	11 (100)	7 (100)			89 (96)	2 (100)	
UIV, n (%)								
T12	4 (5.2)	0 (0)	0 (0)	NS	NS	4 (4)	0 (0)	NS
L1	13 (16.9)	1 (9.1)	1 (14.3)			15 (16)	0 (0)	
L2	46 (59.7)	10 (90.9)	6 (85.7)			60 (65)	2 (100)	
L3	14 (18.2)	0 (0)	0 (0)			14 (15)	0 (0)	
LIV, n (%)								
L4	2 (2.6)	0 (0)	0 (0)	NS	NS	2 (2)	0 (0)	NS
L5	75 (97.4)	11 (100)	7 (100)			91 (98)	2 (100)	
Mean Op time [SE], mins	155.6 [3.7]	162.5 [13.9]	171.4 [13.2]	NS	NS	157.6 [3.6]	158 [21.0]	NS
Mean EBL [SE], mL	100.2 [10.9]	81.3 [15.5]	101.4 [36.7]	NS	NS	97.9 [9.6]	112 [52.0]	NS

Values are presented as mean with [SE] or number of patients with (%) unless stated otherwise

PJK = proximal junctional kyphosis; PJF = proximal junctional failure; DJF = distal junctional failure; BMD = bone mineral density; PI = pelvic incidence; LL = lumbar lordosis measured between L1 and S1; PT = pelvic tilt; TK = thoracic kyphosis measured between T5 and T12; ACR = anterior column realignment; UIV = uppermost instrumented vertebra; LIV = lowest instrumented vertebra; EBL = estimated blood loss; SVA = sagittal vertical axis; SDA = segmental dis angle as the angle subtended by the lines along the respective endplates;

§Statistical power obtained by post-hoc power analysis using JMP® Pro version 18.0.2 software

*$p < 0.05$; NS = not significant; NA = not applicable

3 and 4), which further complicates interpretation. Furthermore, Fig. 5, which depicts operation-induced ΔUAL for each patient, reveals extensive overlap between non-PJK/PJF and PJF groups. This suggests that additional factors likely shape the postoperative course, leading to two distinct outcomes. Larger ΔUAL may contribute to PJF risk and require further investigation. Consistent with this perspective, Pressman et al. [23] recently reported a significantly higher PJK rate in the ACR group compared to the three-column osteotomy group following long-segment fusion for ASD (32.4% vs. 6.3%; $p = 0.007$). However, their study did not evaluate the location or distribution of LL.

In contrast to PJK/PJF, our "floating" fusion yielded markedly lower rates of DJK/DJF (0%/2.1%) than those reported in a recent systematic review [8] (47.9% [307/641] for DJK; 12.9% [83/641] for DJF). We observed neither screw pullout nor rod breakage, which a recent report [24] cited as the two most common causes of DJF.

Table 4 Analysis of sagittal spinopelvic parameters as risk factors for PJK/PJF/DJF

Parameter	Non-PJK/PJF group ($n=77$) mean [SE]	PJK group ($n=11$) mean [SE]	PJF group ($n=7$) mean [SE]	p Value (Power)§		Non-DJF group ($n=93$) mean [SE]	DJF group ($n=2$) mean [SE]	p Value DJF vs. Non-DJF mean [SE]
				PJK vs. Non-PJK/PJF	PJF vs. Non-PJK/PJFP			
PI,° Preop	47.1 [1.2]	42.8 [2.7]	48.0 [3.6]	NS	NS	46.6 [1.1]	47.8 [19.8]	NS
LL, ° Preop	16.4 [1.7]	12.6 [3.1]	20.8 [5.3]	NS	NS	16.4 [1.5]	9.6 [3.1]	NS
Early Postop	37.8 [1.2]	34 [3.1]	38.2 [4.5]	NS	NS	37.5 [1.1]	33.1 [0.8]	NS
Change (ΔLL)	21.4 [1.0]	21.3 [3.5]	17.4 [2.5]	NS	NS	21.1 [0.9]	23.5 [3.8]	NS
PI-LL, ° Preop	30.7 [1.3]	30.1 [3.5]	27.3 [2.9]	NS	NS	30.2 [1.1]	38.3 [16.8]	NS
Early Postop	9.7 [0.9]	8.4 [2.5]	9.0 [1.1]	NS	NS	9.4 [0.7]	14.8 [19.0]	NS
Change (ΔPI/LL)	-21 [1.0]	-21.8 [2.7]	-18.3 [3.2]	NS	NS	-20.8 [0.9]	-23.5 [2.2]	NS
PT, ° Preop	29.1 [0.9]	27.5 [2.3]	27.5 [2.0]	NS	NS	28.6 [0.8]	40.3 [6.8]	NS
Early Postop	22.0 [0.7]	21.4 [1.5]	20.3 [1.9]	NS	NS	21.7 [0.6]	28.5 [8.4]	NS
Change (ΔPT)	-7.1 [0.7]	-6.1 [1.7]	-7.3 [1.5]	NS	NS	-6.9 [0.6]	-11.8 [1.7]	NS
TK, ° Preop	22.5 [1.4]	19.1 [2.5]	20.2 [4.6]	NS	NS	22.0 [1.2]	17.7 [10.3]	NS
Early Postop	27.5 [1.2]	25.2 [3.3]	26.4 [4.0]	NS	NS	27.2 [1.1]	27.5 [10.2]	NS
Change (ΔTK)	5.0 [0.7]	6.1 [2.5]	6.1 [3.2]	NS	NS	5.1 [0.7]	9.9 [0.1]	NS
SVA, mm Preop	74.1 [6.3]	64.9 [14.3]	54.4 [15.1]	NS	NS	72.1 [5.5]	47.4 [39.6]	NS
Early Postop	28.4 [4.4]	15.6 [15.4]	7.3 [10.0]	NS	NS	25.6 [4.0]	14.9 [63.4]	NS
Change (ΔSVA)	-45.7 [5.5]	-49.3 [14.1]	-47.1 [14.1]	NS	NS	-46.5 [4.9]	-32.6 [23.8]	NS
SDA, ° Preop	2.0 [0.3]	1.7 [0.4]	2.3 [1.5]	NS	NS	2.0 [0.3]	1.6 [0.1]	NS
Early Postop	19.3 [0.3]	20.6 [0.4]	19.6 [0.6]	NS	NS	19.5 [0.3]	18.5 [1.4]	NS
Change (ΔSDA)	17.3 [0.4]	19 [0.6]	17.3 [1.5]	NS	NS	17.5 [0.4]	16.9 [1.3]	NS
PJA, ° Preop	7.0 [1.3]	11.1 [2.9]	6.4 [2.6]	NS	NS	7.3 [1.2]	15.2 [13.4]	NS
Early Postop	9.2 [1.3]	11.6 [2.2]	9.2 [4.1]	NS	NS	9.4 [1.2]	12.5 [7.7]	NS
Change (ΔPJA)	2.2 [0.5]	0.5 [1.1]	2.8 [2.1]	NS	NS	2.1 [0.4]	-2.7 [5.7]	NS
DJA, ° Preop	8.7 [0.7]	10.2 [1.7]	9.2 [2.4]	NS	NS	8.9 [0.6]	7.4 [3.1]	NS
Early Postop	7.5 [0.6]	8.9 [1.4]	8.7 [2.1]	NS	NS	7.9 [0.5]	2.9 [4.8]	NS
Change (ΔDJA)	-1.2 [0.3]	-1.2 [0.5]	-0.5 [0.7]	NS	NS	-1.0 [0.3]	-4.6 [1.7]	NS
UAL, ° Preop	6.0 [0.8]	5.5 [2.1]	2.6 [2.6]	NS	NS	5.8 [0.7]	2.8 [1.0]	NS
Early Postop	11.7 [0.6]	11.6 [1.6]	13.9 [2.0]	NS	NS	12.0 [0.5]	7.6 [2.4]	NS
Change (ΔUAL)	5.7 [0.7]	6.1 [1.9]	11.3 [2.3]	NS	0.0200* (0.4226)	6.2 [0.7]	4.8 [3.3]	NS
LAL, ° Preop	20.7 [1.1]	19.0 [2.9]	23.8 [3.6]	NS	NS	21.0 [1.0]	10.8 [9.6]	NS
Early Postop	28.4 [1.0]	23.7 [2.6]	26.7 [3.1]	NS	NS	27.7 [0.9]	29.6 [10.2]	NS
Change (ΔLAL)	7.6 [0.9]	4.8 [2.2]	2.9 [2.7]	NS	NS	6.7 [0.7]	18.8 [0.6]	NS
SLR (=UAL/LAL)	0.20 [0.2]	0.66 [0.6]	0.10 [0.8]	NS	NS	0.22 [0.2]	1.59 [1.5]	NS
Preop	0.49 [0.04]	0.61 [0.1]	0.54 [0.1]	NS	NS	0.51 [0.04]	0.26 [0.01]	NS
Early Postop	0.29 [0.3]	-0.05 [0.6]	0.44 [0.8]	NS	NS	0.29 [0.2]	-1.33 [1.5]	NS
Change (ΔSLR)	2.0 [0.3]	1.7 [0.4]	2.3 [1.5]	NS	NS	16.4 [1.5]	9.6 [3.1]	NS

Values are presented as mean [SE] unless stated otherwise

LL = lumbar lordosis measured between L1 and S1; PJK = proximal junctional kyphosis; PJF = proximal junctional failure; PI = pelvic incidence; LL = lumbar lordosis measured between L1 and S1; PT = pelvic tilt; TK = thoracic kyphosis measured between T5 and T12; SVA = sagittal vertical axis; SDA = segmental dis angle at the ACR level; PJA = proximal junctional angle measured between the inferior endplate of the uppermost instumented vertebra (UIV) and the superior end plate of the vertebra 2 level proximal to the UIV (UIV + 2); DJA = Distal junctional angle measured between the superior endplate of the lowest instrumented vertebra (LIV) and the adjacent distal vertebra; UAL = upper arc lordosis; LAL = lower arc lordosis; SLR = spinal lordosso ratio (i.e. UAL/LAL) FU = follow-up

§Statistical power obtained by post-hoc power analysis using JMP® Pro version 18.0.2 software

*$p < 0.05$; NS = not significant; NA = not applicable

The low incidence of DJK/DJF in the current series may reflect shorter lever arm associated with short-segments constructs, preservation of posterior stabilizer through MIS techniques, and strict inclusion of patients with stable distal segments. However, one of the 2 DJF patients had the second highest PI (68°) in this series, resulting in under-correction of PI/LL mismatch from 55° preoperatively to 34° postoperatively. This patient developed progressive LBP and ultimately required distal extension of the fusion 2

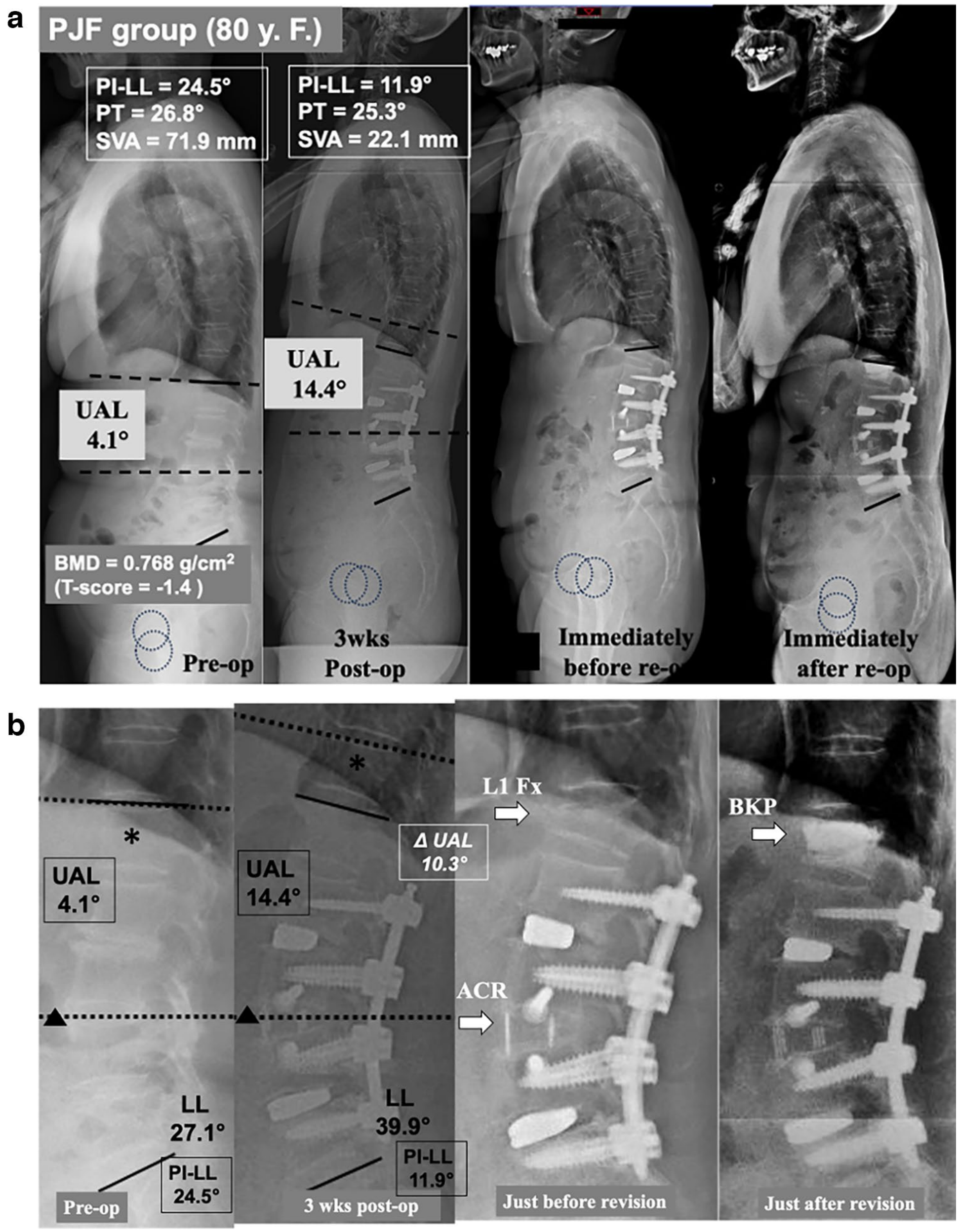

Fig. 4 Full-length (**A**) and close-up (**B**) plain radiographs, respectively showing the global balance and regional alignment in an 80-year-old woman from the PJF group. An inflection point shifted rostrally from L1 preoperatively to T12 postoperatively with an increase in UAL by 10.3°. The patient had painful L1 vertebral collapse without a fall 4 months after initial surgery, which we treated with balloon-assisted kyphoplasty and PMMA cement (BKP)

years after initial surgery, suggesting that "floating" fusion may be inappropriate for patients with markedly high PI.

Study limitations

Limitations include: single-institution study with a modest cohort (n = 95), limiting generalizability; longer-term follow-up may alter current ≥ 2-year findings, although most PJK/PJF cases emerge within 2 years [18, 25]; inherent selection bias exists, as patient enrollment followed exclusion criteria; and absence of a control group for direct comparison; the data were not necessarily associated with high statistical power. According to a post-hoc power analysis, differences detected at $p < 0.01$ had power levels exceeding 80% (i.e., > 0.8), but this was not consistently true for lower significance thresholds.

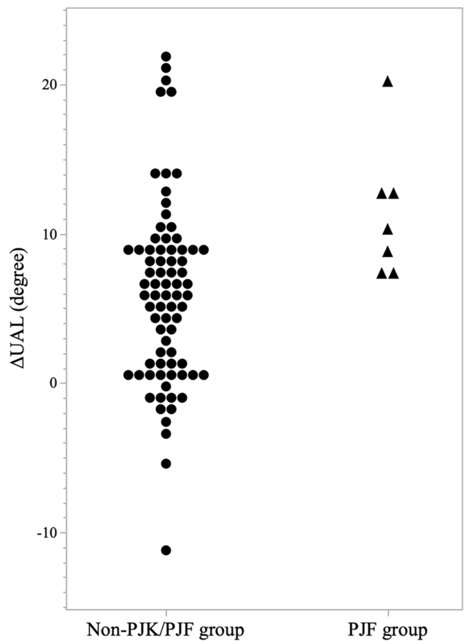

Fig. 5 The scatterplots comparing the angles of ΔUAL (i.e., operation-induced additional UAL) for 77 non-PJk/PJF patients (*left*) and 7 PJF patients (*right*). Mean-value analysis revealed a significantly smaller ΔUAL in the former group than the latter (5.7±0.7° vs. 11.3±2.3°; $p=0.0200$ [power= 0.4226]). Note an extensive overlap between the two groups, which suggests that additional factors likely shape the postoperative course, leading to two distinct outcomes

Author contributions Y.T. contributed to the conception and design of the study.Y.T., T.T., N.N., N.O., K.K., M.P., M.I., and T.A. contributed to the acquisition of data.Y.T., S.T., and M.A. contributed to the analysis and interpretation of data.Y.T. and S.T. performed the statistical analysis.Y.T. drafted the main manuscript text, and all authors contributed to its revision.S.T. and T.S. provided supervision.All authors read and approved the final manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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