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ORIGINAL ARTICLE

Possible factors associated with sagittal malalignment recurrence after pedicle subtraction osteotomy

David Eichler[1] · Yann Philippe Charles[1] · Florent Baldairon[1] · Yves Ntilikina[1] · Erik André Sauleau[2] · Jean-Paul Steib[1]

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Abstract

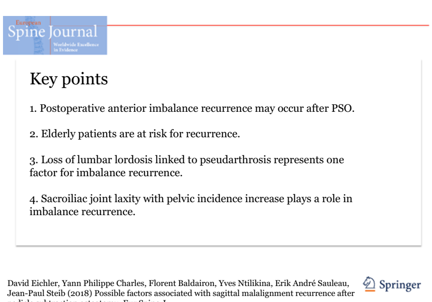
Purpose This retrospective study investigates sagittal alignment after pedicle subtraction osteotomy (PSO). The purpose was to investigate factors associated with malalignment recurrence.

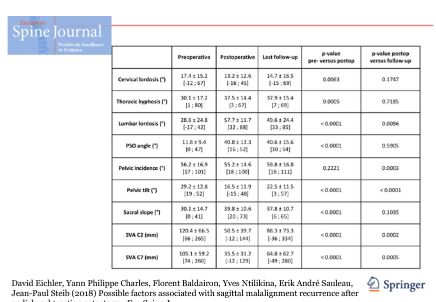
Methods Full spine radiographs were analyzed in 66 patients (average age 54.5 years, follow-up 3.8 years). Measurements were taken preoperatively, 3 months postoperatively, at follow-up: SVA C2 and C7, C2–C7 lordosis, T4–T12 kyphosis, L1–S1 lordosis, PSO lordosis, pelvic incidence, pelvic tilt, sacral slope. Follow-up CTs were screened for pseudarthrosis and gas in sacroiliac joints.

Results PSO lordosis increased from 11.8° to 40.8° ($p < 0.0001$) and kept stable. Lumbar lordosis increased from 28.6° to 57.7° ($p < 0.0001$) and decreased to 49.7° ($p = 0.0008$). Pelvic tilt decreased from 29.2° to 16.5° ($p < 0.0001$) and increased to 22.5° ($p < 0.0001$). SVA C7 decreased from 105.1 to 35.5 mm ($p < 0.0001$) and increased to 64.8 mm ($p = 0.0005$). Twenty-eight patients (42%) had an SVA C7 increase of more than 70 mm in the postoperative course: recurrence group. These patients were older: 62.8 years versus 52.3 years ($p = 0.0031$). Loss of lordosis was 11.9° (recurrence group) versus 5.0° (non-recurrence group). Eleven patients (17%) had pseudarthrosis. Pelvic incidence increased by 9.3° (recurrence group) versus 3.8° (non-recurrence group). In 23 patients (35%), pelvic incidence increased > 10°. Gas was evidenced in sacroiliac joints in 22 patients (33%).

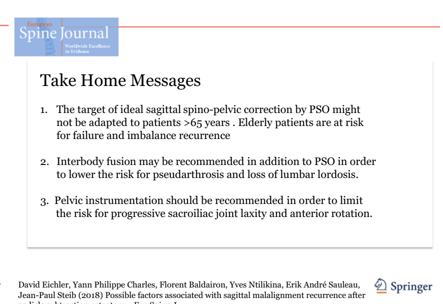
Conclusion Postoperative anterior malalignment recurrence may occur after PSO. Elderly patients were at risk of recurrence. Loss of lumbar lordosis linked to pseudarthrosis represented another factor. With malalignment recurrence, anterior trunk rotation and pelvic retroversion might additionally have augmented moments across sacroiliac joints with subsequent ligament laxity and pelvic incidence increase.

Graphical abstract These slides can be retrieved under Electronic Supplementary Material.





	Preoperative	Postoperative	Last follow-up	p-value pre- versus postop	p-value postop versus follow-up
Cervical lordosis (°)	17.4 ± 15.2 [-12 ; 67]	13.2 ± 12.6 [-16 ; 45]	14.7 ± 16.5 [-15 ; 69]	0.0063	0.1747
Thoracic kyphosis (°)	30.1 ± 17.2 [1 ; 80]	37.5 ± 14.4 [3 ; 67]	37.9 ± 15.4 [7 ; 69]	0.0005	0.7185
Lumbar lordosis (°)	28.6 ± 24.8 [-17 ; 42]	57.7 ± 11.7 [32 ; 88]	49.6 ± 24.4 [33 ; 85]	< 0.0001	0.0056
PSO angle (°)	11.8 ± 9.4 [0 ; 47]	40.8 ± 13.3 [16 ; 52]	40.6 ± 15.6 [10 ; 54]	< 0.0001	0.5905
Pelvic incidence (°)	56.2 ± 16.9 [17 ; 101]	55.2 ± 14.6 [18 ; 100]	59.8 ± 16.8 [16 ; 111]	0.2221	0.0003
Pelvic tilt (°)	29.2 ± 12.8 [19 ; 52]	16.5 ± 11.9 [-15 ; 48]	22.5 ± 11.5 [3 ; 57]	< 0.0001	< 0.0001
Sacral slope (°)	30.1 ± 14.7 [0 ; 41]	39.8 ± 10.6 [20 ; 73]	37.8 ± 10.7 [6 ; 65]	< 0.0001	0.1035
SVA C2 (mm)	120.4 ± 66.5 [66 ; 265]	50.5 ± 39.7 [-12 ; 144]	88.3 ± 73.3 [-36 ; 334]	< 0.0001	0.0002
SVA C7 (mm)	105.1 ± 59.2 [74 ; 260]	35.5 ± 31.2 [-12 ; 129]	64.8 ± 62.7 [-49 ; 280]	< 0.0001	0.0005



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Keywords Sagittal balance · Thoracolumbar alignment · Pedicle subtraction osteotomy · Malalignment recurrence · Lumbar pseudarthrosis · Loss of reduction · Sacroiliac joint laxity

Introduction

Adult spinal deformity with anterior malalignment influences health-related quality of life (QoL) [1–3]. Correction of sagittal malalignment can be performed by Smith–Petersen or Ponte osteotomies in deformities with remaining intersomatic mobility. Pedicle subtraction osteotomy (PSO) is usually indicated in severe rigid deformities. Severe deformities may require a transdiscal lumbar osteotomy or vertebral column resection in angular thoracic deformities [4]. Improvement in sagittal alignment and QoL was reported after PSO [5]. However, PSO does not always ensure optimal realignment, and malalignment recurrence has been described [6–9]. Several hypothesis and mechanisms might explain anterior malalignment recurrence.

Proximal junctional kyphosis (PJK) represents one cause. The increase in kyphosis of the non-instrumented thoracic spine shifts C2 and C7 plumblines anteriorly. Several risk factors have been advocated: age, female gender, comorbidities, obesity, osteoporosis, posterior elements disruption, proximal anchor types, high lumbar lordosis and thoracic kyphosis [10, 11]. The restoration of lordosis apex according to pelvic incidence and Roussouly type [12] was recently described as a reliable predictive method for PJK [13].

Loss of lordosis within instrumented levels is often related to nonunion and represents a second risk factor for anterior malalignment. Risk factors for pseudarthrosis are prior laminectomy, a large remaining disk height and inflammatory or neurologic disorders [14]. High preoperative sagittal vertical axis (SVA), long instrumentations with pelvic fixation and lack of interbody fusions have higher rod fracture rates and postoperative alignment changes [15].

Distal implant failure may be encountered in osteoporosis, and sacral or iliac screw loosening can indicate destabilization of the lumbosacral junction [16, 17]. Little attention has been paid to failure at the sacroiliac level. Pelvic incidence (PI) is recognized as a constant anatomical parameter in adults, independent of the pelvic position, as long as the sacroiliac joint (SIJ) remains stable [18, 19]. An age-related PI increase has been described and seems to correlate with malalignment recurrence [20]. Severe SIJ destruction and dislocation after PSO have been reported [21].

The purpose of this retrospective radiographic study was to analyze possible factors associated with severe sagittal malalignment recurrence in patients who underwent PSO. The role of SIJ degeneration and motion was investigated.

Materials and methods

Patients

Seventy-nine consecutive patients underwent PSO between 2004 and 2014. PSO was indicated for fixed malalignment in flat or kyphotic degenerative lumbar spines, postoperative flat backs and pseudarthrosis after scoliosis correction. Patients with ankylosing spondylitis were excluded as SIJ degeneration may be related to the disease. The same applied to patients with neurologic deficit, where standing radiographic analysis was impossible. Patients with incomplete pre- and postoperative radiographs were also excluded. Sixty-six of 79 patients had a complete clinical and radiographic documentation with minimum 2-year follow-up. The average follow-up was 42.3 (24–117) months. There were 16 male and 50 female patients with an average age of 54.5 (19–74) years.

Operative methods

Two spine surgeons using a standardized method operated all patients. Osteotomy levels were L1 in 2, L2 in 4, L3 in 23 and L4 in 39 patients. Four rods were used with bilateral domino connectors to close the PSO by compression and telescoping cranial and caudal rods in combination with in situ bending. Two additional satellite rods were implanted in five cases. Hybrid constructs with thoracic hooks, thoracic and lumbar pedicle screws were used. The cranial fixation was cranial to T4 in 16 patients and T9 or T10 in 37 patients. The distal instrumentation was an S2-ala fixation in 28 patients and an iliac screw fixation in 32 patients. Transforaminal (TLIF) or oblique lateral (OLIF) interbody fusion was usually performed at the cranial disk adjacent to the osteotomy to prevent pseudarthrosis.

Radiologic assessment

Preoperative, 3 months postoperative and last follow-up lateral full spine standing radiographs including femoral heads and external auditory conducts were considered. All radiographs were taken in the same radiology department following a standardized protocol: patients held their arms forward while holding fixed handles. They were asked, if capable, to fix one point straightforward at eyes' height. Following measurements were taken with SpineView software (Surgiview, Paris, France) [22]: SVA C2 and C7, cervical lordosis (C2–C7), thoracic kyphosis (T4–T12), lumbar lordosis (L1–S1), pelvic incidence, pelvic tilt and sacral slope.

PSO lordosis was defined as the angle between caudal endplate of the osteotomized vertebra and cranial endplate of the adjacent cranial vertebra.

All patients underwent a CT preoperatively. Patients presenting with persistent pain had a CT in search of nonunion or implant failure. Asymptomatic patients had a systematic follow-up CT at last follow-up for comparison. This imaging allowed assessing fusion at instrumented levels. Axial views were screened for gas formation at the SIJ.

A lumbar dual-energy X-ray absorptiometry was available for 29 patients, but not systematically assessed preoperatively. Seven patients had osteoporosis (*T* score lower than −2.5). This factor might be underestimated retrospectively and was therefore not analyzed.

Statistical analysis

Data were analyzed using R software (R Foundation, Vienna, Austria) using a Wilcoxon test. Radiographic measurements were compared pre- and postoperatively, between postoperative and last follow-up, between preoperative and last follow-up. A Bayesian approach was used in determining the cutoff value of SVA C7 increase between postoperative and last follow-up. An increase of more than 70 mm predicted a pelvic incidence increase of more than 10°, and a value above 30° at follow-up, indicating severe malalignment recurrence with failure of sagittal compensation by pelvic retroversion in any case. A linear mixed model then was used to compare differences between postoperative and last follow-up values of thoracic kyphosis, lumbar lordosis and pelvic incidence in patients with malalignment recurrence versus patients without recurrence. Ages at surgery were compared in both groups. The significance level was 0.05.

Results

Pre- and postoperative radiographic measurements are summarized in Table 1. The average SVA C2 decreased by 69.9 mm postoperatively and increased by 37.8 mm during follow-up. The same applied to SVA C7, which decreased by 69.6 mm postoperatively and then increased by 29.3 mm. The average pelvic tilt decreased by 12.7° postoperatively and then increased by 6.0°. All variations were significant ($p < 0.001$), indicating initial alignment correction and global malalignment recurrence during follow-up. Twenty-eight of 66 patients had an SVA C7 increase of more than 70 mm in the postoperative course: malalignment recurrence group. Average ages were higher in patients with (62.8 ± 6.7 years) compared to patients without (52.3 ± 9.2 years) recurrence ($p = 0.0031$). Figures 1, 2 and 3 illustrate a representative case evidencing several factors that might contribute to malalignment recurrence.

Cervical and thoracic alignment

Average cervical lordosis decreased by 4.2° and thoracic kyphosis increased by 7.4° postoperatively. Both parameters remained stable during follow-up. Average thoracic kyphosis decreased by 2.3° in patients with recurrence and increased by 1.8° in patients without recurrence ($p = 0.8200$) (Table 2). This indicated that kyphosis

Table 1 Radiographic sagittal alignment measures: average ± standard deviation [minimum; maximum]

	Preoperative	Postoperative	Last follow-up	*p* value pre- versus post-op	*p* value post-op versus follow-up	*p* value pre-op versus follow-up
Cervical lordosis (°)	17.4 ± 15.2 [−12; 67]	13.2 ± 12.6 [−16; 45]	14.7 ± 16.5 [−15; 69]	0.0063	0.1747	0.0231
Thoracic kyphosis (°)	30.1 ± 17.2 [1; 80]	37.5 ± 14.4 [3; 67]	37.9 ± 15.4 [7; 69]	0.0005	0.7185	0.0002
Lumbar lordosis (°)	28.6 ± 24.8 [−17; 42]	57.7 ± 11.7 [32; 88]	49.6 ± 24.4 [33; 85]	< 0.0001	0.0056	< 0.0001
PSO angle (°)	11.8 ± 9.4 [0; 47]	40.8 ± 13.3 [16; 52]	40.6 ± 15.6 [10; 54]	< 0.0001	0.5905	< 0.0001
Pelvic incidence (°)	56.2 ± 16.9 [17; 101]	55.2 ± 14.6 [18; 100]	59.8 ± 16.8 [16; 111]	0.2221	0.0003	0.0429
Pelvic tilt (°)	29.2 ± 12.8 [19; 52]	16.5 ± 11.9 [−15; 48]	22.5 ± 11.5 [3; 57]	< 0.0001	< 0.0001	0.0014
Sacral slope (°)	30.1 ± 14.7 [0; 41]	39.8 ± 10.6 [20; 73]	37.8 ± 10.7 [6; 65]	< 0.0001	0.1035	< 0.0001
SVA C2 (mm)	120.4 ± 66.5 [66; 265]	50.5 ± 39.7 [−12; 144]	88.3 ± 73.3 [−36; 334]	< 0.0001	0.0002	0.0005
SVA C7 (mm)	105.1 ± 59.2 [74; 260]	35.5 ± 31.2 [−12; 129]	64.8 ± 62.7 [−49; 280]	< 0.0001	0.0005	0.0013

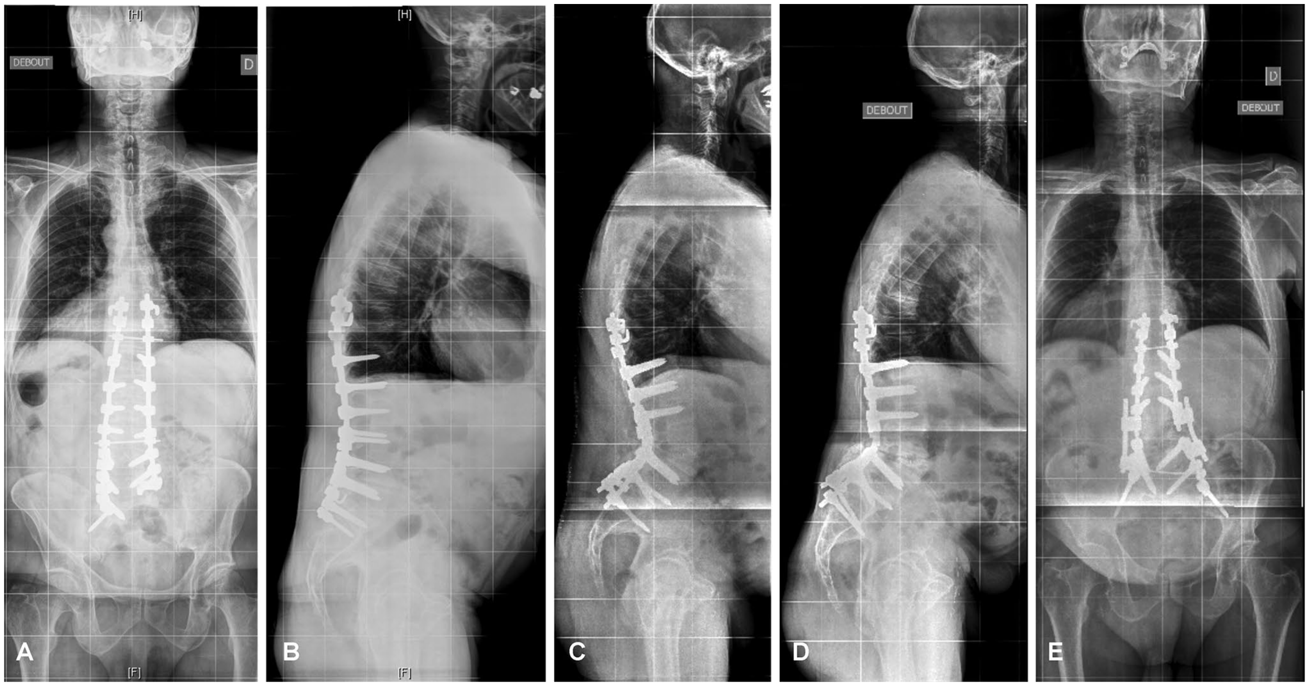

Fig. 1 A 64-year old male with flat back after posterior fusion T10-sacrum, preoperative posterior–anterior (**a**) and lateral (**b**) radiographs prior revision surgery showing anterior imbalance: SVA C7 136 mm, thoracic kyphosis 41°, lumbar lordosis 27°, pelvic incidence 52°, pelvic tilt 32°, sacral slope 27°. Postoperative lateral radiograph (**c**) after PSO at L4 showing a normalization of spinopelvic parameters but a global kyphosis increase in the non-instrumented thoracic spine: SVA C7 72 mm, thoracic kyphosis 50°, lumbar lordosis 66°, pelvic incidence 54°, pelvic tilt 7°, sacral slope 45°. Five-year follow-up lateral (**d**) and posterior–anterior (**e**) radiographs showing anterior imbalance recurrence with loss of lordosis and pelvic incidence increase: SVA C7 145 mm, thoracic kyphosis 52°, lumbar lordosis 55°, pelvic incidence 65°, pelvic tilt 22°, sacral slope 37°

increase in the non-instrumented thoracic spine was not the main mechanism of malalignment recurrence. PJK was not observed in this cohort, but 23 of 37 patients (62%) with cranial instrumentation at T9 or T10 evidenced a kyphosis increase in the entire non-instrumented thoracic spine.

Lumbar lordosis, PSO lordosis and pseudarthrosis

Average lumbar lordosis increased by 29.1° postoperatively ($p < 0.0001$) and decreased by 8.1° during follow-up ($p = 0.0056$). At PSO level, lordosis increased by 29.0° ($p < 0.0001$) and remained stable at follow-up. Lumbar lordosis decreased by 11.9° in patients with malalignment recurrence and by 5.0° in patients without recurrence ($p = 0.8837$). Eleven patients (17%) evidenced pseudarthrosis and rod breakage during follow-up. Among them, 8 were in the recurrence group and 7 had instrumentation cranial to T4. Although the difference in postoperative lordosis decrease was not significant between both groups, this observation indicated that pseudarthrosis and loss of lordosis might contribute to malalignment recurrence.

Pelvic incidence and sacroiliac joint

Average PI was comparable pre- and postoperatively, but increased by 4.7° during follow-up ($p = 0.003$). These average changes for the entire cohort might be below the threshold of measurable changes. Average PI increased by 9.3° in patients with malalignment recurrence and by 3.8° in patients without recurrence ($p = 0.3150$). Although this difference was not significant, PI increased by more than 10° in 23 patients in the postoperative course, and all of them belonged to the recurrence group. Gas was evidenced in the SIJ on CT in 22 of 23 patients with PI increase superior to 10°. Sacroiliac joint dislocation was clearly evidenced on three-dimensional CT reconstruction in 2 patients. These observations indicated that SIJ motion might be one additional factor contributing to malalignment recurrence. Eighteen of 23 patients with PI increase superior to 10° had an S2-ala fixation, and 5 patients had an iliac screw fixation. A radiologic halo indicating screw loosening was evidenced on CT in these patients. In this cohort, S2-ala screws were shorter (6.5 mm diameter, 55–70 mm lengths) compared to iliac screws (7.5–8.5 mm

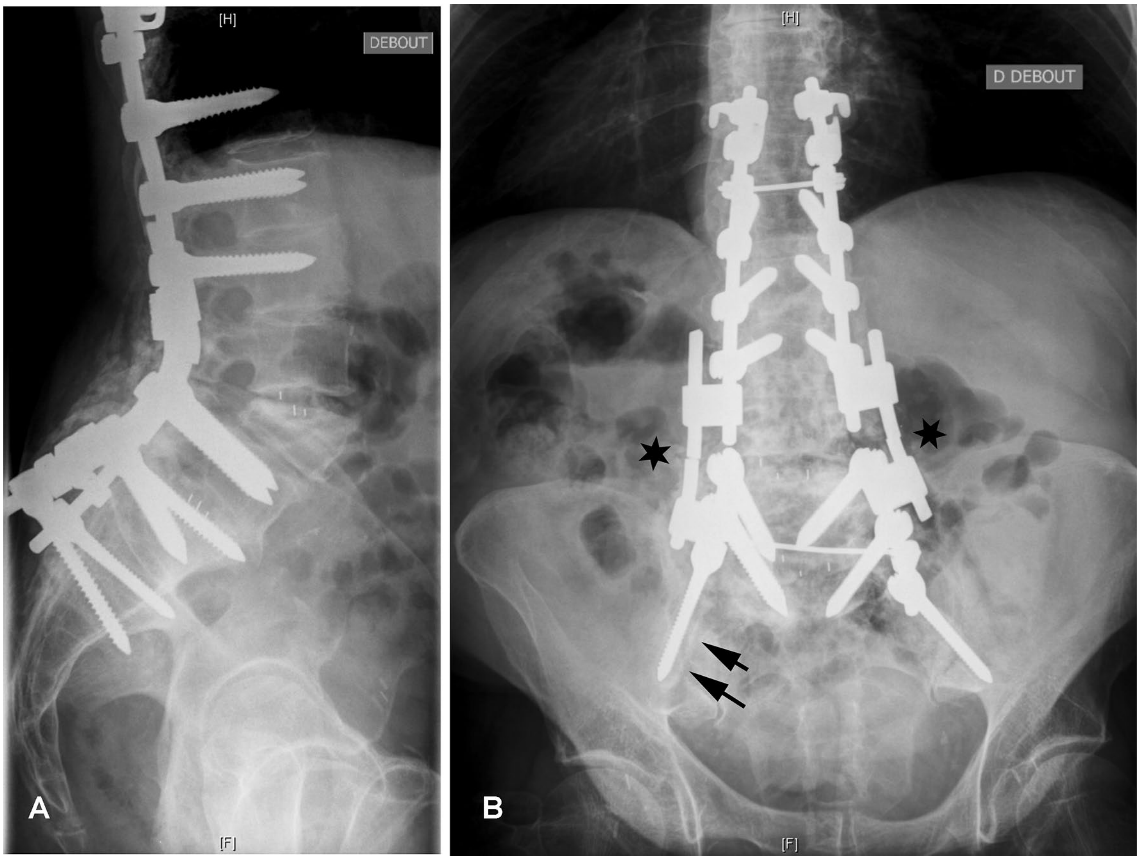

Fig. 2 Five-year follow-up lateral (**a**) and posterior–anterior (**b**) radiographs of the same patient showing rod fractures (stars) suggesting pseudarthrosis and a halo (arrows) indicating S2-ala screw loosening

diameters, 65–90 mm lengths). An SIJ violation by too short S2-ala screws might play a role in PI increase.

Discussion

Satisfactory clinical and radiologic results were reported at long-term after PSO [23–25]. Although fixed sagittal malalignment is efficiently corrected by PSO, this procedure is associated with risks of mechanical complication, which might lead to imbalance recurrence [6–9]. Kim et al. [23] demonstrated an average SVA correction from 140 mm preoperatively to 20 mm postoperatively and a progressive loss to 50 mm at 5-year follow-up. Rose et al. [24] showed and an SVA improvement from 150 mm before surgery to 30 mm after surgery and to 45 mm at 2 years. Yagi et al. [25] demonstrated an SVA decrease from 104 mm preoperatively to 36 mm postoperatively and an increase to 54 mm at minimum 5-year follow-up. The results of our study are in line with these findings, indicating that PSO improves sagittal alignment (SVA and pelvic retroversion) during the early postoperative period. However, partial recurrence of malalignment seems a common phenomenon in patients who underwent PSO. Mechanical complications and imbalance recurrence might be linked to intrinsic patient-related factors, such as underlying neurologic disorders, back muscle strength and age. Theologis et al. [15] showed that age older than 65 years was predictive for alignment deterioration after adult spinal deformity surgery. In our cohort, patients with imbalance recurrence were older than patients without recurrence. Compensatory mechanisms and the amount of required sagittal alignment correction might be different in the elderly population. Age should be therefore taken into account when planning surgery [26]. The present study further investigated thoracic and lumbar segments as well as the SIJ in detail in order to explain deleterious factors and possibly prevent them in the future.

In the thoracic segment, a postoperative global kyphosis increase or PJK might represent factors that explain imbalance recurrence. Theologis et al. [15] reviewed 183 patients: worsening of thoracic alignment was seen in 64% of their patients, and 27% had a kyphosis increase superior to 10° of the non-instrumented spine. Kim et al. [23] reported an average kyphosis increase of 9° and a proximal junctional angle increase of 8° at the cranial end of instrumentation. Both parameters changed in the early postoperative period

Fig. 3 Five-year follow-up CT of the same patient: coronal view (**a**) of the lumbar spine shows posterior pseudarthrosis (black arrows) and TLIF with intersomatic nonunion at L3-L4 on sagittal view (**b**). The axial sacroiliac view (**c**) demonstrates signs of S2-ala screw loosening (white arrows) and gas in sacroiliac joints

Table 2 Comparison of thoracic, lumbar and sacroiliac sagittal alignment in patients with malalignment recurrence versus patients without recurrence: average ± standard deviation [minimum; maximum] and significance comparing evolution from postoperative to last follow-up in both groups

	Malalignment recurrence group ($n=28$)			No recurrence group ($n=38$)			
	Pre-op	Post-op	Follow-up	Pre-op	Post-op	Follow-up	*p* value
Thoracic kyphosis (°)	31.4 ± 18.7 [1; 80]	39.5 ± 14.0 [16; 67]	37.2 ± 14.6 [12; 69]	28.5 ± 15.1 [1; 53]	34.6 ± 14.7 [3; 62]	36.4 ± 15.9 [7; 60]	
		− 2.3			+ 1.8		0.8200
Lumbar lordosis (°)	27.4 ± 28.3 [− 10; 42]	59.9 ± 10.9 [40; 88]	48.0 ± 31.6 [35; 85]	30.2 ± 19.6 [− 17; 39]	54.3 ± 12.3 [32; 75]	49.3 ± 18.1 [33; 74]	
		− 11.9			− 5.0		0.8837
Pelvic incidence (°)	54.2 ± 17.6 [17; 92]	54.7 ± 15.1 [18; 99]	64.0 ± 19.3 [16; 111]	54.0 ± 16.1 [32; 101]	55.1 ± 14.4 [31; 100]	58.9 ± 15.5 [32; 104]	
		+ 9.3			+ 3.8		0.3150

but remained stable after 2-year follow-up. Lee et al. [7] described a thoracic decompensation type after lumbar kyphosis correction by Smith–Peterson osteotomies or PSO. The global malalignment recurrence rate was 38.3% in their cohort of 23 patients. The average preoperative thoracic kyphosis was 7.9° preoperatively, 21.6° postoperatively and 31.7° at minimum 2-year follow-up. The kyphosis increase was observed at non-fused segments, and an MRI investigation indicated a possible link with paravertebral muscle atrophy. Yagi et al. [25] demonstrated that a proximal fusion level caudal to T8 presented a higher risk of postoperative kyphosis increase in comparison to instrumentation levels cranial to T6. The PSO level might further influence proximal sagittal alignment. Sebaaly et al. [13] demonstrated that a mismatch between postoperative and theoretical lumbar apex according to Roussouly et al. [12] was highly predictive for PJK. The PSO level should not be higher than L4 if PI is < 55°. Only patients with PI > 55° tolerate an apex at L3. In a similar manner, Yilgor et al. [27] have developed a global alignment proportion score with deformity correction targets based on the patient's individual spinopelvic configuration. This score was predictive for mechanical complications such as PJK or pseudarthrosis.

In the lumbar spine, loss of lordosis has been reported after PSO. Kim et al. [23] reported an average lordosis increase from 16° to 50° that decreased to 45° at follow-up. The lordosis at PSO level kept relatively stable postoperatively, comparable with our results. Lee et al. [7] measured an average loss of lordosis of 9.4° during follow-up, whereas Rose et al. [24] found a minor decrease of 2.3° at 2 years. Pseudarthrosis represents one explanation for loss of lordosis within instrumented segments. Dickson et al. [14] reported an incidence of 10.5%, Yang et al. [6] 15%, Chiffolot et al. [9] 23%, Kim et al. [23] 29%. The pseudarthrosis rate in our cohort (17%) fits within this range. Nonunion can occur at the osteotomy level in large posterior bone resections. The lack of intersomatic fusion represents one additional factor leading to pseudarthrosis, especially if the remaining disks are high and if the lumbosacral junction and pelvis are instrumented [15].

The SIJ might further play an underestimated role in imbalance recurrence. Legaye [20] and Merill et al. [27] demonstrated that PI could increase with age as lumbar lordosis decreases with degenerative changes. Prolonged forward projection of the gravity line increases the lever arm resulting from the center of rotation at the SIJ. Retroversion of the pelvis further increases this lever arm and stress across SIJ, which could lead to progressive twisting mobilization within the SIJ and weakening of sacroiliac ligaments [21]. This phenomenon might have occurred in our patients as PI has slowly increased in the postoperative course. Ha et al. [28] demonstrated that SIJ degeneration might occur after long lumbosacral instrumentation. Cecchinato et al. [29] found a significant increase in PI after surgery in patients older than 65 undergoing long fusion to the sacrum without pelvic fixation, related to SIJ degeneration causing increased rotational mobility. Finger et al. [30] and Volkheimer et al. [31] demonstrated that pelvic fixation using long iliac screws is aimed to distribute load from the lumbar spine to the pelvis and thus lowers stress at L5–S1, sacral implants and the SIJ. This construct type might be preferable in patients undergoing PSO. It appears essential to prevent SIJ violation when using iliac screws, since damage to the syndesmosis might increase pelvic instability by premature SIJ degeneration. The risk of iliac screw loosening increases with misplacement across the SIJ, osteoporosis, lumbosacral pseudarthrosis and instrumentation to the cranial thoracic spine [16]. A distal S2-ala fixation using long screws might limit the risk of loosening since the bone purchase is tri-cortical [32].

Although mechanisms of imbalance recurrence were analyzed, this radiologic study has limitations. Correlation between pre- and postoperative clinical outcome measures and malalignment recurrence on radiographs was not possible retrospectively. An assessment of patient-related factors, bone mineral density, back muscle strength and a detailed examination of the central nervous system might be implemented in future studies. A larger prospective cohort would further allow a multivariate analysis of different factors influencing imbalance recurrence in order to better predict and prevent the risk preoperatively.

Conclusion

Postoperative recurrence of anterior malalignment may occur after PSO despite local lumbar lordosis correction. Elderly patients are at risk of malalignment recurrence. The postoperative increase in thoracic kyphosis indicates a compensation of the non-instrumented spine. Loss of lumbar lordosis may be linked to nonunion or osteoporosis. Retroversion of the pelvis progressively increases to compensate anterior malalignment. The recurrence of anterior malalignment increases the lever arm between the plumbline of C7 and the sacroiliac center of rotation. Anterior trunk rotation and pelvic retroversion might increase moments across sacroiliac joints, which might lead to progressive ligament laxity and increase in pelvic incidence.

Compliance with ethical standards

Conflict of interest None of the authors has any conflict of interest related to this study.

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Affiliations

David Eichler[1] · Yann Philippe Charles[1] · Florent Baldairon[1] · Yves Ntilikina[1] · Erik André Sauleau[2] · Jean-Paul Steib[1]

✉ Yann Philippe Charles
yannphilippe.charles@chru-strasbourg.fr

[1] Service de Chirurgie du Rachis, Hôpitaux Universitaires de Strasbourg, Fédération de Médecine Translationnelle (FMTS), Université de Strasbourg, 1, Place de l'Hôpital, B.P. 426, 67091 Strasbourg Cedex, France

[2] Département de Santé Publique, Hôpitaux Universitaires de Strasbourg, Université de Strasbourg, Strasbourg, France