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ORIGINAL ARTICLE

Clinical and radiological outcomes of lumbar posterior subtraction osteotomies are correlated to pelvic incidence and FBI index

Prospective series of 63 cases

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Abstract
Purpose Pedicle subtraction osteotomy (PSO) is one of the surgical options for treating alignment disorders of the fused spine (due to post-surgical fusion or related to arthritis). It enables satisfactory sagittal realignment and improved function due to economic sagittal balance. The aim of this study was to analyze clinical and radiological results of PSO after a minimum follow-up of 2 years and demonstrate the benefit of sub-group analysis as a function of pelvic incidence (PI).
Methods A descriptive prospective single center study of 63 patients presenting with spinal global malalignment who underwent correction by PSO. Function was assessed by the Oswestry disability index (ODI), a visual analog scale of lumbar pain (VAS) and a SF-36 questionnaire. Radiographic analyses of pre- and post-operative pelvic-spinal parameters were performed on X-rays obtained by EOS® imaging after 3D modeling. Global analysis and analysis of sub-groups as a function of pelvic incidence were performed and the full balance integrated index (FBI) was calculated.
Results this series showed a marked clinical improvement and significant progress of functional scores. Global post-operative radiological analysis showed a significant improvement in all pelvic and spinal parameters. The mean correction obtained after PSO was $31.7° \pm 8.4°$, hence global improvement of lumbar lordosis of 22°. The sagittal vertical angle (SVA) decreased from +9 cm before surgery to +4.3 cm after surgery. Sub-group analysis demonstrated greater improvement in pelvic tilt, sacral slope and spinal parameters of patients with a small or moderate pelvic incidence; all had an FBI index <10°. Most of the pelvic and spinal parameters of patients with a large pelvic incidence were insufficiently corrected and they had an FBI index >10°
Conclusion PSO is a surgical procedure enabling correction of multiplane rigid spinal deformities that require major sagittal correction. It was seen to be highly effective in patients with a small or moderate pelvic incidence (PI <60°) but was sometimes less effective in patients with large pelvic incidence due to insufficient lordosis correction. Clinical results were highly correlated with the value of the FBI index.

Keywords Pedicular subtraction osteotomy · Sagittal imbalance · Outcomes · Flat back · Prospective series

Introduction

Sagittal spinal balance is ideal when sagittal alignment is in a state of economic balance. The erect position characteristic of man may become altered during certain pathological conditions (related to aging, illness and iatrogenic disease). These may result in postural disorders (affecting the frontal, horizontal and sagittal planes) which cause "imbalance". This leads to compensatory mechanisms that cause low back pain [1].

Alignment disorders on spines that have been fused either by surgery or by arthritis are a surgical challenge if satisfactory spinal alignment is to be accompanied by improved function.

Pedicle subtraction osteotomy (PSO) first described by Thomasen in 1985 [2] is one of the surgical procedures

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used to treat rigid spinal deformities that require major correction. This type of osteotomy enables a gain of 30° in lumbar lordosis [2, 3].

There is little published information concerning PSO and only for small cohorts. This does not always allow detailed analysis of results and complications related to the surgical procedure. These studies performed a global analysis of sagittal alignment using the sagittal vertical axis (SVA) [4] value only. This parameter was correlated with the line of gravity but did not reflect the harmony of curves in the sagittal plane. Moreover, analysis of means of the global population without any sub-group analysis as a function of pelvic incidence was not a very discriminant analysis [5] (Fig. 1).

Most biomechanical and clinical studies have demonstrated the strong correlation between pelvic incidence and lumbar lordosis which is useful for understanding spinal sagittal alignment [6–9]. But no study has analyzed the results of lumbar PSO by stratifying the population according to the type of back and pelvic incidence of patients.

The aim of this study was to analyze clinical and radiological results of PSO after a minimum follow-up of 2 years and demonstrate the benefit of sub-group analysis as a function of pelvic incidence to measure the corrections made.

Materials and methods

Population

Descriptive, prospective, single center study including 80 patients presenting spinal imbalance and requiring correction by PSO between May 2008 and January 2013. The series comprised 50 women and 23 mens with a mean age of 60.6 (27–83) years.

Spinal imbalance was due to the following: 23 arthrogenic kyphosis, including three patients with Parkinson's disease, 30 post-operative flatbacks, six degenerative scoliosis, two cases of ankylosing spondylarthritis, two cases

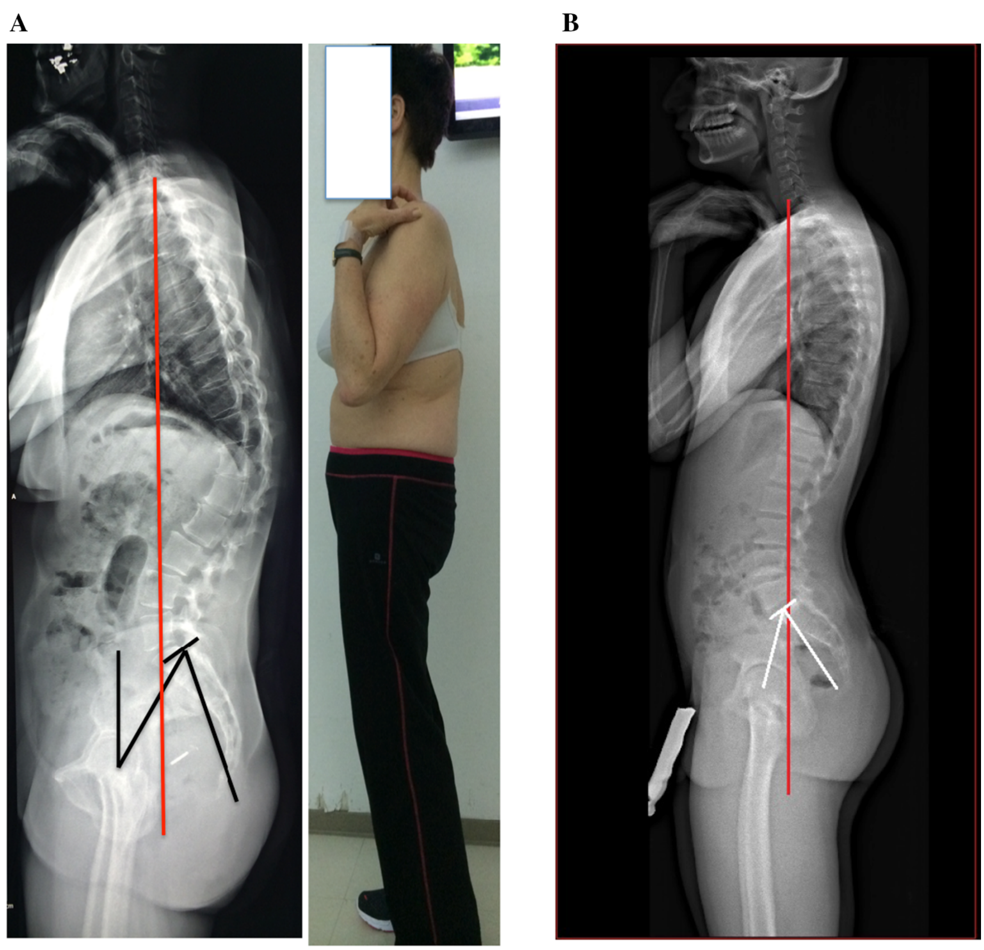

Fig. 1 Normal SVA value (<5 cm in those two cases) is not a guarantee of good spinal economical shape due to compensation phenomenon. **a** Kyphotic thoracolumbar spine with good SVA (2.5 cm), **b** economical good thoracolumbar sagittal aligment SVA (1 cm)

of sequelae to operated spondylolisthesis, ten cases of post-traumatic regional kyphosis and seven of post-infectious kyphosis.

We excluded those with regional post-traumatic or post-infectious kyphosis (17 cases) where it was a localized angular kyphosis. To treat the sagittal imbalance of angular kyphosis, specific treatment is required only at the level of the angulation. Angular kyphosis therefore did not fall within the scope of global imbalance of spinal curve harmony since the cause of the imbalance is identified directly on the abnormal vertebra.

The aim of this study was to analyze clinical and radiological results after a minimum follow-up period of 2 years.

Preoperative assessment

The pre-operative clinical assessment included collecting demographic data and spinal history. The clinical examination found sagittal imbalance with marked compensation mechanisms [10] causing low back pain often associated with radicular pain in the lower limbs or with referred pain.

Pre-operative functional assessment was based on the Oswestry disability index (ODI), a visual analog scale (VAS) of 1–10 for lumbar and radicular pain and the functional score of the SF-36 [11].

All the patients underwent low-dose radiographic evaluation using EOS® imaging (EOS Imaging, Paris, France) [12] which produced 2D images of the standing patient (frontal and profile) including the head and knees [12, 13]. Images were then analyzed using sterEOS® software (version 1.4.5) after 3D modeling [14]. The 3D reconstruction using stereos has been validated on scoliotic population as described by Somoskeoy S. [15, 16] Hence the analyses of pelvic and spinal parameters were performed in the standing position in 3D which, to our knowledge, was not previously reported in the literature for PSO.

The following pelvic and spinal parameters were analyzed (Table 1):

– Pelvic parameters: pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS).
– Spinal parameters: lumbar lordosis (LL), thoracic kyphosis (TK), spino-sacral angle (SSA), sagittal vertical axis (SVA) and Barrey index [5].

The pre-operative planning required to implement accurate correction was performed calculating the full balance integrated (FBI) index = C7TA + FOA + PTCA [17].

The angles used are given below: (Fig. 2).

– C7TA: C7 translation angle—midpoint of C7 (a) is transposed horizontally to the ideal position of the C7 plumb line (b), passing through the sacral endplate. The “c” point represents the anterior edge of L4 representing the apex of lumbar lordosis.

Table 1 Radiographic analysis of standing pelvic and spinal parameters (a), upper level fusion (b)

(a)	
PI	The angle between the line connecting the center of the femoral heads and the sacral plate at its midpoint and the perpendicular to the sacral endplate
PT	The angle between the line connecting the center of the femoral heads and the midpoint of S1 and the vertical line passing through the center of the femoral heads
SS	The angle between the sacral plate and the horizontal line
LL	The angle between the superior L1 endplate and the S1 endplate
TK	The angle between the T4 endplate and T12 endplate
SSA	The angle between the line connecting the centroid of C7 vertebral body and the midpoint of the sacral endplate
SVA	The distance between the C7 plumb line and the posterosuperior corner of S1
Barrey	The ratio of the distance between the posterior corner of the sacral endplate at the C7 plumb line, and the distance between the center of the femoral heads at the posterior corner of the S endplate
LL deficit	Ideal LL (according to Schwab)—measured LL

(b)	
Upper level fusion	*n*
Upper thoracic (T2-T4)	23
Thoraco-lumbar (T11-L1)	41

PI pelvic incidence, *SS* sacral slope, *PT* pelvic tilt, *LL* lumbar lordosis L1S1, *TK* thoracic kyphosis, *SSA* spino sacral angle, *SVA* sagittal vertical axis, *LL deficit* lumbar lordosis deficit = ideal LL (according to Schwab)—post-operative measured LL

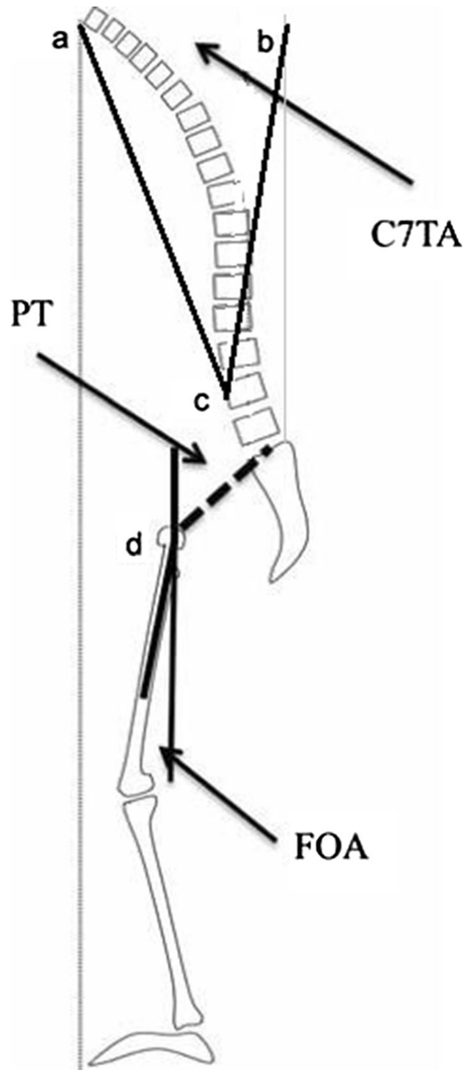

Fig. 2 Pre-operative planning of the necessary correction: FBI technic (full balance integrated). *FOA* femur obliquity angle, *PT* pelvic tilt compensation angle, *C7TA* C7 translation angle. FBI angle = FOA + PT compensation angle + C7TA

- FOA: the angle of femoral obliquity: the angle between the femoral axis and the vertical.
- PTCA: the angle of pelvic tilt compensation (PT <15: 0°, 15° <PT <25: +5, PT >25: +10°).

The superior level of the fusion was determined depending on the degree of the thoracic kyphosis. Fixation was systematically extended to the upper thoracic vertebra in case of severe osteoporosis, inflammatory spine disease, Parkinson disease [18] or fixed thoracic kyphosis superior to 0.75 of the theoretical lumbar lordosis as described by Roussouly [19].

Surgical technique

Vertebral body subtraction corpectomy consists of a triangular uniform resection at the targeted vertebral body by posterior approach. We used the type three osteotomy as described in the recently published Schwab F. [20] Additional Smith Petersen osteotomy was performed to adjacent levels if needed. The patient is operated in the prone position on a radiolucent table. A blood collection system such as Cell-Saver (Haemonetics, Braintree MA) was used for inter-operative blood recovery and auto transfusion.

After a posterior median approach, a computed tomography (CT) scan was obtained using the OARM system (Medtronic, Memphis, USA). The implants were positioned with guidance of the OARM-Stealth-Station (Medtronic, Memphis, USA) computer-assisted navigation system, following the pre-operative planning indications. The osteotomy was done in accordance with the Egg Shell procedure, using impaction of cancellous intervertebral body bone to reinforce the anterior vertebral wall and avoid loss of correction by vertebral collapse.

Reduction of the osteotomy was achieved along a rod centered to correct the lordosis using an instrument placed over the pedicle screws two levels above and below the osteotomy. This instrument enables progressive closure of the osteotomy and preventing the risks of collapse of the anterior vertebral wall or translational movement of the discs adjacent to the osteotomy. This instrument was used only for the last twelve cases. For the previous ones, the compression technic using the domino and table plicature was performed (Fig. 3). The entire procedure was performed under motor evoked potential (PEM) and sensory evoked potential (SEM) neurophysiological monitoring.

Nine patients (14 %) underwent a complementary procedure involving insertion of an intersomatic cage via the lateral approach (lumbotomy). This was done if adjacent discs to the osteotomy were of conserved height so as to reduce the risk of non-union at the PSO level.

After surgery, a thoracolumbar brace was prescribed for 3 months to protect the implants from marked mechanical stress.

Postoperative assessment

Patients were seen in consultation 3, 6, 12 and 24 months after surgery, and then biannually except for cases with complications, which were monitored more frequently. Clinical and functional assessments were based on the ODI score, VAS of lumbar and radicular pain and the SF-36 score. All scores and demographic data were registered in the online computerized database KEOPS (Smaio, Lyon, France) compliant with statutory regulations for security and protection of personal data.

The post-operative radiological analysis was performed in the same way as the pre-operative analysis using sterEOS® software (EOS imaging, Paris, France).

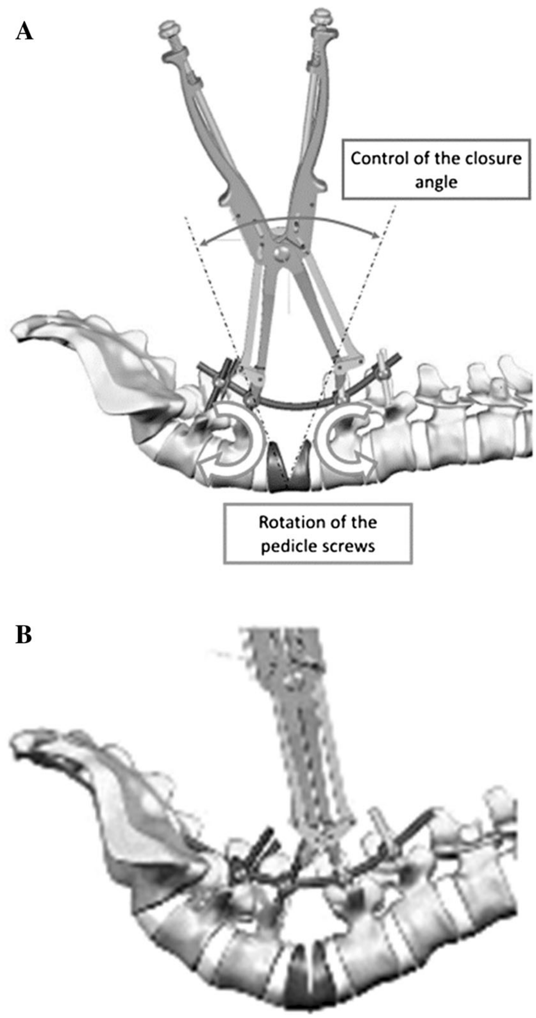

Fig. 3 The Redux Plier system is placed on the pedicle screws two levels above and two levels below. This instrument enabled progressive closing of the osteotomy, preventing the risks of collapse of the enabled anterior vertebra wall and shearing of discs adjacent to the osteotomy. **a** Before closure, **b** after closure of PSO

As for radiographic analysis, the average values of pelvic parameters and the angular measurements are not very discriminating; therefore the population was divided into three groups depending on pelvic incidence. This subdivision method was already used by Barrey et al. [5] to analyze a population of asymptomatic subjects. The subdivision into six groups not being relevant to our population of 63 patients, we decided on three groups allowing us to have sufficient data for each statistical analysis. The three groups were established as follows after calculating the median for this population, which was 51°:

- group 1: PI <45°;
- group 2: 45° <PI <60°;
- group 3: PI >60°.

Statistical analysis was done using SPSS version 20.0 (IBM, New York, US). All variables gathered were subject to a descriptive analysis. Qualitative variables were analyzed in terms of frequency and percentages in each category and included means, standard deviations, and range, as well as Student t tests. Small samples (<30) were analyzed using an F test for comparison of variances. The classic t test was used if the variances were not significantly different and the unequal variance t test if they were. The level of significance was set at 0.05.

Results

The 63 patients retained in the analysis were seen in consultation for a radiological and clinical control after a minimum of 23.5 months (6–60).

The pre-operative analysis revealed: 23 arthrogenic kyphosis including three patients with Parkinson's disease, 30 post-operative flatbacks, six degenerative scoliosis, two cases of ankylosing spondylarthritis and two cases of sequelae to operated spondylolisthesis. Pre-operative spinal radiological characteristics are given in Table 2.

Intervention

The level of osteotomy was L3 in 16 (25 %) and L4 in 47 (75 %) patients, with a posterior instrumentation extended over an average of nine levels [5–15]. The mean duration of operation was 260 min (180–450) and the mean blood loss was 2170 ml (700–5000). The recovery by Cell Saver® and the deferred auto transfusions reduced the need for autologous transfusions. A homologous secondary transfusion was necessary in 14 cases (22 %) in which haemoglobin level was less than 8 g.

Clinical results

All patients ($n = 63$) recorded pre- and post-operative functional scores. The global analysis showed significant improvement in the ODI score 51.7–34.3 at the last examination ($p < 0.05$). Similarly, VAS score decreased from 7.44 to 3.8 at the last examination ($p < 0.05$). The SF-36 physical and mental component summary scores also improved very significantly (Table 3).

Global and sub-group analyses showed the greatest improvement was in the groups with small (group 1) and moderate (group 2) pelvic incidence, but the difference was not significant ($p = 0.122$) (Tables 4, 5).

Radiological results

Tables 6, 7, 8 and 9 present pelvic and spinal parameters after global and sub-group analysis. Post-operative lumbar lordosis deficit was assessed using an ideal LL value based

Table 2 Pre-operative pelvic and spinal radiological parameters

Pre-operative descriptive statistics

	Global population, $n = 63$		PI <45, $n = 10$		PI 45–60, $n = 23$		PI >60, $n = 30$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
PI	60.14 (34–86)	13.506	40 (34–45) ± 4.0	4.000	53 (46–63)	5.065	72.05 (61–86)	6.783
SS	29.35 (0–62)	12.923	19.2 (0–40)	12.6	21.08 (43–40)	15.492	36.95 (13–62)	11.776
PT	31.05 (5–50)	10.166	20.6 (5–36)	10.124	29.08 (14–47)	7.638	35.83 (20–50)	9.099
SSA	106.53 (79–142)	14.731	106.5 (79–125)	13.812	100.6 (80–128)	13.473	111.48 (84–142)	14.466
SVA	9.11 (3.10–24.20)	4.9	8.22 (6.5–10.5)	2.1	8.9 (3.10–15.3)	4.1	9.48 (5.70–24.20)	4.8
Barrey	1.59 (0.39–4.34)	0.94	2.04 (0.57–4.34)	1.43210	1.48 (0.39–3.18)	0.68776	1.5319 (0.54–3.54)	0.92979
FBI°	31.29 (10–67)	13.77	21 (15–35)	6.042	30.9 (10–47)	10.998	35.59 (17–67)	15.39
LL	28.47 (–10 to 66)	14.37	24.8 (5–45)	14.675	21.26 (–10 to 40)	13.072	35.54 (17–66)	11.899
TK	29.57 (4–58)	12.2	29.5 (12–49)	11.293	30.9 (6–58)	13.372	28.44 (4–50)	11.82

Global analysis and analysis of sub-groups as a function of pelvic incidence

PI pelvic incidence, *SS* sacral slope, *PT* pelvic tilt, *SVA* sagittal vertical axis, *FBI* full balance integrated index, *LL* lumbar lordosis L1S1, *TK* thoracic kyphosis, *LL deficit* lumbar lordosis deficit = ideal LL (according to Schwab)—post-operative measured LL

Table 3 Significant improvement in ODI, SF-36 and lumbar VAS scores

	Improvement	*p* value
ODI	17.3 ± 16.151	0.000
SF-36 PCS	6.82 ± 9.2	0.000
SF-36 MCS	6.44 ± 10.8	0.000
Lumbar VAS	3.64 ± 1.3	0.000

on the formula described by Schwab et al.: ideal LL = PI + 9 [21].

There was no significant difference between the immediate post-operative analysis and the last control.

Mean correction obtained by PSO was 31.7° ± 8.4°, enabling global improvement of lumbar lordosis of 21.4° ± 12.2°. Pre-operative SSA was 106.5° ± 14° and had improved to 120.6° ± 9° after surgery. SVA went from +9 cm before surgery to +4.3 cm after surgery ($p < 0.001$) which is considered normal by Schwab (SVA <5) [22] (Fig. 4). The 12 patients operated with the redux plier had a tendency to obtain a higher PSO correction.

Table 5 Analysis of differences in post-operative ODI scores in sub-groups

	Mean	Difference	*p* value
ODI PI <45	28.63 ± 10.3	4.47 ± 11	0.255
ODI PI 45–60	33.10 ± 10.4		
ODI PI <45	28.63 ± 10.3	8.8 ± 16	0.122
ODI PI >60	37.5 ± 11.2		

Difference between small and moderate PI and between small and large PI

Global analysis of pelvic parameters found significant global improvement of both PT and SS ($p < 0.001$) (Table 6). They went from 31.5° to 25.6° and 28.8° to 32.7°, respectively.

Sub-group analyses are grouped in Tables 7, 8 and 9. They found greater improvement in all pelvic and spinal parameters in groups 1 and 2. Group 3 showed insufficient correction of most pelvic and spinal parameters (Table 9). In group 3, mean post-operative SVA was +5.2 cm, mean lumbar lordosis deficit was 25° despite mean post-operative lumbar lordosis of 53° and mean calculated FBI index was 19.5° for a normal value less than 10°. This is because

Table 4 Improvement in functional scores: global and sub-group analyses

	Global, $n = 61$		PI <45, $n = 9$		PI 45–60, $n = 23$		PI >60, $n = 29$	
	Pre-op	Last exam	Pre-op	Last exam	Pre-op	Last exam	Pre-op	Last exam
ODI	51.7 ± 15.1	34.3 ± 12	48.25 ± 6.5	28.6 ± 11	51.4 ± 12.3	32.3 ± 13	54.9 ± 13.8	37.3 ± 12.5
SF-36 PCS	29 ± 6.8	35.82 ± 7	34.1 ± 6	41.8 ± 3.9	26 ± 6	34.8 ± 7.5	29.8 ± 6.4	35.4 ± 8.3
SF-36 MCS	38.4 ± 10.7	44.84 ± 9	40.5 ± 11	47.1 ± 6.8	42.4 ± 11.9	46.6 ± 8.8	33.9 ± 7.9	41.9 ± 8.4
L-VAS	7.44 ± 0.9	3.8 ± 1.4	7.4 ± 1.1	3.4 ± 0.7	7.6 ± 1	3.35 ± 1.6	7.3 ± 0.9	4.3 ± 1.8

Table 6 Pre-and post-operative pelvic and spinal radiological parameters in the global population

$N = 61$	Pre operative	Last follow-up	p value
PI	60.14 ± 13.5	60.10 ± 12.4	0.935
SS	28.84 ± 12.3	32.72 ± 8.7	0.002
PT	31.53 ± 10.1	25.68 ± 10.2	0.001
SSA	106.53 ± 14.7	120.68 ± 9.9	0.001
SVA	9.11 ± 4.9	4.37 ± 4.6	0.001
Barrey	1.59 ± 0.9	1.01 ± 0.6	0.001
FBI	31.05 ± 13.7	14.72 ± 10.3	0.001
LL	28.47 ± 14.3	59.8 ± 10.4	0.001
Def LL	40.34 ± 14	19.72 ± 10	0.001
TK	30 ± 10.9	38.8 ± 10.2	0.001

PI pelvic incidence, *SS* sacral slope, *PT* pelvic tilt, *SVA* sagittal vertical axis, *FBI* full balance integrated index, *LL* lumbar lordosis L1S1, *TK* thoracic kyphosis, *LL deficit* lumbar lordosis deficit = ideal LL (according to Schwab)—post-operative measured LL

Table 7 Pre-and post-operative pelvic and spinal radiological parameters in the sub-group with small PI <45°

$N = 9$	Preoperative	Last follow-up	p value
PI	40° ± 4°	42.78 ± 5.9	ns
SS	19.2° ± 12.6°	27.7 ± 8.9	0.048
PT	20.6° ± 10.12°	13.6 ± 7.5	0.005
SSA	106.5° ± 13.8°	117.3 ± 7.9	0.020
SVA	8.22 ± 2.1	2.8 ± 3.4	0.000
Barrey	2.04° ± 1.43°	0.99 ± 1.06	0.034
FBI	21 ± 6.042	10.3 ± 8.5	0.017
LL	24.8 ± 14.6	43.1 ± 8.63	0.002
Def LL	24 ± 14.2	6 ± 8	0.001
TK	29.5 ± 11.29	38.5 ± 6.06	0.018

the SVA reflects the mean analysis of the population and is not a reliable value for patients with large PI, whereas the FBI index is adapted to the PI value of each patient and is thus far more relevant.

The post-operative FBI index score made it possible to assess obtained correction. Clinical results were analyzed by stratifying the population into two groups: one with post-operative FBI index score <10° and one with post-operative FBI index score >10°. This analysis showed a significant difference in improvement of the ODI score when the post-operative FBI index was <10° ($p < 0.05$) (Table 10).

Analysis of correlations

Analysis of correlations found a close link between pre-operative lumbar lordosis deficit and calculated FBI ($R = 0.465$, $p < 0.05$). There was also a close link between post-operative lumbar lordosis and calculated FBI. ($R = 0.634$, $p < 0.01$). There was a close link between theoretical post-operative lumbar lordosis deficit and improvement in the ODI score ($R = 0.46$, $p < 0.05$), which demonstrated the importance of obtaining lumbar lordosis close to theoretical lumbar lordosis. In addition, a correlation was demonstrated between functional score (ODI) and FBI index. ($R = 0.61$, $p < 0.05$) (Table 11).

Our study yields results similar to those in a series of asymptomatic patients where pelvic incidence was correlated to lumbar lordosis values ($R = 0.5$, $p < 0.001$) [9].

Table 8 Pre- and post-operative pelvic and spinal radiological parameters in the sub-group with moderate PI 45° <PI <60°

$N = 23$	Preoperative	Last follow-up	p value
PI	53.2° ± 5°	54.13° ± 5.9°	ns
SS	23.85° ± 8.3°	30.31° ± 6.6°	0.000
PT	29.2° ± 7.78°	23.63° ± 6.8°	0.002
SSA	100.8° ± 13.7°	119.95° ± 8.5°	0.000
SVA	8.9 ± 4.1	2.85 ± 3.1	0.000
Barrey	1.47° ± 0.70°	0.76° ± 0.71°	0.000
FBI	30.8° ± 11.43°	11.52° ± 6.6°	0.000
LL	21.2° ± 13°	48.30° ± 9.4°	0.000
Def LL	40.74 ± 12	11.6 ± 8	0.000
TK	31.19° ± 21°	40.38° ± 10.2°	0.001

Table 9 Pre-and post-operative pelvic and spinal radiological parameters in the group with large PI > 60°

$N = 29$	Preoperative	Last follow-up	p value
PI	72.05° ± 6.78°	70.44° ± 7.1°	ns
SS	36.1° ± 11.1°	36.35° ± 8.9°	0.891
PT	36.39° ± 8.7°	33.42° ± 8.5°	0.040
SSA	111.4° ± 14.4°	122.3° ± 11.5°	0.000
SVA	9.48 ± 4.8	5.2 ± 4.4	0.000
Barrey	1.53 ± 0.9	1.26 ± 0.77	0.118
FBI	35.2° ± 15°	19.53° ± 11.9°	0.000
LL	35.53° ± 11.9°	53.3° ± 10.6°	0.000
Def LL	44.02 ± 11	25 ± 9	0.001
TK	29.25° ± 12.1°	37.5° ± 11.4°	0.008

Complications

Complications included 15 cases (20.2 %) of bilateral leg pain, with transient neurological deficit in six cases (9.5 %), and nine cases (12.5 %) of early surgical site

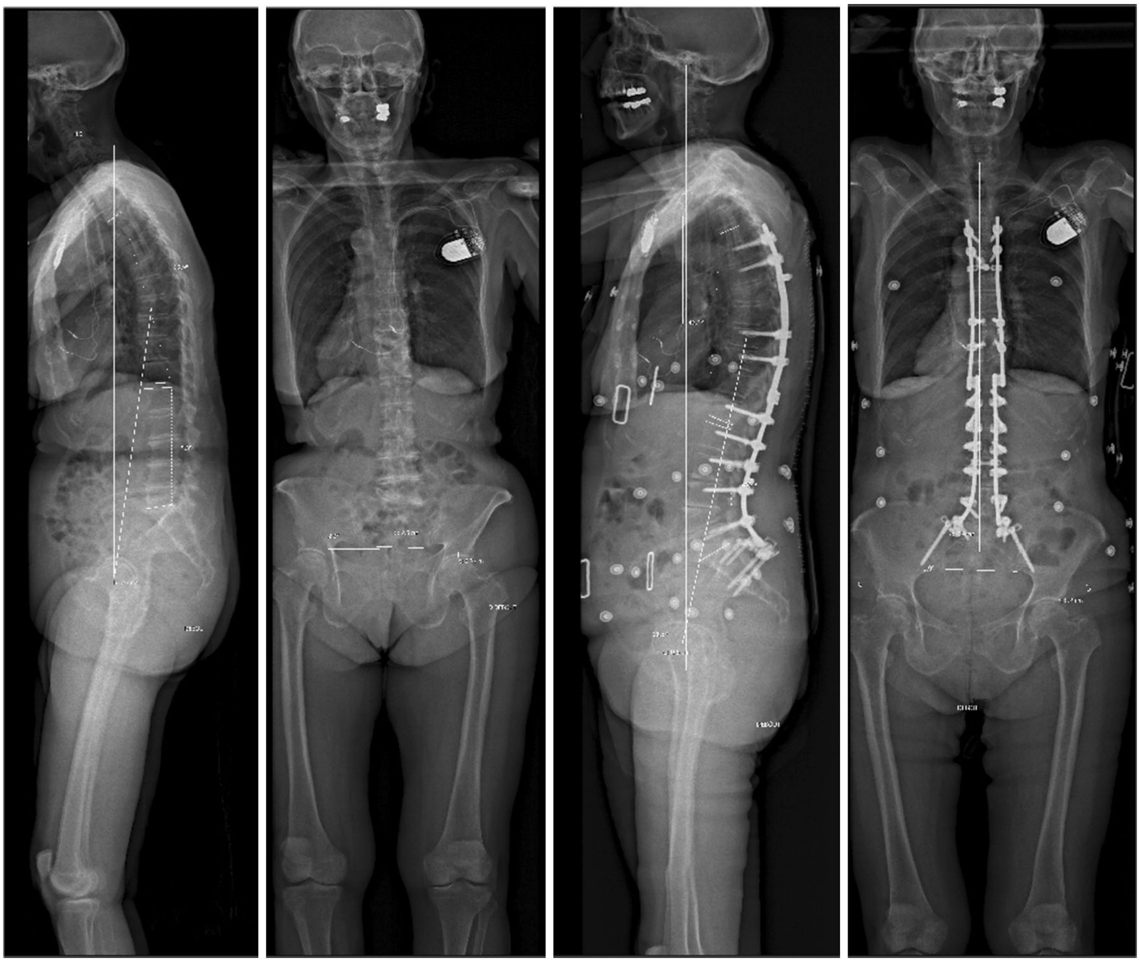

Fig. 4 Pre- and post-operative EOS® radiograph of a patient who had undergone PSO in L4 with T5-pelvis fixation. Pre-operative values were: PI 49°, PT 32°, SS 17°, LL 5°, SVA 11.6°, post-operative values were: PI 49°, PT 17°, SS 32°, LL 50°, SVA −0.8 cm

Table 10 Improved ODI score as a function of the post-operative FBI index score

	FBI <10°, $n = 40$	FBI <10°, $n = 23$	p value
FBI value	7.4	19.4	
Oswestry value	24.7 ± 7.9	17.8 ± 12	$p < 0.05$

infections. Intra-operative complications included five tears of the dura mater and two cases of excessive blood loss (>5000 mL). Two mortalities occurred from major intracerebral bleeds in the early post-operative period. Mechanical complications were principally non-union (nine cases) and junctional kyphosis (three cases). All 19 post-operative complications (28.1 %) were revised at an average of 2 years following surgery. All mechanical complications were found in the patients who had insufficient imbalance correction and this was mainly associated with high PI (>60°) or a moderate PI (45°–60°) combined with excess FBI pre-operatively that remained >10° post-operatively.

Discussion

The aim of this study was to analyze clinical and radiological outcomes of patients who underwent PSO for non-angular kyphosis and who were followed up regularly for 2 years, and then every 2 years thereafter.

All radiological analyses were performed after 3D modeling with data obtained from radiographs acquired using the EOS® imaging system. It has been demonstrated that the quality of parameters measured is equivalent to that of results obtained by scanning [23], only they are obtained with the patient standing which is a great advantage. To our knowledge, no study of this type has yet been published.

In other reports in the literature, PSO was performed at different levels depending on the characteristics of sagittal imbalance. Our patients had global sagittal imbalance caused by degenerative or post-arthrodesis lumbar lordosis.

In most patients, the most suitable site for osteotomy is the L4 vertebra since it represents the apex of lumbar

Table 11 Results of correlations between pelvic and spinal parameter

	Parameters	Pearson coefficent (*R*)
Correlations between parameters	Post-op PI and post-op LL	0.51
	Post-op FBI and post-op LL deficit	0.61
	FBI and Barrey	0.68
	SSA and post-op FBI	0.45
	SSA and post-op LL	0.78
	ODI and FBI Index	0.61

lordosis in the asymptomatic population, as demonstrated by Roussouly [24]. Also, L4S1 lordosis represents 70 % of lumbar lordosis cases, as shown by Roussouly [19]. Therefore, L4 osteotomy provides optimal correction of L4S1 lordosis and restores the normal harmony of the spinal curve. L3 osteotomy may be envisaged for patients with a type 4 back according to the Roussouly classification, since this type of back is characterized by a large PI, increased lordosis and a lumbar lordosis apex at L3 [19]. In our study, osteotomy was performed at L4 in 47 patients and L3 in 16 patients.

If PSO was performed too high, it changed load distribution and increased stress in junctional areas. This enabled to restore harmonious L4S1 lordosis by placing the apex of the curve towards the balancing point.

This series demonstrated marked clinical improvement with significantly better functional scores (Table 3), comparable to the results in other published series [3, 25, 26]. Subgroup analysis as a function of PI showed a trend to greater improvement in groups 1 and 2, but not statistically different to group 3 (PI >60°) (Table 9). Similarly, the radiological analysis showed a significant improvement in pelvic tilt and spinal slope parameters in the global population.

All the PSO series found in the literature [3, 27, 28] made a global analysis of clinical and radiological results. No study analyzed results by stratifying the population as a function of back types or pelvic incidence. Stratification of the population as a function of back type demonstrated that lumbar lordosis was greatly correlated to pelvic incidence [9]. The aim of PSO is to re-establish lumbar lordosis adapted to the angle of pelvic incidence for each patient. It is more difficult to correct lumbar lordosis in patients with large pelvic incidence (>60°) than in those with small pelvic incidence (<45°).

Our series showed that PSO resulted in satisfactory correction in patients with small or moderate pelvic incidence with corrections almost reaching theoretical lumbar lordosis values. However, one PSO alone was insufficient to correct the spinal deformities of patients with large pelvic incidence. The FBI index reflected inter-group difference very well.

Post-operative lumbar lordosis in relation to theoretical lumbar lordosis was 2° in group 1 and 11° in group 2. Group 3 showed insufficient global correction with lumbar lordosis deficit of 25°. This indicated the importance of measuring pelvic incidence before surgery and of restoring adapted lumbar lordosis during surgery. According to the review recently published by Faundez A [29]. Similarly, the post-operative FBI index of groups with small and moderate pelvic incidence (groups 1 and 2) was 10° and 11°, respectively, but more than 20° for the group with large pelvic incidence (group 3). In order to restore lumbar lordosis and regain satisfactory sagittal balance in patients with large pelvic incidence, it is necessary to combine different osteotomy techniques such as Smith-Petersen osteotomy at one or two levels, or even perform a second PSO if pelvic incidence is more than 80°.

Our series showed a marked correlation between the post-operative FBI index and post-operative lumbar lordosis deficit in relation to the ideal theoretical lumbar lordosis value defined according to Schwab's formula [22] ($R = 0.61$). Post-operative FBI index <10° was associated with good clinical and radiological results. Surgical strategies could be defined taking into account the pre-operative FBI index. Depending on the pre-operative FBI index, several strategies could be envisaged: Smith-Petersen osteotomy (SPO) at several levels, single PSO, combined PSO or two separate PSO procedures. It has been demonstrated in the literature that PSO enables mean angular correction of 25°–30° [2, 25, 28, 30]. If pre-operative FBI was >30°, other techniques have to be associated in order to obtain the ideal correction required. The complexity of the procedure must always take into account the patients physiological condition and their capacity to undergo heavy surgery.

This study found a mean angular correction after osteotomy of 31.4° which is comparable to corrections published in the literature. Lumbar lordosis however was improved from 28° to 49.8° which is a mean gain of 21°, which is slightly lower than the corrections reported in other studies which were 29° to 31° [28, 30]. However, the radiological analysis performed in these two series was performed on standard radiographs that lacked the accuracy of the 3D reconstruction obtained with the sterEOS® equipment we used. This is a very important factor since the parallax error may be great, depending on the type of medical imaging used, especially in the event of pelvic rotation with non-aligned femoral heads.

We have found an improvement in osteotomy angles since 2008. Probably due to an improving experience, the last patients had a better corerction. For these ten patients, mean angular correction was 37° ± 4° with mean lumbar lordosis improvement of 39° ± 5°.

Bridwell et al. [3] reported on 33 patients after 2 years: lumbar lordosis increased from 15° to 45° with a mean correction of 31°. The C7 plumb line improved from 16 cm to 4.5 cm. On the functional level, VAS and ODI scores dropped from 7.1 to 4.5 and from 52.6 to 34.20, respectively. However, the SVA did not reflect harmonious sagittal curvature restoration but only correct global balance with varying degrees of compensation.

In a series published by C. Barrey reporting on 25 patients [28], lumbar VAS dropped from 7.5 ± 2 before surgery to 3.2 ± 2.5 after 1 year and ODI improved from 64 ± 12 to 32 ± 18 after 1 year. The mean gain in lumbar lordosis was 29° with correction at the level of the PSO of 27°.

Conclusion

PSO is a surgical procedure enabling correction of multiplane rigid spinal deformities that require major sagittal correction. It is very effective for patients with small or moderate pelvic incidence (PI <60°), but is sometimes not sufficient when performed alone on patients with a large pelvic incidence. For these patients, complementary corrections may be required to obtain correct sagittal balance. This study confirmed the benefit of calculating the FBI index before surgery in order to determine the accurate correction to be made. A normalized FBI index (FBI <10°) after surgery was strongly correlated to good functional results.

Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

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