European Spine Journal (2020) 29:821–830
https://doi.org/10.1007/s00586-019-06255-z

ORIGINAL ARTICLE

Clinical results and functional outcomes after three-column osteotomy at L5 or the sacrum in adult spinal deformity

Haruki Funao[1] · Floreana N. Kebaish[1] · Richard L. Skolasky[1] · Khaled M. Kebaish[1]

Received: 5 February 2019 / Revised: 1 November 2019 / Accepted: 11 December 2019 / Published online: 28 January 2020

Abstract

Purpose Three-column osteotomies at L5 or the sacrum (LS3COs) are technically challenging, yet they may be needed to treat lumbosacral kyphotic deformities. We investigated radiographic and clinical outcomes after LS3CO.

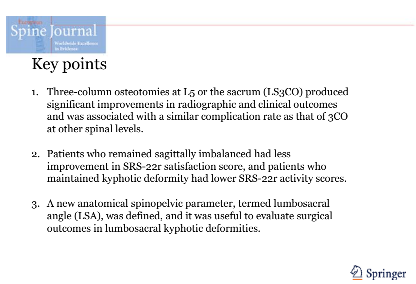
Methods We analyzed 25 consecutive patients (mean age 56 years) who underwent LS3CO with minimum 2-year follow-up. Standing radiographs and health-related quality-of-life scores were evaluated. A new radiographic parameter ["lumbosacral angle" (LSA)] was introduced to evaluate sagittal alignment distal to the S1 segment.

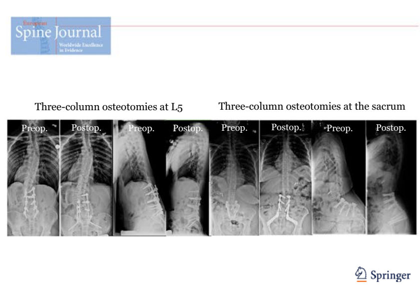
Results From preoperatively to the final follow-up, significant improvements occurred in lumbar lordosis (from −34° to −49°), LSA (from 0.5° to 22°), and sagittal vertical axis (SVA) (from 18 to 7.3 cm) (all, $p < .01$). Mean Scoliosis Research Society (SRS)-22r scores in activity, pain, self-image, and satisfaction ($p < .05$), and Oswestry Disability Index scores ($p < .01$) also improved significantly. Patients with SVA ≥ 5 cm at the final follow-up experienced less improvement in SRS-22r satisfaction scores than those with SVA < 5 cm. Patients with LSA < 20° at the final follow-up had significantly lower SRS-22r activity scores than those with LSA ≥ 20° ($p = .014$). Two patients had transient neurologic deficits, and 11 patients underwent revision for proximal junctional kyphosis (5), pseudarthrosis (3), junctional stenosis (2), or neurologic deficit (1).

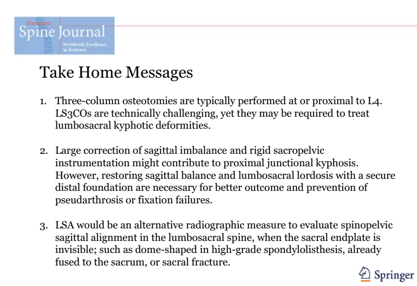
Conclusions LS3CO produced radiographic and clinical improvements. However, patients who remained sagittally imbalanced had less improvement in SRS-22r satisfaction score than those whose sagittal imbalance was corrected, and patients who maintained kyphotic deformity in the lumbosacral spine had lower SRS-22r activity scores than those whose lumbosacral kyphosis was corrected.

Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.







Keywords Adult spinal deformity · Health-related quality of life · Lumbosacral angle · Pedicle subtraction osteotomy · Three-column osteotomy

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-019-06255-z) contains supplementary material, which is available to authorized users.

✉ Khaled M. Kebaish
editorialservices@jhmi.edu

Extended author information available on the last page of the article

Introduction

Fixed global sagittal malalignment is associated with flatback syndrome caused by distraction procedures, such as placement of Harrington rods [1] and sagittal malalignment after instrumented spinal fusion. Other reported causes are postlaminectomy, posttraumatic kyphosis, and ankylosing spondylitis. Rigid lumbosacral kyphotic deformity with severe sagittal imbalance can also be caused by distal junctional failure, which is the fixation failure at the caudal end of a long spinal fusion construct.

The goals of surgery are to relieve pain, prevent deformity progression, and improve global spinal alignment and balance, with the ultimate aim of improving function. Three-column osteotomies (3COs), such as pedicle subtraction osteotomy (PSO) and vertebral column resection, can correct rigid spinal deformities and fixed global spinal imbalance [2, 3]. Several authors have reported that 3COs, with osteotomies typically performed at or proximal to L4, significantly improved radiographic and clinical outcomes with acceptable complication rates [2, 4–11]. Kim et al. [4] reported 140 PSO cases, only 2 of which were performed at L5. 3CO at the sacrum has rarely been reported, and it may be useful after displaced sacral fracture with malunion or fixed sagittal malalignment in the lumbosacral spine [12, 13]. 3COs at L5 or the sacrum, so-called lumbosacral 3COs (LS3COs), can be technically challenging, yet they may be required in patients with lumbosacral kyphotic deformities that are associated with major sagittal imbalance.

To our knowledge, surgical outcomes after LS3CO with assessments of spinopelvic parameters and health-related quality of life (HRQoL) have not been described. Our aims were to investigate radiographic and clinical outcomes after LS3CO.

Materials and methods

After approval of our institutional review board, we reviewed a surgical database to identify consecutive patients who had undergone LS3CO between 2004 and 2012 with at least 2-year follow-up. Patients' demographic information and perioperative data were assessed from medical records. Complete spinopelvic parameters using standing radiographs were measured, and HRQoL scores were evaluated at preoperative, postoperative (6–8 weeks), and final follow-up time points.

Radiographic measurements

Standing anteroposterior and lateral whole-spine radiographs were obtained with the arms in the fists-on-clavicles position (elbows fully flexed with fists resting on clavicles) and knees and hips extended as fully possible at all three time points. Pelvic incidence, sacral slope, and pelvic tilt were measured. Thoracic kyphosis was measured from the superior endplate of T5 to the inferior endplate of T12. Lumbar lordosis was measured from the inferior endplate of T12 to the superior endplate of S1 using Cobb's method. Lumbosacral sagittal alignment distal to S1 was evaluated using a new anatomical parameter termed lumbosacral angle (LSA), which was defined as the angle between the inferior endplate of T12 and the perpendicular line connecting the posterior–inferior endplates of S3 and S4 (Fig. 1a). LSA is useful when the sacral endplate is imprecise or invisible, such as in patients with dome-shaped deformity in high-grade spondylolisthesis (Fig. 1b) or in those with sacral fractures because of the lack of anatomical alignment distal to S1 (Fig. 1c). To evaluate global balance, we measured sagittal vertical axis (SVA), which was defined as the horizontal distance from a C7 plumb line to the superior posterior endplate of S1. Proximal junctional kyphosis (PJK) was defined as (1) a proximal kyphotic angle (PKA) between the inferior endplate of the upper instrumented vertebra and the superior endplate of two supra-adjacent vertebra of $> 10°$ and (2) a PKA 10° greater than the preoperative measurement [14].

Patient outcomes

Clinical and functional outcomes were assessed using HRQoL scores on the Oswestry Disability Index (ODI) and Scoliosis Research Society (SRS)-22r patient questionnaire at preoperative, postoperative, and final follow-up time points. Survey responses were tabulated to calculate the scores for each of the SRS-22r domains (activity, mental health, pain, satisfaction, and self-image) and the ODI. Major complications were defined as fatal cardiovascular events, pulmonary embolism, death from other causes, new neurologic deficits, deep wound infection, pseudarthrosis, symptomatic PJK, and any condition requiring revision surgery.

Statistical analysis

Radiographic parameters and HRQoL data were compared among preoperative, postoperative, and final follow-up time points using one-way analysis of variance. HRQoL scores were compared in several subgroups: sagittally imbalanced patients ($SVA \geq 5$ cm) at the final follow-up versus balanced patients ($SVA < 5$ cm), patients who continued to be kyphotic in the lumbosacral spine ($LSA < 20°$) at the final follow-up versus those who did not ($LSA \geq 20°$), and patients who developed PJK at the final follow-up versus those without PJK. SPSS, version 21.0 (IBM Corp., Armonk, NY, USA), was used, and $p < .05$ was considered significant. Tests were two-tailed.

Surgical techniques for LS3CO

Pre- and postoperative radiographs of representative cases of 3COs at L5 and S1 are shown in Figs. 2 and 3. 3CO at

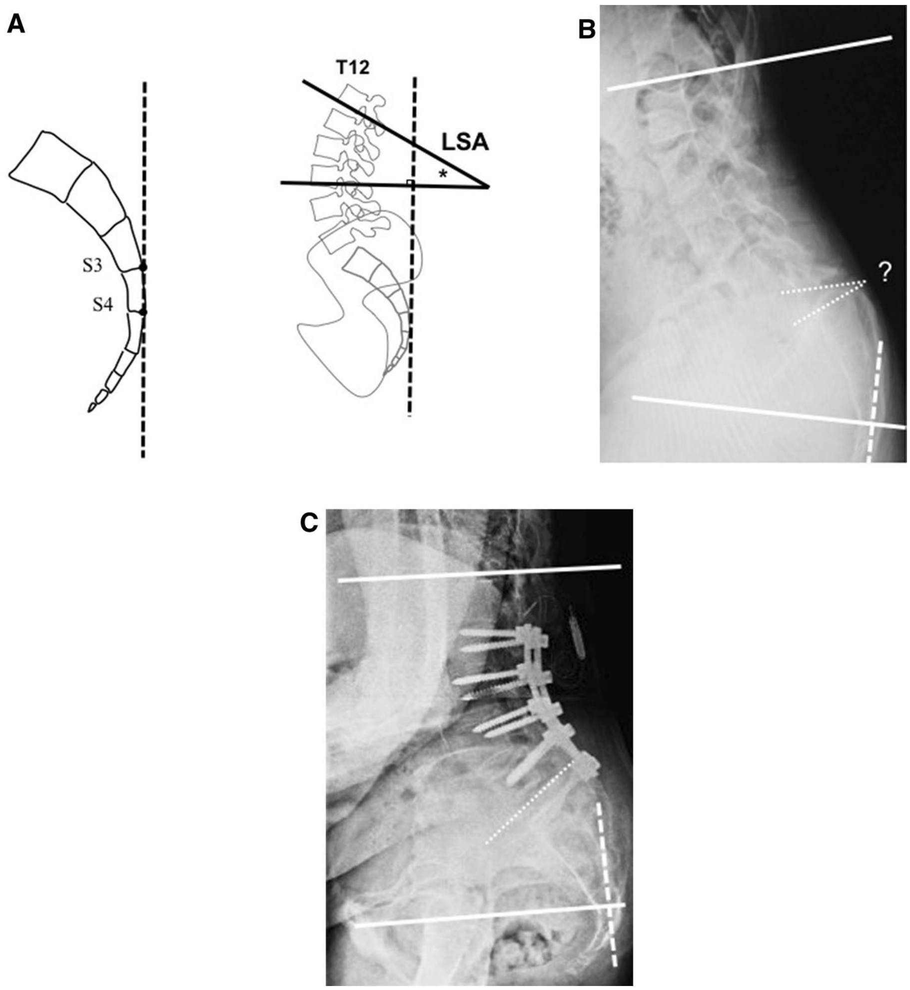


Fig. 1 **a** Lumbosacral angle (LSA) is defined as the angle between the inferior endplate of T12 and the perpendicular line connecting the posterior–inferior endplates of S3 and S4. Black dots are the posterior–inferior endplates of S3 and S4. The dotted line connects the posterior–inferior endplates of S3 and S4. Solid lines are the inferior endplate of T12 and the perpendicular line connecting the posterior–inferior endplates of S3 and S4. The asterisk is LSA. **b** LSA is a useful measure when the sacral endplate is imprecise or invisible, such as in patients with dome-shaped deformity in high-grade spondylolisthesis. The dotted line connects the posterior–inferior endplates of S3 and S4. Solid lines are the inferior endplate of T12 and the perpendicular line connecting the posterior–inferior endplates of S3 and S4. Fine dotted line is the possible range of superior endplates of S1 in high-grade spondylolisthesis. The superior endplates of S1 are imprecise in dome-shaped deformity (question mark). **c** In patients with sacral fracture, lumbar lordosis was difficult to evaluate because of the lack of anatomical alignment distal to S1 (angular deformity at or distal to S1). The dotted line connects the posterior–inferior endplates of S3 and S4. Solid lines are the inferior endplate of T12 and the perpendicular line connecting the posterior–inferior endplates of S3 and S4. The fine dotted line is the superior endplates of S1. Conventional measurement of lumbar lordosis may underestimate lumbosacral kyphotic deformity

L5 was performed using the same technique as 3COs at or proximal to L4. However, laminectomy should be performed thoroughly because postoperative lumbar lordosis can lead to proximal or distal adjacent stenosis, especially in the lower lumbar spine. 3CO at the sacrum was performed for patients with sacral fracture. The excision of bilateral S1 pedicles was performed in an oblique fashion to reshape the sacrum where it had fractured and angled forward. Osteotomies were extended to the bilateral sacral ala to the sacroiliac joint and anterior cortex of the sacrum using an osteotome, high-speed drill, or Kerrison rongeurs. Spinal rods were placed, and compression was performed carefully under intraoperative neuromonitoring. Because it was impossible to use S1 screws, dual S2 alar–iliac screws were used bilaterally to provide a secure rigid distal foundation (Fig. 3). All procedures were performed with intraoperative neuromonitoring using motor-evoked potentials.

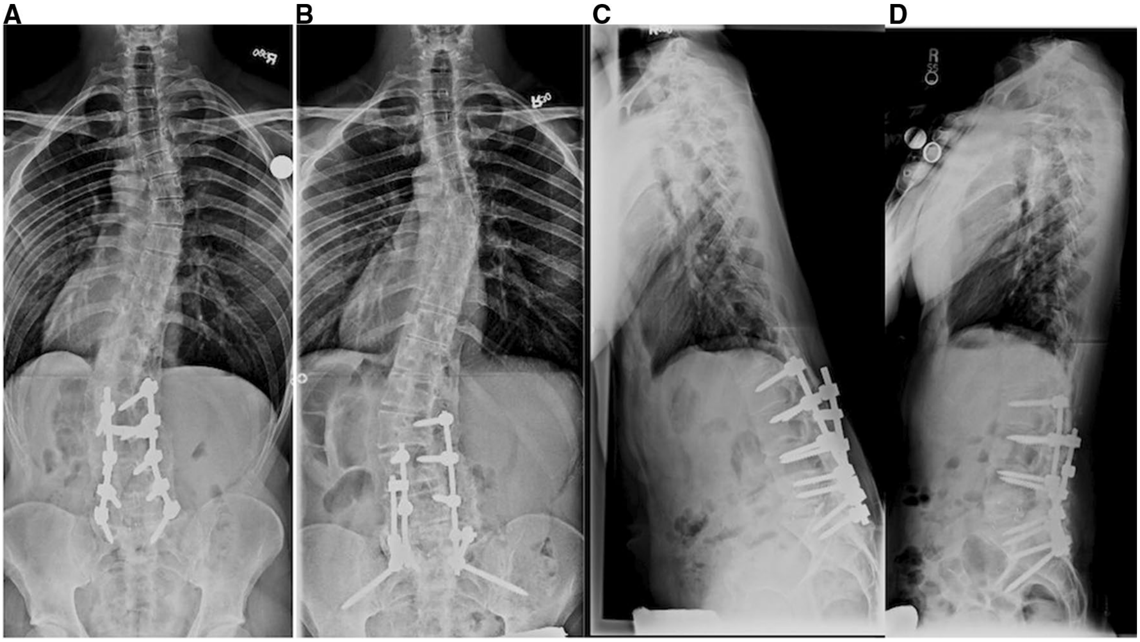


Fig. 2 Radiographs of a 27-year-old man with an extended PSO at L5. The patient presented with severe sagittal imbalance. He had a history of scoliosis, which was treated elsewhere with instrumented posterior spinal fusion to L4. He developed distal junctional kyphosis, and although the fusion construct was extended to the sacrum with interbody fusion at L5-S1, rigid lumbosacral deformity remained. He underwent posterior spinal fusion from L2 to the pelvis with an extended PSO at L5 for correction of kyphotic deformity in the lumbosacral spine. Standing radiographs of the whole spine show the **a** preoperative anteroposterior view, **b** postoperative anteroposterior view, **c** preoperative lateral view, and **d** postoperative lateral view

Results

Twenty-five patients (18 women) who underwent LS3CO with a mean follow-up of 47 months (range 24–101) were enrolled in this study. Three patients were lost to follow-up and were excluded (one patient for a psychological problem and two patients for inability to contact). Patient characteristics are shown in Table 1. Mean age at surgery was 56 years (range 21–76), and mean body mass index value was 28 (range 22–35). Preoperative diagnoses were pseudarthrosis at the lumbosacral junction ($n = 10$), sacral fracture distal to a long spinal fusion ($n = 5$), flatback syndrome with sagittal imbalance ($n = 4$), high-grade (grade ≥ 3) spondylolisthesis ($n = 4$), and L5 fracture distal to a long spinal fusion ($n = 2$). Twenty-four patients underwent surgery as part of a revision procedure, and one patient underwent primary surgery. Pedicle subtraction osteotomy was performed in 24 patients (at L5 in 18; at S1 in 6), and vertebral column resection was performed in one patient (at L5). All patients were fused to the pelvis using S2 alar–iliac screws. The mean number of fused levels was 6.4 (range 3–10). Mean operative time was 465 min (range 344–565), mean estimated blood loss was 2985 mL (range 800–6800), and mean length of hospital stay was 7 days (range 3–21).

Radiographic parameters

Radiographic parameters at preoperative, postoperative, and final follow-up time points are shown in Table 2. Compared with preoperative values, there were improvements in the following radiographic parameters at the final follow-up: lumbar major curve, lumbar lordosis, LSA, and SVA. Compared with preoperative values, pelvic tilt improved at the postoperative time point ($p = .035$), but not at the final follow-up ($p = .095$). Although four patients had PJK (PKA > 10°) preoperatively, PKA increased significantly from preoperatively to the final follow-up ($p = .027$), and 10 of 25 patients had PJK (PKA range 21°–43°) at the final follow-up. Thoracic kyphosis increased significantly from preoperatively to the final follow-up ($p = .022$). Mean SVA in patients with 3CO at the sacrum was larger than in those with 3CO at L5 at all time points: preoperatively, 17 cm (L5) versus 22 cm (sacrum) ($p = .116$); postoperatively, 5.9 cm (L5) versus 6.9 cm (sacrum) ($p = .739$); and the final follow-up, 6.9 cm (L5) versus 8.5 cm (sacrum) ($p = .610$). However, these differences were not significant.

Patient outcomes

HRQoL scores improved between the preoperative and final follow-up time points (Table 3). Mean SRS-22r

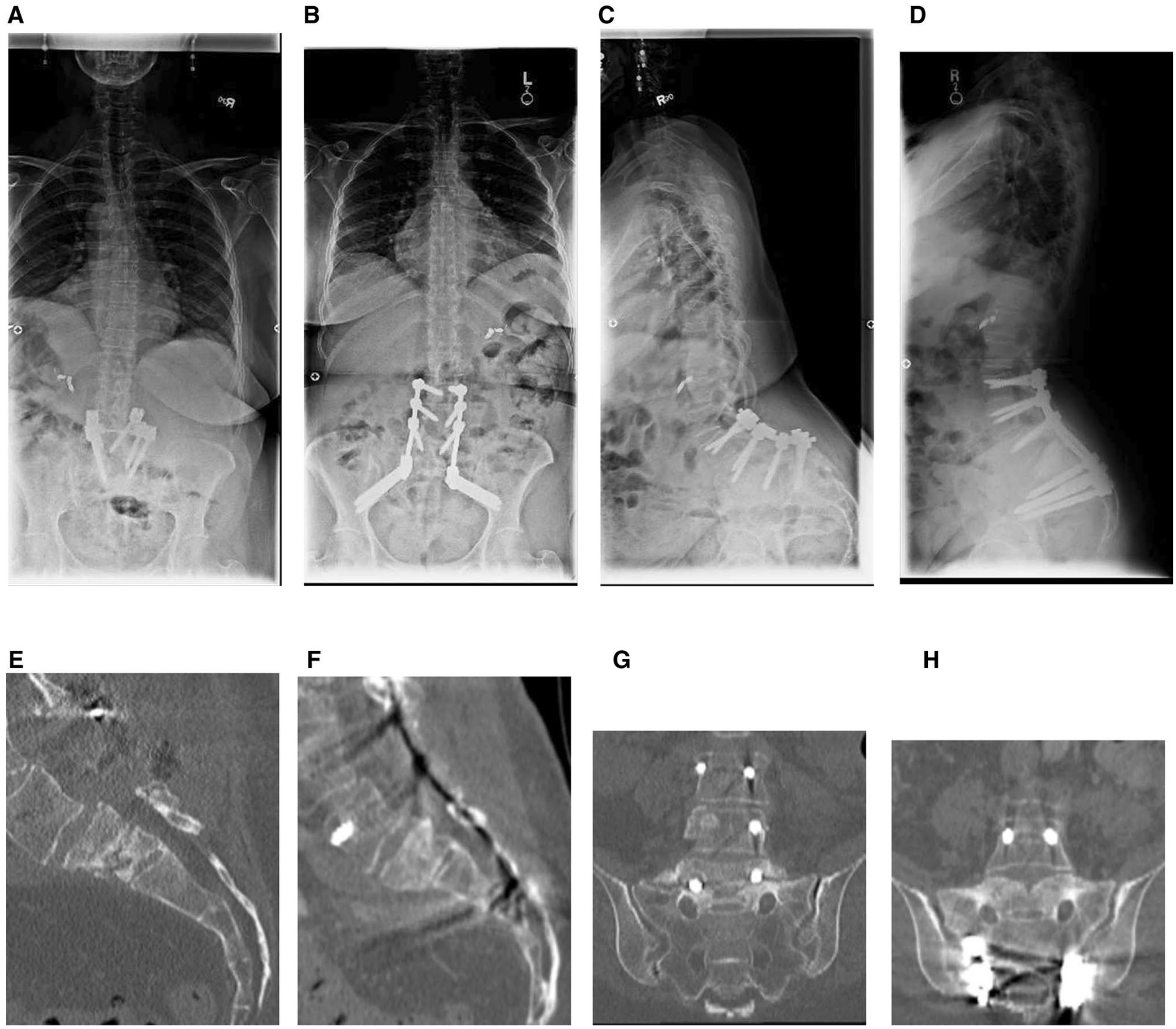


Fig. 3 Radiographs of a 52-year-old woman with a PSO at S1. She presented with intractable pain in the lumbosacral spine and a severe sagittal imbalance. Her radiographs showed sacral fracture after posterior spinal fusion from L3 to S1. A PSO was performed at S1 for correction of kyphotic deformity in the lumbosacral spine, and S2 alar–iliac screws were used bilaterally to provide a secure, rigid distal foundation. Standing radiographs of the whole spine show the **a** preoperative anteroposterior view, **b** postoperative anteroposterior view, **c** preoperative lateral view, and **d** postoperative lateral view. CT images show the **e** preoperative sagittal view, **f** postoperative sagittal view, **g** preoperative coronal view, and **h** postoperative coronal view

scores improved significantly in the following domains (preoperative/final follow-up): activity (2.6/3.5), pain (2.4/3.4), self-image (2.4/3.3), and satisfaction (2.5/3.3). ODI scores also improved significantly from 63 preoperatively to 40 at the final follow-up. Although mean SRS-22r mental health scores improved from preoperatively (3.0) to the final follow-up (3.5), this change was not significant ($p = .077$). We found no significant differences between sagittally imbalanced patients (SVA ≥ 5 cm) ($N = 13$) and balanced patients ($N = 12$) in HRQoL scores at the final follow-up, but sagittally imbalanced patients had no significant improvement in mean SRS-22r satisfaction score from preoperatively to the final follow-up ($p = .435$), whereas balanced patients improved significantly ($p = .017$) (Table 4). Patients with LSA < 20° ($n = 12$) had significantly lower mean SRS-22r activity scores compared with patients with LSA of ≥ 20° ($n = 13$) at immediate postoperative ($p = .043$) and final follow-up ($p = .014$) time points (Table 5). We found no significant differences in HRQoL scores at any time point between patients who developed PJK ($n = 10$) and those who did not ($n = 15$).

Table 1 Characteristics of 25 adults who underwent three-column osteotomy at L5 or the sacrum for lumbosacral deformity correction

Characteristic	No. of patients	Mean (range)
Age at surgery (year)		56 (21–76)
Female sex	18	
Body mass index		28 (22–35)
Diagnosis		
Pseudarthrosis at lumbosacral junction	10	
Sacral fracture distal to long spinal fusion	5	
Flat-back syndrome with sagittal imbalance	4	
High-grade spondylolisthesis	4	
L5 fracture distal to long spinal fusion	2	
Level of osteotomy		
L5	19	
Sacrum	6	
No. of fused vertebrae		6.4 (3–10)
Operative time (m)		465 (344–565)
Estimated blood loss (mL)		2985 (800–6800)
Length of hospital stay (day)		7 (3–21)

Table 2 Mean (± SD) radiographic parameters of 25 adults who underwent three-column osteotomy at L5 or the sacrum for lumbosacral deformity correction

Parameter	Preoperative	Postoperative	Final follow-up	*p* value*	*p* value[†]
Lumbar lordosis (°)	−34 ± 22	−51 ± 15	−49 ± 13	.001	.005
Lumbar major curve (°)	19 ± 9.9	13 ± 7.4	14 ± 7.4	.023	.049
Lumbosacral angle (°)[a]	0.5 ± 13	22 ± 15	22 ± 15	< .001	< .001
Pelvic incidence (°)	67 ± 16	62 ± 11	61 ± 10	.821	.820
Pelvic tilt (°)	28 ± 5.6	23 ± 7.8	24 ± 8.0	.035	.095
Proximal kyphotic angle (°)	−2.7 ± 16	6.0 ± 17	9.7 ± 21	.107	.027
Sacral slope (°)	39 ± 18	40 ± 8.9	39 ± 10	.871	.890
Sagittal vertical axis (cm)	18 ± 7.5	6.2 ± 5.3	7.3 ± 5.4	< .001	< .001
Thoracic kyphosis (°)	25 ± 15	32 ± 13	36 ± 17	.125	.022
Thoracic major curve (°)	14 ± 9.2	14 ± 8.0	14 ± 8.8	.738	.953

**p* value for difference between preoperative and postoperative measurements

[†] *p* value for difference between preoperative and final follow-up measurements

[a] Lumbosacral angle is a new parameter introduced in this study and defined as the angle between the inferior endplate of T12 and the perpendicular line connecting the posterior endplates of S3 and S4

Table 3 Mean (± SD) health-related quality-of-life scores in 25 adults who underwent three-column osteotomy at L5 or the sacrum for lumbosacral deformity correction

Outcome measure	Preoperative	Postoperative[a]	Final follow-up[b]	*p* value*	*p* value[†]
SRS-22r					
Activity	2.6 ± 0.5	2.9 ± 0.8	3.5 ± 0.8	.288	.001
Mental health	3.0 ± 0.8	3.0 ± 0.7	3.5 ± 0.7	.843	.077
Pain	2.4 ± 0.7	2.7 ± 1.0	3.4 ± 0.7	.279	< .001
Satisfaction	2.5 ± 1.0	2.5 ± 1.2	3.3 ± 1.1	.923	.034
Self-image	2.4 ± 0.8	3.2 ± 0.9	3.3 ± 0.8	.005	.002
ODI	63 ± 15	51 ± 18	40 ± 14	.026	< .001

ODI Oswestry Disability Index; *SRS-22r* Scoliosis Research Society-22r questionnaire

**p* value for difference between preoperative and postoperative measurements

[†] *p* value for difference between preoperative and final follow-up measurements

[a] Postoperative values at 6–8 weeks after surgery

[b] Mean length of final follow-up was 47 months (range 24–101 months)

Table 4 Mean (±SD) health-related quality-of-life scores in 25 adults who underwent three-column osteotomy for lumbosacral deformity correction, stratified by SVA at the final follow-up

Outcome measure*	SVA ≥ 5 cm at the final follow-up (n = 13)					SVA < 5 cm at the final follow-up (n = 12)				p value§	p value¶	p value**
	Preoperative	Postoperative	p value†	Final follow-up	p value‡	Preoperative	Postoperative	Final follow-up	p value‡			
SRS-22r												
Activity	2.7 ± 0.6	3.0 ± 0.8	.385	3.3 ± 0.8	.042	2.6 ± 0.5	2.8 ± 0.8	3.7 ± 0.7	.002	.798	.668	.212
Mental health	3.0 ± 0.7	3.1 ± 0.8	.836	3.6 ± 0.4	.073	3.1 ± 0.9	2.9 ± 0.7	3.3 ± 1.0	.633	.752	.704	.440
Pain	2.5 ± 0.7	2.8 ± 1.4	.394	3.3 ± 0.8	.021	2.4 ± 0.7	2.6 ± 0.7	3.6 ± 0.6	.006	.743	.658	.580
Satisfaction	2.6 ± 1.1	2.6 ± 1.6	.959	3.0 ± 1.3	.435	2.3 ± 1.0	2.4 ± 0.6	3.7 ± 0.6	.017	.491	.705	.217
Self-image	2.4 ± 0.9	3.4 ± 1.1	.012	3.2 ± 0.8	.029	2.5 ± 0.8	3.1 ± 0.7	3.5 ± 0.9	.025	.756	.411	.502
ODI	60 ± 14	42 ± 17	.012	39 ± 15	.002	66 ± 16	60 ± 15	41 ± 13	.001	.409	.018	.747

ODI, Oswestry Disability Index; SRS-22r, Scoliosis Research Society-22r questionnaire; SVA, sagittal vertical axis

*There were no significant differences in any of the following: (1) preoperative and postoperative outcomes in patients with SVA < 5 cm at the final follow-up; (2) patients with SVA of ≥ 5 cm preoperatively versus patients with SVA < 5 cm preoperatively; (3) patients with SVA > 5 cm preoperatively and < 5 cm postoperatively; and (4) patients with SVA > 5 cm preoperatively and < 5 cm at the final follow-up

†p value for difference between preoperative and postoperative measurements

‡p value for difference between preoperative and the final follow-up measurements

§p value for difference between preoperative measurements in patients with SVA ≥ 5 cm and those with SVA < 5 cm at the final follow-up

¶p value for difference between postoperative measurements in patients with SVA ≥ 5 cm and those with SVA < 5 cm at the final follow-up

**p value for difference between final follow-up measurements in patients with SVA ≥ 5 cm and those with SVA < 5 cm at the final follow-up

Table 5 Mean (±SD) health-related quality-of-life scores in 25 adults who underwent three-column osteotomy for lumbosacral deformity correction, stratified by LSA* at the final follow-up

Outcome measure	LSA < 20° at the final follow-up ($n=12$)					LSA ≥ 20° at the final follow-up ($n=13$)					p value§	p value¶	p value**
	Preoperative	Postoperative	p value†	Final follow-up	p value‡	Preoperative	Postoperative	p value†	Final follow-up	p value‡			
SRS-22r													
Activity	2.6 ± 0.6	2.6 ± 0.8	.976	3.0 ± 0.8	.134	2.7 ± 0.5	3.2 ± 0.6	.089	3.8 ± 0.5	< .01	.645	.043	.014
Mental health	2.8 ± 0.9	2.9 ± 0.7	.678	3.5 ± 0.7	.032	3.3 ± 0.4	3.1 ± 0.8	.45	3.4 ± 0.6	.785	.105	.698	.713
Pain	2.3 ± 0.8	2.5 ± 1.2	.682	3.6 ± 0.5	.001	2.5 ± 0.6	2.9 ± 0.9	.277	3.2 ± 0.8	.055	.630	.305	.295
Satisfaction	2.0 ± 1.0	2.4 ± 1.4	.463	3.3 ± 0.8	.018	3.0 ± 0.9	2.6 ± 1.0	.505	3.2 ± 1.4	.577	.065	.701	.916
Self-image	2.5 ± 0.8	3.4 ± 1.0	.033	3.2 ± 0.9	.102	2.4 ± 0.8	3.1 ± 0.9	.067	3.5 ± 0.8	.009	.807	.589	.510
ODI	66 ± 15	46 ± 19	.006	39 ± 13	< .01	59 ± 15	56 ± 17	.734	41 ± 15	.011	.291	.158	.781

LSA, lumbosacral angle; ODI, Oswestry Disability Index; SRS-22r, Scoliosis Research Society-22r questionnaire

*LSA is a new parameter introduced in this study and defined as the angle between the inferior endplate of T12 and the perpendicular line connecting the posterior endplates of S3 and S4

†p value for difference between preoperative and postoperative measurements

‡p value for difference between preoperative and final follow-up measurements

§p value for difference between preoperative measurements in patients with LSA < 20° and those with LSA of ≥ 20° at the final follow-up

¶p value for difference between postoperative measurements in patients with LSA < 20° and those with LSA of ≥ 20° at the final follow-up

**p value for difference between the final follow-up measurements in patients with LSA < 20° and those with LSA of ≥ 20° at the final follow-up

Table 6 Complications in 25 adults after three-column osteotomy for lumbosacral spinal deformity correction

Complication type	No. of patients
Major*	
Death	0
Neurologic deficit	1
Proximal junctional kyphosis	5
Proximal junctional stenosis	2
Pseudarthrosis at the osteotomy site†	1
Pseudarthrosis at a remote site	2
Minor	
Dural tear	4
Ileus	1
Infection	0
Excessive bleeding (> 4 L)	1
Mild respiratory disorder (atelectasis)	1
Neurologic deficit (transient)	2
Urinary tract infection	1

*Patients with all major complications except death required revision surgery

†Rod fracture at S1

Complications

There were no perioperative deaths. Twenty-one complications occurred in 18 patients. There were 11 major complications in 10 patients and 10 minor complications in 8 patients (Table 6). Two patients (8%) had transient neurologic deficits, and one of the two patients underwent revision surgery. We could not identify substantial intraoperative neuromonitoring alerts in these patients. One patient who underwent PSO at L5 had transient postoperative motor weakness. The patient was treated with intravenous administration of a steroid. Another patient who underwent PSO at L5 developed motor weakness in the tibialis anterior. A computed tomographic myelogram showed newly developed stenosis related to impingement of the proximal lamina of L4. Laminectomy was performed at L4 2 weeks after the surgery. There were no superficial or deep wound infections. Revision surgeries were performed for symptomatic PJK ($n=5$) and proximal junctional stenosis ($n=2$). Twenty-four patients (96%) showed radiographic fusion at the osteotomy site. However, one patient who underwent PSO at the sacrum required revision surgery because of a rod fracture at S1. Two patients developed pseudarthrosis with rod fractures at levels remote from the osteotomy sites, which had been instrumented in prior surgeries, and both required revision surgery.

Discussion

For years, 3COs have been used to correct rigid spinal deformities and fixed global spinal imbalance. 3COs are typically performed at or proximal to L4 [2, 4–11]; however, some patients who present with rigid kyphotic deformity at the lumbosacral junction may require LS3CO. Because recent studies have suggested the importance of lordosis distribution index (L4-S1 lordosis/L1-S1 lordosis × 100) [15] and restoring lordosis at lower lumbar levels [16], correction should be focused on the most kyphotic spinal region, at the lumbosacral junction. In the present study, LS3CO produced significant improvements in sagittal alignment and HRQoL scores. Although mean SVA and ODI score at the final follow-up seemed not to achieve "successful" results compared with previous reports of adult spinal deformity surgeries [4, 17], our patients had severe preoperative disease. The goals of LS3CO were correction of severe sagittal imbalance and kyphotic deformity at the lumbosacral junction, with the ultimate goal of improving function. In fact, our data showed that sagittally imbalanced patients (SVA ≥ 5 cm) had less improvement in SRS-22r satisfaction score than those whose sagittal balance was corrected, and those who maintained a kyphotic deformity in the lumbosacral spine (LSA < 20°) had lower SRS-22r activity scores than those whose lumbosacral kyphosis was corrected. The complication rate we observed is similar to those reported after 3CO at other levels [4–9]. In our study, 24 of 25 patients were revision cases, and our results are comparable to those in previous reports describing revision surgery in adult spinal deformity correction [18, 19].

The incidence of PJK at 7.8 years after long posterior spinal instrumented fusion was reported to be 39% in patients with adult spinal deformity [20]. In our study, thoracic kyphosis increased significantly from preoperatively to the final follow-up, which was considered a reciprocal change. PKA also increased significantly after surgery, and 10 of 25 patients developed PJK at 3.9 years. Five patients underwent revision surgery for PJK, as did two patients with proximal junctional stenosis. One reason for this phenomenon was believed to be the large difference (> 10 cm) in preoperative to final SVA to correct severe sagittal imbalance [21]. Another possibility is that the rigid sacropelvic instrumentation contributed to progression of thoracic kyphosis and the higher incidence of PJK [22]. However, a secure distal foundation is necessary to resist the strong flexion moments and cantilever forces present at the lumbosacral junction, thus preventing fixation failures. Indeed, we observed a lower rate of pseudarthrosis at the osteotomy site than that previously reported [9]. The S2 alar–iliac technique has been adopted at our institution and elsewhere for adults and children undergoing pelvic fixation. In patients undergoing 3CO at the sacrum, pelvic fixation using dual S2 alar–iliac screws on each side (four-point fixation) can be a reliable technique to provide a rigid distal foundation. We found no significant differences in HRQoL scores between patients with and without PJK. However, Bridwell et al. [23] reported that patients with PJK ≥ 20° had lower SRS-22 scores than patients with PJK < 20°. Although substantial correction of kyphotic deformity and SVA, as well as a secure distal foundation with sacropelvic instrumentation are critical to LS3CO, mid- to long-term follow-up is needed to assess potential risks of poor outcomes and need for revision surgery for PJK.

Pelvic incidence is widely used to evaluate spinal sagittal alignment [24] and predict sagittal correction after PSO [25] and surgical outcomes in adult spinal deformity [26]. However, it can be difficult to obtain pelvic incidence measurements using the sacral endplate when the endplate is dome-shaped in patients with high-grade spondylolisthesis and in those already fused to the sacrum, especially in those with interbody fusion. In patients with sacral fracture, lumbar lordosis (Th12-S1) should not be used to evaluate lumbosacral kyphosis because of the lack of anatomical alignment distal to S1 (angular deformity at or distal to S1). For these patients, we defined a new anatomical spinopelvic parameter, termed LSA, to serve as an alternative radiographic measure of spinopelvic sagittal alignment in the lumbosacral spine. Furthermore, LSA was helpful in evaluating surgical outcomes, especially in this series of patients with lumbosacral kyphotic deformities. Although few patients require LSA measurement, the reliability of this angle should be confirmed in large case series.

A limitation of this study was the small sample size from one institution. However, to our knowledge, this is the first study to report surgical outcomes after LS3CO with assessments of spinopelvic parameters and HRQoL. Another limitation was the retrospective study design, although most data were collected prospectively. A prospective, larger-scale, multicenter study with long-term follow-up is needed to provide more information about surgical outcomes and factors associated with poor outcomes after LS3CO for this challenging problem.

Conclusions

LS3CO produced significant improvements in radiographic and clinical outcomes from preoperatively to postoperatively and was associated with a similar complication rate as that of 3CO at other spinal levels. However, patients who remained sagittally imbalanced (SVA ≥ 5 cm) had less improvement in SRS-22r satisfaction score than those whose sagittal balance was corrected, and those who maintained a kyphotic deformity in the lumbosacral spine (LSA < 20°) had lower SRS-22r activity scores than those whose lumbosacral kyphosis was corrected.

Acknowledgements The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication. No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

Compliance with ethical standards

Conflict of interest The author(s) declare that they have no conflict of interest.

References

1. Booth KC, Bridwell KH, Lenke LG, Baldus CR, Blanke KM (1999) Complications and predictive factors for the successful treatment of flatback deformity (fixed sagittal imbalance). Spine 24:1712–1720
2. Bridwell KH (2006) Decision making regarding Smith–Petersen vs. pedicle subtraction osteotomy vs. vertebral column resection for spinal deformity. Spine 31:S171–S178
3. Suk SI, Kim JH, Lee SM, Chung ER, Lee JH (2003) Anterior–posterior surgery versus posterior closing wedge osteotomy in post-traumatic kyphosis with neurologic compromised osteoporotic fracture. Spine 28:2170–2175
4. Kim KT, Lee SH, Suk KS, Lee JH, Jeong BO (2012) Outcome of pedicle subtraction osteotomies for fixed sagittal imbalance of multiple etiologies: a retrospective review of 140 patients. Spine 37:1667–1675
5. Boachie-Adjei O, Ferguson JAI, Pigeon RG, Peskin MR (2006) Transpedicular lumbar wedge resection osteotomy for fixed sagittal imbalance: surgical technique and early results. Spine 31:485–492
6. Bridwell KH, Lewis SJ, Lenke LG, Baldus C, Blanke K (2003) Pedicle subtraction osteotomy for the treatment of fixed sagittal imbalance. J Bone Joint Surg Am 85-A:454–463
7. Buchowski JM, Bridwell KH, Lenke LG et al (2007) Neurologic complications of lumbar pedicle subtraction osteotomy: a 10-year assessment. Spine 32:2245–2252
8. Chen IH, Chien JT, Yu TC (2001) Transpedicular wedge osteotomy for correction of thoracolumbar kyphosis in ankylosing spondylitis: experience with 78 patients. Spine 26:E354–E360
9. Kim YJ, Bridwell KH, Lenke LG, Cheh G, Baldus C (2007) Results of lumbar pedicle subtraction osteotomies for fixed sagittal imbalance. A minimum 5-year follow-up study. Spine 32:2189–2197
10. Lafage V, Schwab F, Vira S et al (2011) Does vertebral level of pedicle subtraction osteotomy correlate with degree of spinopelvic parameter correction? J Neurosurg Spine 14:184–191
11. Suk SI, Kim JH, Kim WJ et al (2002) Posterior vertebral column resection for severe spinal deformities. Spine 27:2374–2382
12. Czyz M, Forster S, Holton J et al (2017) New method for correction of lumbo-sacral kyphosis deformity in patient with high pelvic incidence. Eur Spine J 26:2204–2210
13. Hsieh PC, Ondra SL, Wienecke RJ, O'Shaughnessy BA, Koski TR (2007) A novel approach to sagittal balance restoration following iatrogenic sacral fracture and resulting sacral kyphotic deformity. Technical note. J Neurosurg Spine 6:368–372
14. Glattes RC, Bridwell KH, Lenke LG et al (2005) Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion. Incidence, outcomes, and risk factor analysis. Spine 30:1643–1649
15. Yilgor C, Sogunmez N, Boissiere L et al (2017) Global Alignment and Proportion (GAP) Score: development and validation of a new method of analyzing spinopelvic alignment to predict mechanical complications after adult spinal deformity surgery. J Bone Joint Surg Am 99:1661–1672
16. Lafage R, Obeid I, Liabaud B et al (2018) Location of correction within the lumbar spine impacts acute adjacent-segment kyphosis. J Neurosurg Spine 30:69–77
17. Smith JS, Lafage V, Shaffrey CI et al (2016) Outcomes of operative and nonoperative treatment for adult spinal deformity: a prospective, multicenter, propensity-matched cohort assessment with minimum 2-year follow-up. Neurosurgery 78:851–861
18. Cho SK, Bridwell KH, Lenke LG et al (2012) Major complications in revision adult deformity surgery: risk factors and clinical outcomes with 2- to 7-year follow-up. Spine 37:489–500
19. Hassanzadeh H, Jain A, El Dafrawy MH et al (2013) Clinical results and functional outcomes of primary and revision spinal deformity surgery in adults. J Bone Joint Surg Am 95:1413–1419
20. Kim YJ, Bridwell KH, Lenke LG et al (2008) Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion: minimum five-year follow-up. Spine 33:2179–2184
21. Liu FY, Wang T, Yang SD et al (2016) Incidence and risk factors for proximal junctional kyphosis: a meta-analysis. Eur Spine J 25:2376–2383
22. Yagi M, Hosogane N, Okada E et al (2014) Factors affecting the postoperative progression of thoracic kyphosis in surgically treated adult patients with lumbar degenerative scoliosis. Spine 39:E521–E528
23. Bridwell KH, Lenke LG, Cho SK et al (2013) Proximal junctional kyphosis in primary adult deformity surgery: evaluation of 20 degrees as a critical angle. Neurosurgery 72:899–906
24. Duval-Beaupere G, Schmidt C, Cosson P (1992) A Barycentremetric study of the sagittal shape of spine and pelvis: the conditions required for an economic standing position. Ann Biomed Eng 20:451–462
25. Rose PS, Bridwell KH, Lenke LG et al (2009) Role of pelvic incidence, thoracic kyphosis, and patient factors on sagittal plane correction following pedicle subtraction osteotomy. Spine 34:785–791
26. Schwab FJ, Blondel B, Bess S et al (2013) Radiographical spinopelvic parameters and disability in the setting of adult spinal deformity: a prospective multicenter analysis. Spine 38:E803–E812

Affiliations

Haruki Funao[1] · Floreana N. Kebaish[1] · Richard L. Skolasky[1] · Khaled M. Kebaish[1]

[1] Department of Orthopaedic Surgery, The Johns Hopkins University, 601 North Caroline Street, Baltimore, MD 21287, USA