



Indications and limitations of minimally invasive lateral lumbar interbody fusion without osteotomy for adult spinal deformity

Tetsuro Ohba¹ · Shigeto Ebata¹ · Shota Ikegami² · Hiroki Oba^{1,2} · Hiroataka Haro¹

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Abstract

Purpose The global alignment and proportion (GAP) score was recently developed to consider proportional analysis of spinopelvic alignment and has been indicated for setting surgical goals to decrease the prevalence of mechanical complications. The goal of this study was to clarify the limitations and problems with spinal corrective surgery with minimally invasive lateral lumbar interbody fusion (LLIF) without osteotomy using GAP score, and to establish a preoperative radiographical evaluation to understand the necessity for three-column osteotomy.

Methods We included data from 57 consecutive patients treated with spinal corrective surgery with LLIF and without Schwab grade 3–6 osteotomy for ASD. To evaluate flexibility of the pelvis and lumbar spine, we examined full-length lateral radiographs with patients standing and prone. Correlations between pre- and postoperative radiographic parameters and GAP score were determined.

Results Most patients achieved a sufficiently ideal lumbar lordosis (87.7%), but ideal sacral slope (SS) was achieved in only 50.8% of patients. Preoperative prone SS showed a significant positive correlation with postoperative SS and a significant negative correlation with GAP score. Patients whose preoperative prone SS was larger than pelvic incidence \times 0.59–7.5 tended to achieve proportioned spinopelvic alignment by using LLIF.

Conclusions The cause of poor outcome of GAP score for ASD corrective surgery with LLIF without osteotomy is a postoperative small SS. Preoperative prone SS is useful for predicting postoperative SS. When preoperative SS in prone patients is relatively small to ideal as calculated using PI, osteotomy or other correctors should be considered to achieve satisfactory spinopelvic parameters.

Level of evidence III.

Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.

The graphic abstract consists of three slides from the Spine Journal. The first slide, titled 'Key points', lists: 1. Adult spinal deformity, 2. Minimally invasive lateral lumbar interbody fusion, and 3. SS in prone position. The second slide shows two diagrams of the spine: 'Low prone SS' and 'High prone SS', with corresponding lateral radiographs below them. The third slide, titled 'Take Home Messages', lists: 1. The cause of poor outcome of GAP score for ASD corrective surgery with LLIF without osteotomy was postoperative small SS value. 2. Preoperative SS with prone patients was useful to evaluate flexibility of the pelvis and lumbar spine. 3. When preoperative SS with the patient prone was small, osteotomy or an alternative corrector should be considered to achieve satisfactory postoperative spinopelvic parameters. Each slide includes the Spine Journal logo and the Springer logo.

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Extended author information available on the last page of the article

Keywords Adult spinal deformity · Minimally invasive lateral lumbar interbody fusion · SS in prone position · Lordosis distribution index · Global alignment and proportion score · Mechanical complications

Introduction

In the elderly, adult spinal deformity (ASD) remains controversial within the field of spinal disorders due to the important effect it might have on health-related quality of life [1, 2]. Despite advances in surgical techniques and implant selection, surgical treatment for ASD remains one of the most challenging because of the high risk of perioperative complications [3]. Minimally invasive lateral lumbar interbody fusion (LLIF) techniques have attracted attention as alternative or adjuvant procedures in ASD surgery with a goal of reduced surgical access morbidity and perioperative complications. Past study reported elderly patients can successfully be treated using LLIF techniques [4]. Advantages of LLIF include significantly less bleeding, and fewer neurological and operative complications [5–8]. Substantial sagittal and coronal correction by LLIF has been reported [7, 9]. However, the necessity for three-column osteotomy in the treatment of severe sagittal imbalance or rigid deformities has been indicated despite the risk of massive blood loss and complications [10–12]. Several preoperative radiographic methods to assess curve flexibility and preoperative planning of surgery to correct spinal deformity have been suggested such as fulcrum bending radiographic images and lateral radiographs with the patients sitting, prone, or supine [2, 13, 14]. The indications and preoperative evaluation for osteotomy in ASD surgery remain controversial. To establish an optimal strategy for ASD surgery, the limitations and problems surrounding spinal corrective surgery with LLIF without osteotomy should be known.

A novel pelvic-incidence-based proportional method to analyze the sagittal plane to predict mechanical complications after surgery for ASD, the global alignment and proportion (GAP) score has been developed [15]. The formula for the GAP score was developed under the concept of a continuum of states that provides a pelvic incidence-based proportional indication of pelvic version, magnitude and distribution of lumbar lordosis, and global spinopelvic alignment to assess disproportion compared with the calculated “ideal” for any given individual.

This study aimed to clarify the limitations and issues of spinal corrective surgery with LLIF without osteotomy using the GAP score, and to establish preoperative radiographical evaluation to understand the necessity for three-column osteotomy.

Methods

Patients and surgical techniques

We conducted a retrospective observational study of a cohort of consecutive patients with a diagnosis of ASD who underwent corrective spinal surgery. The study was approved by our institutional review board (Application no. 1183). We received written informed consent from all eligible patients. Patients were considered candidates for thoracolumbar correction if fusion was indicated because of ASD and if a full course of conservative care had been exhausted. The inclusion criteria were age > 60 years and a radiographic diagnosis of ASD defined by at least one of the following parameters: a coronal Cobb angle > 30°; a C7 sagittal vertical axis (SVA), which is the distance between the C7 plumb line and the posterosuperior edge of S1, > 5 cm; and/or pelvic tilt (PT), which is the orientation of the pelvis with respect to the femurs and the rest of the body, > 30°. Patients were excluded if they had ankylosing spondylitis, or a rounded back because of Parkinson’s disease. A total of 103 spinal correction surgeries for ASD were performed between April 2012 and March 2017 by two board-certified spinal surgeons at our institution. In this study, we included data from 57 consecutive patients treated with spinal correction surgery with LLIF and followed up for a minimum of 2 years. Patients who demonstrated corrective surgery with Schwab grade 3–6 osteotomy [16] were excluded in this study. Basic demographic and surgical data: age, sex, bone mineral density (BMD), type of procedure and area of fusion were noted (Table 1).

Surgical procedure

We used an anterior approach to lateral interbody fusion (LIF) from L1–L2 or L2–L3 to the level of the L4–5 disk to obtain adequate coronal and sagittal global spine alignment in patients with ASD [17]. Subsequently the patient was placed in a prone position to undergo posterior lumbar interbody fusion (PLIF) at the level of the L5–S disk. Intraoperative lateral lumbosacral radiographs were taken to evaluate how much additional correction was needed using the rod cantilever technique to achieve ideal LL determined in a preoperative plan according to previous reports [18–20]. After setting dual iliac screws as previously described [21], the S1 pedicle screws were connected to the rod with the iliac screws using an offset connector. The spinopelvic deformity was corrected using a cantilever force technique with the

Table 1 Preoperative patient characteristics

Variable	(N=57)
Age at surgery (years)	71.9 ± 7.5
Female/male (n)	50/7
BMI (kg/m ²)	22.3 ± 3.51 (15.7–29.9)
BMD (%YAM)	73.2 ± 14.2
<i>Location of UIV (n)</i>	
T4	3
T5	5
T6	0
T8	7
T9	19
T10	23

Interval and ratio values represent the mean ± standard deviation

BMI body mass index, BMD bone mineral density, UIV upper instrumented vertebra

pelvis retroverted, raising the pelvis to an optimal alignment. A rod was connected to each pedicle screw from caudal to cranial aspects. Where flexibility of spinal motion was lost, we added a suitable osteotomy, which was classified as grade 1–6 by SRS-Schwab [16]. Allogenic and local autogenous bone grafts were used.

Radiographic measurements

Radiographic data consisted of full-length lateral radiographs obtained pre- and 4–6 weeks postoperatively, and at 2 years postoperatively, with the patient in a freestanding posture with their fingers placed on their clavicles. To evaluate flexibility of the pelvis and lumbar spine, full-length lateral radiographs were obtained with the patients prone with both arms next to the trunk and without any cushions under the body (Fig. 1). The following radiographic parameters were measured pre- and postoperatively using a lateral view: T5–T12 TK; T12–S1 LL angles; pelvic incidence (PI); PT; sacral slope (SS); SVA; T1 pelvic angle (TPA), which is the angle between the line from the center of femoral heads to the center of S1 and the line from the femoral head to the center of T1 vertebra [22]; and global tilt (GT), which is the angle formed by the intersection of two lines, the first line drawn from the center of C7 to the center of the sacral endplate and the second line drawn from the center of the femoral heads to the center of the sacral endplate [23]; spino-sacral angle (SSA) is defined as the angle connecting the center of the C7 vertebra to the center of the S1 endplate and the line parallel to the superior S1 endplate [24]. L1–S1 lordosis and L4–S1 lordosis were measured on postoperative radiographs to assess the distribution of the lordosis

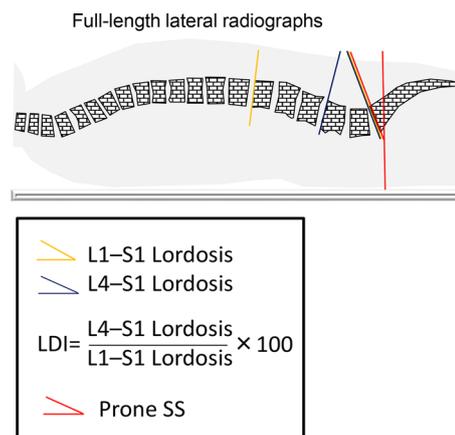


Fig. 1 The lumbar lordosis construction described by the lordosis distribution index (LDI; L4–S1 lordosis/L1–S1 lordosis × 100) and SS while the patient was prone

(LDI). Kyphosis was expressed as a positive value, and lordosis was expressed as a negative value. The proximal junctional angle was measured as the angle between the caudal endplate of the UIV to the cephalad endplate of 2 proximal vertebrae. Increased proximal junctional angle (PJA) was calculated as increased angle between the PJA obtained on postoperative radiographs and the PJA obtained 2 years postoperatively. Radiographic measurements were obtained by two board-certified spine surgeons (HO and TO). These surgeons had > 10 years of experience in spinal surgery and were blinded to patient data before the measurements were taken.

GAP score

GAP scores were calculated using early postoperative radiographic parameters following methods previously described by adding the scores for relative pelvic version (RPV), relative lumbar lordosis (RLL), LDI, relative spinopelvic alignment (RSA), and age, and can range from 0 to 13 points. Additionally, a GAP score of 0 to 2 was categorized as indicating a proportioned spinopelvic state; 3 to 6 as moderately disproportioned; and ≥ 7 as a severely disproportioned spinopelvic alignment [15] (Suppl. Table).

Clinical outcomes

Postoperative baseline patient health status was measured (for lumbar pain-related factors) using a Roland–Morris Disability Questionnaire (RDQ) and Oswestry Disability Index (ODI), where 0% indicates no disability and 100% indicates extreme debilitating disability [25] at 2 years after surgery.

Statistical analyses

All data are reported as mean \pm SD. Data were analyzed using a two-sided Student *t* test, or a Fisher exact test to determine significant differences. Correlations between pre- and postoperative radiographic parameters and GAP score were determined using Pearson's correlation coefficient. We examined whether SS in a prone position (prone SS) preoperatively impacted the insufficient alignment correction. We employed logistic regression analysis with disproportioned spinopelvic alignment, which was considered as a GAP score of more than 2 points, as the response variable, and the prone SS–ideal SS based on preoperative PI as the explanatory variable. Then, we used a receiver operating characteristic curve (ROC curve) to determine the threshold of prone SS–ideal SS for insufficient alignment correction. All statistical calculations were performed using Prism (version 6.0; GraphPad Software, La Jolla, CA) and the statistical package R (version 3.6.1; available at <http://www.r-project.org>). $P < 0.05$ was considered significant (* $P < 0.05$, ** $P < 0.0001$).

Results

Patient population

We included 57 eligible patients in this study; 88% were female, mean age was 71.9 years (± 7.5), body mass index (BMI) was 22.3 (± 3.71) and bone mineral density (BMD) (%YAM) was 73.2% (± 14.2) (Table 1). Postoperatively, the spinopelvic alignment of patients improved significantly. Preoperative SS and LL with the patient prone were significantly greater than while they were standing. The mean pre- and postoperative alignments are summarized in Table 2.

Comparison of pre- and postoperative spinopelvic parameters between high and low PI

Based on a past report [17], patients were divided into groups of those with low PI Preop ($PI \leq 50^\circ$) or high PI Preop ($PI > 50^\circ$) and spinopelvic parameters were compared between groups (Tables 2 and 3). Preoperative SS and LL of those in the high PI group were significantly higher than preoperative SS and LL of those in the low PI group. However, significantly worse GT and TPA were observed in those in the high PI group compared with those in the low PI group. There was no significant difference in postoperative SS and LL between the groups. By contrast, PI–LL, GT, and TPA were significantly larger in the high PI group compared with these variables in the low PI group. These findings indicated patients with high PI should undergo correction to restore a larger SS and LL to achieve balanced spinopelvic alignment.

Postoperative GAP score

Postoperative GAP score is summarized in Table 4. Based on total GAP score, 23 (40.4%) patients were grouped into proportioned, 26 (45.6%) into moderately disproportioned, and 8 (14%) into severely disproportioned spinopelvic alignment. According to subgroup analysis, 50 (87.7%) of the RLL subgroup and 48 (66.7%) of the LDI subgroup accomplished “alignment.” By contrast, only 29 (50.8%) of the RPV subgroup and 29 (50.9%) of the RSA group were “aligned.” This result indicated parameters of the lumbar spine were more easily “aligned” than pelvic parameters by corrective surgery with LLIF without osteotomy.

Table 2 Comparison of preoperative spinopelvic parameters between high and low PI

Preop variable	Preop $PI \leq 50^\circ$ ($n = 32$)	Preop $PI > 50^\circ$ ($n = 25$)	Statistics
PT ($^\circ$)	31.6 \pm 9.2	38.6 \pm 9.3	NS
SS ($^\circ$)	12.5 \pm 11.5	23.6 \pm 9.1	<0.0001**
LL ($^\circ$)	6.5 \pm 18.6	19.6 \pm 17.9	<0.05*
PI–LL ($^\circ$)	36.5 \pm 17.5	41.4 \pm 19.9	NS
SVA (mm)	105.2 \pm 56.2	132.4 \pm 76.5	NS
GT ($^\circ$)	45.1 \pm 15.3	54.9 \pm 18.9	<0.05*
TPA ($^\circ$)	33.5 \pm 13.2	44.1 \pm 14.6	<0.05*
SSA ($^\circ$)	86.9 \pm 17.1	96.0 \pm 13.0	<0.05*
Prone SS ($^\circ$)	18.5 \pm 5.9	25.7 \pm 8.8	<0.0001**
Prone LL ($^\circ$)	23.6 \pm 9.7	32.8 \pm 9.3	<0.05*

Interval and ratio values are presented as the mean \pm standard deviation

Preop preoperative, PT pelvic tilt, SS sacral slope, LL lumbar lordosis, PI pelvic incidence, SVA sagittal vertical axis, GT global tilt, TPA T1 pelvic angle, SSA Spino-sacral angle

Table 3 Comparison of postoperative spinopelvic parameters between high and low PI

Postop variable	Preop PI $\leq 50^\circ$ ($n=32$)	Preop PI $> 50^\circ$ ($n=25$)	Statistics
PT ($^\circ$)	12.8 \pm 5.5	23.1 \pm 7.5	<0.0001**
SS ($^\circ$)	29.4 \pm 7.5	32.4 \pm 8.3	NS
LL ($^\circ$)	51.8 \pm 8.4	54.7 \pm 8.3	NS
PI–LL ($^\circ$)	– 9.84 \pm 8.6	1.16 \pm 9.7	<0.0001**
SVA (mm)	15.1 \pm 32.1	19.2 \pm 24.3	NS
GT ($^\circ$)	12.6 \pm 6.2	22.6 \pm 8.9	<0.0001**
TPA ($^\circ$)	8.28 \pm 5.7	17.5 \pm 8.2	<0.0001**
SSA ($^\circ$)	118.2 \pm 7.7	119.6 \pm 7.6	NS

Interval and ratio values are presented as the mean \pm standard deviation

Postop postoperative, PT pelvic tilt, SS sacral slope, LL lumbar lordosis, PI pelvic incidence, SVA sagittal vertical axis, GT global tilt, TPA T1 pelvic angle, SSA Spino-sacral angle

Table 4 Postoperative GAP score

Relative pelvic version (RPV)	Score	LLIF ($N=57$)
Measured–ideal SS	0	29 (50.8%)
Ideal SS = PI \times 0.59 + 9	1	2 (3.5%)
	2	19 (33.3%)
	3	7 (12.3%)
Relative lumbar lordosis (RLL)	0	50 (87.7%)
Measured–ideal LL	2	5 (8.8%)
Ideal LL = PI \times 0.62 + 29	3	2 (3.5%)
Lordosis distribution index (LDI)	0	48 (66.7%)
L4–S1 lordosis/L1–S1 lordosis	1	11 (19.3%)
	2	2 (3.5%)
	3	6 (10.5%)
Relative spinopelvic alignment (RSA)	0	29 (50.9%)
Measured–ideal GT	1	23 (40.4%)
Ideal GT = PI \times 0.48–15	3	5 (8.8%)
Age factor	0	3 (5.3%)
	1	54 (94.7%)
Total score	0–2	23 (40.4%)
	3–6	26 (45.6%)
	≥ 7	8 (14.0%)

N number of patients (%); SS sacral slope, LL lumbar lordosis, PI pelvic incidence, GT global tilt

Comparison of ODI, RDQ, and increased PJA 2 years after surgery between categories of total GAP score

The frequency of rod fractures was not significantly different between categories of total GAP score (Table 5). Increased PJA 2 years after surgery was significantly larger in the disproportioned group than it was in the proportioned group (Table 4). There was no significant difference in preoperative ODI or RDQ between the proportioned and disproportioned groups (data not shown). By contrast, ODI 2 years postoperatively was significantly worse in the disproportioned group than it was in the proportioned group (Table 4).

Correlation between pre- and postoperative spinopelvic parameters in the standing position

The correlation between pre- and postoperative parameters is summarized in Table 6.

We found a significant positive correlation between preoperative SS while the patients were standing and postoperative SS ($r=0.32$, $P<0.05$). By contrast, there was no significant correlation between any other pre- or postoperative parameters while the patients were standing.

Table 5 Comparison of ODI, RDQ, and increased PJA 2 year after surgery between categories of total GAP score

Variable	Proportioned ($n=24$)	Disproportioned ($n=33$)	Statistics
<i>Complication</i>			
Increased PJA ($^\circ$)	4.9 \pm 6.2	7.9 \pm 6.9	$P<0.05$
Rod fracture (\pm)	5/24 (20.8%)	7/33 (21.2%)	NS
<i>Clinical outcomes</i>			
2 y ODI (%)	14.8 \pm 15.2	25.1 \pm 13.1	$P<0.05$
2 y RDQ	8.81 \pm 5.2	9.79 \pm 6.9	NS

PJA proximal junctional angle, ODI Oswestry disability index, RDQ Roland–Morris Disability Questionnaire

Table 6 Correlation between pre- and postoperative spinopelvic parameters

	Postop		
	LL (°)	LDI (%)	SS (°)
Preop			
Standing			
LL (°)	NS	NS	NS
LDI (%)	NS	NS	NS
SS (°)	NS	NS	0.32*
Prone			
LL (°)	NS	NS	0.38*
SS (°)	NS	0.29*	0.70**
LDI (%)	NS	NS	NS

The numbers represent correlation coefficient (r)

NS no significant difference, *Preop* preoperative, *Postop* postoperative, SS sacral slope, LL lumbar lordosis, LDI distribution of the lordosis

* $P < 0.05$ in the comparison with preop

** $P < 0.0005$ in the comparison with preop

Utility of preoperative radiographic assessment with the patients prone

We found a significant positive correlation between preoperative LL while the patients were prone and postoperative SS ($r = 0.38$, $P < 0.05$). We found a significant positive correlation between preoperative prone SS and postoperative LDI ($r = 0.29$, $P < 0.05$) (Table 6). Importantly, a significant positive correlation was found between prone SS and postoperative SS ($r = 0.7$, $P < 0.0001$) and significant negative correlation with GAP score ($r = 0.31$, $P < 0.05$) (Fig. 2a, b). Prone SS–ideal SS was significantly associated with disproportionate spinopelvic alignment, considered as that with an odds ratio of 3.3 (95% confidence interval 1.8 to 7.1, $P < 0.05$) per -5° . The cut-off value was determined as -16.5° using ROC curve analysis, which indicated a sensitivity of 78.6%, specificity of 69.0%, and area under the curve of 0.804 (Fig. 2c). After the formula transformation, a patient whose prone SS was larger than $PI \times 0.59 - 7.5$ preoperatively tended to achieve sufficient spinopelvic alignment using LLIF.

These results indicate that preoperative LL and prone SS are useful to evaluate flexibility of the pelvis and lumbar spine, and to predict postoperative SS, LDI, and GAP score in ASD surgery with LLIF without osteotomy.

Discussion

The present study has clarified the indications and limitations of spinal corrective surgery for ASD with LLIF without osteotomy. Based on total GAP score, we found that 23

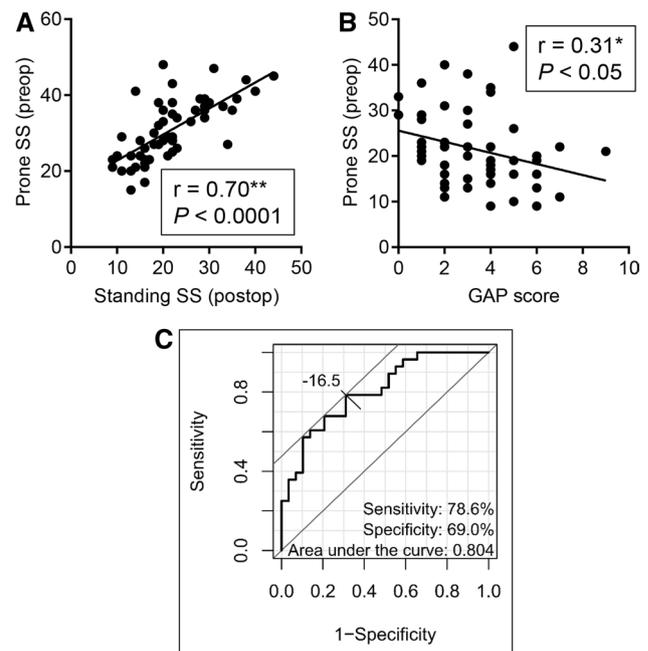


Fig. 2 a Correlation between preoperative SS while prone and postoperative SS while standing (** $P < 0.0001$), b correlation between preoperative SS while prone and postoperative global alignment and proportion (GAP) score (* $P < 0.05$), c receiver operating characteristic curve to determine the threshold of prone SS–ideal SS for insufficient alignment correction

(40.4%) patients were grouped into proportioned, 26 (45.6%) into moderately disproportioned, and 8 (14.0%) into severely disproportioned spinopelvic alignment. This result indicated LLIF was useful and effective for surgery to correct ASD and an acceptable surgical outcome was achieved in the majority of patients. By contrast, detailed examination of patients who had a poor GAP score should be conducted using subgroup analysis to clarify which spinopelvic parameters are problems. Formulas following Schwab's system have been used by many to calculate an ideal LL to establish an optimal surgical strategy for patients with ASD [19, 20, 26]. However, a remaining high rate of reoperation due to mechanical revision has been reported despite achieving goals based on these formulas [3, 27, 28]. The GAP score was developed because of the limitations of existing formulas that focus on only LL values and the score has been used to set surgical goals to decrease the prevalence of mechanical complications [15, 29]. Actually, the critical importance of harmony among SS, upper LL and lower LL has been long known to maintain a favorable global spine balance [30–32]. Studies have been conducted to correct not only LL but also pelvic alignment with surgery for ASD patients [17, 33–35]. In our retrospective observational cohort study, GAP score has clarified the limitations and problems of spinal corrective surgery with LLIF without osteotomy for ASD. The present study showed most patients

achieved a sufficiently ideal LL in RLL subgroups (87.7%). By contrast, ideal SS in RPV subgroups was achieved in only 50.8% of all patients (Table 4). This result indicates preoperative radiographic evaluation should be established to predict postoperative SS value after ASD surgery with LLIF without osteotomy to decide the optimal surgical strategy including use of osteotomy.

There is a limitation to evaluate flexibility of the pelvis and lumbar spine and to predict postoperative spinopelvic parameters with radiographs while the patient is standing. Several preoperative radiographic methods to assess curve flexibility and preoperative planning of spinal deformity have been suggested such as fulcrum bending radiographical images, and lateral radiographs while the patients are sitting, prone, or supine [2, 13, 14]. However, to our knowledge, there are no reports of radiographic methods to predict postoperative SS value. In the present study, we found preoperative prone SS had a significant positive correlation with LDI, a strong positive correlation with postoperative SS and a significant negative correlation with GAP score (Fig. 2a, b and Table 5). Finally, we showed that when preoperative prone SS was relatively small to ideal as calculated using PI, the resulting GAP score was clearly worse. The present study suggests preoperative SS in prone patients was useful to evaluate flexibility of the pelvis and lumbar spine, and moreover to predict postoperative SS, LDI, and GAP score in ASD surgery with LLIF without osteotomy (Fig. 3). This result indicates that when preoperative SS in prone patients is small relative to PI, osteotomy and alternative correctors such as oblique lateral interbody fusion at L5–S1 should be considered to achieve satisfactory postoperative spinopelvic parameters.

Limitations of this study include its small sample size, and retrospective nature. Differences in the thickness of the soft tissue around the abdomen and thorax might make the measurements in the prone position unreliable. The patients were followed up for only 2 years, and longer-term follow-up is necessary to determine the reliability of the results.

Conclusions

The cause of poor outcome of GAP score of ASD corrective surgery with LLIF without osteotomy is postoperative small SS value, and preoperative prone SS is useful to predict postoperative SS. When preoperative SS in prone patients is relatively small to ideal as calculated using PI, osteotomy, or other correctors should be considered to achieve satisfactory postoperative spinopelvic parameters.

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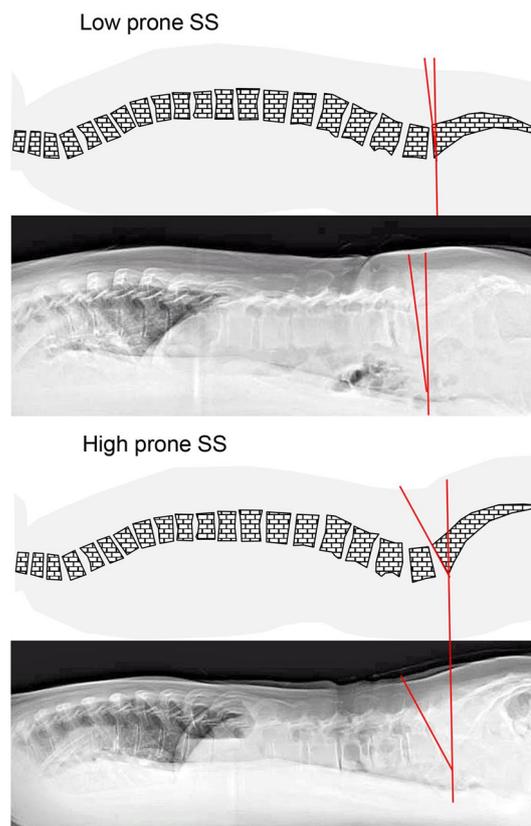


Fig. 3 Representative schemas and radiographs of patients with low or high SS while prone

research. The manuscript submitted does not contain information about medical device(s)/drug(s).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The study was approved by our institutional review board (Approval No. 1183).

References

- Gum JL, Bridwell KH, Lenke LG, Bumpass DB, Sugrue PA, Karikari IO, Carreon LY (2015) SRS22R appearance domain correlates most with patient satisfaction after adult deformity surgery to the sacrum at 5-year follow-up. *Spine (Phila Pa 1976)* 40:1297–1302. <https://doi.org/10.1097/brs.0000000000000961>
- Ohba T, Ebata S, Koyama K, Haro H (2018) Prevalence and key radiographic spinal malalignment parameters that influence the risk for gastroesophageal reflux disease in patients treated

- surgically for adult spinal deformity. *BMC Gastroenterol* 18:8. <https://doi.org/10.1186/s12876-018-0738-6>
3. Soroceanu A, Burton DC, Oren JH, Smith JS, Hostin R, Shaffrey CI, Akbarnia BA, Ames CP, Errico TJ, Bess S, Gupta MC, Deviren V, Schwab FJ, Lafage V, International Spine Study G (2016) Medical complications after adult spinal deformity surgery: incidence, risk factors, and clinical impact. *Spine (Phila Pa 1976)*. <https://doi.org/10.1097/brs.0000000000001636>
 4. Rodgers WB, Gerber EJ, Rodgers JA (2010) Lumbar fusion in octogenarians: the promise of minimally invasive surgery. *Spine (Phila Pa 1976)* 35:S355–360. <https://doi.org/10.1097/brs.0b013e3182023796>
 5. Isaacs RE, Hyde J, Goodrich JA, Rodgers WB, Phillips FM (2010) A prospective, nonrandomized, multicenter evaluation of extreme lateral interbody fusion for the treatment of adult degenerative scoliosis: perioperative outcomes and complications. *Spine (Phila Pa 1976)* 35:S322–330. <https://doi.org/10.1097/brs.0b013e3182022e04>
 6. Phillips FM, Isaacs RE, Rodgers WB, Khajavi K, Tohmeh AG, Deviren V, Peterson MD, Hyde J, Kurd M (2013) Adult degenerative scoliosis treated with XLIF: clinical and radiographical results of a prospective multicenter study with 24-month follow-up. *Spine (Phila Pa 1976)* 38:1853–1861. <https://doi.org/10.1097/brs.0b013e3182a43f0b>
 7. Park HY, Ha KY, Kim YH, Chang DG, Kim SI, Lee JW, Ahn JH, Kim JB (2018) Minimally invasive lateral lumbar interbody fusion for adult spinal deformity: clinical and radiological efficacy with minimum two years follow-up. *Spine (Phila Pa 1976)* 43:E813–e821. <https://doi.org/10.1097/brs.0000000000002507>
 8. Than KD, Mummaneni PV, Bridges KJ, Tran S, Park P, Chou D, La Marca F, Uribe JS, Vogel TD, Nunley PD, Eastlack RK, Anand N, Okonkwo DO, Kanter AS, Mundis GM Jr (2017) Complication rates associated with open versus percutaneous pedicle screw instrumentation among patients undergoing minimally invasive interbody fusion for adult spinal deformity. *Neurosurg Focus* 43:E7. <https://doi.org/10.3171/2017.8.Focus17479>
 9. Kanter AS, Tempel ZJ, Ozpinar A, Okonkwo DO (2016) A review of minimally invasive procedures for the treatment of adult spinal deformity. *Spine (Phila Pa 1976)*. <https://doi.org/10.1097/brs.0000000000001481>
 10. Eskilsson K, Sharma D, Johansson C, Hedlund R (2017) Pedicle subtraction osteotomy: a comprehensive analysis in 104 patients. Does the cause of deformity influence the outcome? *J Neurosurg Spine* 27:56–62. <https://doi.org/10.3171/2016.12.Spine16585>
 11. Qiao J, Xiao L, Sun X, Shi B, Liu Z, Xu L, Zhu Z, Qian B, Qiu Y (2018) Vertebral subluxation during three-column osteotomy in surgical correction of adult spine deformity: incidence, risk factors, and complications. *Eur Spine J* 27:630–635. <https://doi.org/10.1007/s00586-017-5285-2>
 12. Dangelmajer S, Zadnik PL, Rodriguez ST, Gokaslan ZL, Sciubba DM (2014) Minimally invasive spine surgery for adult degenerative lumbar scoliosis. *Neurosurg Focus* 36:E7. <https://doi.org/10.3171/2014.3.FOCUS144>
 13. Janjua MB, Tishelman JC, Vasquez-Montes D, Vaynrub M, Errico TJ, Buckland AJ, Protosaltis T (2018) The value of sitting radiographs: analysis of spine flexibility and its utility in preoperative planning for adult spinal deformity surgery. *J Neurosurg Spine*. <https://doi.org/10.3171/2018.2.spine17749>
 14. Yasuda T, Hasegawa T, Yamato Y, Togawa D, Kobayashi S, Yoshida G, Banno T, Arima H, Oe S, Matsuyama Y (2018) Effect of position on lumbar lordosis in patients with adult spinal deformity. *J Neurosurg Spine*. <https://doi.org/10.3171/2018.3.spine1879>
 15. Yilgor C, Sogunmez N, Boissiere L, Yavuz Y, Obeid I, Kleinstuck F, Perez-Grueso FJS, Acaroglu E, Haddad S, Mannion AF, Pellise F, Alanay A, European Spine Study G (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. <https://doi.org/10.2106/JBJS.16.01594>
 16. Schwab F, Blondel B, Chay E, Demakakos J, Lenke L, Tropiano P, Ames C, Smith JS, Shaffrey CI, Glassman S, Farcy JP, Lafage V (2015) The comprehensive anatomical spinal osteotomy classification. *Neurosurgery* 76(Suppl 1):33–41. <https://doi.org/10.1227/01.neu.0000462076.73701.09> (discussion S41)
 17. Oba H, Ebata S, Takahashi J, Ikegami S, Koyama K, Haro H, Kato H, Ohba T (2018) Loss of pelvic incidence correction after long fusion using iliac screws for adult spinal deformity: cause and effect on clinical outcome. *Spine (Phila Pa 1976)*. <https://doi.org/10.1097/brs.0000000000002775>
 18. Hasegawa K, Okamoto M, Hatsushikano S, Shimoda H, Ono M, Watanabe K (2016) Normative values of spino-pelvic sagittal alignment, balance, age, and health-related quality of life in a cohort of healthy adult subjects. *Eur Spine J* 25:3675–3686. <https://doi.org/10.1007/s00586-016-4702-2>
 19. Inami S, Moridaira H, Takeuchi D, Shiba Y, Nohara Y, Taneichi H (2016) Optimum pelvic incidence minus lumbar lordosis value can be determined by individual pelvic incidence. *Eur Spine J* 25:3638–3643. <https://doi.org/10.1007/s00586-016-4563-8>
 20. Yamato Y, Hasegawa T, Kobayashi S, Yasuda T, Togawa D, Arima H, Oe S, Iida T, Matsumura A, Hosogane N, Matsumoto M, Matsuyama Y (2016) Calculation of the target lumbar lordosis angle for restoring an optimal pelvic tilt in elderly patients with adult spinal deformity. *Spine (Phila Pa 1976)* 41:E211–217. <https://doi.org/10.1097/brs.0000000000001209>
 21. Ebata S, Ohba T, Oba H, Haro H (2018) Bilateral dual iliac screws in spinal deformity correction surgery. *J Orthop Surg Res* 13:260. <https://doi.org/10.1186/s13018-018-0969-9>
 22. Ryan DJ, Protosaltis TS, Ames CP, Hostin R, Klineberg E, Mundis GM, Obeid I, Kebaish K, Smith JS, Boachie-Adjei O, Burton DC, Hart RA, Gupta M, Schwab FJ, Lafage V, International Spine Study G (2014) T1 pelvic angle (TPA) effectively evaluates sagittal deformity and assesses radiographical surgical outcomes longitudinally. *Spine (Phila Pa 1976)* 39:1203–1210. <https://doi.org/10.1097/brs.0000000000000382>
 23. Obeid I, Boissiere L, Yilgor C, Larrieu D, Pellise F, Alanay A, Acaroglu E, Perez-Grueso FJ, Kleinstuck F, Vital JM, Bourghli A, European Spine Study Group E (2016) Global tilt: a single parameter incorporating spinal and pelvic sagittal parameters and least affected by patient positioning. *Eur Spine J* 25:3644–3649. <https://doi.org/10.1007/s00586-016-4649-3>
 24. Le Huec JC, Thompson W, Mohsinaly Y, Barrey C, Faundez A (2019) Sagittal balance of the spine. *Eur Spine J*. <https://doi.org/10.1007/s00586-019-06083-1>
 25. Fujiwara A, Kobayashi N, Saiki K, Kitagawa T, Tamai K, Saotome K (2003) Association of the Japanese orthopaedic association score with the Oswestry disability index, Roland-Morris Disability Questionnaire, and short-form 36. *Spine (Phila Pa 1976)* 28:1601–1607
 26. Schwab F, Lafage V, Patel A, Farcy JP (2009) Sagittal plane considerations and the pelvis in the adult patient. *Spine (Phila Pa 1976)* 34:1828–1833. <https://doi.org/10.1097/brs.0b013e3181a13c08>
 27. Kato S, Fehlings MG, Lewis SJ, Lenke LG, Shaffrey CI, Cheung KMC, Carreon LY, Dekutoski MB, Schwab FJ, Boachie-Adjei O, Kebaish KM, Ames CP, Qiu Y, Matsuyama Y, Dahl BT, Mehdian H, Pellise F, Berven SH (2018) An analysis of the incidence and outcomes of major versus minor neurological decline after complex adult spinal deformity surgery: a subanalysis of Scolio-RISK-1 study. *Spine (Phila Pa 1976)* 43:905–912. <https://doi.org/10.1097/brs.0000000000002486>

28. Passias PG, Soroceanu A, Yang S, Schwab F, Ames C, Boniello A, Smith J, Shaffrey C, Boachie-Adjei O, Mundis G, Burton D, Klineberg E, Hart R, Hamilton DK, Sciubba DM, Bess S, Lafage V (2016) Predictors of revision surgical procedure excluding wound complications in adult spinal deformity and impact on patient-reported outcomes and satisfaction: a two-year follow-up. *J Bone Joint Surg Am* 98:536–543. <https://doi.org/10.2106/JBJS.14.01126>
29. Yilgor C, Yavuz Y, Sogunmez N, Haddad S, Mannion AF, Abul K, Boissiere L, Obeid I, Kleinstuck F, Perez-Gruoso FJS, Acaroglu E, Pellise F, Alanay A (2018) Relative pelvic version: an individualized pelvic incidence-based proportional parameter that quantifies pelvic version more precisely than pelvic tilt. *Spine J*. <https://doi.org/10.1016/j.spinee.2018.03.001>
30. Ohba T, Ebata S, Oba H, Koyama K, Haro H (2018) Correlation between postoperative distribution of lordosis and reciprocal progression of thoracic kyphosis and occurrence of proximal junctional kyphosis following surgery for adult spinal deformity. *Clin Spine Surg*. <https://doi.org/10.1097/bsd.0000000000000702>
31. Roussouly P, Nnadi C (2010) Sagittal plane deformity: an overview of interpretation and management. *Eur Spine J* 19:1824–1836. <https://doi.org/10.1007/s00586-010-1476-9>
32. Roussouly P, Pinheiro-Franco JL (2011) Sagittal parameters of the spine: biomechanical approach. *Eur Spine J* 20(Suppl 5):578–585. <https://doi.org/10.1007/s00586-011-1924-1>
33. Lee JH, Na KH, Kim JH, Jeong HY, Chang DG (2016) Is pelvic incidence a constant, as everyone knows? Changes of pelvic incidence in surgically corrected adult sagittal deformity. *Eur Spine J* 25:3707–3714. <https://doi.org/10.1007/s00586-015-4199-0>
34. Cecchinato R, Redaelli A, Martini C, Morselli C, Villafane JH, Lamartina C, Berjano P (2017) Long fusions to S1 with or without pelvic fixation can induce relevant acute variations in pelvic incidence: a retrospective cohort study of adult spine deformity surgery. *Eur Spine J* 26:436–441. <https://doi.org/10.1007/s00586-017-5154-z>
35. Riviere C, Hardijzer A, Lazennec JY, Beaulieu P, Muirhead-Allwood S, Cobb J (2017) Spine-hip relations add understandings to the pathophysiology of femoro-acetabular impingement: a systematic review. *Orthop Traumatol Surg Res* 103:549–557. <https://doi.org/10.1016/j.otsr.2017.03.010>

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Affiliations

Tetsuro Ohba¹ · Shigeto Ebata¹ · Shota Ikegami² · Hiroki Oba^{1,2} · Hirotaka Haro¹

✉ Tetsuro Ohba
tooba@yamanashi.ac.jp

² Department of Orthopaedic Surgery, School of Medicine, Shinshu University, Matsumoto, Japan

¹ Department of Orthopaedic Surgery, University of Yamanashi, 1110, Shimokato, Chuo, Yamanashi 409-3898, Japan