CLINICAL ARTICLE

Spino-Pelvic Thresholds for Prevention of Proximal Junctional Kyphosis Following Combined Anterior Column Realignment and Short Posterior Spinal Fusion in Degenerative Lumbar Kyphosis

Ki Young Lee, MD[1], Jung-Hee Lee, MD[1], Kyung-Chung Kang, MD[1], Sang-Kyu Im, MD[1], Dong-Gune Chang, MD[2], Sun Hwan Choi, MD[1]

[1]*Department of Orthopaedic Surgery, Graduate School, College of Medicine, Kyung Hee University and* [2]*Department of Orthopaedic Surgery, Sanggye Paik Hospital, Inje University, Seoul, Korea*

Objective: To analyze ideal indication for combined anterior column realignment (ACR) with short posterior spinal fusion (PSF) and posterior column osteotomy (PCO) for preventing proximal junctional kyphosis (PJK) in adult spinal deformity (ASD) patients with lower lumbar kyphosis and compensatory thoracolumbar lordosis.

Methods: A retrospective study was conducted. This study included 27 ASD patients (average age of 66.6 years; one male and 26 females) with lower lumbar kyphosis and compensated thoracolumbar lordosis who underwent short PSF with PCO following ACR from 2006 to 2010. The minimum follow-up period was 5 years. The patients were divided into two groups based on the sagittal vertical axis (SVA) of the last follow-up radiographs, and a comparative analysis was performed evaluating spino-pelvic parameters and clinical outcomes including the Oswestry Disability Index (ODI), Visual Analog Scale (VAS), and complications.

Results: The mean follow-up time of included patients was 109.7 months, and the mean number of fused segments was 3.7. The uppermost instrumented vertebra was L_2 in 18 patients or L_3 in nine patients, and lowermost instrumented vertebra was sacrum in all patients. The mean lumbar lordosis (LL) values in the optimal SVA and sub-optimal SVA groups were 4.4° and 4.2° preoperatively ($P = 0.639$), −48.1° and −35° postoperatively ($P = 0.007$), and −45.2° and −20.7° at the last follow-up ($P < 0.05$). Overcorrection was seen in seven patients in the optimal SVA group, whereas all of the patients of the suboptimal SVA group were in the category of undercorrection ($P = 0.021$). Pelvic incidence (PI) of optimal SVA group (<50 mm, $n = 16$) and suboptimal SVA group (≥50 mm, $n = 11$) was 44.1° and 53.8° ($P = 0.009$). The prevalence of PJK was significantly higher in the suboptimal SVA group ($P = 0.008$), and last follow-up VAS for back pain ($P < 0.05$), and postoperative and last follow-up ODI ($P = 0.002$ and $P < 0.05$) were statistically larger for the suboptimal group than the optimal group.

Conclusions: Combined ACR with short PSF and PCO could effectively prevent sagittal decompensation of PJK and help achieve sagittal balance in the treatment of ASD patients with lower lumbar kyphosis, compensatory thoracolumbar lordosis, and especially low PI (<50°).

Key words: Adult spinal deformity (ASD); Anterior column realignment (ACR); Kyphosis; Spinal fusion; Thoracolumbar lordosis

Address for correspondence Jung-Hee Lee, MD, Department of Orthopaedic Surgery, Graduate School, College of Medicine, Kyung Hee University 23, Kyungheedae-ro, Dongdaemun-gu, Seoul, 130-872, Korea Tel: 82-2-958-8357, 8346; Fax: 82-2-964-3865; Email: ljhspine@gmail.com
Grant Sources: There were no financial and material support received for this work from any of the following organizations: National Institutes of Health (NIH); Wellcome Trust; Howard Hughes Medical Institute (HHMI); and others.
Disclosure: There is nothing to disclose.
Received 31 October 2019; accepted 5 February 2020

Introduction

Adult spinal deformity (ASD) is a devastating condition that induces pain and disability because of spinal malalignment, which negatively affect a patient's quality of life[1]. The recent increase in the average life expectancy has increased the prevalence of ASD, and surgical treatment for senior patients with active lifestyles has drawn attention.

Restoration of sagittal balance following appropriate surgical correction is the main goal in the treatment of ASD with sagittal malalignment. Optimal lumbar lordosis (LL) is essential for prevention of sagittal decompensation and closely correlated with pelvic incidence (PI)[2]. According to several studies, correlations between pelvic parameters and normal sagittal plane alignment are helpful for making a preoperative plan to achieve postoperative optimal sagittal balance. In addition, based on these correlations, various mathematical formulae have been developed to improve the accuracy of predicting the sagittal balance after the correction of deformities[3–7]. Legaye *et al.*[8] demonstrated that the PI is an important anatomic parameter that is used to describe the anatomical shape of the pelvis, and it greatly affects the sagittal spino-pelvic alignment. It is widely accepted that the positive sagittal balance has a negative impact on patients with ASD. According to Farcy and Schwab[9], flatback and kyphotic decompensation syndrome might have a correlation with the amount of residual sagittal imbalance, and Booth *et al.*[10] reported a treatment failure to achieve the negative sagittal balance that might be the most reliable indicator of unsatisfactory surgical outcomes. Moreover, Glassman *et al.*[11] reported that sagittal balance was the most important predictive factor for 2-year clinical outcomes, and restoration of a more normal sagittal balance is the critical goal for any reconstructive spine surgery for ASD patients. Likewise, spino-pelvic alignment affects sagittal balance and should be considered during surgical decision making to decrease postoperative complications[12].

Therefore, optimal surgical correction in patients with ASD is necessary to improve clinical outcomes and prevent sagittal decompensation[7,10,11], and surgical techniques for sagittal balance correction involve complex and challenging deformity correction. Traditionally, osteotomy, such as anterior open wedge osteotomy (Smith-Petersen osteotomy [SPO]), polysegmental dorsal osteotomy (Ponte osteotomy, posterior column osteotomy [PCO]), pedicle subtraction osteotomy (PSO), and posterior vertebral column resection, have been used to recover spinopelvic harmony in patients with ASD[13–15]. In particular, three column osteotomies are the most powerful methods for achieving optimal sagittal balance, but there are still problems originating not only from the complexity of the procedure itself but also from the complications that have been reported, with rates up to 37%[16,17]. Among these complications, proximal junctional kyphosis (PJK) is one of the common complications in long-term follow-up with reported incidences of 0% to 61%, and it is still controversial with regard to determining the uppermost instrumented vertebrae (UIV) as well[18,19]. PJK is a common pathological entity and complication after instrumented spinal fusion surgery and is a potentially catastrophic complications that could lead to progressive decompensation in the sagittal plane, neurologic compromise, and worse clinical outcomes[20–22]. Glattes *et al.*[20] reported medium-term follow-up studies that focused on PJK in the adult deformity with specific attention paid to patient outcomes; therefore, preventing sagittal decompensation of PJK is important for sagittal balance in the treatment of ASD.

There are various curve patterns according to the compensatory mechanism in ASD with sagittal malalignment and it is important to find an optimal indication of specific curve patterns for a short fusion level for achieving optimal correction with less complications[23–26]; this is because all patients with ASD do not need to require long fusion from the sacrum to the thoracic spine and corrective three-column osteotomies for obtaining sagittal balance. Furthermore, there are various factors for deciding a proper surgical plan, includding surgical approaches (staged anterior and posterior surgery *vs* single posterior), surgical procedures (three column osteotomy *vs* PCO), and level of UIV (upper thoracic, lower thoracic, upper lumbar)[27]. Recent advancements in minimally invasive spine surgery (MIS) have allowed ASD correction through posterior instrumentation of open or percutaneous techniques with interbody fusion grafts[28–32]. Dakwar *et al.*[31] first evaluated recovery in sagittal balance after lateral lumbar interbody fusion in 2010, and the advancement in surgical techniques, including anterior longitudinal ligament release and ACR treatment, allowed for a significant correction of LL using a lateral approach[33–35]. Therefore, in this study, efforts have been made to analyze ideal indication for combined anterior column realignment (ACR) with short posterior spinal fusion (PSF) for preventing PJK in ASD patients with thoracolumbar (TL) compensation and lower lumbar kyphosis[23,36].

There still remains a paucity of literature regarding proper indications for preventing late postoperative sagittal malalignment such as PJK in ASD patients. Therefore, the purpose of this study was: i) to compare the radiographic and PJK parameters between the optimal group and suboptimal group; ii) to compare the clinical outcomes between the optimal group and suboptimal group; and iii) to analyze ideal indication for combined ACR with short PSF and PCO for preventing PJK in ASD patients with lower lumbar kyphosis and compensatory TL lordosis.

Materials and Methods

Patient Selection

In this study, 78 patients with ASD aged ≥60 years who were followed up for at least 5 years between 2006 and 2010 were retrospectively evaluated.

The inclusion criteria were as follows: (i) patients were over 60 years with ASD accompanied by sagittal malalignment, and showed TL compensation and lower lumbar kyphosis; patients clearly showed atrophy of the back musculature on magnetic resonance imaging (a diagnostic criterion for degenerative lumbar kyphosis [DLK]) and clinical signs such as difficulty in walking with stooping, inability to lift heavy objects, difficulty in climbing slopes, and need for elbow support when working in the kitchen, with evidence of a corn on the extensor surface of the elbow[24]; (ii) patients underwent short PSF and PCO to the sacrum combined with ACR as a surgical treatment performed by a single surgeon at a single institution; (iii) patients were divided into the following two groups based on the sagittal vertical axis (SVA) of the last follow-up radiographs: optimal SVA group (SVA < 50 mm) and suboptimal SVA group (SVA > 50 mm); (iv) we analyzed the radiographic and clinical outcomes inducing PJK parameters; and (v) patients were retrospectively reviewed in this study (retrospective cohort study).

And the exclusion criteria were as follows: patients with deformities resulting from (i) trauma, (ii) spinal infection, (iii) ankylosing spondylitis, (iv) rheumatoid arthritis, (v) neuromuscular disease, or (vi) tumors.

Ideal LL

The primary goal of surgical correction in all patients was to obtain the ideal LL. The ideal LL was the theoretical value calculated according to the Korean version of the Legaye formula (sacral slope [SS] = 0.80 + 0.74 × PI, and ideal [maximal] LL = 17.42 + 0.96 × SS)[3,37]. Based on the estimated ideal LL, patients with a postoperative LL more than the ideal were categorized as overcorrection, and patients with less were categorized as undercorrection.

Radiographic Measurements

Sagittal alignment was evaluated by lateral 14 × 36-inch full spine X-rays, for which the patients stood in a neutral unsupported position with their arms in the clavicle position[38]. All the digital radiographs were measured using a picture archiving communication system (PACS) (Infinitt, Seoul, Korea): a software developed to accurately calculate parameters by magnifying anatomic landmarks of the spine and pelvis on lateral views. On radiography, we evaluated the PI, SS, pelvic tilt (PT), thoracic kyphosis (TK), TL, LL, lumbosacral junction (LS), and SVA.

Sagittal Vertical Axis

SVA was defined as the horizontal distance between the posterosuperior corner of the sacrum and the C_7 plumb line. Optimal and suboptimal sagittal balances were defined as SVA ≤50 mm and >50 mm, respectively[39].

Pelvic Parameters

PI was measured using a standing lateral radiograph of the pelvis, and the angle was defined between a perpendicular line from the sacral plate and a line connecting the midpoint of the sacral plate to the bicoxofemoral axis. SS corresponded to the angle between the sacral plate and horizontal plane, and PT corresponded to the angle between a line connecting the midpoint of the sacral plate to the bicoxofemoral axis and vertical plane[8].

Sagittal Cobb Angles

Cobb angle is defined as the greatest angle at a particular region of the vertebral column when measured from the superior endplate of a superior vertebra to the inferior endplate of an inferior vertebra[40]. And a sagittal Cobb angle is one measured in the sagittal plane such as on lateral radiographs. Sagittal Cobb angles were measured for TK (T_5–L_2), TL (T_{10}–L_2), LL (T_{12}–S_1), and LS (L_4–S_1)[41,42].

PJK

The proximal junctional angle (PJA) was measured from the inferior endplate of the UIV to the superior endplate of two vertebrae above the UIV, and PJK was defined by the following two criteria: (i) proximal junction sagittal Cobb angle greater than or equal to +10°; and (ii) proximal junction sagittal Cobb angle at least 10° greater than the preoperative measurement[43].

Clinical Outcome Assessment

Clinical outcome assessment was done using the Oswestry Disability Index (ODI) and Visual Analog Scale (VAS) for the preoperative, postoperative, and last follow-up periods. Comparisons were done in optimal SVA group vs suboptimal SVA groups and low PI group vs high PI group.

ODI

ODI is the most commonly used indicator of the condition-specific outcome measure[44–46], and it consists of 10 items that assess the level of pain and interference with several physical activities; pain intensity, personal care, lifting, walking, sitting, standing, sleeping, sex life, social life, and traveling. Each item asks how the pain affects the activities of daily living (ADL), and is scored. For each section of six statements the total score is 5. If all 10 sections are completed the score is calculated as follows: total scored out of total possible score × 100. If one section is missed (or not applicable) the score is calculated: (total score / [5 × number of questions answered]) × 100%. The scores are as follows: 0%–20% is considered mild dysfunction, 21%–40% is moderate dysfunction, 41%–60% is severe dysfunction, and 61%–80% is considered as disability. For cases with a score of 81% – 100%, the person is either long-term bedridden or exaggerating the impact of pain on their life. The greater outcome percentage, the more extreme the disability.

Visual Analogue Scale

VAS is a simple and frequently used method of measuring pain intensity[47], and the percentage of the pain relief measured by the VAS score is considered a method of the treatment efficacy[48]. The VAS pain scoring standard (scores from 0 to 10) was as follows: 0 = painless; less than 3 = mild pain that the patient could endure; 4–6 = patient was in pain that could be endured and was able to sleep; and 7–10 = patient had intense pain and was unable to tolerate the pain[49].

TABLE 1 Radiographic and PJK parameters between the optimal and suboptimal SVA groups

Radiographic parameters	Optimal SVA (*n* = 16)	Suboptimal SVA (*n* = 11)	*P*-value
SVA (mm, mean ± SD)			
Preoperative	157.0 ± 61.6	116.7 ± 64.1	0.112
IMPO	−0.4 ± 26.6	18.6 ± 44.5	0.176
Last follow-up	20.9 ± 23.0	88.9 ± 53.0	0.016*
Thoracic kyphosis (°, mean ± SD)			
Preoperative	4.0 ± 16.1	−0.7 ± 12.3	0.505
IMPO	14.9 ± 14.8	9.3 ± 8.0	0.264
Last follow-up	19.5 ± 13.2	5.4 ± 9.4	0.005*
Thoracolumbar junction (°, mean ± SD)			
Preoperative	−9.7 ± 6.7	−9.7 ± 7.4	0.981
IMPO	−3.9 ± 11.8	−0.6 ± 11.6	0.479
Last follow-up	−4.2 ± 9.4	16.0 ± 16.1	0.004*
LL (°)			
Preoperative	4.4 ± 15.1	4.2 ± 23.2	0.639
IMPO	−48.1 ± 4.6	−35.0 ± 12.9	0.007*
Last follow-up	−45.2 ± 4.4	−20.7 ± 14.7	< 0.001*
Estimated - ideal	−49.6 ± 5.0	−56.1 ± 8.0	0.015*
Postoperative - ideal	1.5 ± 5.7	21.1 ± 10.3	< 0.001*
Fused segments angle (°, mean ± SD)			
Preoperative	2.2 ± 7.4	5.2 ± 20.6	0.088
IMPO	−44.4 ± 5.4	−40.3 ± 9.9	0.227
Last follow-up	−42.7 ± 5.3	−38.1 ± 10.4	0.200
Lumbosacral junction (°, mean ± SD)			
Preoperative	2.3 ± 8.8	1.3 ± 21.3	0.901
IMPO	−35.3 ± 11.1	−32.5 ± 12.7	0.556
Last follow-up	−34.3 ± 12.8	−26.7 ± 15.0	0.168
Pelvic incidence (°, mean ± SD)	44.1 ± 6.9	53.8 ± 11.0	0.009*
Pelvic tilt (°, mean ± SD)			
Preoperative	28.4 ± 14.1	42.5 ± 12.6	0.013*
IMPO	15.3 ± 8.1	21.4 ± 11.6	0.079
Last follow-up	17.2 ± 11.5	32.3 ± 11.7	0.001*
PT ratio (PT/PI × 100%, mean ± SD)			
Preoperative	62.5 ± 23.9	83.0 ± 12.6	0.059
IMPO	31.9 ± 14.5	39.0 ± 22.4	0.328
Last follow-up	32.5 ± 18.6	54.8 ± 16.9	0.003*
Sacral slope (°, mean ± SD)			
Preoperative	15.7 ± 10.0	10.8 ± 17.5	0.358
IMPO	32.3 ± 8.0	35.5 ± 15.3	0.534
Last follow-up	32.7 ± 9.5	26.9 ± 11.3	0.159
PJK prevalence			
Patients with PJK (11 cases)	3 (18.8%)	8 (72.7%)	0.008*
Postoperative SVA(cases)			
Optimal (25)	16	9	0.156†
Suboptimal (2)	0	2	
Correction (cases)			
Overcorrection (7)	7	0	0.021*†
Undercorrection (20)	9	11	
PJA (°, mean ± SD)			
Preoperative	−3.2 ± 7.7	−4.1 ± 3.4	0.671
IMPO	−2.7 ± 5.9	4.0 ± 11.1	0.152
Last follow-up	1.5 ± 9.9	17.7 ± 11.6	0.001*

Data represent the mean values for each group; SVA, sagittal vertical axis; IMPO, immediate postoperative; PT, pelvic tilt; PI, pelvic incidence; PJK, proximal junctional kyphosis; PJA, proximal junctional angle; * Statistically significant (*P*-value <0.05); † Fisher's exact test.

Statistical Analysis

For continuous variables, analysis of variance with an unpaired *t*-test was used for variables with normality, and Wilcoxon's rank sum test was used for variables without normality. Categorical variables were assessed using the Fisher's exact test to evaluate every considerable risk factor (SAS 9.3, SAS Institute Inc., Cary, MC, USA). A *P*-value of <0.05 was considered statistically significant. Inter-observer reliability was calculated with Fleiss' kappa statistics or intra-class correlation coefficient (ICC) as appropriate for each radiological measurement. ICC values for all radiographic parameters exceeded 0.90.

Results

Baseline Characteristics of the Patients

At the time of the study, the database included 78 surgical patients and, based on the inclusion criteria, 27 patients were selected for analysis. The average age at the time of surgery was 66.6 years, and the average follow-up period was 109.7 months. In these patients, combined ACR with short PSF were performed, and the mean number of fused segments was 3.7. The UIV was L_2 in 18 patients or L_3 in nine

TABLE 2 Radiographic and PJK parameters between the low PI and high PI groups

Radiographic parameters	Low PI (<50°) (*n* = 17)	High PI (> 50°) (*n* = 10)	*P*-value
SVA (mm, mean ± SD)			
Preoperative	146.1 ± 59.9	131.1 ± 74.4	0.568
IMPO	3.84 ± 27.2	13.5 ± 47.5	0.566
Last follow-up	42.0 ± 53.1	59.9 ± 46.1	0.167
Thoracic kyphosis (°, mean ± SD)			
Preoperative	0.8 ± 12.6	4.2 ± 18.0	0.561
IMPO	12.2 ± 11.2	13.5 ± 15.2	0.796
Last follow-up	16.2 ± 12.1	9.6 ± 15.5	0.166
Thoracolumbar junction (°, mean ± SD)			
Preoperative	−10.6 ± 8.2	−9.7 ± 7.4	0.311
IMPO	−4.2 ± 10.7	−0.6 ± 11.6	0.321
Last follow-up	0.5 ± 15.5	10.0 ± 15.6	0.138
LL (°, mean ± SD)			
Preoperative	4.8 ± 15.1	3.5 ± 24.0	0.633
IMPO	−42.1 ± 11.7	−43.9 ± 10.2	0.979
Last follow-up	−36.4 ± 18.5	−33.1 ± 9.6	0.093
Estimated - ideal	48.0 ± 3.4	59.5 ± 5.4	< 0.001*
Postoperative - ideal	5.9 ± 12.3	15.6 ± 10.8	0.019*
Fused segments angle (°, mean ± SD)			
Preoperative	4.5 ± 9.2	1.6 ± 20.3	0.980
IMPO	−40.6 ± 6.6	−46.4 ± 8.5	0.058
Last follow-up	−38.8 ± 7.7	−44.3 ± 7.6	0.082
Lumbosacral junction (°, mean ± SD)			
Preoperative	5.7 ± 11.6	−4.5 ± 17.9	0.901
IMPO	−32.4 ± 10.5	−37.1 ± 13.4	0.556
Last follow-up	−30.6 ± 12.3	−32.2 ± 17.1	0.168
Pelvic incidence (°, mean ± SD)	41.8 ± 4.7	58.7 ± 6.6	< 0.001*
Pelvic tilt (°, mean ± SD)			
Preoperative	28.4 ± 12.3	43.9 ± 14.7	0.006*
IMPO	16.2 ± 7.8	20.5 ± 12.8	0.288
Last follow-up	18.1 ± 10.1	32.2 ± 14.8	0.007*
PT ratio (PT/PI × 100%, mean ± SD)			
Preoperative	68.0 ± 30.0	75.6 ± 24.8	0.506
IMPO	35.8 ± 17.2	33.1 ± 20.3	0.709
Last follow-up	36.5 ± 20.3	50.3 ± 19.8	0.102
Sacral slope (°, mean ± SD)			
Preoperative	13.5 ± 12.4	14.2 ± 15.9	0.782
IMPO	29.4 ± 9.0	40.8 ± 11.7	0.009*
Last follow-up	30.2 ± 10.4	30.6 ± 11.1	0.926
PJK prevalence (cases)			
Patients with PJK (11)	4 (23.5%)	7 (70%)	0.040*
Postoperative SVA (cases)			
Optimal (25)	17	8	0.128†
Suboptimal (2)	0	2	
Correction (cases)			
Overcorrection (7)	6	1	0.204†
Undercorrection (20)	11	9	
PJA (°, mean ± SD)			
Preoperative	−4.7 ± 6.3	−1.7 ± 6.0	0.231
IMPO	−2.5 ± 7.0	3.6 ± 10.3	0.119
Last follow-up	4.7 ± 14.5	13.9 ± 8.4	0.023*

Data represent the mean values for each group; PI, pelvic incidence; SVA, sagittal vertical axis; IMPO, immediate postoperative; PT, pelvic tilt; PJK, proximal junctional kyphosis; PJA, proximal junctional angle; LL, Lumbar lordosis; * Statistically significant (*P*-value <0.05); † Fisher's exact test.

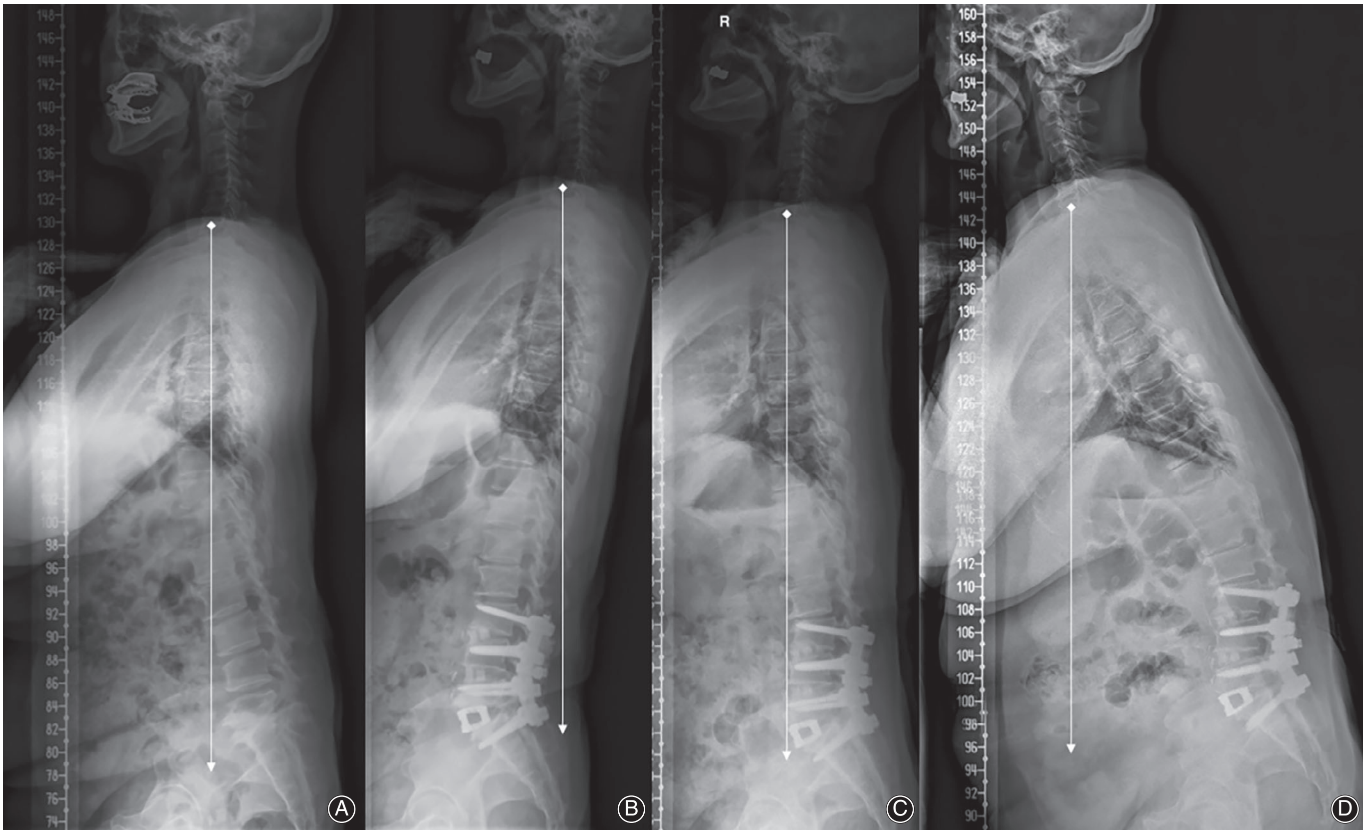

Fig. 1 (A) Preoperative whole spine lateral radiograph of a 60-year-old female with degenerative sagittal malalignment (TK –20°, TL –14°, LL 8°, PI 50°, SVA 55 mm, estimated LL calculated by Korean version of Legaye formula –54°). (B) Postoperative whole spine lateral radiograph taken after ACR with posterior instrumentation and fusion at L_2-S_1 leading to a correction of lumbar lordosis (LL) of –44° (10° undercorrection compared to the estimated ideal LL) and a decrease in SVA (–51 mm). The preoperative PJA increased to –6° postoperatively (TK –3°, TL –14°). (C) Postoperative 5-year radiograph showing a hypokyphotic thoracic curve (TK –1°) and an increase in SVA (2 mm) with decrease in TL (–1°) and LL (–23°). (D) Postoperative 6-year radiograph showing a hypokyphotic thoracic curve (TK 2°) and an increase in SVA (172 mm) with decrease in TL (10°) and LL (–7°).

patients. For the lowest instrumented vertebra (LIV), fusion was performed to the sacrum by using pedicle screws in all patients and sacropelvic fixation was performed by using iliac screws in three patients. Surgical correction included anterior lumbar interbody fusion (ALIF, $n = 27$, 99 segments) and PCO.

Radiographic Parameters: Optimal SVA Group vs Suboptimal SVA Group

There was no significant difference in the angle of fused segments between the two groups postoperatively ($P = 0.227$) and at the last follow-up ($P = 0.200$). The corrected LL was 1.5° less than the ideal LL in the optimal SVA group and was 21.1° less than the ideal LL in the suboptimal SVA group ($P < 0.05$). LL was significantly different between the two groups postoperatively ($P = 0.007$) and at the last follow-up ($P < 0.05$) (Table 1).

There were no significant differences in TK and TL between the two groups preoperatively, postoperatively; however, at the last follow-up there was a significant difference between the two groups (TK: $P = 0.005$; TL: $P = 0.004$). TK and TL of the optimal SVA group improved at final follow-up, but TK and TL of the suboptimal SVA group decreased from 9.3° to 5.4° and from –0.6° to +16.0°, respectively.

Regarding pelvic parameters, there was significant difference in the preoperative PI and PT between the two groups (PI: $P = 0.009$; PT: $P = 0.013$). There was no significant difference in PT postoperatively ($P = 0.079$), however there was a significant difference at the last follow-up ($P = 0.001$) showing that suboptimal SVA group was significantly greater PT by a greater postoperative increase compared to that of the optimal SVA group.

PJK Parameters: Optimal SVA vs Suboptimal SVA Groups

The overall prevalence of PJK was 41% (11/27 patients), and the prevalence was 19% (3/16) in the optimal SVA group

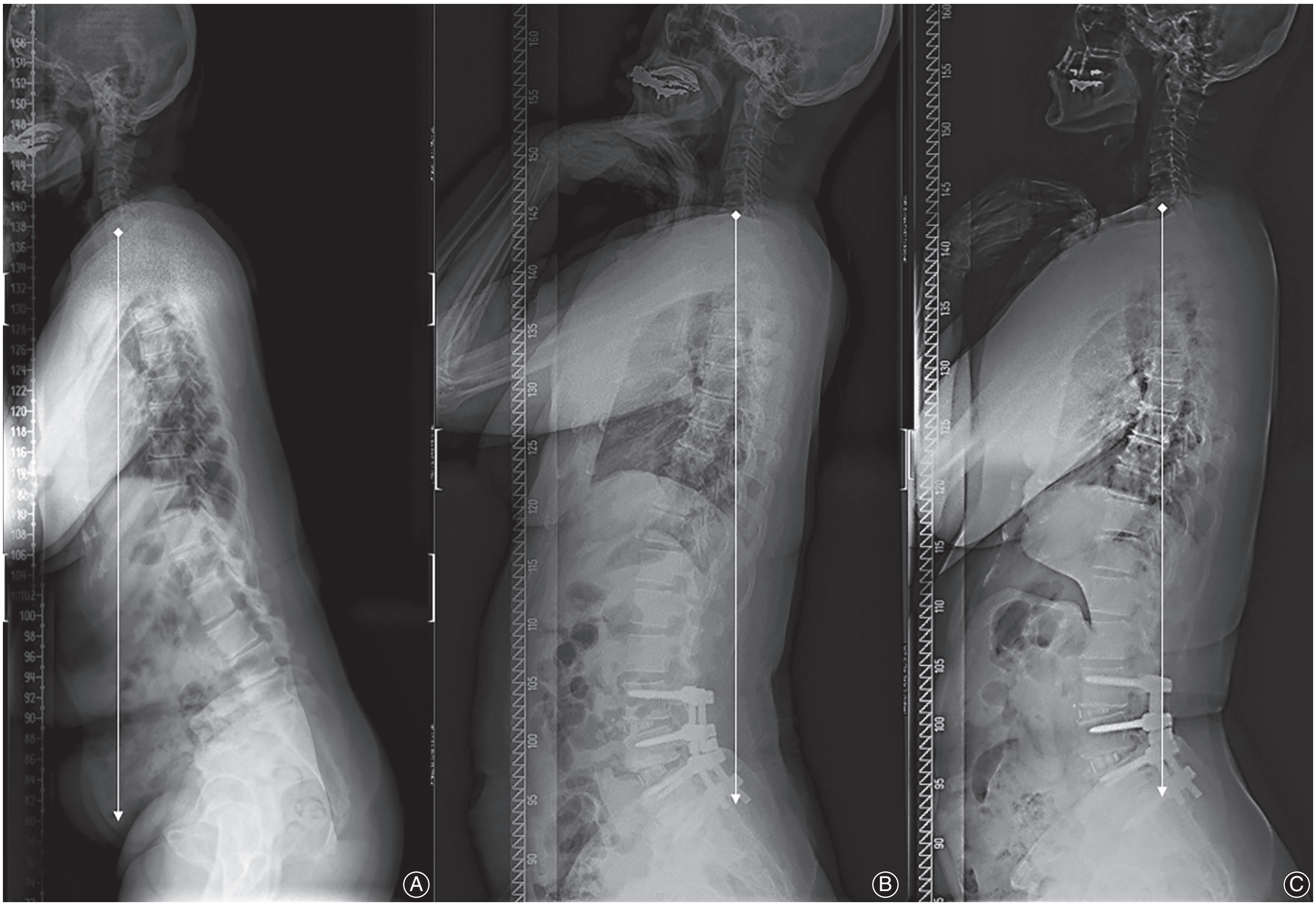

Fig. 2 (A) Preoperative whole spine lateral radiograph of a 54-year-old female with degenerative sagittal malalignment (TK −7°, TL −27°, LL 10°, PI 48°, SVA 169 mm, estimated LL calculated by Korean version of Legaye formula −52°). (B) Postoperative whole spine lateral radiograph taken ACR with posterior instrumentation and fusion at L_3-S_1 leading to a correction of LL of −56° (4° overcorrection compared to the estimated ideal LL) and a decrease in SVA (−30 mm) (TK −2°, TL −20°). (C) Whole spine lateral radiograph taken 5 years postoperatively. LL was −52° with a normal sagittal balance (SVA −10 mm) without progression of PJA (−5°) (TK 10°, TL −17°).

and 73% (8/11) in the suboptimal SVA group, which was significantly different ($P = 0.008$). There was no significant difference in PJA between the two groups preoperatively ($P = 0.671$), postoperatively ($P = 0.152$), however, there was a significant difference at the last follow-up ($P = 0.001$) with significant prevalence of PJK (Figure 1 and Table 1).

Overcorrection was seen in seven patients in the optimal SVA group (Figure 2), whereas all of the patients of the suboptimal SVA group were in the category of undercorrection with significant difference ($P = 0.021$).

Spinopelvic Parameters: Low PI Group vs High PI Group

As shown in Table 2, further evaluation was divided into the following two groups based on the preoperative PI: low PI group (PI <50°) and high PI group (PI >50°). There was no significant difference in fused segment angle between the two groups preoperatively ($P = 0.980$), postoperatively ($P = 0.058$), and at the last follow-up ($P = 0.082$).

The mean LL values in the low PI and high PI groups were 4.8° and 3.5° preoperatively, −42.1° and − 43.9° postoperatively, and − 36.4° and − 33.1° at the last follow-up, respectively. The corrected LL was 5.9° less than the ideal LL in the low PI group and was 15.6° less than the ideal LL in the high PI group ($P = 0.019$). LL was not significantly different between the two groups preoperatively ($P = 0.633$), postoperatively ($P = 0.979$), and at the last follow-up ($P = 0.093$).

There was no significant difference in TK, TL, and LS between the two groups preoperatively (TK: $P = 0.561$; TL: $P = 0.311$; LS: $P = 0.901$), postoperatively (TK: $P = 0.796$; TL: $P = 0.321$; LS: $P = 0.556$), and at the last follow-up (TK: $P = 0.166$; TL: $P = 0.138$; LS: $P = 0.168$).

TABLE 3 Clinical outcomes (mean ± SD)

Clinical Parameters	Optimal SVA (*n* = 16)	Suboptimal SVA (*n* = 11)	*P*-value
VAS			
Preoperative back pain	7.8 ± 1.0	7.8 ± 1.5	1.000
Postoperative 3 months back pain	4.2 ± 1.5	4.8 ± 0.9	0.295
Last follow-up back pain	1.7 ± 1.0	4.3 ± 1.3	< 0.001*
Preoperative leg pain	8.0 ± 1.0	7.7 ± 1.2	0.319
Postoperative 3 months leg pain	2.0 ± 1.0	2.3 ± 1.4	0.388
Last follow-up leg pain	1.2 ± 1.4	1.6 ± 1.4	0.425
ODI			
Preoperative	37.4 ± 2.0	37.3 ± 1.9	0.789
Postoperative 3 months	17.8 ± 7.8	25.8 ± 2.6	0.002*
Last follow-up	8.0 ± 5.7	17.9 ± 4.2	< 0.000*
Clinical parameters	**Low PI (< 50°) (*n* = 17)**	**High PI (> 50°) (*n* = 10)**	***P*-value**
VAS			
Preoperative back pain	7.7 ± 1.2	8.1 ± 1.2	0.342
Postoperative 3 months back pain	4.1 ± 1.4	4.9 ± 1.0	0.077
Last follow-up back pain	2.5 ± 1.8	3.0 ± 1.5	0.457
Preoperative leg pain	7.9 ± 0.9	7.9 ± 1.2	0.807
Postoperative 3 months leg pain	1.8 ± 0.9	2.5 ± 1.4	0.076
Last follow-up leg pain	1.3 ± 1.4	1.4 ± 1.3	0.862
ODI (%)			
Preoperative	37.6 ± 2.1	37.1 ± 1.6	0.475
Postoperative 3 months	17.7 ± 7.4	25.3 ± 4.6	0.003*
Last follow-up	9.6 ± 7.0	15.0 ± 6.2	0.036*

Data represent the mean values for each group; SVA, sagittal vertical axis; VAS, Visual Analog Scale; ODI, Oswestry Disability Index; Mo, month; PI, pelvic incidence; * Statistically significant (*P*-value <0.05).

Regarding pelvic parameters, there was significant difference in PT between the two groups preoperatively ($P = 0.006$), and at the last follow-up ($P = 0.007$); however, there was no significant difference postoperatively ($P = 0.288$). There was significant difference in SS between the two groups postoperatively ($P = 0.009$); however, there was no significant difference at the last follow-up ($P = 0.926$).

PJK Parameters: Low PI Group vs High PI Group

The prevalence of PJK was 23.5% (4/17) in the low PI group and 70% (7/10) in the high PI group, which was significantly different ($P = 0.040$). There was no significant difference in PJA between the two groups preoperatively ($P = 0.231$), postoperatively ($P = 0.119$); however, there was a significant difference at the last follow-up ($P = 0.023$) with significant prevalence of PJK (Table 2).

Overcorrection was seen in six patients in the low PI group, whereas only one patient in the high PI group was in the category of overcorrection with no significant difference ($P = 0.204$).

Comparison of Clinical Outcome Assessment

The preoperative ODI and VAS scores (back pain and leg pain) did not show differences between the optimal SVA group and suboptimal SVA group. And postoperative and last follow-up VAS for leg pain did not show differences between the two groups. But last follow-up VAS for back pain and postoperative and last follow-up ODI were statistically larger for the suboptimal group than the optimal group ($P<0.05$) (Table 3).

The VAS scores (back pain and leg pain) did not show differences between the low PI group and the high PI group preoperatively, postoperatively, and at the last follow-up. The preoperative ODI did not show differences between the two groups, but postoperative and last follow-up ODI ($P = 0.003$ and $P = 0.036$) were statistically larger for the high PI group than the low PI group.

Complications

There were no permanent neurological, vascular, or visceral injuries including cerebrospinal fluid leakage, abdominal hernia, wound infection, or pseudarthrosis. However, there were transient complications including lower extremity symptoms related to sympathetic chain injury (one case), postoperative ileus (two cases), and ipsilateral psoas paresis (one case). After the conservative treatment, these transient complications have returned to normal over time (sympathetic chain injury 4 months, postoperative ileus 2 weeks, and ipsilateral psoas paresis 3 months).

Discussion

ASD with degenerative causes (DLK) has not been reported in Western countries, but is one of the most common in Asian countries because of different lifestyles and working posture. DLK is a pure positive sagittal malalignment causing serious disability in daily life. Most patients revealed marked atrophy of the back musculature on magnetic resonance imaging and characteristic clinical features: stooping with walking difficulty; inability to lift heavy objects in front; difficulty in climbing slopes; and the need to support oneself with the elbow when working in the kitchen, resulting in the formation of a hard corn on the extensor surface of the elbow[24,50].

Appropriate surgical correction of ASD with sagittal imbalance may affect arthrodesis of fused segments and contribute to adjacent segment degeneration of unfused mobile vertebrae, and proper correction of optimal LL is essential to prevent sagittal decompensation. A variety of reconstructive surgeries can be performed to restore normal sagittal balance in ASD patients, and some of these surgeries, such as three column osteotomies, are highly specialized and complex, with a high risk of complications[2,51,52].

It is important to find an optimal indication for a shorter fusion level for achieving optimal correction with lesser complications; this is because every patient with lower lumbar kyphosis and compensatory TL lordosis does not need to undergo long fusion from the sacrum to the thoracic spine and does not require a UIV up to the thoracic spine or corrective osteotomies, such as PSO, for obtaining sagittal balance from correction of lower LL[23,36].

Although surgeons can predict the postoperative sagittal balance based on the correlation between the PI and LL, which plays key roles in both achieving neutral or negative sagittal balance and preventing sagittal decompensation[2,3,5], there are controversies in determining the amount of lordosis correction due to an increased risk of PJK[21,22,43]. Thus, the LL obtained after a short PSF and PCO following ACR may be less or optimal considering the patient's PI. In our study, considering the amount of LL correction from the ideal LL, overcorrection was seen in only seven patients in all patients that showed less deformity correction compared with three column osteotomies. However, ratio of over correction to under correction was significantly greater in the optimal SVA group than in the suboptimal group. Additionally, the optimal SVA group showed significantly lower prevalence of PJK and lesser PJA with greater postoperative LL, which correlates to previous studies with regard to the importance of postoperative LL in restoring normal sagittal balance and preventing sagittal decompensation[52,53].

According to previous reports regarding ACR, the amount of LL correction ranges from 5° to 29°[54–56], which seems to be a limitation in surgically treating ASD with degenerative sagittal malalignment.[56] In our study, however, a short PSF with PCO and ACR including anterior release allowed to achieve more LL correction (47.1°) than previous reports 59 with 46.1° of fused segment angle.

Optimal SVA Group vs *Suboptimal SVA Group*

Regarding the sagittal balance, postoperative sagittal balance showed no statistical difference in both groups; however, the suboptimal SVA group showed a significant increase in the ratio of PT to PI at the last follow-up, which demonstrated the insufficiency of LL correction resulting in delayed sagittal decompensation and compensatory pelvic retroversion at the last follow-up. Also, the hypokyphotic thoracic curve at the last follow-up of the suboptimal SVA group seems to be compensatory following delayed sagittal decompensation. Additionally, the optimal SVA group showed significantly greater TL lordosis and TK at the last follow-up, which seems to be a restoration of a natural thoracic kyphosis following an increase in LL as seen in the results of previous studies[36].

Low PI Group vs *High PI Group*

In our study, the average postoperative lordosis angle of fused segments of the optimal SVA group was −44.4° and the preoperative TL lordosis was −9.7°, meaning that the maximal theoretical average LL that could be obtained would be 54.1°. The PI for an ideal LL of 54.1° was calculated to be approximately 50° by the Korean version of the Legaye formula ($SS = 0.80 + 0.74 \times PI$, and ideal [maximal] $LL = 17.42 + 0.96 \times SS$)[3,37]. Therefore, further evaluation was done by dividing the group into the low PI group (PI <50°) and high PI group (PI >50°). The high PI group showed significantly higher prevalence of PJK with greater PJA and a higher ratio of suboptimal balance compared to the low PI group, with no significant differences in postoperative and last follow-up for LL, TL junction, and TK. The results may be due to lesser correction of postoperative LL in the high PI group, which was insufficient to fulfill the required amount of LL considering higher PI.

Although the postoperative and last follow up PT ratio (PT/PI) showed no statistical difference between the low PI and high PI groups, there was a significant increase in the ratio of PT to PI in the high PI group in contrast to the low PI group, which may demonstrate insufficient LL correction in the high PI group compared to the low PI group. The insignificant results of comparing the ratio of PT to PI in both groups seems to originate from the relatively smaller proportion of overcorrection as a whole (7/27, 26%), and a lesser amount of postoperative LL compared to the estimated ideal LL.

Limitations

This study has some limitations. Previous studies revealed the possibility of short PSF combined with ACR as a treatment option in degenerative sagittal imbalance with compensated thoracic curve. However, the indication for this surgical correction should also include a PI less than 50°, and there is the limitation of obtaining sufficient LL after short level fusions, even with the addition of PCO other limitations of our study include the relatively small number of patients in both groups, which is expected that further future studies will remedy.

Conclusion

In conclusion, combined ACR with short PSF and PCO could effectively prevent sagittal decompensation of PJK and help achieve sagittal balance in the treatment of ASD patients with lower lumbar kyphosis, TL compensation, and especially low PI (less than 50°).

Acknowledgments

There is no additional person who has contributed to this study except the authors. We certify that no portion of this manuscript has been previously presented. The current study was approved by the Institutional Review Board (IRB) of our medical institution (KMC IRB 2014-6-10) before data collection and analysis.

References

1. Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity—postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine (Phila Pa 1976), 2010, 35: 2224–2231.
2. Lee JH, Kim KT, Lee SH, *et al*. Overcorrection of lumbar lordosis for adult spinal deformity with sagittal imbalance: comparison of radiographic outcomes between overcorrection and undercorrection. Eur Spine J, 2016, 25: 2668–2675.
3. Legaye J, Duval-Beaupere G. Sagittal plane alignment of the spine and gravity: a radiological and clinical evaluation. Acta Orthop Belg, 2005, 71: 213–220.
4. Vialle R, Levassor N, Rillardon L, Templier A, Skalli W, Guigui P. Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. J Bone Joint Surg Am, 2005, 87: 260–267.
5. Schwab F, Lafage V, Patel A, Farcy JP. Sagittal plane considerations and the pelvis in the adult patient. Spine (Phila Pa 1976), 2009, 34: 1828–1833.
6. Rose PS, Bridwell KH, Lenke LG, *et al*. Role of pelvic incidence, thoracic kyphosis, and patient factors on sagittal plane correction following pedicle subtraction osteotomy. Spine (Phila Pa 1976), 2009, 34: 785–791.
7. Kim YJ, Bridwell KH, Lenke LG, Rhim S, Cheh G. An analysis of sagittal spinal alignment following long adult lumbar instrumentation and fusion to L5 or S1: can we predict ideal lumbar lordosis?. Spine (Phila Pa 1976), 2006, 31: 2343–2352.
8. Legaye J, Duval-Beaupere G, Hecquet J, Marty C. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. Eur Spine J, 1998, 7: 99–103.
9. Farcy JP, Schwab FJ. Management of flatback and related kyphotic decompensation syndromes. Spine (Phila Pa 1976), 1997, 22: 2452–2457.
10. Booth KC, Bridwell KH, Lenke LG, Baldus CR, Blanke KM. Complications and predictive factors for the successful treatment of flatback deformity (fixed sagittal imbalance). Spine (Phila Pa 1976), 1999, 24: 1712–1720.
11. Glassman SD, Berven S, Bridwell K, Horton W, Dimar JR. Correlation of radiographic parameters and clinical symptoms in adult scoliosis. Spine (Phila Pa 1976), 2005, 30: 682–688.
12. Smith MW, Annis P, Lawrence BD, Daubs MD, Brodke DS. Acute proximal junctional failure in patients with preoperative sagittal imbalance. Spine J, 2015, 15: 2142–2148.
13. Bridwell KH, Lewis SJ, Rinella A, Lenke LG, Baldus C, Blanke K. Pedicle subtraction osteotomy for the treatment of fixed sagittal imbalance. Surgical Technique. J Bone Joint Surg Am, 2004, 86: 44–50.
14. Berjano P, Aebi M. Pedicle subtraction osteotomies (PSO) in the lumbar spine for sagittal deformities. Eur Spine J, 2015, 24: S49–S57.
15. Bridwell KH. Decision making regarding Smith-Petersen vs. pedicle subtraction osteotomy vs. vertebral column resection for spinal deformity. Spine (Phila Pa 1976), 2006, 31: S171–S178.
16. Bridwell KH, Lewis SJ, Edwards C, *et al*. Complications and outcomes of pedicle subtraction osteotomies for fixed sagittal imbalance. Spine (Phila Pa 1976), 2003, 28: 2093–2101.
17. Hyun SJ, Rhim SC. Clinical outcomes and complications after pedicle subtraction osteotomy for fixed sagittal imbalance patients: a long-term follow-up data. J Korean Neurosurg Soc, 2010, 47: 95–101.
18. Lee JH, Kim JU, Jang JS, Lee SH. Analysis of the incidence and risk factors for the progression of proximal junctional kyphosis following surgical treatment for lumbar degenerative kyphosis: minimum 2-year follow-up. Br J Neurosurg, 2014, 28: 252–258.
19. Kim YJ, Bridwell KH, Lenke LG, Rhim S, Kim YW. Is the T9, T11, or L1 the more reliable proximal level after adult lumbar or lumbosacral instrumented fusion to L5 or S1?. Spine (Phila Pa 1976), 2007, 32: 2653–2661.
20. Glattes RC, Bridwell KH, Lenke LG, Kim YJ, Rinella A, Edwards C 2nd. Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: incidence, outcomes, and risk factor analysis. Spine (Phila Pa 1976), 2005, 30: 1643–1649.
21. Maruo K, Ha Y, Inoue S, *et al*. Predictive factors for proximal junctional kyphosis in long fusions to the sacrum in adult spinal deformity. Spine (Phila Pa 1976), 2013, 38: E1469–E1476.
22. Kim HJ, Bridwell KH, Lenke LG, *et al*. Patients with proximal junctional kyphosis requiring revision surgery have higher postoperative lumbar lordosis and larger sagittal balance corrections. Spine (Phila Pa 1976), 2014, 39: E576–E580.
23. Jang JS, Lee SH, Min JH, Han KM. Lumbar degenerative kyphosis: radiologic analysis and classifications. Spine (Phila Pa 1976), 2007, 32: 2694–2699.
24. Takemitsu Y, Harada Y, Iwahara T, Miyamoto M, Miyatake Y. Lumbar degenerative kyphosis. Clinical, radiological and epidemiological studies. Spine (Phila Pa 1976), 1988, 13: 1317–1326.
25. Lee JH, Kim KT, Suk KS, *et al*. Analysis of spinopelvic parameters in lumbar degenerative kyphosis: correlation with spinal stenosis and spondylolisthesis. Spine (Phila Pa 1976), 2010, 35: E1386–E1391.
26. Phan K, Xu J, Maharaj MM, *et al*. Outcomes of short fusion versus long fusion for adult degenerative scoliosis: a systematic review and meta-analysis. Orthop Surg, 2017, 9: 342–349.
27. Jang JS, Lee SH, Min JH, Maeng DH. Changes in sagittal alignment after restoration of lower lumbar lordosis in patients with degenerative flat back syndrome. J Neurosurg Spine, 2007, 7: 387–392.
28. Alimi M, Hofstetter CP, Cong GT, *et al*. Radiological and clinical outcomes following extreme lateral interbody fusion. J Neurosurg Spine, 2014, 20: 623–635.
29. Akbarnia BA, Mundis GM Jr, Moazzaz P, *et al*. Anterior column realignment (ACR) for focal kyphotic spinal deformity using a lateral transpsoas approach and ALL release. J Spinal Disord Tech, 2014, 27: 29–39.
30. Anand N, Rosemann R, Khalsa B, Baron EM. Mid-term to long-term clinical and functional outcomes of minimally invasive correction and fusion for adults with scoliosis. Neurosurg Focus, 2010, 28: E6.
31. Dakwar E, Cardona RF, Smith DA, Uribe JS. Early outcomes and safety of the minimally invasive, lateral retroperitoneal transpsoas approach for adult degenerative scoliosis. Neurosurg Focus, 2010, 28: E8.
32. Wang MY, Mummaneni PV. Minimally invasive surgery for thoracolumbar spinal deformity: initial clinical experience with clinical and radiographic outcomes. Neurosurg Focus, 2010, 28: E9.
33. Beckman JM, Marengo N, Murray G, Bach K, Uribe JS. Anterior longitudinal ligament release from the minimally invasive lateral retroperitoneal transpsoas approach: technical note. Oper Neurosurg (Hagerstown), 2016, 12: 214–221.
34. Berjano P, Cecchinato R, Sinigaglia A, *et al*. Anterior column realignment from a lateral approach for the treatment of severe sagittal imbalance: a retrospective radiographic study. Eur Spine J, 2015, 24: 433–438.
35. Manwaring JC, Bach K, Ahmadian AA, Deukmedjian AR, Smith DA, Uribe JS. Management of sagittal balance in adult spinal deformity with minimally invasive anterolateral lumbar interbody fusion: a preliminary radiographic study. J Neurosurg Spine, 2014, 20: 515–522.
36. Jang JS, Lee SH, Min JH, Maeng DH. Influence of lumbar lordosis restoration on thoracic curve and sagittal position in lumbar degenerative kyphosis patients. Spine (Phila Pa 1976), 2009, 34: 280–284.
37. Lee CS, Chung SS, Park SJ, Kim DM, Shin SK. Simple prediction method of lumbar lordosis for planning of lumbar corrective surgery: radiological analysis in a Korean population. Eur Spine J, 2014, 23: 192–197.
38. Horton WC, Brown CW, Bridwell KH, Glassman SD, Suk S-I, Cha CW. Is there an optimal patient stance for obtaining a lateral 36″ radiograph?: a critical comparison of three techniques. Spine (Phila Pa 1976), 2005, 30: 427–433.
39. Smith JS, Bess S, Shaffrey CI, *et al*. Dynamic changes of the pelvis and spine are key to predicting postoperative sagittal alignment after pedicle subtraction osteotomy: a critical analysis of preoperative planning techniques. Spine (Phila Pa 1976), 2012, 37: 845–853.
40. Cobb J. Outline for the study of scoliosis. Instr Course Lect AAOS, 1948, 5: 261–275.
41. Roussouly P, Pinheiro-Franco JL. Sagittal parameters of the spine: biomechanical approach. Eur Spine J, 2011, 20: 578–585.
42. Lowe T, Berven SH, Schwab FJ, Bridwell KH. The SRS classification for adult spinal deformity: building on the King/Moe and Lenke classification systems. Spine (Phila Pa 1976), 2006, 31: S119–S125.
43. Yagi M, Akilah KB, Boachie-Adjei O. Incidence, risk factors and classification of proximal junctional kyphosis: surgical outcomes review of adult idiopathic scoliosis. Spine (Phila Pa 1976), 2011, 36: E60–E68.
44. Deyo RA, Battie M, Beurskens AJ, *et al*. Outcome measures for low back pain research. A proposal for standardized use. Spine (Phila Pa 1976), 1998, 23: 2003–2013.
45. Fairbank JC, Couper J, Davies JB, O'Brien JP. The Oswestry low back pain disability questionnaire. Physiotherapy, 1980, 66: 271–273.
46. Roland M, Fairbank J. The Roland-Morris disability questionnaire and the Oswestry disability questionnaire. Spine (Phila Pa 1976), 2000, 25: 3115–3124.

47. Scott J, Huskisson EC. Graphic representation of pain. Pain, 1976, 2: 175–184.
48. Carlsson AM. Assessment of chronic pain. I. Aspects of the reliability and validity of the visual analogue scale. Pain, 1983, 16: 87–101.
49. Dong Q, Han Z, Zhang YG, Sun X, Ma XL. Comparison of transverse cancellous lag screw and ordinary cannulated screw fixations in treatment of vertical femoral neck fractures. Orthop Surg, 2019, 11: 595–603.
50. Lee CS, Lee CK, Kim YT, Hong YM, Yoo JH. Dynamic sagittal imbalance of the spine in degenerative flat back: significance of pelvic tilt in surgical treatment. Spine (Phila Pa 1976), 2001, 26: 2029–2035.
51. Cho KJ, Bridwell KH, Lenke LG, Berra A, Baldus C. Comparison of Smith-Petersen versus pedicle subtraction osteotomy for the correction of fixed sagittal imbalance. Spine (Phila Pa 1976), 2005, 30: 2030–2037 discussion 2038.
52. Kim YJ, Bridwell KH, Lenke LG, Rhim S, Cheh G. Sagittal thoracic decompensation following long adult lumbar spinal instrumentation and fusion to L5 or S1: causes, prevalence, and risk factor analysis. Spine (Phila Pa 1976), 2006, 31: 2359–2366.
53. Cho KJ, Suk SI, Park SR, *et al*. Risk factors of sagittal decompensation after long posterior instrumentation and fusion for degenerative lumbar scoliosis. Spine (Phila Pa 1976), 2010, 35: 1595–1601.
54. Caputo AM, Michael KW, Chapman TM, *et al*. Extreme lateral interbody fusion for the treatment of adult degenerative scoliosis. J Clin Neurosci, 2013, 20: 1558–1563.
55. Molloy S, Butler JS, Benton A, Malhotra K, Selvadurai S, Agu O. A new extensile anterolateral retroperitoneal approach for lumbar interbody fusion from L1 to S1: a prospective series with clinical outcomes. Spine J, 2016, 16: 786–791.
56. Strom RG, Bae J, Mizutani J, Valone F 3rd, Ames CP, Deviren V. Lateral interbody fusion combined with open posterior surgery for adult spinal deformity. J Neurosurg Spine, 2016, 25: 697–705.