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CASE SERIES

Contemporary utilization of three-column osteotomy techniques in a prospective complex spinal deformity multicenter database: implications on full-body alignment and perioperative course

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Abstract

Background Research has focused on the increased correction from a three-column osteotomy (3CO) during adult spinal deformity (ASD) surgery. However, an in-depth analysis on the performance of a 3CO in a cohort of complex spinal deformity cases has not been described.

Study design/setting This is a retrospective study on a prospectively enrolled, complex ASD database.

Purpose This study aimed to determine if three-column osteotomies demonstrate superior benefit in correction of complex sagittal deformity at the cost of increased perioperative complications.

Methods Surgical complex adult spinal deformity patients were included and grouped into thoracolumbar 3COs compared to those who did not have a 3CO (No 3CO) (remaining cohort). Rigid deformity was defined as ΔLL less than 33% from standing to supine. Severe deformity was defined as global (SVA > 70 mm) or C7-PL > 70 mm, or lumbopelvic (PI-LL > 30°). Means comparison tests assessed correction by 3CO grade/location. Multivariate analysis controlling for baseline deformity evaluated outcomes up to six weeks compared to No 3CO.

Results 648 patients were included (Mean age 61 ± 14.6 years, BMI 27.55 ± 5.8 kg/m^2, levels fused: 12.6 ± 3.8). 126 underwent 3CO, a 20% higher usage than historical cohorts. 3COs were older, frail, and more likely to undergo revision (OR 5.2, 95% CI [2.6–10.6]; p < .001). 3COs were more likely to present with both severe global/lumbopelvic deformity (OR 4), 62.4% being rigid. 3COs had greater use of secondary rods (OR 4st) and incurred 4 times greater risk for: massive blood loss (> 3500 mL), longer LOS, SICU admission, perioperative wound and spine-related complications, and neurologic complications when performed below L3. 3COs had similar HRQL benefit, but higher perioperative opioid use. Mean segmental correction increased by grade (G3–21; G4–24; G5–27) and was 4 × greater than low-grade osteotomies, especially below L3 (OR 12). 3COs achieved 2 × greater spinopelvic correction. Higher grades properly distributed lordosis 50% of the time except L5. Pelvic compensation and non-response were relieved more often with increasing grade, with greater correction in all lower extremity parameters (p < .01). Due to the increased rate of complications, 3COs trended toward higher perioperative cost ($42,806 vs. $40,046, p = .086).

Conclusion Three-column osteotomy usage in contemporary complex spinal deformities is generally limited to more disabled individuals undergoing the most severe sagittal and coronal realignment procedures. While there is an increased perioperative cost and prolongation of length of stay with usage, these techniques represent the most powerful realignment techniques available with a dramatic impact on normalization at operative levels and reciprocal changes.

Keywords Adult spine deformity · Sagittal alignment · Osteotomy · Three-column osteotomy

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Introduction

Spine surgery has seen a wave of influential surgical strategies, minimally invasive techniques, and comprehensive, individualized preoperative and postoperative care, thus expanding the population eligible for surgical intervention [1–6]. As management is optimized for patients with higher comorbidities and frailty, so too is the correction for even more complex deformities [7–11]. Multi-dimensional and severe deformity has seen dramatic improvements in corrective strategies, along with tailored goals to fit a patient's realignment needs to be based both on fixed, individualized parameters and relative to their age [12–15]. Historically, patients presenting with complex adult spinal deformities are inherently at greater risk for postoperative complications, diminished improvement, and future reoperations due to mechanical or radiographic complications. Therefore, it is important to assess the current techniques employed within this cohort to improve the outcomes for such invasive and taxing procedures.

Numerous prior studies have established the correlation between reaching alignment goals and patient outcomes [7]. Additionally, failure to meet alignment goals has been shown to potentially correlate with complications such as rod fracture and PJK [14, 15]. Complex ASD patients present an additional challenge in that they require significant correction relative to standard ASD patients; therefore, the use of posterior column osteotomies, multilevel interbody fusions, or contoured rods are not sufficient for 30 + degree corrections.

Three-column osteotomies (3COs), consisting of pedicle subtraction osteotomies (PSOs) or vertebral column resections (VCRs), allow for a greater degree of correction than other less invasive techniques and may be necessary in the case of severe, rigid deformity and flat-back syndrome. However, complication rates for 3COs were previously found to be as high as 60% with increasing rates seen in older patients (> 60 years old), those with > 1 3CO, a thoracic 3CO (vs. lumbar or sacral), or massive blood loss (> 4 L) (3–6).

Although the rates of 3CO usage are declining overall, this technique is still a necessary option for patients with severe, rigid deformities [16]. Previous literature has described the greater correction seen with 3CO in typical adult spinal deformity populations [17]. We sought to analyze the perioperative outcomes of 3COs particularly in patients with highly complex deformities. We hypothesized that these patients would experience more perioperative complications but greater correction of alignment and reciprocal changes.

Materials and methods

Study design and inclusion criteria

This study was a retrospective review of the prospectively enrolled, multicenter complex adult spinal deformity database from 2018 to 2022. This dataset collects clinical, surgical, and outcome data from 18 participating centers across the United States and Canada. Patients aged 18 or older included for retrospective review enrolled in the registry from 2020 to present with either radiographic evidence, procedural or geriatric criteria characteristic of complex adult spinal deformity (ASD). Radiographic evidence for complex ASD is defined as follows: PI-LL ≥ 25°, T1PA ≥ 30°, SVA > 15 cm, thoracic scoliosis ≥ 70°, thoracolumbar/lumbar scoliosis ≥ 50°, or global coronal malalignment > 7 cm. Procedural details characteristic of complex ASD include 3-column osteotomies (3COs) and/or anterior column reconstruction (ACR) of the spine or posterior spinal fusion > 12 levels. Geriatric complex ASD criteria are defined as age > 65 years and a minimum of seven levels of spinal instrumentation during surgery with an intention to treat deformity. We included operative complex adult spinal deformity patients who had complete radiographic and health-related quality of life (HRQL) data at baseline and perioperative (up to six weeks) follow-up in the current maturity of this dataset.

Data collection

Demographic data that were abstracted for eligible individuals consisted of age, biological sex, body mass index (BMI), history of prior fusion, *Passias* et al. modified adult spinal deformity frailty index (modified ASD-FI), and baseline comorbidities categorized using the Charlson Comorbidity Index (CCI) [4, 5]. Surgical parameters consisted of levels fused, operative time, length of stay, surgical approach, use of decompressions, and osteotomies. A standardized complications reporting form was completed for the perioperative time interval for each clinical follow-up and at any point the site became aware of a new complication or adverse event. The de-identified data from each center were sent to a central site where the collective datasets were summarized and analyzed and the complications were reviewed. Patient-reported outcome measures, prospectively collected at baseline and follow-up intervals, included modified Oswestry Disability Index for low back pain (ODI), Scoliosis Research Society Questionnaire 22r (SRS-22r), Veterans RAND-12 (VR-12), numeric pain rating scale (NRS), and the Patient-Reported Outcomes Measurement Information System (PROMIS)

Domains—PROMIS anxiety, depression, pain interference, physical function, and social satisfaction. Outcome assessments were completed via patient surveys at baseline and during subsequent follow-up encounters up to six weeks following surgery. Abbreviations for each variable are displayed in Table 1.

Radiographic data collection

Full-length free-standing lateral spine radiographs (36-inch cassette) were collected and assessed at baseline and follow-up. Radiographs will be reviewed for postoperative correction and revision surgery. All radiographic analyses of the spinal axis will be performed using full spine EOS imaging that includes sagittal and coronal visualization of the top of the skull to the bottom of the foot. Sagittal and coronal radiographic parameters will obtained from the EOS radiographs using appropriate radiographic imaging and measurement software including Spineview®, (Laboratory of Biomechanics, Paris, France), and Surgimap® as previously published. [1–3]. Spinopelvic radiographic parameters measured were pelvic tilt (PT), pelvic incidence (PI), sagittal vertical axis (SVA), thoracic kyphosis (TK, T4-12), T1 pelvic angle (T1PA), lumbar lordosis (LL, T12-S1), and mismatch between pelvic incidence and lumbar lordosis (PI-LL). Lumbar flexibility was assessed by supine radiographs. Lower extremity parameters measured were sacrofemoral angle (SFA), knee angle, ankle angle (AA), pelvic shift (PS), and Global Spinal Angle (GSA).

Table 1 Table of abbreviations

Abbreviation	Definition
3CO	Three-column osteotomy
ACR	Anterior column reconstruction
AA	Ankle angle
ASD	Adult spinal deformity
ASD-FI	Adult spinal deformity frailty index
BMI	Body mass index
CCI	Charlson comorbidity index
EBL	Estimated blood loss
%EBV	Percent of estimated blood volume
GSA	Global spinal angle
HAC	Hospital-acquired condition
HRQL	Health-related quality of life
KA	Knee angle
LL	Lumbar lordosis
LOS	Length of stay
MCID	Minimal clinically importance difference
NRS	Numeric pain rating scale
ODI	Oswestry disability index
PI	Pelvic incidence
PI-LL	Mismatch between pelvic incidence and lumbar lordosis
PROMIS	Patient-reported outcomes measurement information system
PS	Pelvic shift
PSO	Pedicle subtraction osteotomy
PT	Pelvic tilt
SFA	Sacrofemoral angle
SICU	Surgical intensive care unit
SRS-22r	Scoliosis research society questionnaire 22r
SVA	Sagittal vertical axis
TK	Thoracic kyphosis
T1PA	T1 pelvic angle
VCR	Vertebral column resection
VR-12	Veterans RAND-12

Clinical outcomes

To evaluate improvement in outcomes, minimal clinically importance difference (MCID) thresholds were utilized based on published values in the literature: ODI (12.8), SRS-Pain (0.587), SRS-Mental (0.42), SRS-Activity (0.375), and SRS-Appearance (0.8) [6–11].

Radiographic assessment

Changes in L1-S1 lordosis < 33% between their preoperative standing and supine radiographs were considered "rigid." Severe deformity was classified as global (SVA > 80 mm), lumbopelvic (PI-LL > 30°), and coronal (C7 plumb line > 70 mm).

Complication assessment

The reported complications were classified as minor or major, with complications that involved invasive intervention or prolonged or permanent morbidity or mortality classified as major. Complications were grouped based on time of occurrence as perioperative (within 90 days of surgery, including hospital-acquired conditions [HACs; DVT/PE, UTI, deep/superficial infection]) and longer term (recorded from 90 days to at least two years following surgery) [13]. Medical complications were defined as cardiovascular, pulmonary, musculoskeletal, central nervous system, gastrointestinal, wound, or neurological complications not directly related to the procedure. Spine complications were defined as any complication related to the spine, implant, or radiographic alignment.

Group categorization

Patients receiving a 3CO (grade 3 or above Schwab classification osteotomy: pedicle subtraction osteotomy [PSO], extended pedicle subtraction osteotomy, vertebral column resection [VCR], multiple-level VCR) performed between T10 and L5 were compared with No 3CO patients (remaining cohort). Patients undergoing a 3CO were stratified based on Schwab osteotomy grade (3–6) and location of the three-column osteotomy. The thoracolumbar three-column osteotomies within this cohort were performed by 13 Scoliosis research society active fellows with 10–30 + years of experience in spinal deformity surgery.

Cost calculation

The PearlDiver database was utilized to calculate costs using job order cost accounting ("charge analysis"). Reflecting both Medicare reimbursement and private insurance, the PearlDiver database is one of the most comprehensive datasets with access to Medicare reimbursement charges, outcome data, and trends. Using mean costs associated with procedures based on 2018 adult spinal deformity diagnosis-related groups, procedural costs for cases, cases with complications and comorbidities (CC), major complications and comorbidities (MCC), and revisions were determined according to CMS.gov manual definitions [18]. Our estimates for two-year reimbursement consisted of a standardized determination using regression analysis of Medicare pay scales for all services rendered within a 30-day window, including costs of postoperative complications, outpatient healthcare encounters, revisions, and medical-related readmissions, as per previously published methods [18–23].

Statistical analysis

The primary outcomes included surgical details, hospital stay outcomes, complications, HACs, radiographic global and segmental correction, reoperations, and clinical HRQL outcomes. Baseline demographic, radiographic, and clinical data were compared between the cohorts using chi-squared and t-tests for categorical and continuous variables, respectively. Means comparison tests assessed spinopelvic correction by location and grade of 3CO. Multivariate analysis of patients controlling for baseline PI-LL and the number of levels fused evaluated complication rates, radiographic, and patient-reported outcomes. Statistical significance for all analyses corresponded to a p-value less than 0.05. All statistical analyses were conducted using SPSS, version 28.1 (Armonk, NY).

Results

Patient demographics

Of 381 total patients, there were 249 complex ASD patients eligible and meeting inclusion criteria with full baseline and perioperative data. Mean cohort demographics were as follows: age of 61.0 ± 14.6 years, BMI of 27.5 ± 5.8 kg/m^2, CCI of 1.0 ± 1.5, and modified ASD frailty index of 7.4 ± 4.4.

Surgical details

During surgery, patients endured a mean operative time of 469 ± 160 min and estimated blood loss (EBL) of 1629 ± 1287 mL or percent of estimated blood volume (%EBV) of 32.6 ± 25.7%, while 59% underwent a decompression and 72% underwent an osteotomy. Three-column osteotomies (3CO) were performed in 20.5% of procedures, with a mean 12.6 ± 3.8 levels fused. Regarding surgical approach, 83% were posterior-only and 17% were combined.

Cohort radiographic assessment

Patients had the following mean baseline radiographic measurements: SVA: 67.9 ± 79.8 mm, PI-LL: 16.3 ± 23.5°, PI: 54.6 ± 13.0°, T1PA: 24.2 ± 14.2°, PT: 24.5 ± 12.0°, GSA: 5.3 ± 6.1°, KA: 5.5 ± 9.3°, and AA: 5.2 ± 4.5°. The mean baseline GAP score of the cohort was 8.3 ± 4.2. Upon correction, the cohort showed improvement in all parameters (all $p < 0.001$). Patients had the following mean six-week radiographic measurements: SVA: 23.8 ± 41.7 mm, PI-LL: 3.4 ± 13.7°, T1PA: 16.8 ± 10.0°, PT: 21.1 ± 10.6°, global sagittal angle (GSA): 1.8 ± 3.8°, Knee Angle (KA): 2.9 ± 7.5°, and Ankle Angle (AA): 4.9 ± 4.4°. The mean six-week GAP score was 5.3 ± 3.6, with 22.6% being proportioned.

Categorization

Of those included, 51 patients (21%) had a 3CO. This is a 20% greater usage than earlier ASD databases (17%).

Baseline demographic differences

The demographic differences between groups are displayed in Table 2. Patients undergoing a 3CO were older (65.6 vs. 60.9, $p = 0.023$), with frailty increasing with 3CO grade ($r = 0.537$, $p < 0.001$). Compared to No 3COs, 3COs were more likely to present as a revision (OR 5.2, 95% CI [2.6–10.6]; $p < 0.001$).

Baseline radiographic differences

The baseline radiographic differences between groups are displayed in Table 2. Patients undergoing a 3CO were more likely to present with severe deformity in PI-LL (OR 10.5, 95% CI [4.5–24.6]; $p < 0.001$) and PT (OR 5.1, 95% CI [2.7–9.8]; $p < 0.001$). Patients undergoing a 3CO more often presented with the most complex deformities, more likely to present with both severe global and lumbopelvic

Table 2 Baseline and surgical comparison between 3CO and non-3CO groups

	3CO	No 3CO	p-value
Demographics			
Age (years)	65.9 ± 9.1	60.6 ± 14.8	.003
Gender (% female)	53%	74%	.009
BMI	29.5 ± 5.4	27.0 ± 5.7	.005
CCI	1.2 ± 1.6	0.9 ± 1.5	.298
Frailty	8.6 ± 4.4	7.1 ± 4.3	.029
Osteoporosis	18%	24%	.328
History of TKA/THA	31%	19%	.092
History of thoracolumbar fusion	76%	38%	< .001
Surgical/admission characteristic			
Number of levels fused	10.9 ± 3.3 levels	13.0 ± 3.8 levels	< .001
Estimated blood loss	2479 ± 1539 mL	1406 ± 1127 mL	< .001
Percent estimated blood volume	47.7 ± 22.3%	26.9 ± 19.7%	< .001
Operative time	492 ± 162 min	455 ± 153 min	.137
Decompression	76%	63%	.063
Secondary rod	80%	53%	< .001
PJK prophylaxis	57%	67%	.181
Invasiveness index	83.3	104.3	< .001
Length of stay	8.7 ± 12.6 days	6.6 ± 3.4 days	.048
SICU admission	86%	64%	< .001
SNF or rehab discharge	37%	25%	.107
Baseline radiographic assessment			
PI	57.8 ± 15.0	54.4 ± 12.3	.098
L1-S1	21.7 ± 18.6	40.8 ± 22.4	< .001
PI-LL	36.0 ± 16.8	13.6 ± 20.9	< .001
PT	32.6 ± 12.0	23.5 ± 10.5	< .001
SVA	127.9 ± 49.3	54.5 ± 59.6	< .001
T1PA	37.1 ± 11.4	21.9 ± 12.2	< .001
C2-C7	12.0 ± 15.5	9.7 ± 16.6	.391
T4-T12	-30.7 ± 21.7	-36.5 ± 20.1	.072
L1PA	18.4 ± 12.0	9.9 ± 9.3	< .001
L4PA	12.3 ± 6.7	10.2 ± 5.1	.039
L4-S1	23.8 ± 17.9	35.4 ± 13.9	< .001
LDI	182 ± 881	107 ± 171	.545
GAP score	11.1 ± 2.4	7.8 ± 4.2	< .001
SAAS score	-4.9 ± 3.2	-1.2 ± 3.8	< .001
SFA	205.9 ± 12.2	203.8 ± 9.4	.185
KA	13.2 ± 7.9	4.2 ± 8.8	< .001
AA	8.1 ± 4.3	4.8 ± 4.3	< .001
Pelvic shift	62.7 ± 39.3	26.1 ± 48.3	< .001
GSA	11.3 ± 3.9	4.1 ± 5.6	< .001
Baseline HRQLs			
ODI	45.5 ± 17.3	41.8 ± 18.4	.200
SRS-22 total	2.8 ± 0.6	2.9 ± 0.6	.152
VR-12 PCS	25.8 ± 9.5	30.9 ± 11.4	.004
VR-12 MCS	49.7 ± 12.7	49.4 ± 11.5	.848
PROMIS anxiety	56.2 ± 7.4	54.5 ± 8.7	.212
PROMIS pain interference	65.6 ± 5.7	62.6 ± 8.0	.014
PROMIS physical functioning	32.3 ± 4.9	35.6 ± 7.7	< .001
NRS-back pain	6.6 ± 2.3	6.6 ± 2.4	.996
NRS-leg pain	4.2 ± 3.1	4.2 ± 3.3	.997

BMI body mass index, *CCI* Charlson comorbidity index, *TKA* total knee arthroplasty, *THA* total hip arthroplasty, *PJK* proximal junctional kyphosis, *SICU* surgical intensive care unit, *SNF* skilled nursing facility, *PI* pelvic incidence, *PT* pelvic tilt, *LL* lumbar lordosis, *SVA* sagittal vertical axis, *T1PA* T1 pelvic angle, *L1PA* L1 pelvic angle, *L4PA* L4 pelvic angle, *LDI* lordosis distribution index, *SFA* sacrofemoral angle, *KA* knee

Table 2 (continued)

angle, *AA* ankle angle, *GSA* global spinal angle, *ODI* Oswestry disability index, *PCS* physical component score, *MCS* mental component score

Table 3 Complication comparison

	3CO (%)	No 3CO (%)	p-value
90-day complications			
Any	58.8	52.2	.423
Intraoperative	27.5	12.6	.009
Medical	21.6	25.8	.539
Cardiopulmonary	13.7	11.6	.681
Central nervous system	0.0	3.6	.175
Gastrointestinal	5.9	6.6	.860
Genitourinary	3.9	3.0	.749
Wound	19.6	5.6	.001
Neurological	27.5	18.7	.168
Spine-related	54.9	37.9	.028
PJK	29.4	24.7	.499
PJF	3.9	2.6	.610
Reoperation	25.5	15.2	.082
Mortality	0.0	1.0	.613

PJK proximal junctional kyphosis, *PJF* proximal junctional failure

Table 4 Perioperative clinical improvement comparison

	3CO	No 3CO	p-value
Clinical outcome improvement			
ODI	−1.8 ± 22.9	1.6 ± 21.3	.336
MCID in ODI	28.9%	17.3%	.077
SRS-22 total	0.4 ± 0.6	0.3 ± 0.6	.214
MCID in SRS-22 total	26.7%	21.5%	.454
VR-12 PCS	1.4 ± 10.9	−2.6 ± 12.8	.057
VR-12 MCS	2.1 ± 11.4	−0.7 ± 13.4	.203
PROMIS anxiety	−4.3 ± 7.1	−3.6 ± 8.3	.634
PROMIS pain interference	−4.4 ± 7.8	−0.7 ± 9.6	.022
PROMIS physical functioning	−0.9 ± 6.9	−4.3 ± 8.8	.019
NRS-back pain	−2.0 ± 3.1	−2.4 ± 3.2	.483
NRS-leg pain	−0.8 ± 3.2	−1.5 ± 3.9	.244
Neuro deficit resolution	33.3%	49.4%	.038
Opioid usage	71.3%	53.1%	.041

ODI Oswestry disability index, *MCID* minimal clinically important difference, *PCS* physical component score, *MCS* mental component score, *NRS* numerical rating scale

deformity compared to No 3CO (OR 11.9, 95% CI [5.9–24.2]; $p < 0.001$).

In-hospital, complication, and clinical improvement comparison

The surgical details between groups are displayed in Table 2. The total cohort length of stay is 7.0 ± 6.2 days. 3COs had four times greater use of a secondary rod, incurring a four times greater risk of massive blood loss (> 3500 mL), along with longer length of stay, and higher rates of SICU admission, perioperative wound, and spine-related complications, and, specifically, neuro complications when performed below L3 (32.4% vs. 18.7%) (Table 3). 3COs saw similar benefits in HRQLs, although less resolution of baseline sensory and motor deficits and higher opioid usage perioperatively (Table 4). Of note, when comparing only patients undergoing primary 3COs (n = 12) to those not undergoing a 3CO, there were no differences in any complication rates or clinical improvement measures (all $p > 0.1$).

Six-week radiographic assessment

Upon correction, degree of segmental correction increased by 3 degrees with increased grade of 3CO (G3–20.5; G4–23.4; G5–26.6) and demonstrated at least 4 times greater correction at each level compared to lower-grade osteotomies, including 12 times greater correction at L4 and L5. 3COs achieved double the correction in lumbopelvic and global parameters ($p < 0.001$). Specifically, 3COs had the best impact on T1PA at L2-4, with a 4° correction gain per grade. Pelvic compensation was normalized best at L1 and L2, while L1PA and L4PA were best corrected at L5. Grades 4 and 5 properly distributed lordosis in the lower lumbar spine 50% of the time at all levels except L5. Pelvic non-response and lower extremity compensation (assessed through sacrofemoral, knee, and ankle flexion angles) were relieved more often with increasing 3CO grade. Notably, 3CO patients also had greater correction in all eight lower extremity parameters (all $p < 0.01$).

Cost outcomes

The increased invasiveness, length of stay, and complication rates trended toward a higher perioperative cost for 3CO patients ($42,806.04 vs. $40,045.60, p = 0.086). However, upon follow-up, 3CO patients had significantly higher rates of improvement from preoperative state and would more often to choose to have the surgery again (79% vs. 55%, p = 0.013).

Discussion

Adult spinal deformity has been shown to have detrimental impacts on quality of life [6–11]. As technologies continue to improve, spine surgeons are presented with expanding opportunities to treat patients with increasingly severe frailty and comorbidities [4]. This further drives the development of newer, less invasive techniques which have been shown to improve patient outcomes. However, outcomes in adult spinal deformity have previously been shown to correlate strongly with meeting certain realignment goals [14]. Thus, there exists a point at which baseline deformity is too severe for these less invasive approaches and techniques.

While standard ASD patients may achieve correction without highly invasive techniques, the complex ASD population represents a unique challenge in which the use of 3CO may be necessitated despite the increased rates of complications [16].

In this study, patients presented with a high degree and complexity of baseline deformity and, accordingly, underwent 3COs at a higher rate than previous ASD cohorts. Consistent with prior literature, 3CO patients experienced greater perioperative and postoperative complications. Importantly, significantly greater radiographic correction in multiple parameters (lumbopelvic, global alignment, lower extremity compensation) was seen. Additionally, increasing grade of 3CO was associated with incrementally greater correction. While 3CO patients did incur higher costs, this was not significant compared to No 3CO patients and is potentially offset by greater rates of postoperative improvement reported by 3CO patients. Despite greater rates of complications and potentially higher cost, this study affirms that 3CO represents a powerful and necessary realignment tool for patients with the most severe spinal deformities.

Our study was not without limitations. Of most importance was our decision to utilize Medicare allowable rates for our cost comparison, as previous studies have found significant differences in direct hospital costs compared to Medicare allowable rates in adult spinal deformity surgery [21]. However, we felt Medicare rates would represent a suitable means of standardizing costs across different participating centers and improve the generalizability of study findings [17]. Similarly, due to recent dispute for carrying the utility gained over two years out to life expectancy in order to calculate QALYs gained for the remaining amount of a patient's life, we did not determine or report the comparison of those values [24, 25]. Due to the availability of data for all patients at the time of this analysis, we also examined the 6-week outcomes of this cohort, and we plan to further elaborate on the results of our current study with mid-term data once finalized for this cohort. However, due to the unique aspects of our cohort and the high perioperative risk encountered with three-column osteotomies, we believe these findings provide a suitable addition to the current literature. Future studies should assess the durability of these realignment strategies in long-term studies to further delineate the attributable benefit of meeting radiographic targets. Although data were collected prospectively, there is the prospect for a surveillance and classification bias that cannot be quantified. These findings are meant to be informative for future follow-up studies and trials with strict protocols to investigate factors for improvement of current reimbursement standards and practices. Furthermore, while modeled to the best of our ability, surgical decision-making is challenging to model and there may be aspects of residual confounding that influence the results of this study, not limited to expertise and selection bias.

Conclusion

Three-column osteotomy usage in contemporary complex spinal deformities is generally limited to more disabled individuals undergoing the most severe sagittal and coronal realignment procedures. While there is a perioperative cost and prolongation with usage, these techniques represent the most powerful realignment techniques available with dramatic impact on normalization at operative levels and reciprocal.

Author contributions The authors made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; or the creation of new software used in the work; drafted the work or revised it critically for important intellectual content; approved the version to be published; and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; Tyler K. Williamson and Peter Passias contributed to conception and design and drafting of the manuscript; Tyler K. Williamson, Jamshaid Mir, Justin Smith, Virginie Lafage, Renaud Lafage, Breton Line, Bassel Diebo, Alan Daniels, Jeffrey Gum, D. Kojo Hamilton, Justin Scheer, Robert Eastlack, Andreas Demetriades, Khaled Kebaish, Stephen Lewis, Lawrence Lenke, Richard Hostin, Munish Gupta, Han Jo Kim, Christopher Ames, Douglas Burton, Christopher Shaffrey, Eric Klineberg, Shay Bess, and Peter Passias performed acquisition, analysis, and interpretation of data and critical revision of the manuscript for important intellectual content; approved the version to be published; and agree to be accountable for all aspects of the work; Tyler K. Williamson was involved in statistical analysis; Peter Passias was involved in administrative, technical, or material support and did supervision.

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Data availability The data used in this study is not publicly available, but institution-specific data may be available upon request from the different institutions involved in this study.

Declarations

Conflict of interest None.

Ethical approval Institutional Review Board approval was obtained before enrolling patients in the prospective database. Informed consent was obtained from each patient prior to enrollment.

Consent to participate Informed consent was obtained from all individual participants included in this study.

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