Spine Deformity (2023) 11:175–185
https://doi.org/10.1007/s43390-022-00576-8

CASE SERIES

The postoperative course of mechanical complications in adult spinal deformity surgery

Hani Chanbour[1] · Steven G. Roth[1] · Matthew E. LaBarge[2] · Anthony M. Steinle[2] · Jeffrey Hills[3] · Amir M. Abtahi[1,2] · Byron F. Stephens[1,2] · Scott L. Zuckerman[1,2]

Received: 2 February 2022 / Accepted: 20 August 2022 / Published online: 5 September 2022

Abstract

Purpose (a) Describe the time course of each mechanical complication, and (b) compare radiographic measurements and preoperative patient-reported outcome measures (PROMs) among each mechanical complication type.

Methods A single-institution case–control study was undertaken of patients undergoing adult spinal deformity (ASD) surgery from 2009–2017. Exposure variables included patient demographics, operative variables, radiographic measurements, and preoperative PROMs, including Oswestry Disability Index (ODI), Numeric Rating Scale Back/Leg-pain scores (NRS-Back/Leg), and EuroQol-5D (EQ-5D). The primary outcomes were occurrence of a mechanical complication and time to complication. Due to overlapping occurrence, rod fracture and pseudarthrosis were grouped into one composite category.

Results 145 patients underwent ASD surgery and were followed for at least 2 years. 30/47 (63.8%) patients with proximal junctional kyphosis (PJK) required reoperation, whereas 27/31 (87.1%) patients with pseudarthrosis/rod fracture required reoperation (63.8% vs. 87.1%, $X^2 = -0.23$, 95% CI −0.41, −0.05, $p = 0.023$). Cox regression showed no significant difference in time to reoperation between PJK and rod fracture/pseudarthrosis (HR = 0.97, 95% CI 0.85–1.11, $p = 0.686$). Distal junctional kyphosis (DJK) ($N = 3$; 2 reoperation) and implant failures ($N = 4$; 0 reoperations) were rare. Patients with PJK had significantly lower Hounsfield Units preoperatively compared to those with pseudarthrosis/rod fracture (138.2 ± 43.8 vs. 160.3 ± 41.0, mean difference (MD) = −22.1, 95% CI −41.8, −2.4, $p = 0.028$), more prior fusions (51.1% vs. 25.8%, $X^2 = 0.253$, 95% CI 0.41, 0.46, $p = 0.026$), fewer instrumented vertebrae (9.2 ± 2.6 vs. 10.7 ± 2.5, MD = −1.5, 95% CI −2.7, −0.31, $p = 0.013$), and higher postoperative thoracic kyphosis (TK) (46.3 ± 12.7 vs. 34.9 ± 10.6, MD = 11.4, 95% CI 5.9, 16.9, $p < 0.001$). Higher postoperative C7 sagittal vertical axis (SVA) did not achieve a significant difference (80.7 ± 72.1 vs. 51.9 ± 57.3, MD = 28.8, 95% CI −1.9, 59.5, $p = 0.066$). No differences were seen in preoperative PROMs.

Conclusion Patients with pseudarthrosis/rod fracture had a higher reoperation rate compared to those with PJK with similar time to reoperation. Moreover, patients with PJK had higher postoperative TK, lower Hounsfield Units, more prior fusions, and fewer instrumented levels compared to those with pseudarthrosis/rod fracture. The results of this single-institution study suggest that even though mechanical complications are often analyzed as a single group, important differences may exist between them.

Level of evidence III.

Keywords Adult spinal deformity · Mechanical complications · Pseudarthrosis · Junctional kyphosis · Rod fracture · Implant failure

✉ Scott L. Zuckerman
scott.zuckerman@vumc.org

1 Department of Neurological Surgery, Vanderbilt University Medical Center, Medical Center North T-4224, Nashville, TN 37212, USA

2 Department of Orthopedic Surgery, Vanderbilt University Medical Center, Nashville, TN, USA

3 Department of Orthopedic Surgery, University of Texas Health Science Center-San Antonio, San Antonio, TX, USA

Introduction

Progressive adult spinal deformity (ASD) is a debilitating condition leading to severe disability [1]. With improved medical care and higher life expectancy in the United States [2], some reports suggest a 68% prevalence of ASD in individuals older than 65 years [3]. Although ASD is symptomatic in a smaller subset of patients, progressive spinal deformity can result in axial back pain, gait instability, and neurological impairment [4].

Despite improvements in surgical treatment of ASD, the risk of complications is high, even in a perfectly executed ASD surgery [5, 6]. Prior studies endorse a reoperation rate of 15–20% following ASD surgery [7], with complications as high as 70% [8], and a 20–50% incidence of mechanical complications [9], which include proximal/distal junctional kyphosis (PJK/DJK), rod fracture, pseudarthrosis, and implant failure [10]. Recent data have shown that outcomes between patients with and without mechanical complications are similar, as long as the mechanical complication is adequately treated [10].

Researchers and surgeons have often grouped mechanical complications together as a single entity; however, it remains unknown what differences exist between mechanical complication sub-types. Moreover, strategies to treat each respective mechanical complication differ. While PJK occurs at the proximal end of a construct and requires extension of fusion, pseudarthrosis and implant failure often occur at more distal segments involving the lumbosacral junction. The complexity and invasiveness of how to treat each mechanical complication varies considerably.

Considering previously unstudied differences between mechanical complications in ASD surgery, we sought to further evaluate mechanical complication sub-types with respect to one another. In a group of ASD patients undergoing surgery, we aimed to: (a) describe the time course of each mechanical complication, and (b) compare different types of mechanical complications amongst each other in the areas of demographic factors, operative variables, radiographic measurements, and preoperative patient-reported outcomes measures (PROMs).

Methods

Study design

A single-institution, retrospective, case–control study was designed using prospectively collected data from our institution's spine outcomes registry from 2009–2017. The registry team includes three full-time employees whose role includes contacting patients to collect PROMs data at several pre- and postoperative timepoints. A total of 12 fellowship-trained neurosurgery and orthopedic spine surgeons have contributed patients in the decade of the registry's existence. Institutional review board (IRB) approval was obtained for this study (IRB#211290). Informed consent was obtained for all patients.

Patient population

Registry data were obtained for patients who underwent elective ASD surgery from 2009–2017. Inclusion criteria were: ≥ 5-level fusions with sagittal/coronal deformity and/or regional scoliosis requiring surgical reconstruction. All patients had a minimum of 2-year follow-up to assess of the occurrence of a mechanical complication. Therefore, all patients were included in the same analysis regardless of their specific follow-up period in an effort to increase study power. Patients who were lost to follow-up were also noted.

Exposure variables

Several exposure variables were evaluated and included the following: (1) demographic factors, (2) operative variables, (3) radiographic measurements, and (4) preoperative PROMs. Demographic variables included age, sex, body mass index (BMI), comorbidities, and Hounsfield Units. The latter were measured on three axial slices of one vertebra, either at the upper instrumented vertebra (UIV) itself or at a vertebra within UIV ± 4 from computed tomography (CT) scans preoperatively [11]. Operative variables included: UIV region, UIV implant, total instrumented levels (TIL). Radiographic variables included pelvic incidence (PI), pelvic tilt (PT), thoracic kyphosis (TK), sagittal vertical axis (SVA), lumbar lordosis (LL) L1-S and L4-S1, PI:LL mismatch, and lordosis distribution index (LDI). Though LDI is an imperfect measurement, as it does not consider whether the total LL is enough for the PI, it nonetheless captures the distribution of lordosis. All radiographic variables were taken preoperatively and at 6 weeks postoperatively and were measured by an orthopedic/neurosurgery resident. Any complex radiographs were confirmed by a fellowship-trained spine surgeon. Preoperative PROMs included Oswestry Disability Index (ODI), Numeric Rating Scale (NRS)-Back, NRS-Leg, EuroQol-5 Dimension (EQ-5D).

Outcome variables

The primary outcomes were occurrence of a mechanical complication and time to mechanical complication. To fit the case–control design, patients with mechanical complications were obtained, and several exposure variables were retrospectively evaluated after dividing our sample into those with and without mechanical complications. In keeping with prior literature [12], mechanical complications were defined as follows. PJK occurred if there was ≥ 10° increase in kyphosis between the upper instrumented vertebrae (UIV) and UIV + 2 on postoperative imaging [13]. Proximal junctional failure (PJF), a common complication of PJK, was defined as ≥ 10° postoperative increase in kyphosis between the UIV and UIV + 2, along with one or more of the following features: fracture of the vertebral body of the UIV or UIV + 1, posterior osseoligamentous disruption, or pullout of UIV instrumentation [14]. DJK occurred if there was ≥ 10° increase in kyphosis between lowest instrumented vertebra (LIV) and LIV-1 on postoperative radiographs. A rod fracture was defined as a single or double rod breakage. Lastly, implant failure included any case of screw pullout, breakage, loosening, or dislodgement.

Due to the common co-occurrence of rod fracture with pseudarthrosis, these two diagnoses were grouped together to form a composite outcome. Though both rod fracture and pseudarthrosis can occur independently of one another, we a-priori decided to group these complications together due to their similarity. Pseudarthrosis increases the risk of rod fracture by almost 29-fold [15], and anecdotally, many times pseudarthrosis can be missed in the presence of a rod fracture if not assessed for diligently. Hence, combining rod fracture and pseudarthrosis in the same category was deemed in accordance with previous literature [16–19].

In addition to the occurrence of a mechanical complication, the time that each complication occurred was recorded in relation to the index surgery. Of note, for the initial baseline analysis, mechanical complication was treated as an outcome. However, for subsequent analysis comparing types of mechanical complication to each other, type of mechanical complication was treated as an independent, exposure variable.

Statistical analysis

Descriptive statistics were compiled for all demographic, preoperative, and postoperative characteristics. Mean ± standard deviation (SD) and median (IQR) for continuous variables and frequency for categorical variables were computed. Continuous data was compared using student's *t* test and mean difference (MD) was reported. Nominal data were compared by Chi-square or Fisher's Exact test, and a one-way analysis of variance tests (ANOVA) was used to differentiate among four groups of continuous variables. The log-rank test was used to differentiate the time to reoperation between PJK and pseudarthrosis/rod fracture groups. Both pseudarthrosis and rod fracture occurred in 23 (15.8%) of patients. As rod fracture commonly occurs following pseudarthrosis [15], and due to the overlapping nature of patients with pseudarthrosis and rod fracture in our sample, patients with either complication were analyzed as a single group. Given the likely event that there was some sort of non-union present with most rod fractures, it was decided a priori to analyze this group as a single group. An alpha level of 0.05 was regarded as statistically significant. To the best of our ability, we included 95% CI with all *p* values when appropriate to provide more granular details of the data and variance of the data. The analysis was performed using Stata version 14 (StataCrop LP).

Results

Patient sample

A total of 145 patients underwent ASD surgery during the study period with completed 2-year follow-up. An additional 153 patients underwent ASD surgery but did not have complete follow-up, including both x-rays and complete PROMs to the 2-year mark, and were thus excluded from analysis. A baseline comparison of patients with and without 2-year follow-up is presented in Supplementary Information. Of note, those lost to follow-up appeared to have some notable differences, specifically having more males, more comorbidities (COPD, CHF, HTN), more prior fusions, less often fused to the sacrum, and lower TIL.

In patients with 2-year follow-up, mean age was 63.8 ± 11.3 years, 118 (81.4%) were female, and 56 (38.6%) had undergone a previous fusion operation. Median (range) follow-up was 26.5 (24.0–48.7) months. A total of 131 (90.3%) were fused to sacrum, and 113 (77.9%) had iliac/S2 Alar-iliac (S2AI) screws inserted. Mechanical complications occurred in 85 (58.6%) patients. Patients who developed mechanical complications had more comorbidities ($p = 0.005$) including higher rates of COPD ($p = 0.033$), and higher NRS-leg pain preoperatively ($p = 0.011$) compared to patients without mechanical complications. The presence or absence of mechanical complications did not differ in terms of having undergone a prior fusion ($p = 0.272$), Hounsfield unit average ($p = 0.065$), total instrumented levels ($p = 0.668$), or any preoperative radiographic variables. Full demographic and perioperative characteristics are shown in Table 1 and Table 2.

Time to mechanical complications

Of the 85 patients (58.6%) suffering from mechanical complications, 59 (40.7%) required reoperation. Of the 47 patients with PJK, 27 (47.4%) had PJF, and 30 (63.8%) required reoperation at a median of 16.3 months. Of note, 6/30 (20%) of the patients required reoperation within 6 months of the index surgery. Of the 31 patients with pseudarthrosis/rod fracture, 27 (87.1%) underwent

Table 1 Demographics, operative variables, and PROMs between those with and without mechanical complications

	Total sample $N=145$	No mechanical complication $N=60$	Yes mechanical complication $N=85$	*p* value
Age, mean ± SD	63.9 ± 11.3	64.4 ± 11.6	63.5 ± 11.3	0.652
Female, *n* (%)	118 (81.4%)	48 (80.0%)	70 (82.4%)	0.995
BMI, mean ± SD	29.8 ± 6.6	30.6 ± 7.1	29.4 ± 6.1	0.472
CCI weighted score, mean ± SD	2.0 ± 2.7	1.3 ± 1.6	2.4 ± 3.1	0.012*
Comorbidities, *n* (%)				
Diabetes	29 (20.0%)	11 (18.3%)	18 (20.2%)	0.673
COPD	41 (28.3%)	11 (18.6%)	30 (35.3%)	0.026*
CHF	17 (11.7%)	4 (6.8%)	13 (15.3%)	0.112
HTN	106 (73.1%)	40 (66.7%)	66 (77.7%)	0.142
Dependent	17 (13.1%)	3 (5.2%)	14 (19.4%)	0.016*
Hounsfield unit average, mean ± SD	153.5 ± 52.8	165.1 ± 64.1	146.7 ± 43.9	0.065
Prior fusion, *n* (%)	56 (38.6%)	20 (33.3%)	36 (42.4%)	0.272
UIV region upper thoracic, *n* (%)				
Upper thoracic	28 (19.3%)	11 (18.3%)	17 (20.0%)	
Thoracolumbar	117 (80.7%)	49 (81.7%)	68 (80.0%)	0.802
UIV implant, *n* (%)				
Pedicle screws	137 (94.5%)	56 (93.3%)	81 (95.3%)	
Hooks	8 (5.5%)	4 (6.7%)	4 (4.7%)	0.611
Fused to sacrum, *n* (%)	131 (90.3%)	52 (86.7%)	79 (92.9%)	0.208
Total instrumented levels, mean ± SD	9.8 ± 2.6 (5–16)	9.7 ± 2.4	9.9 ± 2.7	0.668
Preoperative PROs, mean ± SD				
ODI	50.3 ± 13.0	48.2 ± 14.0	52.1 ± 11.9	0.087
VAS-back	7.2 ± 1.8	7.1 ± 1.7	7.3 ± 2.0	0.447
VAS-leg	6.0 ± 2.8	5.3 ± 2.9	6.6 ± 2.6	0.011*
EQ-5D	0.49 ± 0.21	0.52 ± 0.22	0.46 ± 0.20	0.123

*Represents statistical significance

reoperation at a median of 18.4 months. Patients with PJK had significantly higher reoperation rate than pseudarthrosis/rod fracture (63.8% vs. 87.1%, $X^2 = -0.23$, 95% CI −0.41, −0.05, $p = 0.023$). Cox regression analysis assessing the difference between the time to reoperation in pseudarthrosis/rod fracture vs. PJK showed no significant difference (HR = 0.97, 95% CI 0.85–1.11, $p = 0.686$) (Fig. 1). DJK ($N = 3$; 2 reoperation) and implant failures ($N = 4$; 0 reoperations) had low numbers, which limited further analysis. Reoperation rate for each mechanical complication along with time to reoperation are summarized in Table 3.

Demographic and preoperative factors

Demographic and preoperative variables for each mechanical complication subtype are compared in Table 4. Among preoperative factors, patients with PJK had significantly lower Hounsfield Units preoperatively (138.2 ± 43.8 vs. 160.3 ± 41.0, MD = −22.1, 95% CI −41.8, −2.4, $p = 0.028$) and underwent more prior fusion operations (51.1% vs. 25.8%, $X^2 = 0.253$, 95% CI 0.41, 0.46, $p = 0.026$), compared with patients with pseudarthrosis/rod fracture. Furthermore, though patients with PJK were more frequently fused to the sacrum compared to three other groups ($p < 0.001$), no significant difference in fusion to sacrum was found between PJK and pseudarthrosis/rod fracture ($p = 0.817$). Patients with PJK also had significantly fewer instrumented levels compared to patients with pseudarthrosis/rod fracture (9.2 ± 2.6 vs. 10.7 ± 2.5, MD = −1.5, 95% CI −2.7, −0.31, $p = 0.013$).

Radiographic factors

No differences were seen in any measured preoperative radiographic values (Table 5). Postoperatively, patients with PJK had higher postoperative thoracic kyphosis (TK) compared to patients with pseudarthrosis/rod fracture (46.3 ± 12.7 vs. 34.9 ± 10.6, MD = 11.4, 95% CI 5.9, 16.9, $p < 0.001$). A similar but non-significant difference was seen for C7 SVA, where PJK patients had a higher C7 SVA than pseudarthrosis/rod fracture patients (80.7 ± 72.1 vs. 51.9 ± 57.3,

Table 2 Preoperative radiographic measurements

Preoperative radiographic	Total sample $N=145$	No mechanical complication $N=60$	Yes mechanical complication $N=85$	p value
PI				
Mean ± SD	51.7 ± 11.1	52.1 ± 11.0	51.4 ± 11.2	0.719
Median (IQR)	50.9 (43.5–59.7)	50.4 (44.4–59.7)	51.1 (42.4–59.6)	
PT				
Mean ± SD	26.0 ± 10.1	24.9 ± 9.7	26.7 ± 10.4	0.309
Median (IQR)	25.8 (19.7–32.0)	24.8 (19.1–31.0)	26.1 (19.72–33.3)	
TK				
Mean ± SD	33.7 ± 17.7	32.9 ± 15.5	34.3 ± 19.0	0.634
Median (IQR)	32.9 (12.6–44.7)	33.1 (22.6–43.6)	31.1 (21.5–46.8)	
SVA				
Mean ± SD	85.4 ± 73.5	82.8 ± 77.7	87.4 ± 70.6	0.718
Median (IQR)	81.4 (33.3–122.8)	82.0 (28.1–120.2)	80.1 (36.7–128.1)	
PI:LL				
Mean ± SD	21.5 ± 19.1	20.8 ± 19.6	22.0 ± 18.9	0.715
Median (IQR)	20.3 (9.1–35.1)	21.9 (7.5–34.5)	20.3 (9.3–36.6)	
LL L1-S1				
Mean ± SD	30.3 ± 19.5	30.8 ± 20.0	29.9 ± 19.3	0.790
Median (IQR)	30.9 (17.1–42.0)	30.3 (16.7–40.3)	32.5 (17.5–43.2)	
LL L4-S1				
Mean ± SD	28.6 ± 12.3	28.1 ± 11.0	28.9 ± 13.3	0.700
Median (IQR)	30.4 (20.9–37.2)	28.1 (20.4–35.8)	30.9 (20.9–38.6)	
LDI				
Mean ± SD	67.8 ± 297.3	59.4 ± 315.5	73.3 ± 285.6	0.784
Median (IQR)	87.8 (58.7–122.3)	90.6 (58.1–112.4)	86.0 (59.0–124.0)	

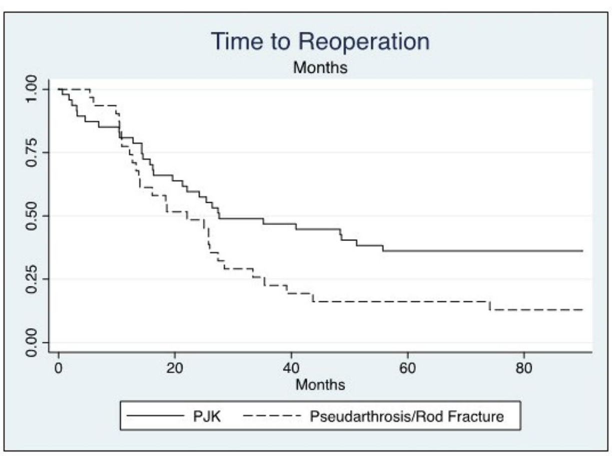

Fig. 1 Graphical display of time to reoperation (months) of PJK and pseudarthrosis/rod fracture

MD = 28.8, 95% CI − 1.9, 59.5, $p=0.066$), but again, this did not achieve statistical significance. Preoperative and postoperative radiographic measurements are presented in Table 5.

Preoperative patient-reported outcomes

No differences were seen with regards to preoperative ODI, NRS-Back, NRS-Leg, EQ-5D. Table 6 summarizes preoperative PROMs in different mechanical complication groups.

Discussion

While the ASD literature discusses the importance of mechanical complications at length, to our knowledge, few studies have examined the clinical impact of different types of mechanical complications. First, our study found that patients with mechanical complications had more comorbidities, higher rates of COPD, and higher preoperative NRS-leg pain. In addition, reoperation rates were higher in patients with pseudarthrosis/rod fracture compared to those with PJK, but time to reoperation did not significantly differ between pseudarthrosis/rod fracture and PJK. Furthermore, PJK patients had higher postoperative TK compared to patients with pseudarthrosis/rod fractures. PJK patients also had lower preoperative Hounsfield Units, more often had a prior fusion procedure,

Table 3 Mechanical complications and median time to mechanical complication

Total $N=145$	N	Reoperation	Time to reoperation (months)
Mechanical complication	85 (58.6%)	59 (40.7%)	Mean: 21.4 ± 15.5 Median (IQR): 16.3 (10.5–27.4) Range: 0.7–86.7
PJK	47 (32.4%)	30 (20.7%) (63.8% of PJK)	Mean: 20.7 ± 15.6 Median (IQR): 16.3 (10.4–27.4) Range 0.7–55.7
DJK*	3 (2.1%)	2 (1.4%) (66.7% of DJK)	Mean: 26.6 ± 35.8 Median (IQR): 26.6 (1.2–51.9) Range 1.2–51.9
Pseudarthrosis/rod fracture	31 (21.4%)	27 (45.8%) (87.1% of Pseudarthrosis/rod fx)	Mean: 21.8 ± 14.6 Median (IQR): 18.4 (10.9–27.4) Range 5.4–86.7
Implant-related	4 (2.8%)	0 (0.0%) (0.0% of Implant)	–
Multiple mechanical complications	21 (14.5%)	19 (90.4%)	Mean: 18.2 ± 12.9 Median (IQR): 16.3 (10.4–24.2) Range (2.3–48.6)

Table 4 Demographics and operative variables by mechanical complication

	PJK $N=47$	DJK $N=4$	Pseudarthrosis/rod fracture $N=31$	Implant failure $N=4$	p value (4 groups)	p value (PJK vs. pseud)
Age, mean ± SD	66.4 ± 7.9	47.9 ± 21.0	62.0 ± 12.8	52.8 ± 7.7	0.013	0.066
Female, n (%)	38 (80.9%)	3 (100.0%)	25 (80.7%)	4 (100.0%)	0.651	0.982
BMI, mean ± SD	29.4 ± 6.1	29.3 ± 14.8	28.5 ± 5.3	31.6 ± 6.1	0.089	0.476
CCI weighted score, mean ± SD	3.2 ± 3.8	0.3 ± 0.6	1.5 ± 1.7	1.8 ± 1.0	< 0.001*	0.016
Comorbidities, n (%)						
Diabetes	10 (21.3%)	0 (0.0%)	7 (23.6%)	1 (25.0%)	0.831	0.891
COPD	19 (40.4%)	0 (0.0%)	10 (32.3%)	1 (25.0%)	0.477	0.465
CHF	8 (17.0%)	1 (33.3%)	4 (12.9%)	0 (0.0%)	0.632	0.622
HTN	43 (91.5%)	1 (33.3%)	20 (64.5%)	2 (50.0%)	0.004*	0.003*
Dependent	8 (19.5%)	0 (0.0%)	5 (18.5%)	1 (50.0%)	0.639	0.919
Hounsfield unit average, mean ± SD	138.2 ± 43.8	131.9 ± 36.3	160.3 ± 41.0	153.7 ± 66.7	0.057	0.028*
Prior fusion, n (%)	24 (51.1%)	1 (33.3%)	8 (25.8%)	3 (75.0%)	0.079	0.026*
UIV region upper thoracic, n (%)						
Upper thoracic	6 (12.8%)	3 (100.0%)	6 (19.4%)	2 (50.0%)		
Thoracolumbar	41 (87.3%)	0 (0.0%)	25 (80.7%)	2 (50.0%)	< 0.001*	0.430
UIV implant, n (%)						
Pedicle screws	45 (95.7%)	3 (100.0%)	30 (96.8%)	3 (75.0%)		
Hooks	2 (4.3%)	0 (0.0%)	1 (3.3%)	1 (25.0%)	0.262	0.817
Fused to sacrum, n (%)	45 (95.7%)	0 (0.0%)	30 (96.8%)	4 (100.0%)	< 0.001*	0.817
Total instrumented levels, mean ± SD	9.2 ± 2.6	12.0 ± 1.0	10.7 ± 2.5	11.0 ± 4.4	0.315	0.013*

*Represents statistical significance

and had fewer instrumented levels. Lastly, no difference in preoperative PROMs were found when comparing each mechanical complication with one another. The results of this preliminary study may provide useful information in avoiding and treating mechanical complications after ASD surgery.

Specific distinguishing features existed between each type of mechanical complication, specifically that pseudarthrosis/

Table 5 Radiographic measurements preoperatively, postoperatively, and change from preoperative to postoperative

	PJK *N* = 47	DJK *N* = 4	Pseudarthrosis/ rod fracture *N* = 31	Implant failure *N* = 4	*p* value (4 groups)	*p* value (PJK vs. pseudo)
Preoperative, mean ± SD						
PI	51.0 ± 10.9	50.6 ± 22.8	54.0 ± 10.4	46.7 ± 5.1	0.135	0.238
PT	27.3 ± 10.5	21.6 ± 16.9	27.2 ± 9.1	23.4 ± 8.1	0.507	0.974
TK	36.0 ± 16.3	73.0 ± 32.8	29.1 ± 16.1	29.2 ± 10.7	0.404	0.079
SVA	101.6 ± 68.7	39.8 ± 37.1	79.9 ± 78.6	76.0 ± 81.3	0.663	0.221
PI:LL	22.8 ± 18.0	−8.3 ± 22.6	23.8 ± 15.8	31.9 ± 21.0	0.775	0.802
LL L1-S1	28.8 ± 18.8	58.2 ± 14.0	30.2 ± 18.2	14.3 ± 22.3	0.923	0.739
LL L4-S1	27.3 ± 14.6	40.3 ± 9.2	29.4 ± 10.7	24.6 ± 9.6	0.289	0.508
LDI	74.4 ± 122.0	71.5 ± 20.5	−49.2 ± 540.8	149.3 ± 358.3	< 0.001*	0.142
Postoperative, mean ± SD						
PT	24.3 ± 8.9	34.1 ± 19.6	24.6 ± 9.3	20.7 ± 7.5	0.271	0.884
TK	46.3 ± 12.7	54.7 ± 14.8	34.9 ± 10.6	30.2 ± 3.8	0.164	< 0.001*
SVA	80.7 ± 72.1	75.8 ± 115.8	51.9 ± 57.3	98.3 ± 40.4	0.288	0.066*
PI:LL	10.5 ± 12.9	22.1 ± 28.3	14.1 ± 13.5	18.4 ± 13.2	0.310	0.235
LL L1-S1	40.6 ± 15.8	28.5 ± 12.6	39.9 ± 12.3	28.2 ± 13.0	0.562	0.834
LL L4-S1	28.9 ± 9.2	22.5 ± 12.6	27.3 ± 8.1	21.8 ± 7.4	0.729	0.432
LDI	75.8 ± 35.5	80.7 ± 34.2	72.2 ± 30.5	83.0 ± 17.8	0.528	0.639
Change Preop to postop, mean ± SD						
PT	−2.9 ± 7.4	12.5 ± 3.9	−2.6 ± 7.0	−2.7 ± 11.3	0.470	0.853
TK	10.0 ± 12.6	−18.3 ± 22.6	5.8 ± 8.6	4.1 ± 9.1	0.078	0.111
SVA	−19.3 ± 65.5	36.0 ± 78.9	−24.1 ± 53.2	27.5 ± 25.5	0.544	0.759
PI:LL	−12.6 ± 15.9	30.4 ± 26.0	−9.7 ± 11.2	−13.5 ± 16.3	0.124	0.389
LL L1-S1	12.6 ± 15.5	−29.7 ± 26.6	9.6 ± 11.3	13.9 ± 15.2	0.145	0.363
LL L4-S1	2.0 ± 10.7	−17.8 ± 7.8	−2.1 ± 8.5	−2.8 ± 8.5	0.568	0.079
LDI	0.5 ± 121.1	9.2 ± 25.0	121.4 ± 548.7	−66.3 ± 344.7	< 0.001*	0.156

*Represents statistical significance

Table 6 Preoperative PROMs of different mechanical complication groups

	PJK *N* = 47	DJK *N* = 4	Pseudarthrosis/ rod fracture *N* = 31	Implant failure *N* = 4	*p* value (4 groups)	*p* value (PJK vs. pseudo)
Preoperative, mean ± SD						
ODI	53.6 ± 11.5	36 ± 2.8	51.0 ± 11.8	67.0 ± 9.9	0.663	0.364
VAS-back	7.4 ± 2.0	6.0 ± 1.4	7.3 ± 2.2	7.0 ± 1.4	0.919	0.839
VAS-leg	7.0 ± 2.0	2.5 ± 3.5	6.5 ± 2.7	2.5 ± 3.5	0.420	0.362
EQ-5D	0.45 ± 0.21	0.61 ± 0.23	0.48 ± 0.22	0.25 ± 0.12	0.902	0.579

rod fracture had a higher reoperation rate than PJK, but similar time to reoperation. A meta-analysis of 26 studies reported an average time of 33.0 months to diagnose pseudarthrosis after ASD surgery [20], much longer than our current cohort (mean 21.8 months). Jung et al. [21] found a 9.2% revision rate following rod fractures after ASD surgery, and mean time to rod fracture of 27.3 ± 6.9 months (range 20–42 months), with no differences in demographic variables and radiological parameters when compared to patients without rod fractures. Similar revision rates for rod fractures were found in Yamato et al. [22] where 11.8% of the patients with rod fracture underwent reoperation. Both these values were significantly lower than our study, which may have been due to us grouping pseudarthrosis/rod fracture as one group. With respect to PJK, one study [23] compared the average onset of PJK in distal thoracic versus proximal thoracic surgery and found a significantly earlier onset of PJK in the distal thoracic group (65 ± 14 vs. 560 ± 322 days, $p < 0.01$). A systematic review performed by Lau et al. [24] indicated that 66% of PJK occurs within 3 months and 80% within 18 months after surgery, with reported revision rates ranging from 13 to 55%. Our reoperation rates for PJK were lower than for pseudarthrosis/rod fracture but higher than previously reported in the literature. Though our time to reoperation for PJK was 16.3 months, 20% of patients required reoperation within 6 months.

PJK patients had lower Hounsfield units, more prior fusions, and fewer instrumented levels than those with pseudarthrosis/rod fracture. While lower bone density is a well-known risk factor for PJK, the number of prior surgeries is not a well-described risk factor for PJK [25]. One potential explanation is that patients had several smaller operations leading to adjacent segment disease or PJK, without addressing the underlying malalignment and lack of distal lumbar lordosis. Moreover, if a patient had PJK once, they may be more likely to have it again during subsequent spine operations. Prior studies have shown that older age, number of fused vertebrae, and thoracic kyphosis > 20° are all considered risk factors for pseudarthrosis [26], and these factors are also closely associated with developing PJK. With respect to rod fractures, some studies suggest that failure to restore optimal sagittal alignment increases the risk of rod fracture [27]. Thus, appropriate correction of sagittal alignment is paramount to preventing pseudarthrosis by reducing stress in the screw/rod construct, and subsequently decreasing the odds of rod fractures [28–30].

PJK is a vexing complication even to the most expert deformity surgeons, and controversies exist surrounding the etiology of PJK. Risk factors for PJK include end vertebrae selection, facet violation proximal to UIV, significant soft tissue disruption, and loss of posterior tension band integrity [13, 31]. While some studies found no relationship between PJK and appropriateness of sagittal restoration [26, 32], others have found a higher risk of PJK after a large amount of correction due to potential overcorrection [23, 33]. In our study, although preoperative malalignment did not increase the odds of mechanical complications, higher postoperative TK and C7 SVA was found to be more associated with PJK compared to pseudarthrosis/rod fracture. Of note, postoperative TK and C7 SVA were recorded in the immediate postoperative period before the development of PJK. These results seem to agree with the literature, that persistent deformity, particularly a high postoperative TK, is a risk factor for PJK.

Newer areas to assess spinal alignment may hold promise for further study of mechanical complications. Yilgor et al. [12] found that the Global Alignment and Proportion (GAP) score accurately correlated with the development mechanical complications (AUC = 0.92, CI = 0.85–0.98, $p < 0.001$). Jacobs et al. [34] showed that the GAP score significantly predicted mechanical complications ($p = 0.003$) and proved to be superior compared with Schwab classification. Other studies found no association between the GAP score and the incidence of mechanical complications [35, 36]. Our study showed that the LDI—a component of the GAP score—had no difference in type of mechanical complications. While the GAP score may have utility in predicting the occurrence of a mechanical complication, it appeared to provide little assistance in distinguishing types of mechanical complications. The Roussouly classification has also been extensively studied in the context of mechanical complications after ASD surgery. Pizones et al. [37] performed a study on 96 patients with ASD and found that postoperative Roussouly-type mismatch (OR = 41.9; CI = 5.5–315.7; $p < 0.001$), iliac instrumentation (OR = 19.4; CI = 2.6–142.5; $p = 0.004$), and age (OR = 1.1; CI = 1.02–1.16; $p = 0.004$) are the most important predictors of mechanical complications. Whether the Roussouly classification can help predict different types of mechanical complication remains to be seen.

The current study has several limitations that are worth discussing. First, data was collected from a single institution, and sample size was relatively small for each type of mechanical complication. A larger, multi-center dataset may yield differing results as ASD practice patterns may vary between institutions. Second, only preoperative PROMs were retrieved and included in the analysis, as it was not clear in our registry if postoperative PROMs were recorded before or after the occurrence of mechanical complications. It would have been imprecise to compare PROMs between patients who encountered a reoperation with those who did not. Postoperative PROMs are an important component of assessing outcomes of ASD surgery and further studies are warranted to assess differences in PROMs following mechanical complications in ASD surgery. Third, we did not group the patients according to the follow-up period in aim of increasing the number of patients who encountered a mechanical complication or required reoperations with such a tight follow-up period (range 24.0–48.7). We included patients who only had 2-year follow-up. Fourth, we imposed strict inclusion criteria of having completed 2-year X-rays and 2-year PROMs, which led to a high exclusion and lost to follow-up rate of 153 patients. Though some variables were missing from the Supplementary Information, the baseline comparison provided between patients with and without 2-year follow-up showed that patients with 2-year follow-up had more comorbidities, which means that our analysis may have focused on more sick individuals with more comorbidities and undergoing more complex surgeries. Patients that were indeed lost to follow-up appeared to be a healthier, less complex population, which might have created a selection bias with a subsequent decreased generalizability of our findings. Other reasons contributing to the selection bias originate from having a greater proportion of males and revision surgeries in the non-attendant group, Fifth, we did not perform a separate analysis for patients with and without fusion to the sacrum or ilium, as the vast majority of patients (90.3%) being fused to the sacrum, and 77.9% having additional iliac screws below S1 screws. Sixth, we grouped PJK as a single entity regardless of severity, in keeping with prior literature [13, 24, 33, 38, 39, 39, 40], though this may bring forth some inaccuracy in reporting reoperations, as some PJKs are very mild and non-significant, and others can lead to PJF. Seventh, though the use of composite variables is rarely reproducible and difficult to interpret [41], combining pseudarthrosis with rod fracture seemed to be in accordance with previous literature [16, 18, 19], serving the purpose of increasing the sample size while preserving external validity. Eighth, we did not have a way of following patients who chose not to follow-up with their original surgeon. Several patients may have had complications and gone to another surgeon, and we had no way of obtaining this information. Future investigation should include prospective cohort studies with larger sample sizes, to discern further differences and provide additional insights of each type of mechanical complications following ASD surgery.

Conclusion

In a single-center, preliminary study of patients undergoing ASD surgery, those with mechanical complications had more comorbidities, higher rates of COPD, and higher preoperative NRS-leg pain compared to those without mechanical complications. Patients with pseudarthrosis/rod fracture had a higher rate of reoperation compared to patients with PJK, though time to reoperation was similar between both groups. Patients with PJK also had higher postoperative TK, lower preoperative Hounsfield Units, more prior fusions, and fewer instrumented levels compared to patients with pseudarthrosis/rod fracture. Preoperative PROMs were similar between all types of mechanical complications. Taken together, even though mechanical complications are often regarded as a single outcome, several important differences may exist between them.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43390-022-00576-8.

Author contributions HC, SGR: data curation, drafting the paper. MEL, AMS: design and execution of the formal analysis. JH: designed research, conceptualization, interpretation of the analysis. AMA, BFS: conducted review and editing. SLZ: designed research, data acquisition, conceptualization, interpretation of the analysis. Final approval of the version to be published. All authors are contributed effort to the study.

Funding This study did not receive funding from any institution or grant.

Declarations

Conflict of interest The other authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. The authors have no personal or institutional financial interest in drugs, materials, or devices described in their submissions.

Ethical approval This study was approved by the IRB committee at Vanderbilt University Medical Center (IRB#211290). We certify that the study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

References

1. Diebo BG, Shah NV, Boachie-Adjei O, Zhu F, Rothenfluh DA, Paulino CB, Schwab FJ, Lafage V (2019) Adult spinal deformity. Lancet 394:160–172. https://doi.org/10.1016/S0140-6736(19)31125-0
2. Youssef JA, Orndorff DO, Patty CA, Scott MA, Price HL, Hamlin LF, Williams TL, Uribe JS, Deviren V (2013) Current status of adult spinal deformity. Glob Spine J 3:51–62. https://doi.org/10.1055/s-0032-1326950
3. Ritter MA (2014) Commentary on "postoperative radiotherapy after radical prostatectomy for high-risk prostate cancer: long-term results of a randomised controlled trial (EORTC trial 22911)" Bolla M, van Poppel H, Tombal B, Vekemans K, Da Pozzo L, de Reijke TM, Verbaeys A, Bosset JF, van Velthoven R, Colombel M, van de Beek C, Verhagen P, van den Bergh A, Sternberg C, Gasser T, van Tienhoven G, Scalliet P, Haustermans K, Collette L; European Organisation for Research and Treatment of Cancer, Radiation Oncology and Genito-Urinary Groups. Department of Radiation Oncology, Centre Hospitalier Universitaire A Michallon, Grenoble, France.: Lancet 2012;380(9858):2018–27. doi: 10.1016/S0140-6736(12)61253-7. [Epub 2012 Oct 19]. Urol Oncol 32:372–373. https://doi.org/10.1016/j.urolonc.2013.09.023
4. Lafage V, Schwab F, Patel A, Hawkinson N, Farcy J-P (2009) Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. Spine 34:E599–E606. https://doi.org/10.1097/BRS.0b013e3181aad219
5. Daubs MD, Lenke LG, Cheh G, Stobbs G, Bridwell KH (2007) Adult spinal deformity surgery: complications and outcomes in patients over age 60. Spine 32:2238–2244. https://doi.org/10.1097/BRS.0b013e31814cf24a
6. 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 Group (2016) Medical complications after adult spinal deformity surgery: incidence, risk factors, and clinical impact. Spine 41:1718–1723. https://doi.org/10.1097/BRS.0000000000001636
7. Scheer JK, Tang JA, Smith JS, Klineberg E, Hart RA, Mundis GM, Burton DC, Hostin R, O'Brien MF, Bess S, Kebaish KM, Deviren V, Lafage V, Schwab F, Shaffrey CI, Ames CP, International Spine Study Group (2013) Reoperation rates and impact on outcome in a large, prospective, multicenter, adult spinal deformity database: clinical article. J Neurosurg Spine 19:464–470. https://doi.org/10.3171/2013.7.SPINE12901

8. Yadla S, Maltenfort MG, Ratliff JK, Harrop JS (2010) Adult scoliosis surgery outcomes: a systematic review. Neurosurg Focus 28:E3. https://doi.org/10.3171/2009.12.FOCUS09254
9. Sebaaly A, Gehrchen M, Silvestre C, Kharrat K, Bari TJ, Kreichati G, Rizkallah M, Roussouly P (2020) Mechanical complications in adult spinal deformity and the effect of restoring the spinal shapes according to the Roussouly classification: a multicentric study. Eur Spine J 29:904–913. https://doi.org/10.1007/s00586-019-06253-1
10. Yagi M, Hosogane N, Fujita N, Okada E, Suzuki S, Tsuji O, Nagoshi N, Nakamura M, Matsumoto M, Watanabe K (2020) The patient demographics, radiographic index and surgical invasiveness for mechanical failure (PRISM) model established for adult spinal deformity surgery. Sci Rep 10:9341. https://doi.org/10.1038/s41598-020-66353-7
11. Schreiber JJ, Anderson PA, Rosas HG, Buchholz AL, Au AG (2011) Hounsfield units for assessing bone mineral density and strength: a tool for osteoporosis management. J Bone Jt Surg Am 93:1057–1063. https://doi.org/10.2106/JBJS.J.00160
12. Yilgor C, Sogunmez N, Boissiere L, Yavuz Y, Obeid I, Kleinstück F, Pérez-Grueso FJS, Acaroglu E, Haddad S, Mannion AF, Pellise F, Alanay A (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. JBJS 99:1661–1672. https://doi.org/10.2106/JBJS.16.01594
13. Glattes RC, Bridwell KH, Lenke LG, Kim YJ, Rinella A, Edwards C (2005) Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: incidence, outcomes, and risk factor analysis. Spine 30:1643–1649. https://doi.org/10.1097/01.brs.0000169451.76359.49
14. Hart RA, McCarthy I, Ames CP, Shaffrey CI, Hamilton DK, Hostin R (2013) Proximal junctional kyphosis and proximal junctional failure. Neurosurg Clin N Am 24:213–218. https://doi.org/10.1016/j.nec.2013.01.001
15. Barton C, Noshchenko A, Patel V, Cain C, Kleck C, Burger E (2015) Risk factors for rod fracture after posterior correction of adult spinal deformity with osteotomy: a retrospective case-series. Scoliosis 10:30. https://doi.org/10.1186/s13013-015-0056-5
16. Merrill RK, Kim JS, Leven DM, Kim JH, Cho SK (2017) Multi-rod constructs can prevent rod breakage and pseudarthrosis at the lumbosacral junction in adult spinal deformity. Glob Spine J 7:514–520. https://doi.org/10.1177/2192568217699392
17. Jung J, Hyun S-J, Kim K-J, Jahng T-A (2019) Rod fracture after multiple-rod constructs for adult spinal deformity. J Neurosurg Spine 32:407–414. https://doi.org/10.3171/2019.9.SPINE19913
18. Bourghli A, Boissière L, Kieser D, Larrieu D, Pizones J, Alanay A, Pellise F, Kleinstück F, Obeid I, European Spine Study Group (2021) Multiple-rod constructs do not reduce pseudarthrosis and rod fracture after pedicle subtraction osteotomy for adult spinal deformity correction but improve quality of life. Neurospine 18:816–823. https://doi.org/10.14245/ns.2142596.298
19. Dinizo M, Srisanguan K, Dolgalev I, Errico TJ, Raman T (2021) Pseudarthrosis and rod fracture rates after transforaminal lumbar interbody fusion at the caudal levels of long constructs for adult spinal deformity surgery. World Neurosurg 155:e605–e611. https://doi.org/10.1016/j.wneu.2021.08.099
20. How NE, Street JT, Dvorak MF, Fisher CG, Kwon BK, Paquette S, Smith JS, Shaffrey CI, Ailon T (2019) Pseudarthrosis in adult and pediatric spinal deformity surgery: a systematic review of the literature and meta-analysis of incidence, characteristics, and risk factors. Neurosurg Rev 42:319–336. https://doi.org/10.1007/s10143-018-0951-3
21. Jung J-M, Hyun S-J, Kim K-J, Jahng T-A (2019) Rod fracture after multiple-rod constructs for adult spinal deformity. J Neurosurg Spine. https://doi.org/10.3171/2019.9.SPINE19913
22. Yamato Y, Hasegawa T, Kobayashi S, Yasuda T, Togawa D, Yoshida G, Banno T, Oe S, Mihara Y, Matsuyama Y (2018) Treatment strategy for rod fractures following corrective fusion surgery in adult spinal deformity depends on symptoms and local alignment change. J Neurosurg Spine 29:59–67. https://doi.org/10.3171/2017.9.SPINE17525
23. Ha Y, Maruo K, Racine L, Schairer WW, Hu SS, Deviren V, Burch S, Tay B, Chou D, Mummaneni PV, Ames CP, Berven SH (2013) Proximal junctional kyphosis and clinical outcomes in adult spinal deformity surgery with fusion from the thoracic spine to the sacrum: a comparison of proximal and distal upper instrumented vertebrae: clinical article. J Neurosurg Spine 19:360–369. https://doi.org/10.3171/2013.5.SPINE12737
24. Lau D, Clark AJ, Scheer JK, Daubs MD, Coe JD, Paonessa KJ, LaGrone MO, Kasten MD, Amaral RA, Trobisch PD, Lee J-H, Fabris-Monterumici D, Anand N, Cree AK, Hart RA, Hey LA, Ames CP, Adult Spinal Deformity Committee SRS (2014) Proximal junctional kyphosis and failure after spinal deformity surgery: a systematic review of the literature as a background to classification development. Spine 39:2093–2102. https://doi.org/10.1097/BRS.0000000000000627
25. Leven D, Cho SK (2016) Pseudarthrosis of the cervical spine: risk factors, diagnosis and management. Asian Spine J 10:776–786. https://doi.org/10.4184/asj.2016.10.4.776
26. Kim YJ, Bridwell KH, Lenke LG, Rinella AS, Edwards C, Edward C (2005) Pseudarthrosis in primary fusions for adult idiopathic scoliosis: incidence, risk factors, and outcome analysis. Spine 30:468–474. https://doi.org/10.1097/01.brs.0000153392.74639.ea
27. Lee KY, Lee J-H, Kang K-C, Im S-K, Lim HS, Choi SW (2021) Strategies for prevention of rod fracture in adult spinal deformity: cobalt chrome rod, accessory rod technique, and lateral lumbar interbody fusion. J Neurosurg Spine. https://doi.org/10.3171/2020.8.SPINE201037
28. Guler UO, Cetin E, Yaman O, Pellise F, Casademut AV, Sabat MD, Alanay A, Grueso FSP, Acaroglu E, European Spine Study Group (2015) Sacropelvic fixation in adult spinal deformity (ASD); a very high rate of mechanical failure. Eur Spine J 24:1085–1091. https://doi.org/10.1007/s00586-014-3615-1
29. Pateder DB, Park Y-S, Kebaish KM, Cascio BM, Buchowski JM, Song EW, Shapiro MB, Kostuik JP (2006) Spinal fusion after revision surgery for pseudarthrosis in adult scoliosis. Spine 31:E314–E319. https://doi.org/10.1097/01.brs.0000217619.57333.96
30. Cho W, Mason JR, Smith JS, Shimer AL, Wilson AS, Shaffrey CI, Shen FH, Novicoff WM, Fu K-MG, Heller JE, Arlet V (2013) Failure of lumbopelvic fixation after long construct fusions in patients with adult spinal deformity: clinical and radiographic risk factors: clinical article. J Neurosurg Spine 19:445–453. https://doi.org/10.3171/2013.6.SPINE121129
31. Denis F, Sun EC, Winter RB (2009) Incidence and risk factors for proximal and distal junctional kyphosis following surgical treatment for Scheuermann kyphosis: minimum five-year follow-up. Spine 34:E729–E734. https://doi.org/10.1097/BRS.0b013e3181ae2ab2
32. Lee C-S, Park J-S, Nam Y, Choi Y-T, Park S-J (2020) Long-term benefits of appropriately corrected sagittal alignment in reconstructive surgery for adult spinal deformity: evaluation of clinical outcomes and mechanical failures. J Neurosurg Spine. https://doi.org/10.3171/2020.7.SPINE201108
33. Kim DK, Kim JY, Kim DY, Rhim SC, Yoon SH (2017) Risk factors of proximal junctional kyphosis after multilevel fusion surgery: more than 2 years follow-up data. J Korean Neurosurg Soc 60:174–180. https://doi.org/10.3340/jkns.2016.0707.014
34. Jacobs E, van Royen BJ, van Kuijk SMJ, Merk JMR, Stadhouder A, van Rhijn LW, Willems PC (2019) Prediction of mechanical complications in adult spinal deformity surgery-the GAP score

versus the Schwab classification. Spine J 19:781–788. https://doi.org/10.1016/j.spinee.2018.11.013
35. Baum GR, Ha AS, Cerpa M, Zuckerman SL, Lin JD, Menger RP, Osorio JA, Morr S, Leung E, Lehman RA, Sardar Z, Lenke LG (2020) Does the global alignment and proportion score overestimate mechanical complications after adult spinal deformity correction? J Neurosurg Spine 34:96–102. https://doi.org/10.3171/2020.6.SPINE20538
36. Bari TJ, Ohrt-Nissen S, Hansen LV, Dahl B, Gehrchen M (2019) Ability of the global alignment and proportion score to predict mechanical failure following adult spinal deformity surgery-validation in 149 patients with two-year follow-up. Spine Deform 7:331–337. https://doi.org/10.1016/j.jspd.2018.08.002
37. Pizones J, Moreno-Manzanaro L, Sánchez Pérez-Grueso FJ, Vila-Casademunt A, Yilgor C, Obeid I, Alanay A, Kleinstück F, Acaroglu ER, Pellisé F, ESSG European Spine Study Group (2020) Restoring the ideal Roussouly sagittal profile in adult scoliosis surgery decreases the risk of mechanical complications. Eur Spine J 29:54–62. https://doi.org/10.1007/s00586-019-06176-x
38. Lee J, Park Y-S (2016) Proximal junctional kyphosis: diagnosis, pathogenesis, and treatment. Asian Spine J 10:593–600. https://doi.org/10.4184/asj.2016.10.3.593
39. Kim YJ, Bridwell KH, Lenke LG, Glattes CR, Rhim S, Cheh G (2008) Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion: minimum five-year follow-up. Spine 33:2179–2184. https://doi.org/10.1097/BRS.0b013e31817c0428
40. Im S-K, Lee J-H, Kang K-C, Shin SJ, Lee KY, Park JJ, Kim MH (2020) Proximal junctional kyphosis in degenerative sagittal deformity after under- and overcorrection of lumbar lordosis: does overcorrection of lumbar lordosis instigate PJK? Spine 45:E933–E942. https://doi.org/10.1097/BRS.0000000000003468
41. Pocock SJ, Stone GW (2016) The primary outcome is positive—is that good enough? N Engl J Med 375:971–979. https://doi.org/10.1056/NEJMra1601511