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CLINICAL ARTICLE

Clinical outcomes and proximal junctional failure in adult spinal deformity patients corrected to normative alignment versus functional alignment

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OBJECTIVE The objective of this study was to explore the rate of proximal junctional failure (PJF) and functional outcomes of normative alignment goals compared with alignment targets based on age-appropriate physical function.

METHODS Baseline relationships between age, pelvic incidence (PI), and a component of the T1 pelvic angle (TPA) within the fusion were analyzed in adult spinal deformity (ASD) patients and compared with those of asymptomatic patients. Linear regression modeling was used to determine alignment based on PI and age in asymptomatic patients (normative alignment), and in ASD patients, alignment corresponding to age-appropriate functional status (functional alignment). A cohort of 288 ASD patients was split into two groups based on whether the patient was closer to their normative or functional alignment goal at their 6-week postoperative radiographic follow-up. The rates of proximal junctional kyphosis (PJK) and PJF were determined for each cohort.

RESULTS In the 288 ASD patients included in this pre- to postoperative analysis, there was no difference in baseline alignment or health-related quality of life (HRQOL) between the normative alignment and functional alignment groups. At 6 weeks, patients with normative alignment had a smaller TPA (4.45° vs 14.1°) and PI minus lumbar lordosis (−7.24° vs 7.4°) (both $p < 0.0001$) and higher PJK (40% vs 27.2%, $p = 0.03$) and PJF (17% vs 6.8%, $p = 0.008$) rates than patients with functional alignment.

CONCLUSIONS Correction in ASD patients to normative alignment resulted in higher rates of PJK and PJF without improvements in HRQOL. Correction in ASD patients to functional alignment that mirrors the physical function of their age-matched asymptomatic peers is recommended.

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KEYWORDS proximal junctional kyphosis; PJK; proximal junctional failure; PJF; alignment; spine deformity; pelvic incidence; age; normative; functional; health-related quality of life; HRQOL; patient-reported outcome measure; PROM

ABBREVIATIONS ASA = American Society of Anesthesiologists; ASD = adult spinal deformity; HRQOL = health-related quality of life; ODI = Oswestry Disability Index; PCS = Physical Component Summary; PI = pelvic incidence; PI-LL = PI minus lumbar lordosis; PJF = proximal junctional failure; PJK = proximal junctional kyphosis; PT = pelvic tilt; SRS = Scoliosis Research Society; SVA = sagittal vertical axis; TK = thoracic kyphosis; TPA = T1 pelvic angle; T4PA = T4 pelvic angle; UIV = upper instrumented vertebra.

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Adult spinal deformity (ASD) is a chronic, debilitating disorder associated with pain and functional disability, even after corrective surgery. The degree of instrumentation and fusion has profound effects on a patient's ability to complete activities of daily living, including basic hygiene, dressing oneself, and social activities.[1] Undercorrecting a deformity can lead to severe disability from compensatory mechanisms the body enlists to maintain positioning; conversely, aggressive realignment surgery has been shown to result in mechanical complications such as proximal junctional kyphosis (PJK) or proximal junctional failure (PJF).[2,3] PJK is a mechanical complication of spinal realignment surgery that may lead to continued disability and subjects the patient to high rates of surgical revision. Several studies have identified significant risk factors, particularly increased age and overcorrection.[4–8]

As medicine continues to transition into an age of personalized care, there is continued recognition that elderly individuals may not require the aggressive realignment that a younger patient may need.[9] With the goal of improving patient satisfaction, several studies have proposed targeted ASD alignment parameters that correlate with increased health-related quality-of-life (HRQOL) outcome scores. However, there has been no clear consensus on proper corrective alignment for patients with ASD. One school of thought focuses on the use of normative alignment, which has been calculated from an asymptomatic cohort, to assess overcorrections and predict complications in ASD surgery.[10] Another recommends alignment that is based on age-appropriate physical function in combination with individual pelvic incidence (PI) to reduce PJK and PJF.[3,11]

Differences in functional outcomes and PJK between these alignments have not been fully explored. Despite the focus on patient-centered outcomes, there has yet to be a clear assessment of clinical significance between these alignment goals. The purpose of this study was to compare clinical outcomes and rates of PJK and PJF in ASD patients after surgical correction to normative alignment or age- and PI-associated functional alignment. Using a component of T1 pelvic angle (TPA) within the fusion, the T4 pelvic angle (T4PA), allows for measurement of spinopelvic alignment separate from that of the unfused thoracic spine and any PJK that may occur postoperatively. This study uses T4PA to compare normative alignment and age- and PI-associated functional alignment targets in terms of PJK, PJF, and HRQOL measures.

Methods

Study Design

This study was a retrospective analysis of prospectively collected data from ASD patients conducted through a collaboration of spine surgeons from 11 sites across the US. Patients were enrolled through an IRB-approved protocol at each site. Patients older than 18 years of age were retrospectively included if they underwent three-column osteotomy or prospectively enrolled if they had radiographic evidence of spinal deformity (coronal Cobb angle ≥ 20°, sagittal vertical axis [SVA] ≥ 5 cm, pelvic tilt [PT] ≥ 25°, or thoracic kyphosis [TK] ≥ 60°). Criteria for inclusion were patients who underwent surgical fusion to T4 and in whom 36-inch standing radiographs were obtained at baseline and 6 weeks and 2 years of follow-up. For the present study, all patients also had HRQOL outcomes available at baseline and 2 years of follow-up. Patients were excluded if they had a neuromuscular, traumatic, infectious, or malignant cause of scoliosis.

Radiographic Analysis and Data Collection

Data collection at baseline included standardized HRQOL questionnaires as well as clinical, demographic, and radiographic information. Basic demographic and clinical data included patient age, sex, BMI, smoking status, American Society of Anesthesiologists (ASA) Physical Status Classification, and history of prior spine surgery. In all patients, 36-inch standing scoliosis radiographs were obtained for which the patients had no external support, such as walkers. All radiographic measurements were performed at a location using standard techniques for establishing parameters. Radiographic analysis was performed on baseline radiographs using dedicated and validated software (SpineView and SpineLab, ENSAM).[12,13] The radiographic parameters recorded included T4PA, PT, and PI minus lumbar lordosis (PI-LL). For this study, PJK was defined according to the system of Glattes et al.,[14] kyphotic angle > 10° between the upper instrumented vertebra (UIV) and UIV+2, and PJF was defined as severe PJK (kyphotic change > 21.6°), UIV listhesis, or proximal junctional fracture.[31]

HRQOL assessment tools included the Oswestry Disability Index (ODI), Scoliosis Research Society (SRS)–22, and SF-36 questionnaires. Two standard summary scores were calculated based on the SF-36 Physical Component Summary (PCS) score. The SRS-22 provides a summary score and multiple subdomains, including activity, pain, appearance, mental, and satisfaction.

Asymptomatic Patient Population

A cohort of 118 asymptomatic patients was analyzed. These patients had no back pain, neck pain, or complaints related to postural deformity.[11] Associations were assessed between alignment, age, and PI. Linear regression analysis was performed on their T4PA, age, and PI to determine normative T4PA values for different PI and age categories.

Statistical Analysis

Baseline relationships between age, PI, and T4PA were analyzed in the ASD patients and compared with those of the asymptomatic patients. Linear regression modeling was used to determine functional alignment corresponding to age-appropriate functional status in ASD patients. Spinal deformity patients with UIV above T4 were grouped based on their corrections: normative versus functional. Each patient had two individual T4PA realignment goals, a normative T4PA goal based on an asymptomatic population and a functional T4PA goal based on age-adjusted physical function scores. If the postoperative alignment achieved at 6 weeks was up to the midpoint between normative and functional alignment, we considered these

TABLE 1. T4PA values in asymptomatic patients for normative alignment stratified by age and PI

PI	Age, yrs				
	40	50	60	70	80
35°	−3.855°	−2.005°	−0.155°	1.695°	3.545°
45°	0.135°	1.985°	3.835°	5.685°	7.535°
55°	4.125°	5.975°	7.825°	9.675°	11.525°
65°	8.115°	9.965°	11.815°	13.665°	15.515°
75°	12.105°	13.955°	15.805°	17.655°	19.505°

patients to have normative alignment per the normative target. If the postoperative alignment achieved at 6 weeks was higher than the midpoint between normative and functional alignment, we considered these patients to have functional alignment per the functional target. Patients with extreme over- or undercorrection were excluded (> 2 SDs from the mean postoperative T4PA). Baseline demographics, HRQOL, radiographic parameters, and rates of PJK and PJF were compared among the two cohorts using the t-test and chi-square analysis, where appropriate, with significance set to $p < 0.05$.

Results

Linear Regression Analyses

In total, 118 asymptomatic patients (68.1% female, mean age 50.7 ± 17.0 years, mean BMI 28.0 ± 6.0 kg/m^2) were analyzed in a multilinear regression model to determine normative alignment based on T4PA, PI, and age. T4PA was found to correlate with age and PI, generating the following formula: normative T4PA = –25.22 + 0.399 × PI + 0.185 × age ($r = 0.713$, $r^2 = 0.51$, $p < 0.001$). Table 1 provides these T4PA alignment values stratified by age and PI.

A total of 1916 ASD patients (72.2% female, mean age 60.9 ± 14.1 years, mean BMI 28.2 ± 6.0 kg/m^2) were included in the development of our functional alignment formula. The linear relationships among T4PA, PI, and age were used to generate a regression model using the age-readjusted PCS formula (PCSnorm = 66.68 – 0.35 × age) from the published US normative values of SF-36 to derive the following equation: functional T4PA = 0.45 × PI – 0.43 × PCSnorm + 6.85 ($r = 0.6$, $r^2 = 0.36$, $p < 0.001$).

TABLE 2. T4PA values in ASD patients for functional alignment stratified by age-adjusted PCS score and PI

PI	Age-Adjusted Normative PCS Score*				
	52.58°	49.08°	45.58°	42.08°	38.58°
35°	−0.0094°	1.4956°	3.0006°	4.5056°	6.0106°
45°	4.4906°	5.9956°	7.5006°	9.0056°	10.5106°
55°	8.9906°	10.4956°	12.0006°	13.5056°	15.0106°
65°	13.4906°	14.9956°	16.5006°	18.0056°	19.5106°
75°	17.9906°	19.4956°	21.0006°	22.5056°	24.0106°

* The age-adjusted PCS scores are for 40, 50, 60, 70, and 80 years, respectively.

TABLE 3. Baseline demographic data, radiographic parameters, and patient-reported outcomes

	Normative Alignment Group (n = 137)	Functional Alignment Group (n = 151)	p Value
Mean BMI, kg/m^2	26.7	27.2	0.46
Mean ASA class	2.4	2.2	0.059
Female sex	84.7	77.5	0.12
Smoker	3.8	7.6	0.167
Diabetes	2.9	6.0	0.22
Hypertension	27.7	29.1	0.8
Lung disease	4.6	3.6	0.68
Osteoporosis	22.6	13.2	**0.04**
Prior spine surgery	35.6	41.7	0.285
Mean PI-LL, °	10.4	11.33	0.72
Mean PT, °	22.46	22.69	0.85
Mean T4PA, °	16.72	17.55	0.61
Mean ODI	42.66	36.87	0.24
Mean SF-36 PCS score	33.11	34.08	0.47
Mean SRS-22 score	2.78	2.81	0.71

Values are given as percentages unless otherwise indicated. Boldface type indicates statistical significance.

Table 2 provides these T4PA alignment values stratified by age-adjusted PCS score and PI.

Functional Versus Normative Alignment

A total of 304 ASD patients were evaluated. Of these, 16 were excluded for having a postoperative T4PA > 2 SDs from the mean. Thus, 288 ASD patients were included in the pre- to postoperative analysis (137 in the normative alignment group and 151 in the functional alignment group); there was no difference in baseline alignment or HRQOL between the groups (Table 3). Patients in the functional alignment cohort were less likely to have osteoporosis (13.2% vs 22.6%, $p = 0.04$) than patients with normative alignment. No other differences in comorbidities were observed. A comparison of patients excluded from the study with those who were included is shown in Table 4.

Patients in the functional alignment cohort were equally likely to have undergone pedicle subtraction osteotomy (17.1% vs 17.9%, $p = 0.88$) and vertebral column resection (9.5% vs 11.1%, $p = 0.69$) as patients in the normative alignment cohort. Moreover, the average number of Ponte osteotomies was similar in both the functional and normative alignment groups (5.7 vs 5.4, $p = 0.5$). Similarly, use of PJK prophylaxis was observed to be uniform between the functional and normative alignment cohorts (39.1% vs 47.4%, $p = 0.15$). The PJK prophylaxes most commonly used were hooks (28.8%), tethers (10.1%), and hybrid (3.1%).

At 6 weeks postoperatively (Table 5), the normative alignment group had smaller T4PA (4.5° vs 14.1°, $p < 0.001$) and PI-LL (–7.2° vs 7.4°, $p < 0.001$). A Pearson chi-square analysis revealed that patients with normative

TABLE 4. Comparison of patients excluded for overcorrection or undercorrection (> 2 SDs from mean postoperative T4PA) with those included in the study

	Excluded Patients	Included Patients	p Value
Total no. of patients	16	228	
Mean age, yrs	57.9 ± 16.3	55.1 ± 16.4	0.51
Mean BMI, kg/m^2	26.9 ± 4.6	26.9 ± 6.0	0.98
Mean ASA class	2.3 ± 0.6	2.3 ± 0.7	0.78
Female sex	81.3	80.9	0.97
Smoker	12.5	5.2	0.33
Diabetes	0	4.5	0.39
Hypertension	18.8	28.5	0.4
Lung disease	6.3	4.2	0.69
Osteoporosis	12.5	17.7	0.59
Prior spine surgery	43.8	38.9	0.7
PI-LL, °	27.6 ± 38.9	10.9 ± 22.6	0.12
PT, °	31.9 ± 22.0	22.6 ± 11.4	0.11
T4PA, °	26.6 ± 25.2	17.2 ± 14.1	0.17
ODI	42.66 ± 19.1	41.2 ± 19.9	0.85
SF-36 PCS score	31.5 ± 7.6	33.7 ± 11.5	0.49
SRS-22 score	2.83 ± 0.7	2.80 ± 0.6	0.88

Values are given as mean ± SD or percentage unless otherwise indicated.

TABLE 6. Six-week postoperative radiographic parameters in patients with and those without PJK

Radiographic Parameter for Those w/o PJK	Normative (n = 82)	Functional (n = 110)	p Value
T4PA, °	4.1 ± 6.4	13.4 ± 8.1	0.001
PI-LL, °	−8.0 ± 9.4	6.7 ± 12.2	0.001
PT, °	12.7 ± 7.3	20.9 ± 9.4	0.001
TK, °	40.4 ± 15.1	38.5 ± 15.5	0.4
LL, °	60.8 ± 9.1	45.5 ± 12.2	0.001
SVA, mm	−5.6 ± 37.5	28.2 ± 48.0	0.001
TPA, °	7.4 ± 6.7	16.9 ± 8.1	0.001
Radiographic Parameter for Those w/ PJK	**Normative (n = 55)**	**Functional (n = 41)**	**p Value**
T4PA, °	5.4 ± 6.2	15.5 ± 6.2	0.001
PI-LL, °	−5.6 ± 8.9	8.8 ± 8.4	0.001
PT, °	15.7 ± 7.7	24.6 ± 8.4	0.001
TK, °	44.0 ± 13.3	37.6 ± 17.8	0.048
LL, °	61.1 ± 10.0	47.2 ± 11.7	0.001
SVA, mm	−2.2 ± 33.8	29.9 ± 38.0	0.001
TPA, °	9.7 ± 6.4	19.6 ± 6.2	0.001

LL = lumbar lordosis.
Values are given as mean ± SD unless otherwise indicated.

alignment developed higher rates of PJK (40% vs 27.2%, p = 0.03; OR 0.56, 95% CI 0.34–0.92) than the functionally aligned cohort at 6 weeks, but no difference was seen at 2 years postoperatively (48.1% vs 37.3%, p = 0.073). Patients with osteoporosis were found to have similar rates of PJK at both 6 weeks (42.2% vs 32.3%, p = 0.2) and 2 years (50.0% vs 42.1%, p = 0.35) postoperatively. A comparison of the radiographic characteristics of those who did and did not develop PJK between groups is shown in Table 6.

Rates of PJF were higher in the patients with normative alignment (17% vs 6.8%, p = 0.008) than in those with functional alignment. Patients who developed PJF had a mean T4PA offset of –1.2° ± 6.8° from normative alignment and –5.2° ± 6.9° from functional alignment. In contrast, patients without PJF had a mean T4PA offset of 3.9° ± 7.2° from normative alignment and –0.42° ± 7.1° from functional alignment. A greater or positive T4PA offset indicates a more anterior alignment; conversely, a lower or negative offset indicates a more posterior alignment. There was a trend toward worse 2-year SF-36 PCS scores in patients who developed PJF (37.7 vs 41.6, p = 0.09). No other differences in HRQOL were seen between patients with PJF and those without PJF (2-year ODI, 2-year SRS-22 score, ΔODI, and ΔSRS-22 score). The normative and functional alignment groups both showed improvement in outcomes from baseline to the 2-year follow-up (p < 0.001), with no difference in 2-year HRQOL measures.

TABLE 5. Six-week postoperative radiographic parameters

Radiographic Parameter	Normative Alignment Group (n = 137)	Functional Alignment Group (n = 151)	p Value
T4PA, °	4.5	14.1	<0.0001
PI-LL, °	−7.2 ± 9.4	7.4 ± 11.1	<0.0001
PT, °	13.9 ± 7.5	21.8 ± 9.5	<0.0001

Values are given as mean ± SD unless otherwise indicated.

Discussion

The primary goal of realignment surgery is to relieve a patient's symptoms of sagittal malalignment and maximize their cone of economy. Dubousset's cone of economy is frequently discussed in the setting of ASD because it conveys the idea that ideal spinal alignment maintains standing posture with minimal muscular energy expenditure. Deviation of alignment exponentially increases the amount of energy required for one to sustain horizontal gaze and posture; thus, patients with ASD expend a majority of their energy to remain upright. Many patients, particularly elderly individuals, may not have the energy to maintain posture; thus, their alteration in global sagittal alignment drives recruitment of the body's compensatory mechanisms. Individual patient characteristics such as age, sex, and race/ethnicity relate to which compensatory mechanisms their body chooses to alleviate the mechanical load. For example, males have been shown to use more knee flexion, while females tend to use more PT and hip extension.[15,16] Surgical treatment of ASD serves to correct such compensatory mechanisms and achieve proper sagittal alignment in patients; however, the determinants of proper alignment are debated.

With the help of technology, the planning of surgical correction continues to transition toward a personally tailored operation. Each patient poses a particular challenge,

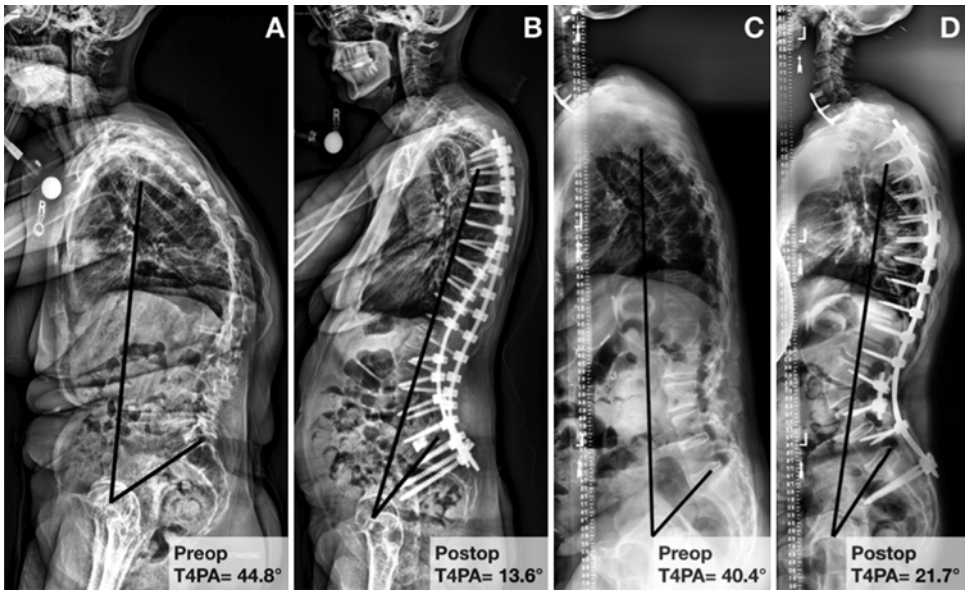

FIG. 1. Preoperative (**A**) and postoperative (**B**) 36-inch standing radiographs obtained in a 63-year-old patient who underwent T3–S1/ilium fusion with correction close to normative alignment (T4PA offset from normative = −0.48°), resulting in PJK/PJF. Preoperative (**C**) and postoperative (**D**) 36-inch standing radiographs obtained in a 65-year-old patient who underwent T3–S1/ilium fusion with correction close to functional alignment (T4PA offset from functional = 0.11°), resulting in no PJK/PJF.

and their personal needs and goals of care may not fit in to what may be considered normal alignment. For instance, there are ASD patients who experience significant clinical improvement following surgery despite not meeting normative alignment criteria, and equally, there are patients in whom the correction may seem to be well aligned, but they experience limitations in functional activity. Correction of spinal alignment should focus on alleviating pain and improving physical function while reducing the risk of complications. Our results suggest that it may not be necessary for older individuals to undergo correction to normative alignment to clinically benefit from surgery; in fact, doing so may lead to a higher rate of PJF.

Alignment targets that incorporate normative parameters such as the global alignment and proportion (GAP) score developed by Yilgor et al. have been shown to predict PJK/PJF with high specificity; however, the GAP score has been demonstrated to have inherently low sensitivity.[10,17] Moreover, external validation studies have demonstrated the overall poor generalization of the score to other populations.[18,19] The use of such methods has driven spinal correction toward mirroring that of asymptomatic individuals, a threshold that may be too extreme for certain patients, particularly those who are older and more frail. Not only does correction to normative alignment subject a patient to a more rigorous operation and the risks that come with it, but it may result in a higher rate of PJF when compared with correction to functional alignment. Because of their reliance on spinal radiographic parameters, normative alignment goals cannot account for enough of a patient's individual characteristics. For example, patient lifestyle should be considered in preparation for surgery. A patient's longevity is heavily associated with their physical activity.[20,21] Overcorrecting alignment in such a way that limits a patient's physical ability to walk, stand, or engage in social activities may decrease their overall quality of life. Furthermore, geographic location, race/ethnicity, and BMI have been shown to play a role in radiographic spinopelvic disability thresholds, suggesting that surgeons should recognize each individual's needs when planning correction.[22,23]

Past literature has revealed that realignment targets should be tailored to patient age and PI.[3,11,24] Although both age and PI are used in determining functional alignment, PI is the primary driver, with a coefficient 150% larger than that for age. The current study provides evidence that normative alignment thresholds do not contribute to clinical improvement in a patient's physical function compared with patients in whom functional alignment is performed. When examining the results, patients with normative alignment underwent significantly greater correction as measured by T4PA and PI-LL than those with functional alignment and went on to develop higher rates of PJK and PJF. Specifically, patients who developed PJF after normative alignment had a T4PA offset that was adjacent to their target. Figure 1 shows the preoperative and postoperative radiographs for 2 patients, one with normative alignment correction and the other with functional alignment correction. Compared with patients in the functional alignment group who subsequently developed PJF, the T4PA offset for the patient in whom normative alignment correction was performed was several degrees away from the target, suggesting that proper functional alignment was not achieved in this patient (Fig. 1A and B). Additionally, those in the functional alignment cohort who did not go on to develop PJF were found to have a T4PA offset near their goal. Conversely, it has also been shown that the relaxed age- and PI-associated alignment targets will not result in the rate of undercorrection being increased in these patients, which reaffirms that normative

planning techniques for ASD surgery may be too aggressive without providing any clinical benefit to the patient. One should note that although the HRQOL was lower for patients who developed PJK than for those who did not, this difference was not statistically significant. This finding may strengthen the argument that HRQOL scores are not as correlated to alignment goals as previous literature claims, but this could also be because of a lower power analysis.[25]

It has been shown that patients with osteoporosis have lower bone density, which can lead to spinal instability and accelerate the development of PJK. In a retrospective cohort study of elderly patients who underwent correction and fusion surgery for ASD, the mean bone density measured using lumbar dual-energy x-ray absorptiometry and spinal CT was found to be associated with revision surgery for PJK or additional vertebral fracture.[26] Although patients in the normatively aligned cohort were found to have an increased rate of osteoporosis than those with functional alignment, a subsequent analysis comparing patients with osteoporosis with those without demonstrated no difference in the rate of PJK. In addition, the use of PJK prophylaxis seemed to have no effect on the development of this complication, suggesting that there is a great deal of complexity surrounding PJK and indicating that further investigation is necessary to fully understand its multifaceted nature.

The use of age- and HRQOL-adjusted goals of measurement in spinal deformity is not novel. Over the past decade, some surgeons have continued to investigate the benefit of including quality-of-life outcomes and patient-specific metrics into spinal alignment goals.[27,28] The SRS-Schwab classification was among the first used for this purpose and has shown great intra- and interobserver reliability.[29,30] More recently, the sagittal age-adjusted score for ASD continues the trend toward a focus on patient-reported outcomes.[28] As with the literature above, we hope the present study emphasizes the importance of incorporating a patient's individual needs and functional outcomes into their alignment goals.

Although prospectively collected radiographic and HRQOL data were used, the primary limitation of the study is its retrospective design, which subjects the data and analysis to inherent biases of the researchers. This study used published age-specific normative values for the SF-36 PCS score and data from a multicenter database of ASD patients to determine the alignments that would correspond to the expected functional status of their similarly aged peers. The SF-36 is a health outcome measure that has been used to quantify health status in many different diseases. Since normative data are available for patients of different ages, the SF-36 can be used to compare patients with a specific pathology, in this case ASD, with their age-matched asymptomatic peers. Although this methodology has its flaws, there are few tools to appropriately quantify functional outcomes in such a population.

Conclusions

Current medical technology continues to focus on developing a tailored approach to each patient. Despite this, some alignment guidelines have continued to be based on parameters seen in a heterogeneous and asymptomatic population. Similar to the SRS-Schwab classification and sagittal age-adjusted score for ASD, our results contribute to the evidence that surgical planning should be based on individual characteristics of the patient, particularly age and PI. The alignment of patients with ASD should not be corrected to match the alignment of their asymptomatic unfused peers; rather, functional realignment to match age-appropriate physical function should be performed. This will lead to no change in patient quality of life but reduce the rate of PJF.

References

1. Sciubba DM, Scheer JK, Smith JS, et al. Which daily functions are most affected by stiffness following total lumbar fusion: comparison of upper thoracic and thoracolumbar proximal endpoints. *Spine (Phila Pa 1976)*. 2015;40(17):1338-1344.
2. Scheer JK, Lafage R, Schwab FJ, et al. Under correction of sagittal deformities based on age-adjusted alignment thresholds leads to worse health-related quality of life whereas over correction provides no additional benefit. *Spine (Phila Pa 1976)*. 2018;43(6):388-393.
3. Lafage R, Schwab F, Glassman S, et al. Age-adjusted alignment goals have the potential to reduce PJK. *Spine (Phila Pa 1976)*. 2017;42(17):1275-1282.
4. Kim HJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis results in inferior SRS pain subscores in adult deformity patients. *Spine (Phila Pa 1976)*. 2013;38(11):896-901.
5. Kim HJ, Lenke LG, Shaffrey CI, Van Alstyne EM, Skelly AC. Proximal junctional kyphosis as a distinct form of adjacent segment pathology after spinal deformity surgery: a systematic review. *Spine (Phila Pa 1976)*. 2012;37(22 suppl):S144-S164.
6. 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(1):E60-E68.
7. Lau D, Clark AJ, Scheer JK, et al. Proximal junctional kyphosis and failure after spinal deformity surgery: a systematic review of the literature as a background to classification development. *Spine (Phila Pa 1976)*. 2014;39(25):2093-2102.
8. Kim YJ, Bridwell KH, Lenke LG, Glattes CR, Rhim S, Cheh G. Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion: minimum five-year follow-up. *Spine (Phila Pa 1976)*. 2008;33(20):2179-2184.
9. Park P, Fu KM, Mummaneni PV, et al. The impact of age on surgical goals for spinopelvic alignment in minimally invasive surgery for adult spinal deformity. *J Neurosurg Spine*. 2018;29(5):560-564.
10. Yilgor C, Sogunmez N, Boissiere L, et al. Global alignment and proportion (GAP) score: development and validation of a new method of analyzing spinopelvic alignment to predict mechanical complications after adult spinal deformity surgery. *J Bone Joint Surg Am*. 2017;99(19):1661-1672.
11. Protopsaltis TS, Soroceanu A, Tishelman JC, et al. Should sagittal spinal alignment targets for adult spinal deformity correction depend on pelvic incidence and age? *Spine (Phila Pa 1976)*. 2020;45(4):250-257.
12. Rillardon L, Levassor N, Guigui P, et al. Validation of a tool to measure pelvic and spinal parameters of sagittal balance. Article in French. *Rev Chir Orthop Reparatrice Appar Mot*. 2003;89(3):218-227.
13. Champain S, Benchikh K, Nogier A, Mazel C, Guise JD, Skalli W. Validation of new clinical quantitative analysis

software applicable in spine orthopaedic studies. *Eur Spine J*. 2006;15(6):982-991.
14. Glattes RC, Bridwell KH, Lenke LG, Kim YJ, Rinella A, Edwards C II. 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(14):1643-1649.
15. Vira S, Diebo BG, Spiegel MA, et al. Is there a gender-specific full body sagittal profile for different spinopelvic relationships? A study on propensity-matched cohorts. *Spine Deform*. 2016;4(2):104-111.
16. Diebo BG, Gammal I, Ha Y, et al. Role of ethnicity in alignment compensation: propensity matched analysis of differential compensatory mechanism recruitment patterns for sagittal malalignment in 288 ASD patients from Japan, Korea, and United States. *Spine (Phila Pa 1976)*. 2017;42(4): E234-E240.
17. Lord EL, Ayres E, Woo D, et al. the impact of global alignment and proportion score and bracing on proximal junctional kyphosis in adult spinal deformity. *Glob Spine J*. 2023; 13(3):651-658.
18. Baum GR, Ha AS, Cerpa M, et al. Does the Global Alignment and Proportion score overestimate mechanical complications after adult spinal deformity correction? *J Neurosurg Spine*. 2021;34(1):96-102.
19. Kwan KYH, Lenke LG, Shaffrey CI, et al. Are higher Global Alignment and Proportion scores associated with increased risks of mechanical complications after adult spinal deformity surgery? An external validation. *Clin Orthop Relat Res*. 2021;479(2):312-320.
20. Stessman J, Hammerman-Rozenberg R, Cohen A, Ein-Mor E, Jacobs JM. Physical activity, function, and longevity among the very old. *Arch Intern Med*. 2009;169(16):1476-1483.
21. Arem H, Moore SC, Patel A, et al. Leisure time physical activity and mortality: a detailed pooled analysis of the dose-response relationship. *JAMA Intern Med*. 2015;175(6): 959-967.
22. Ames C, Gammal I, Matsumoto M, et al. Geographic and ethnic variations in radiographic disability thresholds: analysis of North American and Japanese operative adult spinal deformity populations. *Neurosurgery*. 2016;78(6):793-801.
23. Passias PG, Segreto FA, Imbo B, et al. Defining age-adjusted spinopelvic alignment thresholds: should we integrate BMI? *Spine Deform*. 2022;10(5):1077-1084.
24. Lafage R, Schwab F, Challier V, et al. Defining spino-pelvic alignment thresholds: should operative goals in adult spinal deformity surgery account for age? *Spine (Phila Pa 1976)*. 2016;41(1):62-68.
25. Takemoto M, Boissière L, Vital JM, et al. Are sagittal spinopelvic radiographic parameters significantly associated with quality of life of adult spinal deformity patients? Multivariate linear regression analyses for pre-operative and short-term post-operative health-related quality of life. *Eur Spine J*. 2017;26(8):2176-2186.
26. Uei H, Tokuhashi Y, Maseda M, et al. Exploratory analysis of predictors of revision surgery for proximal junctional kyphosis or additional postoperative vertebral fracture following adult spinal deformity surgery in elderly patients: a retrospective cohort study. *J Orthop Surg Res*. 2018;13(1):252.
27. Terran J, Schwab F, Shaffrey CI, et al. The SRS-Schwab adult spinal deformity classification: assessment and clinical correlations based on a prospective operative and nonoperative cohort. *Neurosurgery*. 2013;73(4):559-568.
28. Lafage R, Smith JS, Elysee J, et al. Sagittal age-adjusted score (SAAS) for adult spinal deformity (ASD) more effectively predicts surgical outcomes and proximal junctional kyphosis than previous classifications. *Spine Deform*. 2022; 10(1):121-131.
29. Nielsen DH, Gehrchen M, Hansen LV, Walbom J, Dahl B. Inter- and intra-rater agreement in assessment of adult spinal deformity using the Scoliosis Research Society-Schwab classification. *Spine Deform*. 2014;2(1):40-47.
30. Liu Y, Liu Z, Zhu F, et al. Validation and reliability analysis of the new SRS-Schwab classification for adult spinal deformity. *Spine (Phila Pa 1976)*. 2013;38(11):902-908.
31. Lovecchio F, Lafage R, Line B, et al. Optimizing the definition of proximal junctional kyphosis: a sensitivity analysis. *Spine (Phila Pa 1976)*. 2023;48(6):414-420.

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Supplemental Information

Previous Presentations

Portions of this work were previously presented as a podium presentation at the 2021 Scoliosis Research Society Annual Meeting, St. Louis, Missouri, September 22–25, 2021; 2021 North American Spine Society Annual Meeting, Boston, Massachusetts, September 28–October 1, 2021; and 2022 American Academy of Orthopedic Surgeons Annual Meeting, Chicago, Illinois, March 22–26, 2022.

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