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ORIGINAL ARTICLE

The spino-pelvic ratio: a novel global sagittal parameter associated with clinical outcomes in adult spinal deformity patients

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Abstract

Purpose Analysis of interactions of spinal alignment metrics may uncover novel alignment parameters, similar to PI-LL. This study utilized a data-driven approach to hypothesis generation by testing all possible division interactions between spinal alignment parameters.

Methods This study was a retrospective cohort analysis. In total, 1439 patients with baseline ODI were included for hypothesis generation. In total, 666 patients had 2-year postoperative follow-up and were included for validation. All possible combinations of division interactions between baseline metrics were assessed with linear regression against baseline ODI.

Results From 247 raw alignment metrics, 32,398 division interactions were considered in hypothesis generation. Conceptually, the TPA divided by PI is a measure of the relative alignment of the line connecting T1 to the femoral head and the line perpendicular to the sacral endplate. The mean TPA/PI was 0.41 at baseline and 0.30 at 2 years postoperatively. Higher TPA/PI was associated with worse baseline ODI ($p < 0.0001$). The change in ODI at 2 years was linearly associated with the change in TPA/PI ($p = 0.0172$). The optimal statistical grouping of TPA/PI was low/normal (≤ 0.2), medium (0.2–0.4), and high (> 0.4). The R-squared for ODI against categorical TPA/PI alone (0.154) was directionally higher than that for each of the individual Schwab modifiers (SVA: 0.138, PI-LL 0.111, PT 0.057).

Conclusion This study utilized a data-driven approach for hypothesis generation and identified the spino-pelvic ratio (TPA divided by PI) as a promising measure of sagittal spinal alignment among ASD patients. Patients with SPR > 0.2 exhibited inferior ODI scores.

Level of evidence III.

Keywords Adult spinal deformity · Sagittal alignment · T1 pelvic angle · Pelvic incidence

IRB Approval This study was approved by IRBs at participating institutions.

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Introduction

Adult spinal deformity (ASD) has a profound impact on patient quality of life, including physical, psychological, and social functioning [1–7]. Operative management of ASD has grown markedly in recent years, and surgery for ASD reliably improves patient-reported outcomes [2, 8–10].

A wide variety of radiographic parameters exist to quantify sagittal spinal alignment. The SRS–Schwab classification modifiers for sagittal alignment are based on both overall sagittal balance and pelvic morphology [11]. Nevertheless, there are relatively few metrics that account for both spinal and pelvic alignment simultaneously. The spino-sacral angle (SSA) quantifies the relationship of the C7 tilt with sacral slope [12, 13]. However, this metric does not capture pelvic morphology beyond the sacral endplate. The global tilt (GT) is the sum of pelvic tilt and C7-vertical angle and therefore accounts for pelvic position but not morphology [14]. The lumbar lordosis index (LLI) is the ratio of lumbar lordosis to pelvic incidence and therefore accounts for pelvic morphology but not global sagittal alignment [15].

Analysis of interactions between existing metrics may uncover novel, important relationships. Pelvic incidence minus lumbar lordosis (PI-LL) is an example of such an interaction [16]. This study utilized a data-driven approach to hypothesis generation and identified the spino-pelvic ratio (SPR), calculated as T1-pelvic angle divided by PI. This metric was subsequently characterized in relation to the Oswestry Disability Index (ODI).

Methods

Patient sample

This study utilized a multi-center, prospectively defined database of adult spinal deformity patients. Inclusion criteria were adults age ≥ 18 years and at least one of the following: diagnosis of adult degenerative or idiopathic scoliosis with maximum Cobb angle ≥ 20 degrees, SVA > 5 cm, PT > 25 degrees, or TK > 60 degrees. Patients ≤ 18 years old and those with a diagnosis of scoliosis other than degenerative or idiopathic were excluded. Measurements on lateral and AP radiographs utilized SpineView software.

Exploratory analyses

All patients with baseline data for HRQOLs were included in the exploratory portion of this study. Out of 451 radiographic parameters initially considered for analysis, 241 had < 10% missing data and were numeric and were included. These variables subsequently underwent hot deck imputation. In total, 32,398 division interactions between these variables were calculated for each patient. These values were linearly regressed against ODI and ranked in descending order by *Z*-value. The top interactions were qualitatively examined.

TPA/PI validation

Only patients with 2-year postoperative follow-up were included in the validation component of the study. Analyses of TPA/PI against HRQOLs (ODI and SRS-22r total score) and Schwab modifier categories utilized linear regression, ANOVA, and t tests, as appropriate.

Statistical analysis

This study utilized SAS 9.4 (SAS Institute, Cary, NC), R 3.5.0 (R Foundation, Vienna, Austria), and the Julia programming language 0.6.4 (JuliaLang) [17, 18]. The optimal statistical cutpoints for TPA/PI were determined based on separation of patients based on ODI. In brief, all possible pairs of cutpoints across the range of ODI within our cohort were determined. Each pair divided patients into three groups, and ODI values were compared using the Kruskal–Wallis test. The optimal pair of cutpoints was selected as that which minimized the resulting p value. For visual simplicity, Fig. 3 is created using only one cutpoint and the Mann–Whitney U test. R^2 values for various models were compared using the F test.

Results

Exploratory analyses

In total, 1439 patients with baseline data were included in the exploratory component of this study. Division interactions between radiographic parameters were plotted by statistical significance (Fig. 1). Various high-thoracic (e.g., T1PA) and low-cervical (e.g., C7PA) pelvic angles divided by pelvic incidence accounted for eight out of the top ten most significant interactions. Conceptually, the TPA/PI—termed the spino-pelvic ratio (SPR)—is a measure of the relative alignment of the line connecting T1 to the femoral head and the line perpendicular to the sacral endplate (Fig. 2). The T1-pelvic angle divided by pelvic incidence was the fourth most significant interaction, and it was selected due to existing wide-spread usage of the T1-pelvic angle.

TPA/PI validation

In total, 666 patients with 2-year follow-up were included for validation. The mean age was 57.9 years (SD 15.1),

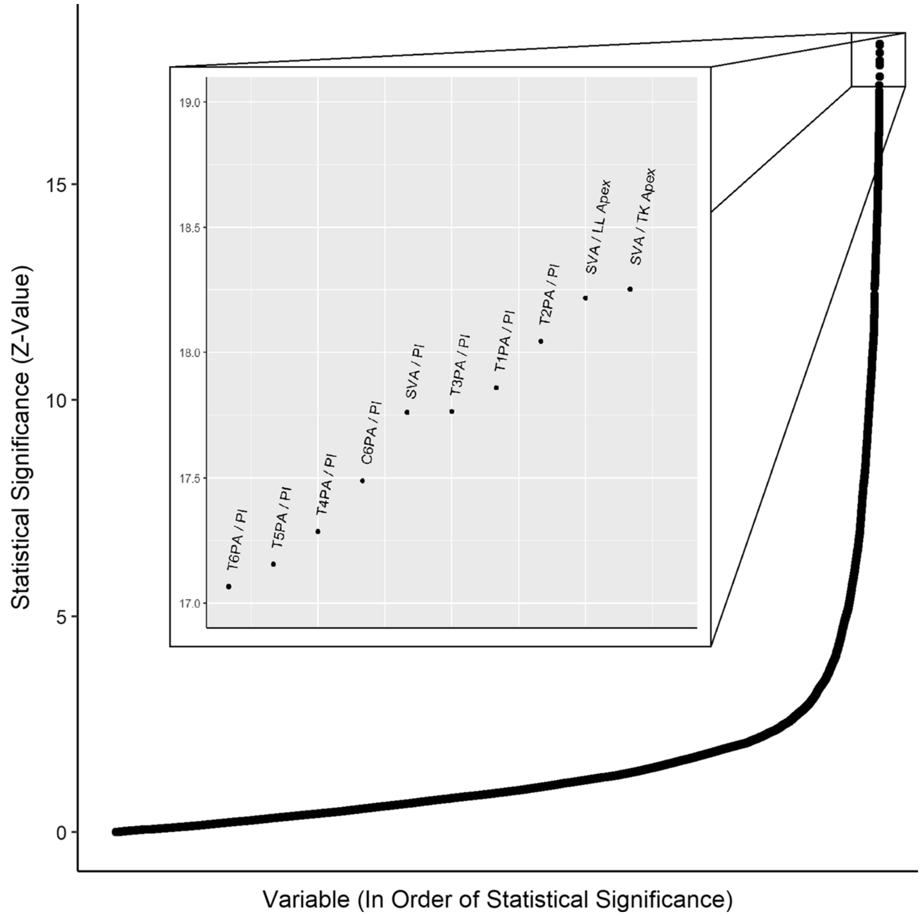

Fig. 1 Division interactions between radiographic parameters by statistical significance in linear regression against ODI

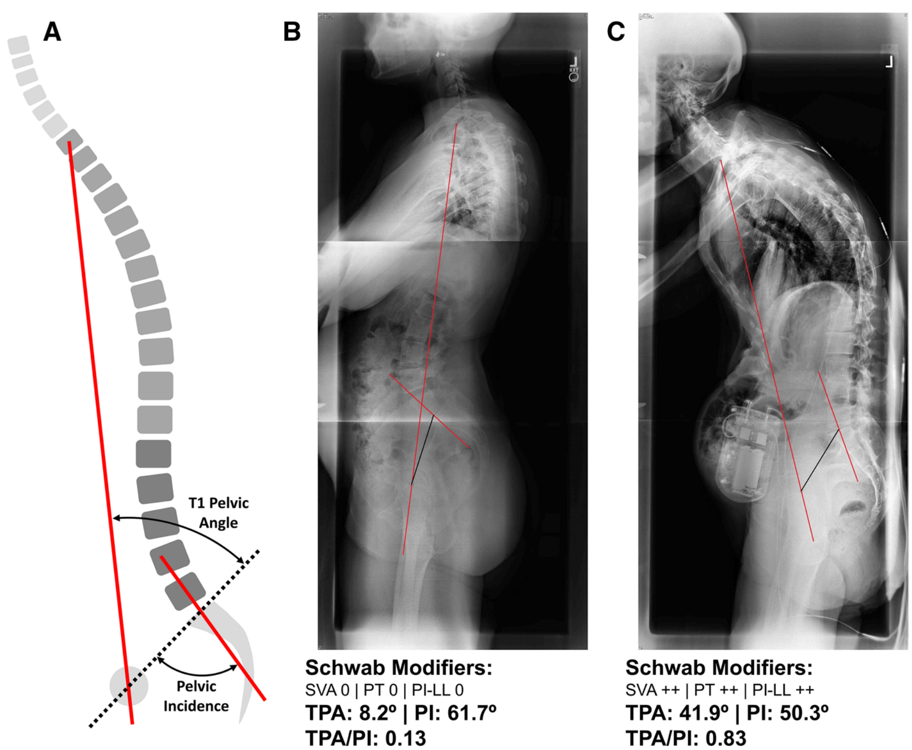

Fig. 2 Spino-pelvic ratio: T1-pelvic angle divided by pelvic incidence

and 78.0% ($n = 519$) were female. The mean TPA/PI at baseline, 1 year, and 2 years postoperatively was 0.41 (SD 0.24), 0.29 (SD 0.18), and 0.30 (SD 0.18), respectively (Table 1). The optimal statistical cutpoints for baseline SPR against ODI were 0.2 and 0.4, creating three baseline groups: low (≤ 0.2, 20.3% of patients), medium (0.2–0.4,

Table 1 Descriptive statistics

	Mean (%)	SD (N)
All patients	666	–
Age	57.9	15.1
Female gender	80.0	519
TPA/PI		
Baseline	0.41	0.24
1 year	0.29	0.18
2 years	0.30	0.18
Δ 1 year—baseline	−0.12	0.20
Δ 2 years—baseline	−0.11	0.20
TPI/PI category	%	N
Baseline		
Low/normal (TPA/PI < 0.21)	20.3	133
Medium (TPA/PI 0.21–0.41)	30.6	201
High (TPA/PI ≥ 0.41)	49.1	322
Missing = 10		
1 year		
Low/normal (TPA/PI < 0.21)	31.5	176
Medium (TPA/PI 0.21–0.41)	45.1	252
High (TPA/PI ≥ 0.41)	23.4	131
Missing = 107		
2 years		
Low/normal (TPA/PI < 0.21)	30.6	158
Medium (TPA/PI 0.21–0.41)	42.2	218
High (TPA/PI ≥ 0.41)	27.3	141
Missing = 149		

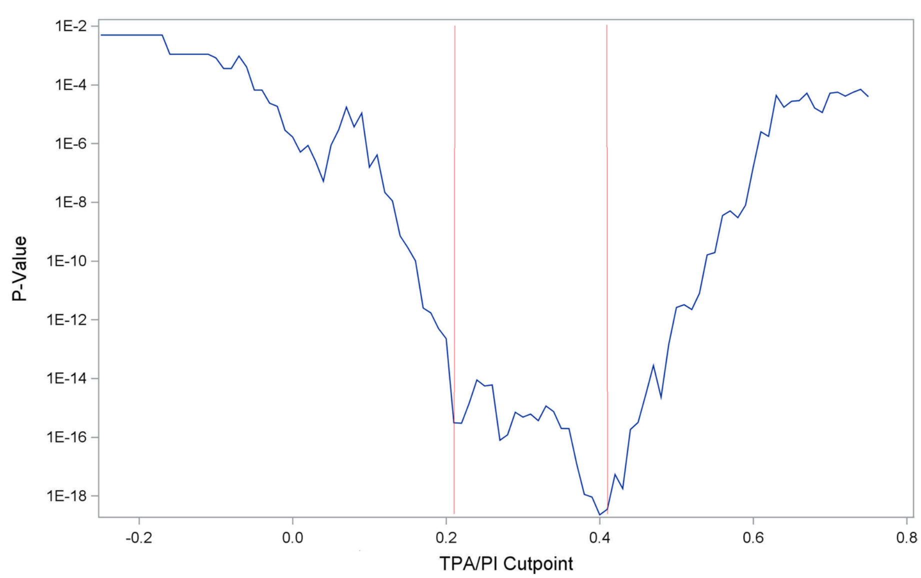

Fig. 3 Optimal cutpoint selection for the spino-pelvic ratio

Fig. 4 Case examples

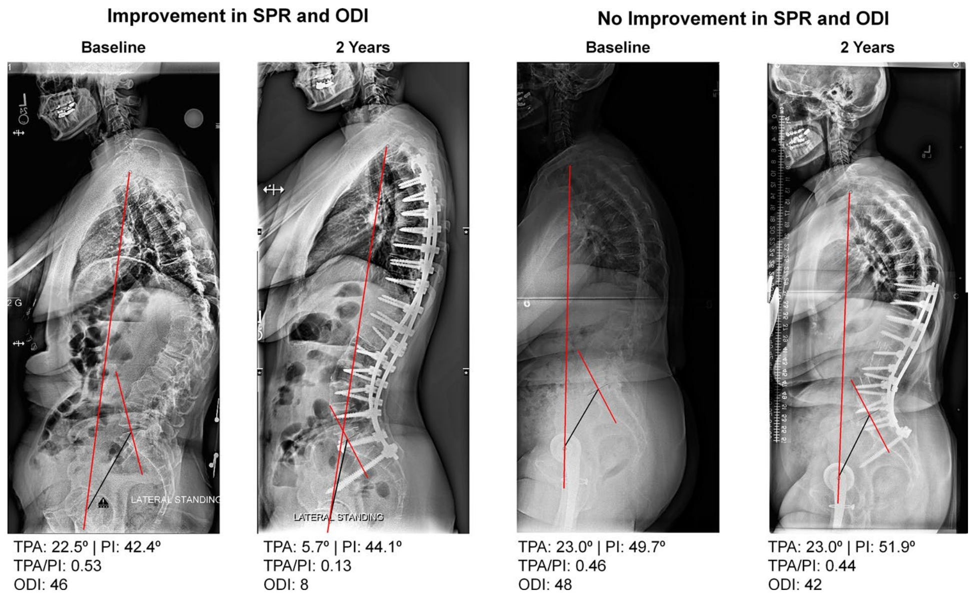

Table 2 Association between SPR and Schwab modifiers

	TPA/PI	*p* value
PT		< 0.0001
0	0.20	
+	0.45	
++	0.64	
PI-LL		< 0.0001
0	0.21	
+	0.41	
++	0.61	
SVA		< 0.0001
0	0.22	
+	0.43	
++	0.64	

Table 3 Association between TPA/PI and ODI at baseline and post-operatively

HRQOL	TPA/PI comparison	*β*	SE	*p* value
ODI				
Baseline	Baseline TPA/PI	28.7	2.8	< 0.0001
1 Year	1 year TPA/PI	16.5	4.6	0.0004
2 Year	2 year TPA/PI	20.0	4.9	< 0.0001
Δ 1 Year	Δ 1 year TPA/PI	11.7	3.7	0.0018
Δ 2 Years	Δ 2 years TPA/PI	9.5	4.0	0.0172
SRS-22r total score				
Baseline	Baseline TPA/PI	− 0.83	0.10	< 0.0001
1 year	1 year TPA/PI	− 0.54	0.17	0.0021
2 year	2 year TPA/PI	− 0.75	0.19	0.0001
Δ 1 year	Δ 1 year TPA/PI	− 0.73	0.14	< 0.0001
Δ 2 years	Δ 2 years TPA/PI	− 0.54	0.16	0.0008

30.6% of patients), and high (> 0.4, 49.1% of patients) (Fig. 3). Case examples of patients with improvement vs. no improvement in SPR and ODI are provided in Fig. 4.

Baseline SPR was strongly associated with Schwab modifiers for PT, PI-LL, and SVA ($p < 0.0001$ for all comparisons) (Table 2). The SPR was strongly associated with ODI at baseline, 1 year, and 2 years postoperatively ($p < 0.0005$ for all comparisons). Further, the change in SPR from baseline was significantly associated with the change in ODI at both 1 year and 2 years postoperatively ($p < 0.05$ for both comparisons) (Table 3). Further, patients with medium vs. low/normal and high vs. low/normal categorical SPR exhibited significant differences in ODI ($p < 0.05$ for all comparisons) (Table 4). Similar results were seen for SPR compared to SRS-22r total score (Tables 3, 4).

Comparison to other alignment parameters

Linear regression models for baseline ODI with various combinations of the SPR and other alignment parameters were constructed and the resulting R^2 values compared. The R^2 for the model including categorical SPR and Schwab modifiers (0.184) was significantly higher than the R^2 for both the model including all Schwab modifiers (0.161, $p < 0.05$) and SPR alone (0.158, $p < 0.0005$) (Fig. 5a). Further, a model with both continuous SPR and continuous TPA exhibited a significantly higher R^2 (0.142) than a model with continuous TPA alone (0.122) ($p < 0.0005$), while no significant difference was observed when compared to continuous SPR alone (0.142) ($p > 0.2$) (Fig. 5b).

Table 4 Association between categorical TPA/PI and ODI

	β	SE	p value
ODI			
Baseline			
Medium vs. low/normal	9.7	1.9	<0.0001
High vs. low/normal	18.6	1.8	<0.0001
1 year			
Medium vs. low/normal	4.3	1.9	0.0270
High vs. low/normal	7.9	2.3	0.0007
2 years			
Medium vs. low/normal	4.3	2.1	0.0438
High vs. low/normal	8.7	2.4	0.0002
SRS-22r total score			
Baseline			
Medium vs. low/normal	−0.16	0.07	0.0279
High vs. low/normal	−0.48	0.07	<0.0001
1 year			
Medium vs. low/normal	−0.16	0.07	0.0261
High vs. low/normal	−0.29	0.09	0.0009
2 years			
Medium vs. low/normal	−0.17	0.09	0.0510
High vs. low/normal	−0.35	0.09	0.0002

Discussion

This investigation utilized a data-driven approach to hypothesis generation for novel spinal alignment metrics significantly associated with baseline, change, and 2-year postoperative ODI. The spino-pelvic ratio is calculated as the T1-pelvic angle divided by pelvic incidence. The SPR was strongly associated with the Schwab modifier system, as well as with pre- and postoperative ODI. Patients with SPR > 0.2 at baseline exhibited particularly poor preoperative ODI. Preoperatively, a model containing SPR alone explained a comparable proportion of variance in ODI as a model containing all Schwab modifiers; SPR and the Schwab modifiers worked synergistically to produce a model that explained a superior proportion of ODI variance. The SPR explained a directionally higher proportion of variance in baseline ODI as compared to TPA alone.

The spino-pelvic ratio represents the relative alignment of the line connecting the T1 vertebrae and the femoral head with the line perpendicular to the sacral endplate, representing the orientation of the T1 vertebrae in relation to the pelvis. While other metrics for global spinal alignment—such as the T1-PA, SSA, and SVA—capture similar dynamics, these parameters do not account for pelvic incidence. The TPA accounts for pelvic tilt, while the SSA incorporates sacral slope [12, 13, 19–21]. The spino-pelvic ratio captures the association between global spinal alignment and pelvic morphology and thus the degree to which increased pelvic incidence can compensate for positive sagittal alignment. As PI = PT + SS, the SPR can be viewed as combining the advantages of both the TPA and SSA [22, 23].

The particular novelty of this study was the computational approach to hypothesis generation of novel radiographic parameters. The generation of interactions between existing metrics was highly quantitative. The interpretation of these results, however, was largely qualitative, with a selection of SPR derived from the top ten interactions due to its potential clinical and research utility. Notably, while the finalized spino-pelvic ratio was calculated as T1-pelvic angle divided by pelvic incidence, this specific value was only the fourth most significant interaction. While the T2-PA divided by PI was directionally a more significant interaction, this ratio was ultimately less ideal given widespread familiarity with the T1-pelvic angle. C7-SVA divided by the apex (expressed as vertebrae number from superior to inferior) of both lumbar lordosis (LL) and thoracic kyphosis (TK) was particularly strongly associated with ODI. In other words, ODI increased as SVA increased and as the apex of LL/TK

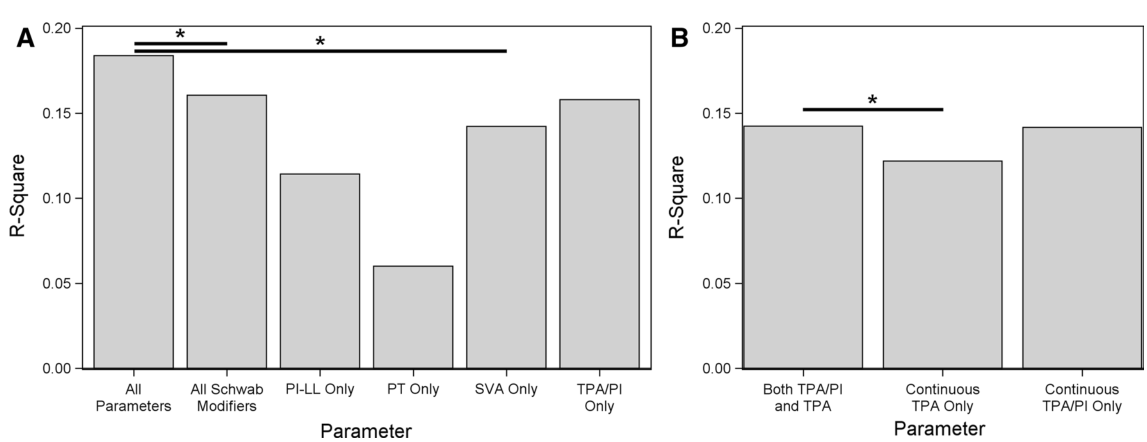

Fig. 5 Comparison of R^2 values from regression models for ODI

moved superiorly. It is possible that this observation reflects differences in the distribution of spinal malalignment over vertebral segments. We were unable, however, to determine a particularly concrete radiographic or clinical rationale for these findings; future studies may seek to determine their significance.

These findings corroborate recent findings by Protopsaltis et al. regarding global alignment targets that are adjusted for both age and pelvic incidence [24, 25]. These authors analyzed a retrospective cohort of ASD patients to derive updated targets for deformity correction based on SF-36 values that were adjusted for age and PI. Their results indicated that sagittal spinal alignment targets may be less stringent with increased PI and age. The conclusions of these two studies are directionally similar: patients with increased pelvic incidence can tolerate a greater degree of positive sagittal balance. The fact that this conclusion was reached via both clinical intuition and data mining increases confidence in the importance of these results.

These findings also corroborate those observed by Yilgor et al. [26] in their development of the Global Alignment and Proportion (GAP) score. The GAP is calculated using age, relative pelvic version, relative lumbar lordosis, lordosis distribution index, and relative spino-pelvic alignment (RSA). The latter is particularly relevant to the present study and is calculated as the measured minus ideal global tilt (GT), with ideal $GT = PI * 0.48 - 15$. The present study's spino-pelvic ratio similarly represents global alignment adjusted for pelvic morphology. Importantly, it provides an intuitive interpretation of this relationship by reflecting the relative alignment of the line connecting T1 and the femoral heads and the line perpendicular to the sacral endplate.

The range of potential novel radiographic parameters in this study was conceptually constrained by the generation of division interactions between known metrics. Assessment of interactions with division was selected to compare relative magnitudes, though it is possible that similarly interesting results could be generated with other mathematical operators. While the SPR is a novel radiographic parameter, it is constructed from values of established importance. Future investigations may seek to quantitatively identify novel parameters de novo from spine radiographs, though this task will undoubtedly be highly technically demanding and may lack everyday clinical utility.

This study had several potential limitations, many of which are discussed above. Additionally, the patients included in this study were evaluated at predominantly academic medical centers by specialists in adult spinal deformity; it is possible that this resulted in selection bias. Further, this study utilized only ODI as the primary outcome measure by which potential novel interactions were evaluated. It is likely that the use of other PROMs might yield different and potentially interesting results. Finally, the variables used in hypothesis generation were exclusively radiographic alignment parameters. HRQOL is a complex interaction between alignment and other variables (e.g., demographics, comorbidities, etc.), thus inherently limiting this study's ability to predict HRQOL. Finally, it may not always be possible to identify T1 on lateral radiographs due to the positioning of the shoulders.

Conclusions

This study utilized a data-driven approach for hypothesis generation and identified TPA divided by PI, the spino-pelvic ratio (SPR), as a promising measure of sagittal spinal alignment among ASD patients. Patients with $SPR > 0.2$ exhibited inferior HRQOL. The SPR and Schwab modifiers worked synergistically to improve model fit for predicting ODI.

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Code availability SAS 9.4, Julia 0.6.4, R 3.5.0

Compliance with ethical standards

Conflict of interest Author-specific potential conflicts of interest have been detailed in the conflict of interest disclosure.

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