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CASE SERIES

The clinical impact of global coronal malalignment is underestimated in adult patients with thoracolumbar scoliosis

Nicolas Plais[1,12] · Hongda Bao[1,2] · Renaud Lafage[1] · Munish Gupta[3] · Justin S. Smith[4] · Christopher Shaffrey[4] · Gregory Mundis[5,6] · Douglas Burton[7] · Christopher Ames[8] · Eric Klineberg[9] · Shay Bess[10] · Frank Schwab[1] · Virginie Lafage[1] · International Spine Study Group[11]

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Abstract

Study design Retrospective review of multicenter adult spine deformity (ASD) database.

Objectives A recent publication demonstrated that the laterality of the coronal offset is a key parameter that directly impacts postoperative outcomes. The objective of this study is to analyze the relationship between global coronal malalignment (GCM) and functional outcomes in a North American population of ASD patients with no history of previous surgery.

Summary of background data The clinical impact of GCM in patients with ASD remains controversial.

Methods Primary patients were drawn from a multicenter database of ASD patients and categorized with the Qiu classification: Type A = GCM < 3 cm; Type B = GCM > 3 cm toward the concave side of the curve; and Type C = GCM > 3 cm toward the convex side. In addition to the classic radiographic parameter, the coronal truncal inclination was investigated in regard to the pelvic obliquity. Clinical outcomes, radiographic parameters, and demographics were compared across the three Qiu Types using analysis of variance. The analysis was repeated after propensity matching of the three types by age and sagittal alignment (PI–LL mismatch, pelvic tilt, and sagittal vertical axis).

Results 576 ASD patients (mean age 58.8 years) were included. Type B patients had significantly worse functional scores (Oswestry Disability Index, 36-item Short Form Survey physical component summary, and Scoliosis Research Society-22) and a more severe coronal deformity in terms of maximum Cobb angle, global coronal deformity angle, and coronal malalignment; they were also older (65.4 vs. 58.8 years, $p = 0.004$) and displayed more severe sagittal malalignment. Similar findings were observed after propensity matching.

Conclusions This study is the first to establish an association between functional outcomes and the severity of the coronal plane deformity in the setting of a specific coronal curve pattern in patients without previous surgery. Coronal malalignment significantly affects the health status of patients when the offset is greater than 3 cm in the direction of curve concavity.

Level of evidence III.

Keywords Adult spine deformity (ASD) · Scoliosis · Coronal malalignment · Global coronal deformity angle · Health-Related Quality of Life (HRQL) scoring

Introduction

With an aging population, the prevalence of adult spinal deformity (ASD) has increased significantly in past decades with reported incidences ranging from 15% [1] to 68% [2] among individuals over 65 years old, and a cumulative incidence from 17% [3] to 29.4% [4] over 10 years.

ASD can have a significant impact on health-related quality of life (HRQOL), with the sagittal plane being recognized as a principal determinant of health status [5–9]. In contrast, deformity in the coronal plane has received substantially less attention. In 2005, Glassman et al. [10] observed that patients without previous surgery and with global coronal malalignment (GCM) greater than 4 cm had increased pain and decreased functional scores. However, coronal plane radiographic measurements have shown inconsistent correlations to clinical outcome scores. In ASD patients without previous surgery, a relationship between the coronal curve

✉ Nicolas Plais
nicolas.plais@me.com

Extended author information available on the last page of the article

magnitude, measured by Cobb angle, and disability has not been clearly established [10, 11]. In addition, the magnitude of coronal plane improvement after surgical correction has been suggested to have limited or no impact on outcomes [12]. Moreover, a clear threshold to define clinically significant GCM has not been established. Bradford et al. [13] reported difficulties in correcting coronal malalignment when the offset was greater than 6 cm. Ploumis et al. [14] observed a coronal offset greater than 4 cm to be associated with poor functional scores, and Lowe et al. [15] and Choi et al. [16] have used 3 cm as a threshold for GCM. In 2016, Ha et al. [17] reported statistically significant but weak correlation between Cobb angle, coronal malalignment, and coronal deviation distance with clinical parameters in the lumbar spine. Collectively, the reported clinical relevance of GCM remains unclear, and the general tendency is for GCM to not be considered a major parameter of functional disability [10].

In contrast to earlier reports, a recent study [18] demonstrated that specific characteristics of scoliotic curves in the coronal plane were associated with poor clinical outcome in ASD patients after corrective surgery. This study, performed on a Chinese population, is the foundation of the Qiu classification; it categorizes patients into three types of coronal alignment according to the GCM and its relation to the concavity or the convexity of the main coronal curve. The authors reported that patients with preoperative GCM with the same laterality as the coronal curve convexity (Type C) were at greater risk of postoperative coronal malalignment and introduced the idea that the relation between GCM and the curve direction may be clinically significant (Fig. 1).

The objective of this study was to analyze the relationship between GCM, stratified by coronal curve pattern, and HRQOL in a North American population of ASD patients with no history of previous surgery. Our hypothesis was that the clinical relevance of GCM may have been underestimated and that, in specific curve patterns, a relationship between poorer health status and GCM can be established.

Materials and methods

Patient population

This is a retrospective review of a prospective multicenter database of ASD patients enrolled across 11 US sites. Patients were prospectively enrolled through an IRB-approved study at each site. Inclusion criteria for the overall database were patients > 18 years with at least one of the following criteria of spinal deformity: Cobb angle > 20°, C7–S1 sagittal vertical axis (SVA) > 5 cm, pelvic tilt (PT) > 25°, or thoracic kyphosis (TK) > 60°. In addition to the database inclusion criteria, only primary patients and with a thoracolumbar or lumbar main curve (i.e., apex below T12) greater than 20° were retained for analysis.

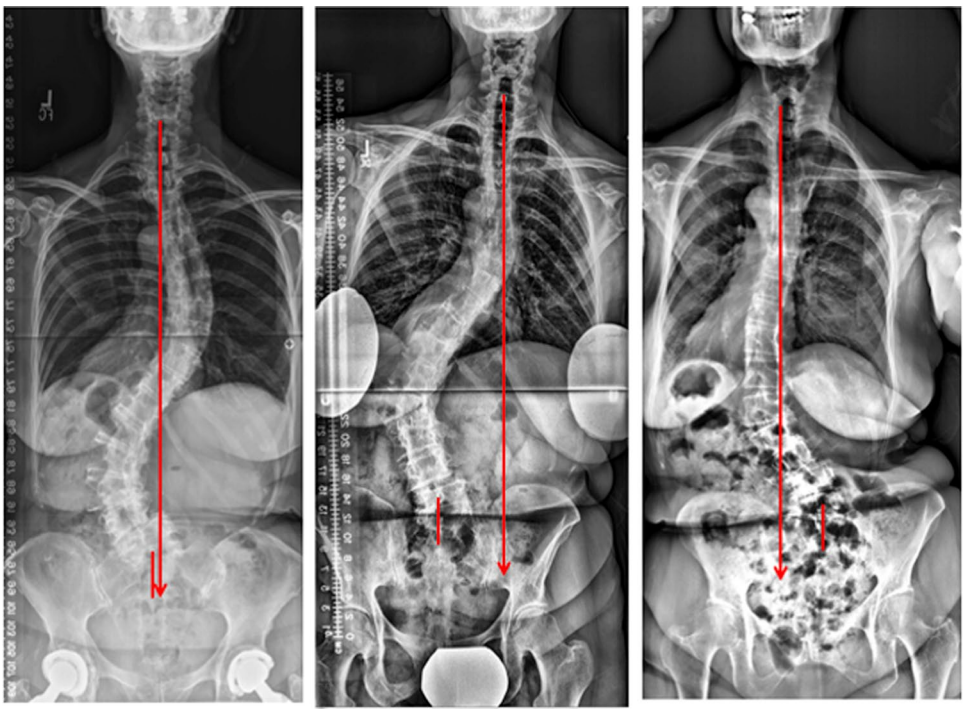

Fig. 1 Example of the Qiu classification. Type A = global coronal malalignment (GCM) < 3 cm; Type B = GCM > 3 cm ipsilateral to the concave side of the coronal curve; and Type C = GCM > 3 cm ipsilateral to the convex side of the coronal curve

Data collection and radiographic parameters

Extracted data included basic demographics, such as age, gender, and body mass index (BMI); HRQOL; and radiographic parameters. Standardized HRQOL questionnaires include Oswestry Disability Index (ODI), the Scoliosis Research Society-22r, and the 36-item Short Form Survey (SF-36) represented by the physical component summary (PCS) and mental component summary (MCS) scores.

Baseline radiographic parameters were measured on full-length free-standing radiographs with a validated software. Evaluation of the sagittal spinopelvic alignment included pelvic incidence (PI), Pelvic Tilt (PT), lumbar lordosis (LL), SVA, mismatch between PI and LL (PI–LL), and T1 pelvic angle (T1PA) [19]. The coronal deformity assessment was based on the Cobb angles, GCM defined as the offset of the C7 plumbline relative to the central sacral vertical line, pelvic obliquity (PO) defined as the angle between a line tangent to the two iliac crests and the horizontal, and coronal inclination (APinc) defined as the angle between the C7–S1 segment and the vertical. A threshold of 3 cm for the GCM has been adopted in the current study at it represents the strictest one reported in the literature.

In addition to the classic coronal measurement, we use the global coronal deformity angle (GCDA), a parameter that hitherto has not been described in the literature. GCDA, which is defined as the angle between the C7 and S1 segment and the line perpendicular to the two iliac crests, was investigated. This angle is similar in concept to the T1PA in the sagittal plane; it provides an assessment of the entire deformity taking into account the compensation effect created by the pelvic obliquity. From a pragmatic point of view, the GCDA reflects both the truncal coronal inclination (APinc) and the pelvic obliquity (PO). As illustrated in Fig. 2, GCDA is greater (i.e., worse) than APinc when the coronal malalignment and the pelvic obliquity are in opposite direction, meaning that the real deformity is underestimated if the compensation of the pelvis is not taken into account (we, therefore, coined the term additive for this configuration). On the other hand, GCDA is smaller than APinc when the coronal malalignment and the pelvic obliquity are in the same direction, meaning that the actual deformity is, in fact, overestimated when analyzing truncal inclination only (subtractive).

Lastly, patients were classified according to two different deformity classifications: the SRS-Schwab Adult Spinal Deformity classification [12] based on coronal type (N, T, L, D) and sagittal modifiers (PT, PI–LL, and SVA), and the Qiu classification [18] organized in three types of coronal alignment: Type A: GCM < 3 cm, Type B: GCM > 3 cm ipsilateral to the concave side of the coronal curve, and Type C: GCM > 3 cm ipsilateral to the convex side of the coronal curve (Fig. 1).

Statistical analysis

For each of the classifications, frequency distribution and summary statistics were calculated for all demographic,

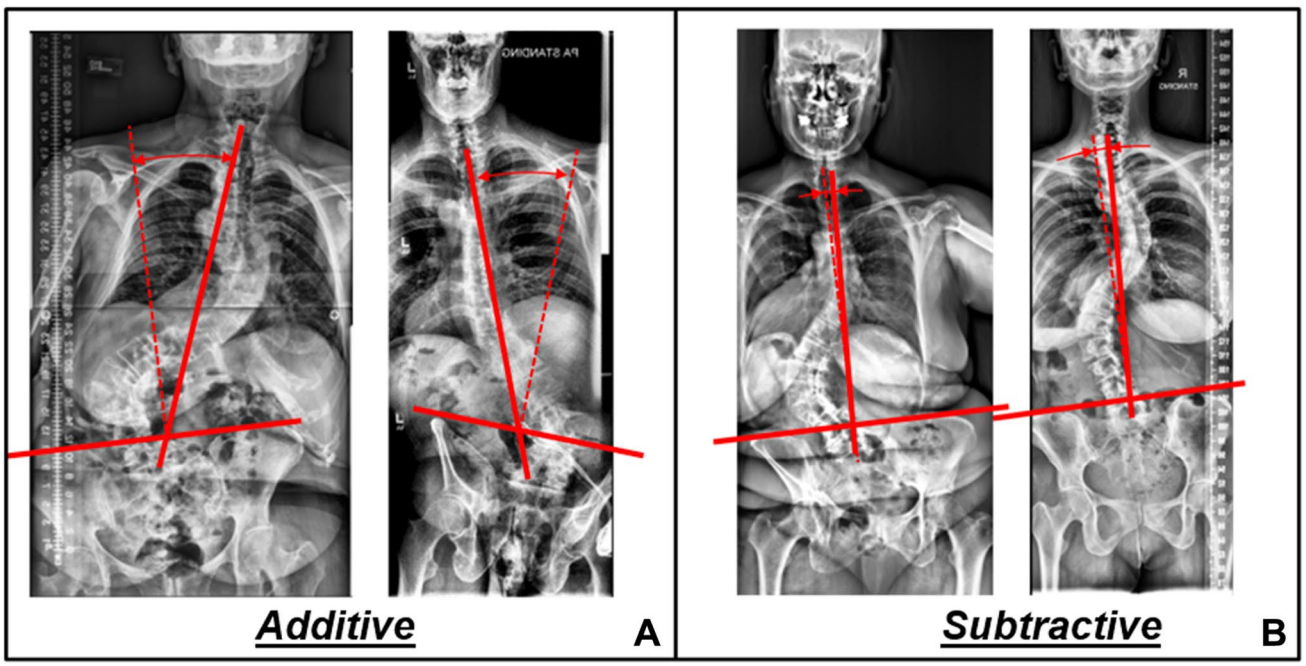

Fig. 2 Global coronal deformity angle (GCDA): (A) additive; (B) subtractive

clinical, and radiographic variables; groups comparisons were carried out using Chi-square tests and analysis of variance. The GCDA was reported according to its mean value as well as its additive/subtractive characteristics.

To eliminate the cofounding effects of age and sagittal malalignment, analysis was repeated across the three types of the Qiu classification after propensity matching based on age, PI–LL mismatch, PT, and SVA. The initial analysis was repeated on the propensity-matched groups.

Results

Patient population

Of the 1413 patients in the database, 620 met the inclusion criteria and 576 (92.9%) had complete data available for the analysis. Women comprised 83.9% of the sample, the mean age was 58.8 years, and the mean BMI, 26.6 (overweight). The stratification by SRS-Schwab ASD classification (Fig. 3) identified 52.6% patients with Type L, 29.9% Type D, and 17.5% type N (i.e., all coronal curves less than 30°). By design, no Type T patients were included. Most patients presented with moderate to severe sagittal deformity, with 39.8% having at least one modifier grade of "++" (severely abnormal) and 72.1% having at least one modifier graded "+" (mildly abnormal). According to the Qiu classification, Type A patients (well aligned in the coronal plane) were the most prevalent (57%), followed by Type C patients (28%). Type B patients appeared to be the least common, representing only 15% of the cohort.

Comparison across Qui types

There were significant differences in age, sex, and disability across the three Qui types. Type B patients were older (65.4 ± 9.9 years vs. 58.9 ± 13.7 years in Type A, and 55.0 ± 15.7 years in Type C; $p < 0.001$), had a larger proportion of male (22.1% vs. 17.8% in Type A, and 9.4% in Type C; $p = 0.015$), and demonstrated greater disability in ODI (48.3 ± 16.4 vs. 37.2 ± 17.5 in Type A, and 36.1 ± 18.2 in Type C; $p < 0.001$) and SF-36 PCS (29.5 ± 8.6 vs. 34.5 ± 10.3 in Type A, and 35.8 ± 11.3 in Type C; $p < 0.001$) (Table 1).

There was no significant difference in SRS-Schwab coronal curves across the Qiu types ($p = 0.239$) (Fig. 4), but Type B patients had a greater sagittal deformity compared with Types A and C for all the sagittal modifiers (Table 2).

In the coronal plane, Type B patient had a greater magnitude of GCM (77.6 vs. 14.5 mm for Type A, and 47.5 mm for Type C, $p < 0.001$), a greater GCDA (10.9° vs. 2.4° in Type A and 3.0° in Type C; $p < 0.001$), and larger maximum coronal Cobb angle (49.3° ± 19.2 vs. 43.4° ± 15.8° in Type A and 46.0° ± 15.0° in Type C) (Table 3). There were also significant differences in terms of PO: in 64.9% of Type A patients and in 83.2% of Type C patients, the PO followed the same direction as the main lumbar or thoracolumbar curve; this is referred to as "subtractive" and decreases the value of GCDA. It also raises the question of PO as an independent driver of deformity in these types of curve. In contrast, for Type B patients, 77.9% of the PO was in the opposite direction of the main curve ("additive"), and its mean absolute value was also higher compared with Types A and C (Table 4). In Type B curves, PO acts as a compensatory mechanism to counteract the magnitude of the major curve.

Comparison across Qiu types: propensity-matched cohort

After propensity matching by PI–LL, PT, and SVA, 192 patients were retained (64 patients in each Qiu type). The repeated measures test showed excellent matching by age (64.1 ± 11.1 years vs. 65.2 ± 9.6 years vs. 61.2 ± 14.3 years; $p = 0.139$), PI–LL (21.4° ± 16.4° vs. 18° ± 16.7° vs. 19.8° ± 15.8°; $p = 0.905$), PT (25.5° ± 9.5° vs. 25.3° ± 9.1° vs. 24.8° ± 9.4°; $p = 0.905$), and SVA (75.6 ± 61.9 mm vs.

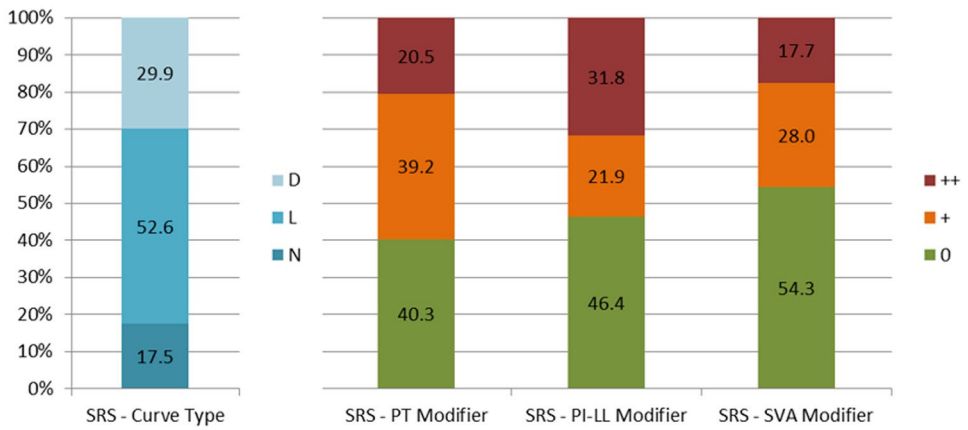

Fig. 3 Distribution of SRS-Schwab classification curve type and modifiers across the entire patient cohort

Table 1 Comparison of demographics and health-related quality of life measures across Qui types using analysis of variance and Chi-square tests

	Qui classification			*p*
	Type A ($n=329$)	Type B ($n=86$)	Type C ($n=161$)	
Age	58.9 ± 13.7	65.4 ± 9.9	55.0 ± 15.7	0.000
BMI	26.7 ± 5.4	26.6 ± 5.4	26.2 ± 6.0	0.636
Gender, % Female	82.20	77.90	90.60	0.015
ODI	37.2 ± 17.5	48.3 ± 16.4	36.1 ± 18.2	0.000
PCS	34.5 ± 10.3	29.5 ± 8.6	35.8 ± 11.3	0.000
MCS	47.9 ± 12.7	43.9 ± 13.8	48.0 ± 13.1	0.034
SRS-Total	3.10 ± 0.70	2.70 ± 0.70	3.10 ± 0.70	0.000
SRS-Activity	3.20 ± 0.90	2.70 ± 0.90	3.30 ± 0.90	0.000
SRS-Pain	2.70 ± 0.90	2.30 ± 0.70	2.70 ± 0.90	0.001
SRS-Appearance	2.80 ± 0.80	2.30 ± 0.80	2.70 ± 0.70	0.000
SRS-Mental	3.60 ± 0.90	3.30 ± 1.00	3.60 ± 0.90	0.022

BMI body mass index, *MCS* mental component summary, *ODI* Oswestry Disability Index, *PCS* physical component summary, *SRS* Scoliosis Research Society-22r

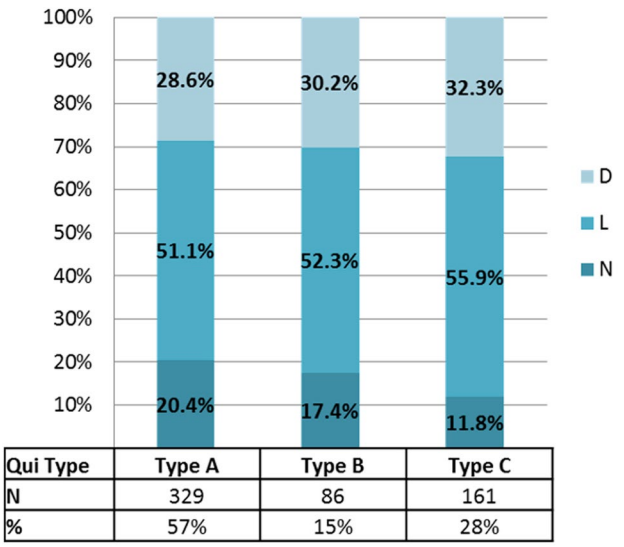

Fig. 4 Comparison of the SRS-Schwab coronal curve types across the Qui classification types

Table 2 Comparison of sagittal alignment stratified by Qui type using an analysis of variance

	Qui classification			*p*
	Type A	Type C	Type B	
PI, °	53.4 ± 12.5	52.1 ± 11.9	52.6 ± 12.1	0.528
PT, °	21.8 ± 9.9	20.9 ± 9.7	27.0 ± 10.0	0.000
PI–LL, °	9.6 ± 17.9	10.7 ± 16.9	23.4 ± 17.9	0.000
SVA, mm	36.0 ± 55.5	30.1 ± 58.8	100.7 ± 66.5	0.000
T1PA, °	18.3 ± 11.0	17.1 ± 11.0	28.2 ± 11.8	0.000

PI pelvic incidence, *PT* pelvic tilt, *LL* lumbar lordosis, *SVA* sagittal vertical axis, *T1PA* T1 pelvic angle

83.9 ± 62.4 mm vs. 73.9 ± 58.6 mm; $p=0.611$). There was also no significant difference in PI and T1PA.

In the coronal plane, Type B patients demonstrated greater coronal deformity with a GCM of 75 mm (vs. 13.2 and 51.3 mm for Types A and C, respectively; $p<0.001$), a GCDA of 10.6° (vs. 2.3° in Type A and 3.3° in Type C; $p<0.001$), and a maximum coronal Cobb angle of 49.5 (vs. 41.7 in Type A and 43.6 in Type C) (Table 5).

Analysis of PO for each type resulted in similar findings as those obtained before matching. In Type B patients, the direction of PO was additive, acting as a compensatory mechanism in 79.7% of the patients. In contrast, in Type A and C curves, PO was subtractive in 61.9% and 76.6% of the cases, respectively. In this setting, PO may act as independent driver of the coronal deformity and not as a compensatory mechanism.

Finally, assessment of the HRQOL scores across Qiu types demonstrated results similar to those obtained before matching; specifically, Type B patients had worse HRQOL scores when compared with the other types in terms of ODI (47.2 ± 17.3 vs. 42.2 ± 15.7 for Type A, and 38.7 ± 19.3 for Type C; $p=0.013$, and SRS-Total scores (2.67 ± 0.68) compared with 2.89 ± 0.62 and 2.98 ± 0.73 for Type A and C, respectively; $p=0.021$ (Table 6).

Discussion

To our knowledge, this study is the first to analyze the relationship between GCM, stratified by coronal curve pattern, and HRQOL in a North American population of ASD patients with no history of previous surgery. Specifically, our results demonstrate that Qui Type B patients had specific characteristics: they were older, more disabled, and

Table 3 Comparison of coronal alignment using analysis of variance and post hoc analysis (Bonferroni) based on Qui type

	Qui classification			*p*	Type A vs. Type B, *p*	Type A vs. Type C, *p*	Type B vs. Type C, *p*
	Type A	Type B	Type C				
GCM, mm	14.5 ± 8.7	77.6 ± 41.2	47.5 ± 17.6	0.000	0.000	0.000	0.000
APINC, °	1.5 ± 0.9	8.4 ± 4.3	4.8 ± 1.8	0.000	0.000	0.000	0.000
PO, °	2.5 ± 1.9	3.4 ± 3.2	2.5 ± 1.8	0.001	0.001	ns	0.006
Maximum Cobb angle, °	43.4 ± 15.8	49.3 ± 19.2	46.0 ± 15.0	0.008	0.008	ns	ns
GCDA, °	2.4 ± 2.0	10.9 ± 6.0	3.0 ± 2.5	0.000	0.000	ns	0.000

APinc coronal inclination, *GCDA* global coronal deformity angle, *GCM* global coronal malalignment, *ns* nonsignificant, *PO* pelvic obliquity

Table 4 Mean value of the AP inclination (APINC), pelvic obliquity (PO), and global coronal deformity angle (GCDA) by Qiu type and by sign

	APINC, cm	PO, °	GCDA, °
Type A			
Additive (35.1%)	1.34 ± 0.95	2.41 ± 1.82	3.75 ± 2.01
Subtractive (64.9%)	1.61 ± 0.89	2.5 ± 1.9	1.67 ± 1.55
Type B			
Additive (77.9%)	8.59 ± 4.38	3.79 ± 3.31	12.38 ± 5.74
Subtractive (22.1%)	7.79 ± 4.23	2.08 ± 2.22	5.76 ± 3.97
Type C			
Additive (16.8%)	5.14 ± 1.73	1.07 ± 1.26	6.21 ± 2.17
Subtractive (83.2%)	4.78 ± 1.8	2.84 ± 1.79	2.35 ± 1.95

had worse sagittal and coronal deformities. After propensity matching for age and sagittal malalignment, Type B patients still had worse health status and greater severity of coronal deformity than the other Qui types. For Type B patients, the magnitude of coronal malalignment was significantly more severe for all assessed parameters. Collectively, these findings demonstrate that coronal deformity can have significant impact on HRQOL and that Qui Type B patients may be the most impacted based on a North American patient population.

Over the last decade, growing evidence has shown that sagittal alignment is a key driver of disability in ASD patients. This concept is not challenged in our study. However, we hypothesized that GCM also significantly impacts HRQOL. Glassman et al. [10] as well as Ha et al. [17] have identified GCM as a factor associated with disability but only weak correlations with HRQOL have been reported. Our study brings a new aspect to light: when a patient presents with coronal malalignment, it is not the magnitude of the offset that matters but the magnitude of the curve and the laterality of the malalignment.

Radcliff et al. [20] have shown that PO can be a physiological compensatory mechanism of coronal malalignment and that it counteracts the scoliotic curve. In our study, PO was significantly greater in Type B patients and for 80% of the cases PO was additive, meaning that PO works as a coronal compensatory mechanism. However, this mechanism was overpowered by the magnitude of the deformity. In the same way that pelvic retroversion can compensate for sagittal malalignment, PO can be recruited as a compensatory mechanism but may be insufficient to maintain coronal alignment. The magnitude of Type B deformities, the failure of compensatory mechanisms and the increased GCM have a

Table 5 Comparison of coronal alignment based on Qiu type after propensity score matching by age and sagittal alignment

	Qui classification			*p*	Type A vs. Type B, *p*	Type A vs. Type C, *p*	Type B vs. Type C, *p*
	Type A	Type B	Type C				
GCM, °	13.2 ± 8.4	75.0 ± 41.2	51.3 ± 22.7	0.000	0.000	0.000	0.001
APINC, °	1.4 ± 0.9	8.0 ± 4.2	5.3 ± 2.2	0.000	0.000	0.000	0.000
PO, °	2.4 ± 1.9	3.4 ± 3.1	2.6 ± 1.9	0.050	ns	ns	ns
Maximum Cobb angle, °	41.7 ± 16.2	49.5 ± 19.7	43.6 ± 14.4	0.036	ns	ns	ns
GCDA, °	2.3 ± 1.9	10.6 ± 6.2	3.3 ± 2.7	0.000	0.000	0.047	0.000

APinc coronal inclination, *GCDA* global coronal deformity angle, *GCM* global coronal malalignment, *s* nonsignificant, *PO* pelvic obliquity

Table 6 Comparison of health-related quality of life scores across the Qui types after propensity matching by age and sagittal alignment

	n	Qui classification			*p*
		Type A	Type B	Type C	
ODI	64	42.2 ± 15.7	47.2 ± 17.3	38.7 ± 19.3	0.013
PCS	59	31.2 ± 9.7	30.4 ± 8.9	32.8 ± 11.2	0.376
MCS	59	47.7 ± 13.8	43.2 ± 14.9	47.9 ± 15.2	0.119
SRS-Total	62	2.89 ± 0.62	2.67 ± 0.68	2.98 ± 0.73	0.021
SRS-Activity	62	3.02 ± 0.80	2.73 ± 0.90	3.11 ± 0.91	0.029
SRS-Pain	62	2.47 ± 0.79	2.31 ± 0.76	2.66 ± 0.97	0.051
SRS-Appearance	62	2.62 ± 0.81	2.34 ± 0.79	2.57 ± 0.78	0.110
SRS-Mental	62	3.44 ± 0.96	3.24 ± 1.04	3.59 ± 0.93	0.125

MCS mental component summary, *ODI* Oswestry Disability Index, *PCS* physical component summary, *SRS* Scoliosis Research Society-22r

direct impact on health status. These findings argue against the idea that coronal malalignment is not a key parameter with clinical relevance.

In this study, we have defined a new angle (GCDA) to measure the deformity while taking into account the PO. Measuring this angle can help to quantify the magnitude of the deformity. The GCDA appears to be more effective for quantifying the severity of coronal deformity than the global coronal offset. Both before and after propensity matching, we found that GCDA was significantly greater in Type B patients; GCDA proved valuable for describing and analyzing the specific characteristics of Type B patients. We believe that this angle accurately reflects the actual severity of the deformities and the impact of the PO as a compensatory mechanism and propose its routine use for the assessment of coronal deformities.

This study draws possible implications for surgical planning and assessment of factors impacting HRQOL. Type B patients tend to present with worse HRQOL and greater severity of deformity. Because these patients may be more prone to undergo operative treatment, identifying patients as Type B may alert the surgeon that the main coronal curve should be a principal focus of surgical treatment. This is specifically important because preoperative GCM has been associated to an increase in implant failures and rate of implant removal [21], and recent literature has observed a 30% rate of iatrogenic coronal malalignment [18, 22]. Surgical planning is important and it is even more important in the presence of a deformity with coronal malalignment.

Finally, this study has established that after propensity matching, Type B patients still had worse health status with significantly lower HRQOL scores. The differences observed are at least equivalent to half of the minimal clinically important difference (MCID). From a clinical aspect, these findings question the lack of coronal modifiers in deformity classifications [12, 23] and raise the question of whether a coronal modifier should be included in a future deformity classifications. Our belief is that coronal alignment deserves greater attention.

Limitations

This study focuses mainly on Type B; further work is necessary to understand the specific characteristics of Type C curves and also include the assessment of the fractional curve and lateral listhesis in addition to the parameters already investigated [18].

Conclusions

This study demonstrated that coronal malalignment significantly affects the HRQOL of patients when the offset is greater than 3 cm in the same direction of the curve concavity. These Type B patients tend to recruit compensatory mechanisms that are overpowered and insufficient to maintain coronal alignment; the magnitude of the global coronal deformity has a direct and independent clinical impact. The Qiu classification has proven to be a useful tool to identify patients with coronal malalignment in a North American population. Understanding the type of curves in the coronal plane can help to identify the drivers of disability, facilitate surgical planning, and decrease the risk of iatrogenic malalignment.

Key points

- Coronal malalignment significantly affects the functional scores of primary patients with adult spine deformity when the offset is greater than 3 cm in the same direction of the curve concavity.
- The Global Coronal Deformity Angle (GCDA) has been defined to measure deformity while taking into account pelvic obliquity. This angle appears to be more effective for quantifying the severity of coronal deformity than the global coronal offset.
- Patients with severe spine coronal deformity tend to recruit compensatory mechanisms that are overpowered and appear to be insufficient to maintain coronal alignment.
- Patients with adult spinal deformity classified as Type B patients of the Qiu classification (Global coronal malalignment > 3 cm toward the concave side of the major lumbar or thoracolumbar curve) not only have poorer functional scores but also present a more severe deformity in the coronal plane expressed by a higher GCDA.

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Compliance with ethical standards

Conflict of interest NP: other from Spinewave and NuVasive, outside the submitted work. HB: none. RL: grants from North American Spine Society, Scoliosis Research Society (SRS), DePuy Spine, NuVasive, Stryker, and K2M; personal fees from Globus, AO Spine, and DePuy Spine; other from Nemaris INC, outside the submitted work. MG: personal fees and nonfinancial support from DePuy and Medtronic; personal fees from Innomed; other from J&J and P&G; grants from AO Spine and OMeGA, outside the submitted work. JSS: grants from DePuy Synthes/International Spine Study Group (ISSG), during the conduct of the study; personal fees from K2M, AlloSource, Cerapedics, Zimmer Biomet, and NuVasive; grants from NREF, AO Spine, and DePuy Synthes/ISSG, outside the submitted work. CS: grants from ISSG Foundation, during the conduct of the study; personal fees from Medtronic, NuVasive, Zimmer Biomet, and EOS, outside the submitted work. GM: personal fees from NuVasive, K2M, Allosource, Viseon, and Seaspine, outside the submitted work; in addition, GM has a patent NuVasive with royalties paid, and a patent K2M with royalties paid; and is on the board of directors of the Society for Lateral Access Surgery, San Diego Spine Foundation, and Global Spine Outreach. DB: grants, personal fees, and other from DePuy Spine; nonfinancial support from International Spine Study Group, Scoliosis Research Society, and University of Kansas Physicians; other from Bioventus and Pfizer, outside the submitted work. CA: personal fees from Stryker, Biomet Zimmer Spine, DePuy Synthes, NuVasive, Next Orthosurgical, K2M, Medicrea, Medtronic, and Biomet Zimmer; other from Titan Spine, DePuy Synthes, ISSG, and Operative Neurosurgery; grants from SRS and ISSG; other from Global Spinal Analytics, outside the submitted work. EK: personal fees from DePuy Synthes, Stryker, and K2M; grants and personal fees from AO Spine; personal fees from Trevena, Springer, Allosource, and Medicrea, outside the submitted work. SB: grants from DePuy Synthes Spine, during the conduct of the study; grants from DePuy Synthes Spine and Orthofix; grants and personal fees from K2 Medical; grants from Stryker Spine and Biomet Spine, outside the submitted work. FS: grants from DePuy Spine, Stryker, NuVasive, and K2M; personal fees from Globus Medical, Medicrea, Zimmer-Biomet, NuVasive, K2M, and MSD; other from Nemaris Inc., outside the submitted work. VL: other from Nemaris, outside the submitted work. ISSG: grants from DePuy Synthes Spine, K2M, NuVasive, and Orthofix, during the conduct of the study; grants from DePuy Synthes Spine, Medtronic, Stryker, Biomet, and Globus, outside the submitted work.

IRB approval Patients were enrolled after obtaining proper consent through an institutional review board (IRB)-approved protocol at each site participating to the study.

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Affiliations

Nicolas Plais[1,12] · Hongda Bao[1,2] · Renaud Lafage[1] · Munish Gupta[3] · Justin S. Smith[4] · Christopher Shaffrey[4] · Gregory Mundis[5,6] · Douglas Burton[7] · Christopher Ames[8] · Eric Klineberg[9] · Shay Bess[10] · Frank Schwab[1] · Virginie Lafage[1] · International Spine Study Group[11]

1 Department of Orthopaedic Surgery, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021, USA

2 Nanjing Drum Tower Hospital, Nanjing University, 321 Zhongshan Rd, Gulou Qu, Nanjing Shi 210008, Jiangsu Sheng, China

3 Department of Orthopaedic Surgery, Washington University School of Medicine, 660 S Euclid Ave, St. Louis, MO 63110, USA

4 Department of Neurosurgery, University of Virginia, P.O. Box 800212, Charlottesville, VA, USA

5 San Diego Spine Foundation, 6190 Cornerstone Ct. Suite 212, San Diego, CA 92121, USA

6 Scripps Clinic, 10666 N Torrey Pines Rd, La Jolla, CA 92036, USA

7 Department of Orthopaedic Surgery, University of Kansas Medical Center, 3901 Rainbow Blvd, Kansas City, KS 66160, USA

8 Department of Neurosurgery, University of California San Francisco, San Francisco, CA 94143, USA

9 Department of Orthopaedic Surgery, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA

10 Presbyterian/St. Luke's Medical Center and Rocky Mountain Hospital for Children, 2055 High Street, Suite 130, Denver, CO 80205, USA

11 Littleton, CO, USA

12 Hospital Universitario San Cecilio, Granada, Spain