Original Article

Analysis of baseline sagittal balance indicators and compensatory mechanisms at adult degenerative scoliosis in elderly patients operated on minimally invasive lateral lumbar interbody fusion

ABSTRACT

Study Design: Retrospective single-center study.

Background: Spinal alignment is crucial for maintaining upright posture, neural protection, and skeletal stability. Surgical treatment of adult degenerative scoliosis (ADS) is complex due to variability in clinical presentations and radiological parameters. Restoration of sagittal and coronal balance through minimally invasive techniques, including minimally invasive lateral lumbar interbody fusion (MI-LLIF), especially in elderly patients has demonstrated efficacy in reducing pain and enhancing quality of life.

Purpose: To evaluate the baseline sagittal alignment and compensatory mechanisms in elderly ADS patients operated on MI-LLIF, emphasizing the predictive value of key radiological parameters.

Materials and Methods: This was a retrospective review of 51 elderly patients with lumbar degenerative scoliosis treated using MI-LLIF. Radiological parameters evaluated were the coronal Cobb angle (CCA), pelvic incidence (PI), sacral slope, pelvic tilt (PT), lumbar lordosis (LL), PI-LL mismatch, L4-S1 lordosis, thoracic kyphosis, sagittal vertical axis, spino-sacral angle (SSA), and the Index Barrey (IB). Radiological assessment with X-ray was used before operation and mean 2.7 years follow-up.

Results: Preoperative CCA was 15 (11;20). The average PT was 21.9 , what confirmed the presence of sagittal imbalance in 98% of elderly patients with ADS. In accordance with IB, 18 (35%) patients were identified as balanced due to compensation mechanisms (IB <0.5). Global sagittal imbalance (IB >0.5) was revealed in 33 (65%) patients. The main reason of sagittal imbalance was L4-S1 lordosis insufficiency (80%). The main compensation mechanisms were retroversion of the pelvis (98%), hypokyphosis (67%), and hyperextension at the L4-S1 level (14%).

Conclusions: All patients have spinopelvic malalignment according to IB, and the main reason for its development was deficiency of L4-S1 and LL. The most sensitive markers of sagittal

Vladimir S. Klimov[1,2,3], Juri V. Kivelev[1,4], Evgeniya V. Amelina[5], Alexey V. Evsukov[6], Alexei L. Krivoshapkin[1,2], Sergei O. Ryabykh[3], Andrei A. Kalinin[7,8], Vadim A. Byvaltsev[7,8,9]

[1]Department of Neurosurgery, European Medical Center, [2]Department of Neurosurgery, Peoples' Friendship University of Russia (RUDN University), [3]Department of Traumatology and Orthopedics, Veltischev Research and Clinical Institute for Pediatrics and Pediatric Surgery of the Pirogov Russian National Research Medical University, Moscow, [5]Department of Neurosurgery, Novosibirsk State University, Novosibirsk, [6]Department of Neurosurgery, National Ilizarov Medical Research Center For Traumatology and Orthopedics, Kurgan, [7]Department of Neurosurgery, Irkutsk State Medical University, [8]Department of Neurosurgery, Railway Clinical Hospital, [9]Department of Traumatology, Orthopedic and Neurosurgery, Irkutsk State Medical Academy of Postgraduate Education, Irkutsk, Russia, [4]Neurocenter Outpatient Clinic, Neurocenter Turku University Hospital, Turku, Finland, Europe

Address for correspondence: Prof. Vadim A. Byvaltsev, 1 Krassnogo Vosstaniya Street, Off 201, 664003, Irkutsk, Irkutskaya Oblast', Russia.
E-mail: vadim75byvaltsev@gmail.com

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imbalance were PT with the calculation of target individual values, IB and SSA. The main compensatory mechanisms of sagittal imbalance are retroversion of the pelvis, thoracic hypokyphosis, and hyperextension in the overlying segments.

Keywords: Adult degenerative scoliosis, elderly patients, geriatric orthopedic surgery, minimally invasive lateral lumbar interbody fusion, minimally invasive surgery, sagittal imbalance

INTRODUCTION

Spinal alignment is crucial for maintaining upright posture, neural protection, and skeletal stability.[1,2] Adult spinal deformity (ASD), affecting approximately 60% of elderly individuals, often leads to significant functional impairment, including pain, mobility reduction, and postural instability.[3-5] The socioeconomic burden of ASD continues to grow, particularly with increased surgical interventions in populations aged over 65 years.[6]

The Scoliosis Research Society (SRS) defines ADS as a subset of ASD characterized by a lumbar curve (Cobb angle <30°) with associated sagittal imbalance.[7] Surgical treatment of ADS is complex due to variability in clinical presentations and radiological parameters. Restoration of sagittal and coronal balance through minimally invasive techniques, including minimally invasive lateral lumbar interbody fusion (MI-LLIF), has demonstrated efficacy in reducing pain and enhancing quality of life (QoL).[8,9]

Radiological parameters, such as coronal Cobb angle (CCA), pelvic tilt (PT), pelvic incidence (PI), lumbar lordosis (PI-LL) mismatch, and sagittal vertical axis (SVA), are abnormal in patients with ADS and correlate with increased pain and lower QoL.[8] Still, it is fundamental to combine these parameters with objective data such as surgical observations and clinical outcomes.[10,11] Studies have shown a correlation between surgical failure and the severity of preoperative malalignment, meaning that poorly corrected posture requires greater levels of lower body compensation to maintain postoperative spinal balance. However, those compensations may occur due to the lack of a detailed preoperative assessment, including the patient's disability condition and sagittal profile.[8,12]

The purposes of this study were to evaluate the baseline sagittal alignment and compensatory mechanisms in elderly ADS patients operated on MI-LLIF, emphasizing the predictive value of key radiological parameters.

MATERIALS AND METHODS

Study design

This retrospective study included 51 elderly patients with lumbar degenerative scoliosis treated at the neurosurgery center (Federal Neurosurgical Center, Novosibirsk, Russian Federation) from 2015 to 2020. The cohort included 44 women (86%) and 7 men (14%) with a mean age of 67 years. Each patient gave voluntary statement regarding informed consent to be included in the study. The course and nature of the surgical intervention were explained to the patients in detail. The study was approved by the ethics committee of (Novosibirsk State Medical University).

The patients' data used to support the findings of this study were restricted by the ethics committee of (Novosibirsk State Medical University, protocol No 2 of February 20, 2018) to protect of the patient privacy. Data are available from the first author (Vladimir S. Klimov) for researchers who meet the criteria for access to confidential data. The analysis of the clinical material was carried out in accordance with the principles of the Declaration of Helsinki.

Primary and secondary endpoints of the study were from preoperative to a mean of 2.7 years postoperative.

Patient inclusion/exclusion

Inclusion criteria

- Patients aged 60–81 years (mean age: 67 years)
- ADS with a Cobb angle of 10–30° (SRS-Schwab type N)
- Failed to respond to conservative therapy for 12 weeks
- Absence of clinical instability, as defined by a White-Panjabi score of <5 points[13]
- Primary surgery in the lumbar spine.

Exclusion criteria

- High surgical risk as determined by the American Society of Anesthesiologists classification of groups 4–5
- Revision cases
- Refusal to participate in the study.

Surgical techniques

All patients underwent MI-LLIF, supplemented with percutaneous transpedicular stabilization. Patients were positioned in the lateral decubitus position under general anesthesia. The MI-LLIF procedure included the use of free running electromyography monitoring to safeguard neural structures and prevent injury. Intraoperative imaging was utilized to guide precise alignment corrections and ensure optimal outcomes. In all cases, we did not use bone morphogenetic protein.

Outcomes of the study

Radiological outcomes were assessed pre- and postoperatively (mean 2.7 years after operation) using an X-ray of the spine with inclusion of the femoral heads in two projections when standing. We measured PI, sacral slope (SS), PT, LL, L4-S1 segmental lordosis, thoracic kyphosis (TK), SVA, and spino-sacral angle (SSA).

Compensation mechanisms were assessed using the Barrey Index (IB) and Roussouly classification system to identify localized and global compensatory adjustments.[14,15]

Statistical analysis

Statistical analysis was carried out on a personal computer using the R software (Vienna, Austria, version 4.0.5). The character of the distribution of signs was evaluated by the Shapiro–Wilk, Kolmogorov–Smirnov, and Lilliefors tests for normality. Considering the presence of statistically significant differences according to these tests ($P < 0.05$), the distribution was considered different from normal. In this regard, the criteria of nonparametric statistics were used to assess the significance of the differences in the samples. The obtained results were presented by the median, the values of the 1st and 3rd quartiles – Me (Q_{25}; Q_{75}). For a comparative subgroup analysis of the obtained values, the Mann–Whitney *U*-test was used. The differences were considered statistically significant at the level of $P < 0.05$.

RESULTS

In all patients, local sagittal imbalance was identified due to the existing type N scoliotic deformity based on the SRS-Schwab classification. The preoperative CCA was 15° (11°–20°). Degenerative spondylolisthesis was observed in 35 (68.6%) patients, with involvement at one level in 9 patients, two levels in 23 patients, and three levels in 3 patients. According to the Meyerding classification, 34 patients had Grade 1 spondylolisthesis, while 1 patient had Grade 2. Functional spinal unit instability was not detected on radiography with functional probes. The White and Panjabi score averaged 4 (2–4), confirming sagittal imbalance in all patients.

Analysis of Sagittal Balance Indicators Radiological parameters characterizing sagittal balance are detailed in Table 1. As shown in Table 1, 63% of patients exhibited high PI values, a proportion double that observed in the general population.

Based on the theoretical calculations, these patients predominantly displayed a type IV sagittal spine profile per Roussouly, a profile seen in only 30% of healthy individuals [Table 2]. Conversely, 43% of patients in the cohort had type II LL, which is typically observed in only 10% of the normal population. These trends correlated with the low SS values recorded.

Table 1: Radiological characteristics of patients

Sagittal modifiers	Study group (n=51)
PI, Me (Q_{25} to Q_{75})	53 (46 to 60)
LL, Me (Q_{25} to Q_{75})	45 (36 to 52.5)
Target LL, Me (Q_{25} to Q_{75})	56.2 (52.2 to 59.7)
L4-S1 Lordosis, Me (Q_{25} to Q_{75})	27 (17.5 to 36)
Target L4-S1, Me (Q_{25} to Q_{75})	37.1 (34.4 to 39.4)
PT, Me (Q_{25} to Q_{75})	22 (17 to 26.5)
Target PT (age-adjusted), Me (Q_{25} to Q_{75})	25.1 (22 to 25.1)
Target PT (formula-derived), Me (Q_{25} to Q_{75})	11.9 (8.6 to 14.8)
SS, Me (Q_{25} to Q_{75})	31 (26 to 36)
SSA, Me (Q_{25} to Q_{75})	120 (113.5 to 125)
SVA, Me (Q_{25} to Q_{75})	43 (16.5 to 67.5)
PI-LL Mismatch, Me (Q_{25} to Q_{75})	8 (0.5 to 17)
TK, Me (Q_{25} to Q_{75})	36 (27 to 41)
CCA, Me (Q_{25} to Q_{75})	15 (11 to 20)

PI - Pelvic incidence; LL - Lumbar lordosis; PT - Pelvic tilt; SS - Sacral slope; SSA - Sagittal spinopelvic alignment; SVA - Sagittal vertical axis; TK - Thoracic kyphosis; CCA - Coronal Cobb angle

Table 2: Distribution of patients by lumbar lordosis type (roussouly criteria)

Type	Theoretical data (%)	Cohort data (%)	Healthy population (%)
I	2	22	20
II	4	43	10
III	31	25	40
IV	63	10	30

These findings suggested that type IV lordosis in older patients is a potential predictor of degenerative scoliosis, with disruptions primarily in the sagittal plane. Such sagittal profile violations contribute to the "flat back" syndrome and significant biomechanical abnormalities, including retroverted LL variants-so-called "False" Retroverted "Type 2" and "False Type 2+ TK" types of the spinal shapes according to the Roussouly classification (43% and 22%, respectively).[16]

All patients displayed sagittal imbalance with deficits in L4-S1 lordosis, LL, SSA, and pelvic retroversion. The average LL deficit did not exceed 20°, while the mean L4-S1 lordosis deficit was 12°. The mean PT was twice as high as values calculated individually for each patient based on their PI. LL deficiency exceeded 10° in most of the cases, confirming significant global imbalance. These deviations are illustrated in Figure 1.

Subgroup analysis patients were divided into two subgroups based on IB calculations: [1] Subgroup A (compensated, IB <0.5) included 18 (35%) patients with balanced sagittal alignment achieved through compensatory mechanisms [Figure 2][2] and Subgroup B (decompensated, IB >0.5) encompassed 33 (65%) patients with global sagittal imbalance [Figure 3].

Characteristics of patients by IB subgroups are presented in Table 3. Subgroup B exhibited significantly greater SVA deviations ($P < 0.001$), confirming pronounced global imbalance. Figures 2 and 3 present typical radiographic findings for each subgroup. Despite differences in SVA, other parameters such as PI and LL did not differ significantly, underscoring the role of compensatory mechanisms in Subgroup A.

Table 4 provides a summary of deviations from normative values in PT, SSA, and other critical markers across subgroups. Notably, 82% of Subgroup B patients had an SVA >40 mm,

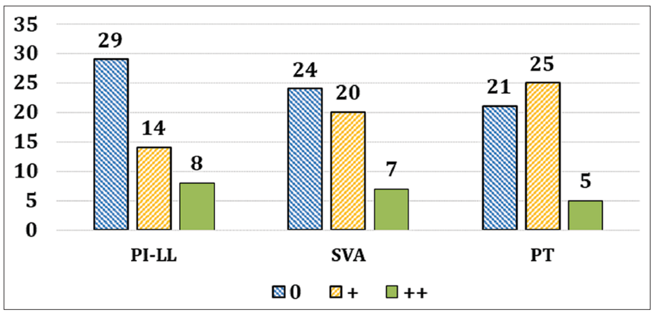


Figure 1: Diagram of the distribution of patients according to the presence of existing deviations in the parameters of sagittal modifiers according to the Scoliosis Research Society-Schwab classification without age adjustment

a hallmark of global imbalance, compared to none in Subgroup A. SSA deviations were also more pronounced in Subgroup B (119° vs. 123°; $P = 0.25$). TK values varied, with 67% of cases displaying reduced TK as a compensatory mechanism for LL deficits. The observed trends were consistent with established literature on compensatory adjustments in elderly ADS patients.

Most of the patients had high PI values (PI >50°); however, the IB subgroups did not differ in this parameter ($P = 0.65$). Consequently, the PI index itself did not significantly affect the likelihood of developing a global sagittal imbalance in this category of patients. The presence of a local sagittal imbalance in all these patients was confirmed by the absence of statistically significant differences in LL ($P = 0.52$) between subgroups; however, in Subgroup A, global sagittal balance was achieved by compensation mechanisms, whereas in Subgroup B, the insufficiency of compensatory mechanisms led to a global sagittal imbalance. It should be noted that sagittal imbalance at the segmental level (L4-S1 deficiency) was found in 41 (80%) patients, and at the regional level (LL deficiency) was detected in 47 patients (92%). We did not obtain statistically significant differences between the subgroups in terms of the angle of deformation in the frontal plane ($P = 0.63$).

The subgroups differed statistically significantly in terms of SVA without considering the correction for age ($P < 0.001$).

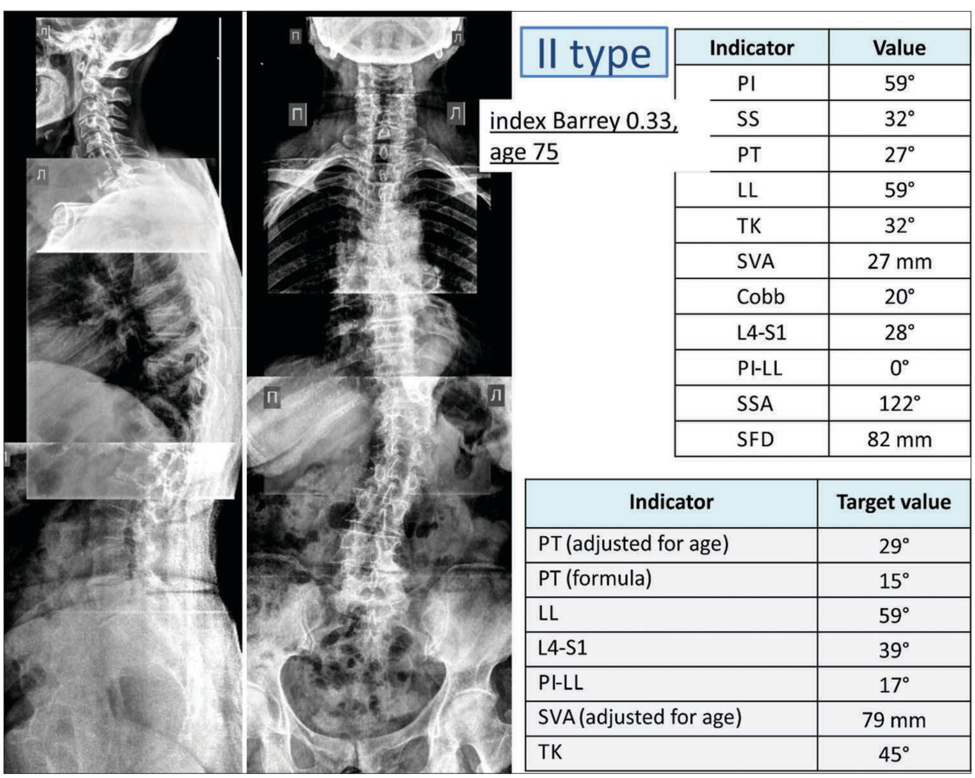
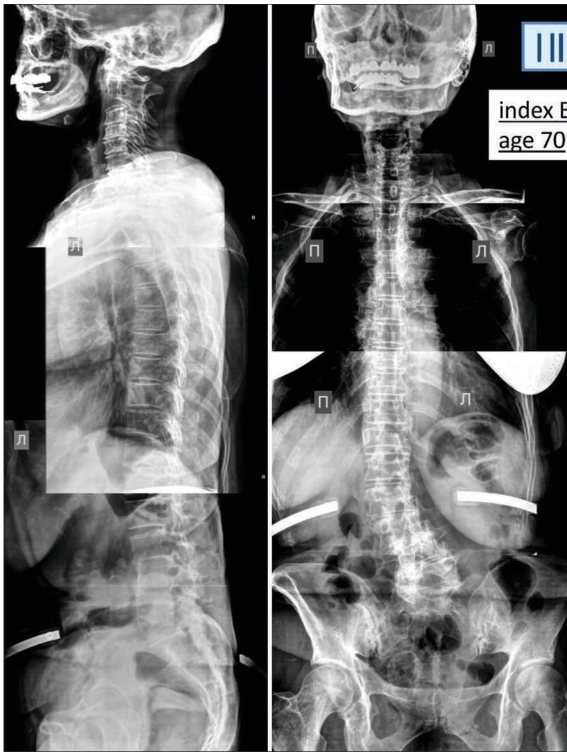


Figure 2: X-ray of a 75-year-old patient with adult degenerative scoliosis, compensated frontal and sagittal imbalance, Index Barrey–0.33



Indicator	Value
PI	60°
SS	26°
PT	34°
LL	18°
TK	16°
SVA	62 mm
Cobb	16°
L4-S1	15°
PI-LL	42°
SSA	111°
SFD	99 mm

Indicator	Target value
PT (adjusted for age)	25°
PT (formula)	15°
LL	60°
L4-S1	40°
PI-LL	11°
SVA (adjusted for age)	55 мм
TK	45°

Figure 3: X-ray of a 70-year-old patient with adult degenerative scoliosis, frontal and decompensated sagittal imbalance, Index Barrey–0.63

Table 3: Characteristics of patients by Index Barrey Subgroups

Indicator	Subgroup A (n=18)	Subgroup B (n=33)	*P*
IB, Me (Q_{25} to Q_{75})	0.2 (0 to 0.3)	1 (0.7 to 1.2)	-
CCA (°), Me (Q_{25} to Q_{75})	15.5 (11 to 24)	15 (11 to 19)	0.63
PI, Me (Q_{25} to Q_{75})	54 (50 to 60)	53 (44 to 59)	0.65
PT, Me (Q_{25} to Q_{75})	23 (20 to 27)	21 (16 to 26)	0.24
LL, Me (Q_{25} to Q_{75})	46.5 (40.2 to 53.8)	43 (35 to 51)	0.52
SVA (°), Me (Q_{25} to Q_{75})	9 (0 to 17)	62 (44 to 86)	<0.001

IB - Index Barrey; PI - Pelvic incidence; CCA - Coronal Cobb angle; LL - Lumbar lordosis; SVA - Sagittal vertical axis; PT - Pelvic tilt

When conducting a detailed analysis of the sagittal SVA modifier, considering the age correction, we found that in Subgroup A, there were no patients with SVA >40 mm, as well as with exceeding its normal age values [Table 4].

The presence of sagittal imbalance, as indicated by the IB criteria, was observed in all patients with ADS. This necessitated a detailed investigation of the compensatory mechanisms underlying vertebral–pelvic alignment impairment. A summary of these compensatory mechanisms is presented in Table 5.

Our findings

- Pelvic retroversion as a dominant compensatory mechanism: Increased PT was observed in almost all patients with degenerative scoliotic deformity (50/51). In addition, hypokyphosis (decreased TK) was noted in the majority (34/51), reflecting significant disruptions in the vertebral–pelvic relationship
- Segmental imbalance and global sagittal imbalance: A decrease in the L4-S1 segment lordosis and LL below individual target values was present in 39 (77%) patients. This highlights segmental imbalance in the lower lumbar region. Among these, pelvic retroversion (↑ PT) was the primary compensatory mechanism, with hypokyphosis (↓ TK) acting as a secondary mechanism in 28 patients. These patients exhibited the most pronounced deviations in SVA and SSA, indicating global sagittal imbalance
- Cases with additional compensatory mechanisms: In 7 patients (3 from Subgroup A and 4 from Subgroup B), the apex of the main scoliotic curvature was located in the upper lumbar region. This contributed to global LL deficiency. These patients employed additional compensatory mechanisms, including hyperextension of the L4-S1 segment (↑L4-S1) and hypokyphosis (↓TK). These cases accounted for 14% of all patients (highlighted in green). In 3 patients with high PI (PI >60°), compensatory hyperextension of the lumbar spine resulted in increased L4-S1 and LL values (1 in subgroup A) or normal LL values (2 in subgroup B). These patients demonstrated significant PT exceeding individual target values, with either compensatory hyperkyphosis (↑TK, 2 patients) or hypokyphosis (↓TK, 1 patient; highlighted in blue)
- Subgroup-specific observations: In Subgroup A, 18 patients maintained global sagittal balance through

Table 4: Values of patient's Index Barrey indices in accordance with various methods for determining normal values

Indicators	Subgroups of patients according to IB	
	Subgroup A (n=18)	Subgroup B (n=33)
SVA data		
SVA, mm, Me (Q_{25} to Q_{75})	9 (0 to 17)	62 (44 to 86)
Deviation from the norm (correction based on age), Me (Q_{25} to Q_{75})	−48 (−63 to−26)	9 (−7 to 33)
Number of patients with SVA>40 mm, n (%)	0	27 (81.8)
The number of patients with excess of the norm, n (%)	0	20 (60.6)
SSA data		
SSA°, Me (Q_{25} to Q_{75})	123 (115 to 129)	119 (113 to 124)
The number of patients with SSA is below normal (134°±8°), n (%)	12 (66.6)	27 (81.8)
PT data		
PT, Me (Q_{25} to Q_{75})	23 (20 to 27)	21 (16 to 26)
Number of patients with PT>20°, n (%)	13 (72.2)	17 (51.5)
The PT standard is calculated taking into account the adjustment for age		
Deviation from the standard, Me (Q_{25} to Q_{75})	−3.1 (−4.8 to 4)	−3.8 (−8.1 to 0.9)
The number of patients with excess of the norm, n (%)	7 (38.9)	9 (27.3)
The PT standard is calculated using the formula 0.44×PI – 11.4		
Deviation from the standard, Me (Q_{25} to Q_{75})	12.3 (9.4 to 14.4)	7.6 (5.6 to 12.9)
The number of patients with excess of the norm, n (%)	17 (94.4)	33 (100)
PI-LL data		
PI-LL, Me (Q_{25} to Q_{75})	7 (2.5 to 13.8)	9 (0 to 18)
Deviation from the norm (correction based on age), Me (Q_{25} to Q_{75})	−0.4 (−10.4 to 6.4)	0 (−7.8 to 7.5)
The number of patients with excess of the norm, n (%)	9 (50)	16 (48.5)
TK data		
TK, Me (Q_{25} to Q_{75})	35.5 (25.5 to 42)	36 (28 to 40)
Deviation from the norm, Me (Q_{25} to Q_{75})	−5.5 (−20.5 to−1.1)	−6.4 (−14.2 to 0.1)
TK is above the norm, n (%)	3 (16.7)	5 (15.1)
TK is within the normal range, n (%)	3 (16.7)	6 (18.2)
TK is below the norm, n (%)	12 (66.6)	22 (66.7)

SVA - Sagittal vertical axis; IB - Index Barrey; SSA - Sagittal spinopelvic alignment; PT - Pelvic tilt; PI - Pelvic incidence; TK - Thoracic kyphosis; LL - Lumbar lordosis

compensatory mechanisms in the lumbosacral spine, with SVA values within normal age-specific limits. In Subgroup B, 13 patients achieved similar balance; however, the remaining 20 patients (61% of Subgroup 3B; 39% of Group 3 overall) showed insufficient compensatory mechanisms, leading to global sagittal imbalance (↑SVA)

Table 5: Characteristics of compensatory mechanisms in group 3 patients

Type	Total	Subgroup A	Subgroup B	↑ SVA	↓ SSA
↓ L4-S1↓LL↑PT↓TK	28	9	19	15	24
↓ L4-S1↓LL↑PT nTK	6	2	4	1	6
↓ L4-S1↓LL↑PT↑TK	5	3	2	1	3
↓ L4-S1 nLL↑PT↓TK	1	-	1	-	-
↓ L4-S1 nLL↑PT nTK	1	-	1	-	1
↑ L4-S1↓LL↑PT↓TK	4	2	2	1	2
↑ L4-S1↓LL↑PT nTK	2	1	1	-	1
↑ L4-S1↓LL ↑PT ↑TK	1	-	1	1	1
↑ L4-S1 nLL ↑PT ↑TK	2	-	2	1	1
↑ L4-S1 ↑LL ↓PT ↓TK	1	1	-	-	-
Total	51	18	33	20 (39%)	39 (77%)

Indices before the indicator signify: ↑ - Exceeds target value; ↓ - Below target value; n - Within normal range; SVA - Sagittal vertical axis; SSA - Sagittal spinopelvic alignment; LL - Lumbar lordosis; PT - Pelvic tilt; TK - Thoracic kyphosis

- SSA as a marker of global sagittal imbalance: A decrease in SSA below normal values was observed in 39 (77%) patients. This highlights SSA as a more sensitive marker of global sagittal imbalance compared to SVA in older adults with degenerative scoliotic deformities. Increased PT, aligned with individual PI, serves as an additional marker of imbalance.

DISCUSSION

Recent years have seen increased emphasis on the preoperative assessment of sagittal spinal alignment and its restoration to reduce implant-related complications and improve clinical outcomes. Precision analysis of sagittal balance indicators during preoperative planning and postoperative evaluation has become a cornerstone in selecting surgical treatment options, particularly for elderly patients with high surgical risks.[17] The tendency to use various MIS technologies in these patients reduces complications and improves treatment results.[18] This is especially relevant in the surgical treatment of elderly patients with ADS, since inadequate restoration of the sagittal profile leads to a significant number of implant-dependent mechanical complications and unsatisfactory clinical outcomes.[19] Inadequate restoration of sagittal alignment in these cases often results in significant implant-related mechanical complications and unsatisfactory clinical outcomes.

Restoration of sagittal spinal alignment and addressing compensatory mechanisms for sagittal imbalance are critical for preventing complications such as proximal junctional kyphosis (PJK) and proximal junctional failure (PJF). Lovecchio *et al*. demonstrated that a proximal junctional angle (PJA) ≥4.3° with a PJA <15.5° was associated with radiographic

PJK in 55.3% of cases, but only 7.9% developed PJF. However, when ΔPJA ≥4.3° and PJA >15.5°, 57.1% developed PJF and 28.6% exhibited radiographic PJK, indicating that such parameters could act as mechanistic breakpoints in the junctional region.[20]

In our study, an analysis of the indicators of sagittal modifiers according to the SRS-Schwab classification revealed pronounced sagittal imbalance in most patients, with PT serving as the most sensitive marker (identified in 59% of cases). Pelvic retroversion emerged as the predominant compensatory mechanism, present in 50 out of 51 patients. This aligns with the findings from Sebaaly *et al*., who identified preoperative and postoperative PT as reliable predictors of mechanical complications in ADS patients. These complications, which occurred in 30.4% of their cohort, were most commonly PJK. Moreover, patients restored to the Roussouly classification-based normative sagittal shapes had a significantly lower complication rate (22.5%) compared to those without restoration (46.8%).[16]

Our findings also highlight that the orientation of the sacrum in the horizontal plane changes with increasing PT, leading to a decrease in SS. This observation may stem from limited hip joint mobility, which restricts compensatory pelvic retroversion. When target PT values were calculated based on each patient's PI using the formula proposed by Le Huec *et al*., pelvic retroversion was identified as a compensatory mechanism in 98% of cases.[21] These results underscore the importance of individualized parameter calculations to assess compensatory mechanisms accurately.

Ohba *et al*. demonstrated the utility of preoperative prone SS in predicting postoperative SS. When preoperative SS is significantly lower than the ideal SS based on PI, corrective procedures such as osteotomy should be considered.[22] Spiessberger *et al*. further emphasized the significant influence of preoperative sagittal balance indicators, including PT, LL, TK, and SVA, on achieving optimal sagittal profiles in ADS patients.[23]

Our data showed that SVA is a highly sensitive sagittal modifier for detecting global imbalance in elderly ADS patients. After applying age corrections, the number of patients with elevated SVA decreased significantly, from 31 to 17, underscoring the relevance of age-adjusted thresholds. Despite this, PT emerged as the most specific and sensitive marker of sagittal imbalance, particularly when target PT values were calculated individually based on PI.[21] This approach identified pelvic retroversion as the primary compensatory mechanism in 98% of elderly ADS patients. SSA was also identified as a more sensitive marker of global sagittal imbalance compared to SVA in this population.

According to Assi *et al*. data, patients with severe pelvic retroversion showed an increased acetabular anteversion, external coverage, and lower anterior coverage during gait. These changes in acetabular orientation, computed during walking, were shown to be related to hip osteoarthritis.[24] The study of Quarto *et al*. showed that with reference to the sagittal plane, three parameters were mainly reported: PT, LL and SVA; all these parameters showed an important postoperative improvement that was maintained at last follow-up.[25]

The relationship between PI, PT, and LL remains pivotal in understanding sagittal imbalance. For example, Sebaaly *et al*. noted that high PI (>50°) is always compensated by pelvic retroversion, often accompanied by decreased TK.[16] In our cohort, TK deviations from target values were identified in 80% of cases, with decreased TK in 67% of patients serving as an important compensatory mechanism to maintain global balance despite LL deficiencies. Conversely, 8 patients exhibited increased TK, likely due to thoracic spine rigidity and limited compensatory capacity.

Radiological analysis confirmed that sagittal imbalance in all patients was primarily attributable to deficiencies in L4-S1 and LL. These findings align with Diebo *et al*., which emphasize the importance of LL redistribution and segmental correction in ASD.[26] Despite compensatory mechanisms, global sagittal imbalance was identified in most cases preoperatively. Statistically significant differences in SVA ($P < 0.001$) were observed between patients with and without global sagittal imbalance. SSA deficiency was present in 77% of patients, highlighting its utility as a sensitive marker for global imbalance in older ADS patients. These findings align with Sachdev *et al*. and Cho *et al*., who emphasized the importance of age and global alignment proportion in guiding surgical correction and predicting postoperative outcomes.[3,27] In a well-balanced spine, SSA is proportional to SS and decreases with loss of LL. This relationship can be used as a guide to determine the need for kyphosis correction. There is a strong correlation between SSA, SS, and LL.[27]

In our opinion, the most sensitive and specific marker of local sagittal imbalance is an increase in PT with the calculation of target individual values in accordance with the value of PI. An additional mechanism is hypokyphosis. It is in these patients that the most pronounced deviations of SSA, indicating a global sagittal imbalance of the body. The study of Cho *et al*.[27] highlights that not all compensatory mechanisms are observed in a single patient, but compensatory mechanisms will be present to varying degrees, depending on the flexibility of the spine, muscle condition, and degree of imbalance. The same data Faraj *et al*. did not analyze such important markers of sagittal imbalance as SSA and IB.[28]

Finally, our study reaffirms that a comprehensive analysis of SB indicators and compensatory mechanisms at the preoperative stage is critical for optimizing surgical outcomes. Key considerations include the mandatory restoration of LL, L4-S1, and PT, as outlined in multiple modern studies. Overcorrection increases the risk of PJF, while under correction raises the likelihood of implant failure, underscoring the need for individualized normative segmental lordosis targets. In a study by Diebo *et al*. was shown, what patients undergoing fusion for ASD suffer higher rates of PJF with overcorrection and increased rates of implant failure with under correction based on normative segmental lordosis.[26]

The importance of precise assessment of these indicators ensures the achievement of better clinical outcomes and reduces the number of implant-dependent complications, which requires further scientific studies, including multicenter and prospective randomized research.

Limitations of the study

The limitations of the study include (1) retrospective nature of the data collection and the impossibility of blinding; (2) nonrandomized sample of examined patients without using an electronic patient data management system; and (3) lack of analysis of results in the early and intermediate postoperative period.

Despite these limitations, the strengths of the study include its mean 2.7 years follow-up on a population of patients with a single diagnosis, treated by a single team without numerous confounding variables.

CONCLUSIONS

Elderly ADS patients with type "N" and Cobb angle ≤30° require detailed preoperative evaluation of sagittal balance parameters and compensatory mechanisms. Our study confirms that spinopelvic malalignment is universal in degenerative deformities, with deficiencies in L4-S1 and LL being the primary contributors. The most sensitive markers of sagittal imbalance are PT (calculated individually based on PI), IB, and SSA. Pelvic retroversion, thoracic hypokyphosis, and hyperextension in adjacent spinal segments serve as the main compensatory mechanisms. A precise assessment of these indicators during preoperative planning is essential for guiding surgical strategies and reducing implant-related complications. Further research, including prospective multicenter trials, is warranted to refine these approaches and improve long-term outcomes in ADS patients.

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Conflicts of interest

There are no conflicts of interest.

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