Research Square

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Associations Between Back Physical Signs and Curve Progression in Adolescent Idiopathic Scoliosis Subtypes in China

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Abstract

Purpose

To elucidate the associations between back physical signs and curve progression across the thoracic, thoracolumbar, and lumbar subtypes of adolescent idiopathic scoliosis (AIS), and to identify subtype-specific factors associated with curve progression.

Methods

We retrospectively analyzed 1,283 patients with AIS who visited our Department of Spine Surgery between January 2019 and December 2023. Patients' baseline demographics, radiological parameters, and physical back signs were collected. Patients were stratified into progression and stable groups according to main Cobb angle changes during follow-up. Univariate and multivariate logistic regression (LR) analyses were performed for each curve subtype to identify subtype-specific independent risk factors for curve progression.

Results

In univariate LR, curve progression was significantly associated with the following variables: for thoracic-curve AIS, Risser sign grade 4, lumbar left concavity, and right thoracic rotation ≥ 5°; for thoracolumbar-curve AIS, female sex, left rib-hump eminence, left thoracic and lumbar angle of trunk rotation (ATR) ≥ 5°, and left lumbar eminence; for lumbar-curve AIS, right rib-hump eminence, left lumbar eminence, left and right thoracic ATR ≥ 5°. In multivariate LR analyses, left lumbar concavity (odds ratio [OR] 2.164, 95% confidence interval [CI] 1.224–3.893; *P* = 0.009) increased progression risk in thoracic-curve AIS. For thoracolumbar-curve AIS, female sex (OR 4.343, 95%CI 1.663–13.967, *P* = 0.006), left thoracic ATR ≥ 5° (OR 14.725, 95%CI 1.558–347.926, *P* = 0.036) and left lumbar ATR ≥ 5° (OR 6.261, 95%CI 1.235–51.570, *P* = 0.046) increased risk, while Risser grade 1 (OR 0.068, 95%CI 0.003–0.506, *P* = 0.027) protected against progression. For lumbar-curve AIS, right lumbar concavity (OR 2.644, 95%CI 1.104–6.796, *P* = 0.035) increased risk, while a right-tilted scapula (OR 0.154, 95% CI 0.028–0.885, *P* = 0.032) was protective.

Conclusion

This large-scale clinical study demonstrated that physical back signs were closely linked to curve progression and varied according to the AIS subtype in Chinese adolescents. These signs, which are easily assessed during routine examination at no extra cost, allow early identification of adolescents at risk of progression and facilitates individualized follow-up.

Introduction

Adolescent idiopathic scoliosis (AIS), a three-dimensional structural deformity of the spine conventionally defined by a lateral Cobb angle of ≥ 10° on standing radiographs, typically manifests during the pubertal growth spurt. AIS affects approximately 0.5%–5.2% of adolescents worldwide, with a marked female predominance [1], particularly in terms of curvature requiring clinical intervention. Its incompletely understood etiology is linked to genetic, hormonal, and biomechanical factors [2]. Although mild curvatures typically remain clinically silent throughout adolescence, early identification and risk stratification is important, given the potential for rapid progression to severe deformities. Unchecked progression may cause significant cosmetic disfigurement, chronic back pain, reduced physical function, restrictive pulmonary disease, and imposes a substantial psychosocial burden [3], with surgical correction required in some patients.

Progression risk stratification has traditionally been based on serial standing full-spine radiography, which facilitates direct quantification of Cobb angle changes over time. However, cumulative ionizing radiation exposure during a biologically sensitive developmental window, high equipment dependency, substantial cost, and restricted availability at primary healthcare facilities limit application of this approach for the high-frequency, large-scale monitoring required for effective AIS management [4].

In China, school-based scoliosis screening (SSS) programs typically incorporate visual inspection of back posture, the Adams forward-bending test (FBT), and scoliometer-based measurement of the angle of trunk rotation (ATR) [5]. Students identified as at-risk are referred for confirmatory radiographic evaluation and clinical management, guided by the Cobb angle [6]. Physical back signs, including postural asymmetry of the shoulders and scapulae, rib-hump prominence, lumbar paraspinal eminence, and trunk rotational asymmetry, complement imaging-based assessments [7]. These signs can be monitored without the use of specialized equipment or radiation, and allow standardized, reproducible evaluation, even in resource-limited settings, making them well-suited for routine population screening. Recent technological advances, including three-dimensional markerless surface topography, integrated with convolutional neural network algorithms, have further improved the objectivity and reproducibility of such assessments [8]. Nonetheless, existing studies have focused predominantly on the utility of back physical signs for AIS detection and screening, whereas their prognostic relevance to curve progression, a clinically decisive parameter guiding treatment selection and follow-up intensity, remains uncertain [9].

AIS is not a homogeneous entity; the thoracic-, thoracolumbar-, and lumbar-curve subtypes differ markedly in their natural histories, biomechanical characteristics, and surface topographic manifestations [10]. Whether the relationships between specific back physical signs and progression risk are consistent across distinct curve subtypes or whether subtype-specific prognostic indicators exist requires systematic examination in large clinical cohorts. Previous studies have demonstrated significant associations between back physical signs and AIS among participants from a SSS population [11], but whether these associations differ according to subtype remains unknown. Such information

may facilitate individualized, radiation-free risk stratification and support more precise, targeted clinical decision-making in individuals with AIS.

Accordingly, we investigated the independent associations between multidimensional back physical signs and curve progression over a 1-year period across thoracic-, thoracolumbar-, and lumbar-curve AIS subtypes.

Materials and Methods

SSS program and ethics

Our Chinese SSS Program, which is part of the National Public Health Project, targets Chinese children and adolescents (aged 6–18 years) admitted to primary, junior high, and senior high schools in Shenzhen. The SSS program is conducted and administered by the the Shenzhen Youth Spine Health Center (SYSHC) at the Shenzhen Second People's Hospital, in accordance with a nationally standardized protocol (GB/T16133-2014).

This study was approved by the Ethics Committee of Shenzhen Second People's Hospital; all participants provided informed consent. Scoliosis screening was conducted in schools by a team of experienced rehabilitation therapists from the SYSHC using visual examination, Adam's FBT, and scoliometer-based ATR measurements. Students suspected of having AIS were referred for further clinical examination and full-spine radiography to assess the degree of spinal curvature.

Study design and participants

For this retrospective study, we collected data from adolescents with idiopathic scoliosis who underwent spinal radiography and had complete baseline and follow-up data. Data were collected from January 2019 to December 2023 at the outpatient clinic of the Department of Spine Surgery, Shenzhen Second People's Hospital.

The inclusion criteria were as follows: definitive diagnosis of idiopathic scoliosis by two senior spine surgeons, based on standardized clinical and radiological assessments, with the diagnostic criterion being a Cobb angle ≥ 10° as measured on standing full-spine posteroanterior radiographs; age between 6 and 18 years at the initial visit, encompassing the critical period of adolescent spinal growth and development; follow-up ≥ 12 months to ensure an adequate observation window for capturing potential scoliosis progression; availability of qualified standing full-spine anteroposterior and lateral radiographs at initial and final follow-up visits; and availability of complete baseline and follow-up data, including radiological and back physical sign measurements.

The exclusion criteria were as follows: non-idiopathic scoliosis (including congenital, neuromuscular, and syndromic scoliosis); history of spinal surgery or major orthopedic intervention prior to baseline

assessment; systemic diseases affecting spinal growth or deformity progression (e.g., neurological diseases, connective tissue diseases, or metabolic bone disorders); and unqualified radiographs precluding reliable Cobb angle measurements due to positioning errors, tissue overlap, or technical inadequacy.

Assessment of back physical signs and data collection

Outpatients underwent a standardized evaluation by two experienced spinal surgeons. Evaluations included coronal (shoulder-height difference, scapular tilt, lumbar concavity, and pelvic tilt) and sagittal back signs (flat back, kyphosis, abnormal lordosis, and abnormal kyphosis), and ATR measurement. Adam's FBT was performed. ATR was measured using a scoliosis goniometer and an ATR ≥ 5° was defined as clinically significantly elevated rotation [12, 13]. All patients underwent standing full-spine anteroposterior and lateral radiographic examinations, and the Cobb angle was measured by experienced spinal surgeons using the PACS. Scoliosis progression was defined as an increase in the primary Cobb angle of ≥ 5° during the follow-up period. Accordingly, patients were allocated to the progressive or stable groups.

Statistical analysis

Statistical analyses were performed using SPSS v.20.0 software (IBM Corp., Armonk, NY). Descriptive statistics were used to analyze demographic characteristics and baseline data. The Mann–Whitney U test was used for comparisons between two groups (sex). For comparisons among three or more independent groups (age and other variables), the Kruskal–Wallis test was used. To evaluate the association between each factor and disease progression (Δ Cobb ≥ 5°), univariate logistic regression (LR) analyses were first employed for preliminary screening, followed by multivariate LR analyses to identify independent predictive factors. The LR results are presented as odds ratios (OR) with 95% confidence intervals (CIs). *P*-values < 0.05 were considered statistically significant.

Results

Demographic baseline characteristics

The demographic data of the 1,283 patients are summarized in Table 1. Female patients accounted for more than three-quarters of the cohort. AIS incidence peaked in the 11–15-year-old age-group. In terms of skeletal maturity, the predominant distribution was Risser grades 0, 4, and 3, with nearly half of the patients in Risser grades 0–2, indicating individuals in the active spinal growth phase. The thoracic curve was the most prevalent primary curve type, followed by lumbar and thoracolumbar curves.

Table 1
Demographic characteristics of patients at baseline

Variables	n	Proportion(%)
Gender		
Male	275	21.43%
Female	1008	78.57%
Age (year)		
6–10	210	16.38%
11–15	1019	79.41%
16–18	54	4.21%
Risser sign		
0	450	35.07%
1	71	5.53%
2	110	8.57%
3	258	20.11%
4	365	28.45%
5	29	2.26%
Primary Curve Type		
Thoracic Curve	528	41.15%
Thoracolumbar Curve	361	28.14%
Lumbar Curve	394	30.71%
Total	1283	100%

Comparison of changes in Cobb angle between the initial and last evaluation

Table 2 presents the changes in the Cobb angle between the initial examination and last follow-up across the three curve subtypes. The mean Cobb angle increased significantly only in the thoracic-curve subgroup ($P = 0.003$), whereas it decreased ($P = 0.082$) and increased non-significantly ($P = 0.401$) in the thoracolumbar- and lumbar-curve subgroups.

Table 2
Comparison of changes in Cobb angle between the initial examination and the last follow-up in patients with adolescent idiopathic scoliosis subtypes

Cobb angle	Thoracic Curve	Thoracolumbar Curve	Lumbar Curve
first visit	18.35 ± 7.8	17.85 ± 7.37	17.29 ± 7.19
last follow-up	19.2 ± 9.28	17.24 ± 8.2	17.55 ± 7.77
Z	-2.966	1.745	-0.841
P	0.003	0.082	0.401
Difference in Cobb angle	0.847	-0.615	0.261

Comparison of back physical signs between progressive and stable thoracic-curve AIS

Beyond the baseline demographic and radiographic characteristics, we further examined whether specific physical back signs were associated with curve progression in the thoracic subgroup. Only lumbar concavity differed significantly between the progressive and stable groups ($P = 0.004$, Table 3). The proportion of patients with left lumbar concavity was greater, whereas that of patients with right lumbar concavity was smaller in the progressive than in the stable group. All other physical signs, including shoulder-height difference, scapular tilt, pelvic tilt, rib-hump, angle of thoracic rotation, thoracolumbar eminence, angle of thoracolumbar rotation, lumbar eminence, and angle of lumbar rotation, were non-significantly different between the groups (all $P > 0.05$).

Table 3
Comparison of back physical signs between progressive and stable groups with thoracic adolescent idiopathic scoliosis

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Gender					
Male	21(17.21%)	96(23.65%)	117(22.16%)	2.25	0.134
Female	101(82.79%)	310(76.35%)	411(77.84%)		
Age (year)					
6–10	24(19.67%)	67(16.50%)	91(17.23%)	1.668	0.434
11–15	95(77.87%)	320(78.82%)	415(78.6%)		
16–18	3(2.46%)	19(4.68%)	22(4.17%)		
Distribution of Cobb angle					
10–19°	78(63.93%)	267(65.76%)	345(65.34%)	1.923	0.382
20–39°	43(35.25%)	128(31.53%)	171(32.39%)		
>40°	1(0.82%)	11(2.71%)	12(2.27%)		
Risser sign					
0	48(39.34%)	123(30.30%)	171(32.39%)	8.224	0.144
1	6(4.92%)	27(6.65%)	33(6.25%)		
2	10(8.20%)	42(10.34%)	52(9.85%)		
3	31(25.41%)	82(20.20%)	113(21.4%)		
4	26(21.31%)	122(30.05%)	148(28.03%)		
5	1(0.82%)	10(2.46%)	11(2.08%)		
Shoulder-height difference					
Normal	11(9.02%)	31(7.64%)	42(7.95%)	0.502	0.778
Left shoulder height	59(48.36%)	189(46.55%)	248(46.97%)		
Right shoulder height	52(42.62%)	186(45.81%)	238(45.08%)		
Scapula tilt					

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Normal	9(7.38%)	36(8.87%)	45(8.52%)	0.749	0.688
Left tilt	61(50.00%)	186(45.81%)	247(46.78%)		
Right tilt	52(42.62%)	184(45.32%)	236(44.7%)		
Lumbar concave					
Normal	28(22.95%)	127(31.28%)	155(29.36%)	11.292	0.004
Left concave	59(48.36%)	129(31.77%)	188(35.61%)		
Right concave	35(28.69%)	150(36.95%)	185(35.04%)		
Pelvic tilt					
Normal	76(62.30%)	255(62.80%)	331(62.69%)	1.287	0.525
Left tilt	21(17.21%)	55(13.55%)	76(14.39%)		
Right tilt	25(20.49%)	96(23.65%)	121(22.92%)		
Flat back					
Normal	121(99.18%)	402(99.01%)	523(99.05%)	0.027	0.869
Abnormal	1(0.82%)	4(0.99%)	5(0.95%)		
Hump back					
Normal	121(99.18%)	402(99.01%)	523(99.05%)	0.027	0.869
Abnormal	1(0.82%)	4(0.99%)	5(0.95%)		
Lumbar lordosis					
Normal	122(100.00%)	404(99.51%)	526(99.62%)	0.603	0.437
Abnormal	0(0%)	2(0.49%)	2(0.38%)		
Lumbar kyphosis					
Normal	122(100.00%)	405(99.75%)	527(99.81%)	0.301	0.583
Abnormal	0(0%)	1(0.25%)	1(0.19%)		
Rib-hump					
Normal	65(53.28%)	237(58.37%)	302(57.2%)	3.241	0.198
Left eminence	8(6.56%)	39(9.61%)	47(8.9%)		

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Right eminence	49(40.16%)	130(32.02%)	179(33.9%)		
Angle of thoracic rotation					
Normal (ATR 0–4°)	69(56.56%)	263(64.78%)	332(62.88%)	4.41	0.110
Left (ATR ≥ 5°)	7(5.74%)	30(7.39%)	37(7.01%)		
Right (ATR ≥ 5°)	46(37.70%)	113(27.83%)	159(30.11%)		
Thoracolumbar eminence					
Normal	117(95.90%)	387(95.32%)	504(95.45%)	0.08	0.961
Left eminence	2(1.64%)	8(1.97%)	10(1.89%)		
Right eminence	3(2.46%)	11(2.71%)	14(2.65%)		
Angle of thoracolumbar rotation					
Normal (ATR 0–4°)	118(96.72%)	388(95.57%)	506(95.83%)	0.453	0.797
Left (ATR ≥ 5°)	2(1.64%)	7(1.72%)	9(1.7%)		
Right (ATR ≥ 5°)	2(1.64%)	11(2.71%)	13(2.46%)		
Lumbar eminence					
Normal	81(66.39%)	264(65.02%)	345(65.34%)	0.142	0.932
Left eminence	30(24.59%)	101(24.88%)	131(24.81%)		
Right eminence	11(9.02%)	41(10.10%)	52(9.85%)		
Angle of lumbar rotation					
Normal (ATR 0–4°)	86(70.49%)	294(72.41%)	380(71.97%)	0.352	0.839
Left (ATR ≥ 5°)	9(7.38%)	32(7.88%)	41(7.77%)		
Right (ATR ≥ 5°)	27(22.13%)	80(19.70%)	107(20.27%)		

LR analysis of the risk of thoracic-curve progression

In the thoracic subgroup, univariate LR analysis (Table 4) showed that left lumbar concavity ($P = 0.005$) and right thoracic rotation angle ≥ 5° ($P = 0.047$) were significantly associated with an increased curve-

progression risk. Additionally, Risser grade 4 (P = 0.028) protected against curve progression.

Table 4
Results of logistic regression analysis to identify the risk factors of thoracic-curve progression in adolescent idiopathic scoliosis

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Gender						
Boys	1	1–1		1	1–1	
Girls	1.489	0.898–2.566	0.135	1.391	0.805–2.484	0.249
Age (year)						
5–10	1	1–1		1	1–1	
11–15	0.829	0.498–1.414	0.479	0.91	0.464-1.8	0.784
16–19	0.441	0.097–1.442	0.218	0.72	0.129–3.152	0.680
Distribution of Cobb angle						
10–19°	1	1–1		1	1–1	
20–39	1.15	0.746–1.757	0.522	0.282	0.015–1.612	0.243
>40°	0.311	0.017–1.637	0.267	0.884	0.547–1.412	0.609
Risser sign						
0	1	1–1		1	1–1	
1	0.569	0.202–1.383	0.243	0.531	0.177-1.4	0.224
2	0.61	0.271–1.272	0.206	0.452	0.178–1.06	0.078
3	0.969	0.566–1.642	0.907	0.851	0.445–1.626	0.624
4	0.546	0.315–0.929	0.028	0.522	0.269–1.004	0.053
5	0.256	0.014–1.392	0.200	0.245	0.012–1.827	0.233
Shoulder-height difference						
Norma	1	1–1		1	1–1	
Left shoulder height	0.88	0.427–1.929	0.737	0.312	0.078-1.2	0.090
Right shoulder height	0.788	0.38–1.736	0.535	0.318	0.078–1.224	0.099
Scapula tilt						
Normal	1	1–1		1	1–1	

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Left tilt	1.312	0.621–3.039	0.498	3.234	0.811–14.451	0.108
Right tilt	1.13	0.531–2.634	0.762	2.584	0.671–11.527	0.188
Lumbar concave						
Normal	1	1–1		1	1–1	
Left concave	2.074	1.253-3.5	0.005	2.164	1.224–3.893	0.009
Right concave	1.058	0.611–1.845	0.84	0.963	0.516–1.806	0.905
Pelvic tilt						
Normal	1	1–1		1	1–1	
Left tilt	1.281	0.717–2.227	0.390	0.879	0.454–1.658	0.695
Right tilt	0.874	0.518–1.438	0.603	0.827	0.46–1.458	0.517
Flat back						
Normal	1	1–1		1	1–1	
Abnormal	0.831	0.042–5.68	0.869	0.771	0.038–5.876	0.824
Hump back						
Normal	1	1–1		1	1–1	
Abnormal	0.831	0.042–5.68	0.869	1.001	0.048–7.705	0.922
Lumbar lordosis						
Norma	1	1–1		1	1–1	
Abnormal	0.01	0.001–1000	0.983	0.01	0.001–1000	0.988
Lumbar kyphosis						
Normal	1	1–1		1	1–1	
Abnormal	0.01	0.001–1000	0.982	0.01	0.001–1000	0.993
Rib-hump						
Normal	1	1–1		1	1–1	
Left eminence	0.748	0.312–1.603	0.481	0.386	0.02–2.407	0.393

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Right eminence	1.374	0.893–2.106	0.145	0.606	0.129–2.093	0.467
Angle of thoracic rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	0.889	0.347–2.005	0.790	1.664	0.222–34.811	0.665
Right (ATR ≥ 5°)	1.552	1.003–2.389	0.047	2.512	0.734–11.719	0.179
Thoracolumbar eminence						
Normal	1	1–1		1	1–1	
Left eminence	0.827	0.124–3.355	0.812	0.01	0.001–1000	0.993
Right eminence	0.902	0.202–2.946	0.876	100	0.001–1000	0.991
Angle of thoracolumbar rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	0.939	0.139–3.949	0.938	100	0.001–1000	0.992
Right (ATR ≥ 5°)	0.598	0.092–2.267	0.507	0.01	0.001–1000	0.990
Lumbar eminence						
Normal	1	1–1		1	1–1	
Left eminence	0.968	0.594–1.548	0.894	0.404	0.087–1.357	0.182
Right eminence	0.874	0.411–1.725	0.711	0.881	0.125–3.905	0.880
Angle of lumbar rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	1.154	0.692–1.881	0.573	3.332	0.95-15.861	0.085
Right (ATR ≥ 5°)	0.961	0.418–2.015	0.921	1.05	0.198–8.129	0.957

In the multivariate LR analysis, left lumbar concavity was the only independent predictor of curve progression ($P = 0.009$, Table 4). All other variables, including the right angle of thoracic rotation and Risser grade 4 were not statistically significant in the multivariate model (all $P > 0.05$).

Comparison of back physical signs between progressive and stable thoracolumbar-curve AIS

In the thoracolumbar subgroup, sex, lumbar concavity, rib-hump, thoracic ATR, lumbar eminence, and angle of lumbar rotation differed significantly between the progressive and stable groups (Table 5). Female sex was more prevalent in the progressive than in the stable group ($P = 0.001$). The proportion of patients with left lumbar concavity was greater, and that of patients with right lumbar concavity was smaller in the progressive than in the stable group ($P < 0.05$). Left rib-hump eminence was more prevalent in the progressive than in the stable group ($P = 0.036$). For thoracic ATR, left rotation (ATR ≥ 5°) was more prevalent in the progressive than in the stable group (P = 0.008). Left lumbar eminence was also more common in the progressive than in the stable group ($P = 0.011$). Additionally, left lumbar ATR ≥ 5° was more prevalent in the progressive group than in the stable group ($P < 0.05$). None of the other variables were significantly different between the groups (all $P > 0.05$).

Table 5
Comparison of back physical signs between progressive and stable groups with thoracolumbar adolescent idiopathic scoliosis

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Gender					
Male	5(7.81%)	79(26.60%)	84(23.27%)	10.409	0.001
Female	59(92.19%)	218(73.40%)	277(76.73%)		
Age (year)					
6–10	12(18.75%)	60(20.20%)	72(19.94%)	1.06	0.589
11–15	51(79.69%)	225(75.76%)	276(76.45%)		
16–18	1(1.56%)	12(4.04%)	13(3.6%)		
Distribution of Cobb angle					
10–19°	47(73.44%)	197(66.33%)	244(67.59%)	2.13	0.345
20–39°	17(26.56%)	94(31.65%)	111(30.75%)		
>40°	0(0%)	6(2.02%)	6(1.66%)		
Risser sign					
0	29(45.31%)	121(40.74%)	150(41.55%)	4.156	0.527
1	1(1.56%)	16(5.39%)	17(4.71%)		
2	4(6.25%)	16(5.39%)	20(5.54%)		
3	13(20.31%)	57(19.19%)	70(19.39%)		
4	15(23.44%)	84(28.28%)	99(27.42%)		
5	2(3.13%)	3(1.01%)	5(1.39%)		
Shoulder-height difference					
Normal	8(12.50%)	30(10.10%)	38(10.53%)	0.646	0.724
Left shoulder height	27(42.19%)	140(47.14%)	167(46.26%)		
Right shoulder height	29(45.31%)	127(42.76%)	156(43.21%)		
Scapula tilt					

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Normal	9(14.06%)	40(13.47%)	49(13.57%)	0.74	0.691
Left tilt	28(43.75%)	147(49.49%)	175(48.48%)		
Right tilt	27(42.19%)	110(37.04%)	137(37.95%)		
Lumbar concave					
Normal	14(21.87%)	65(21.89%)	79(21.88%)	7.986	0.018
Left concave	24(37.50%)	64(21.54%)	88(24.38%)		
Right concave	26(40.63%)	168(56.57%)	194(53.74%)		
Pelvic tilt					
Normal	36(56.25%)	166(55.89%)	202(55.96%)	0.301	0.860
Left tilt	8(12.50%)	31(10.44%)	39(10.8%)		
Right tilt	20(31.25%)	100(33.67%)	120(33.24%)		
Flat back					
Normal	64(100.00%)	295(99.33%)	359(99.45%)	0.433	0.510
Abnormal	0(0%)	2(0.67%)	2(0.55%)		
Hump back					
Normal	63(98.44%)	295(99.33%)	358(99.17%)	0.505	0.477
Abnormal	1(1.56%)	2(0.67%)	3(0.83%)		
Lumbar kyphosis					
Normal	64(100.00%)	293(98.65%)	357(98.89%)	0.872	0.351
Abnormal	0(0%)	4(1.35%)	4(1.11%)		
Rib-hump					
Normal	39(60.94%)	216(72.73%)	255(70.64%)	6.651	0.036
Left eminence	11(17.19%)	22(7.40%)	33(9.14%)		
Right eminence	14(21.87%)	59(19.87%)	73(20.22%)		
Angle of thoracic rotation					
Normal (ATR 0–4°)	43(67.19%)	237(79.80%)	280(77.56%)	9.722	0.008

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Left (ATR ≥ 5°)	10(15.62%)	15(5.05%)	25(6.93%)		
Right (ATR ≥ 5°)	11(17.19%)	45(15.15%)	56(15.51%)		
Thoracolumbar eminence					
Normal	61(95.31%)	278(93.60%)	339(93.91%)	0.778	0.678
Left eminence	2(3.13%)	8(2.70%)	10(2.77%)		
Right eminence	1(1.56%)	11(3.70%)	12(3.32%)		
Angle of thoracolumbar rotation					
Normal (ATR 0–4°)	61(95.31%)	279(93.94%)	340(94.18%)	0.861	0.650
Left (ATR ≥ 5°)	2(3.13%)	7(2.36%)	9(2.49%)		
Right (ATR ≥ 5°)	1(1.56%)	11(3.70%)	12(3.32%)		
Lumbar eminence					
Normal	32(50.00%)	203(68.35%)	235(65.1%)	9.028	0.011
Left eminence	25(39.06%)	65(21.89%)	90(24.93%)		
Right eminence	7(10.94%)	29(9.76%)	36(9.97%)		
Angle of lumbar rotation					
Normal (ATR 0–4°)	35(54.69%)	226(76.09%)	261(72.3%)	12.619	0.002
Left (ATR ≥ 5°)	23(35.93%)	52(17.51%)	75(20.78%)		
Right (ATR ≥ 5°)	6(9.38%)	19(6.40%)	25(6.93%)		

LR analysis of the risk of thoracolumbar-curve progression

In the thoracolumbar subgroup, univariate LR analysis (Table 6) showed that female sex ($P = 0.003$), left rib-hump eminence ($P = 0.013$), left thoracic ATR ≥ 5° ($P = 0.003$), left lumbar eminence ($P = 0.003$), and left lumbar ATR ≥ 5° ($P = 0.002$) were significantly associated with increased curve-progression risk.

Table 6
Results of logistic regression analysis to identify the risk factors of thoracolumbar-curve progression in adolescent idiopathic scoliosis

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Gender						
Boys	1	1–1		1	1–1	
Girls	4.276	1.814–12.579	0.003	4.343	1.663–13.967	0.006
Age (year)						
5–10	1	1–1		1	1–1	
11–15	1.133	0.584–2.349	0.722	1.329	0.542–3.379	0.540
16–19	0.417	0.022–2.438	0.421	0.400	0.016–3.736	0.479
Distribution of Cobb angle						
10–19°	1	1–1		1	1–1	
20–39	0.758	0.404–1.368	0.371	0.593	0.272–1.234	0.173
>40°	0.010	0.001–1000	0.988	0.010	0.001–1000	0.991
Risser sign						
0	1	1–1		1	1–1	
1	0.261	0.014–1.36	0.201	0.068	0.003–0.506	0.027
2	1.043	0.283–3.101	0.944	0.615	0.143–2.218	0.478
3	0.952	0.448–1.935	0.893	0.678	0.258–1.722	0.418
4	0.745	0.369–1.456	0.398	0.431	0.176–1.025	0.060
5	2.782	0.354–17.53	0.274	11.583	0.708–262.19	0.096
Shoulder-height difference						

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Norma	1	1–1		1	1–1	
Left shoulder height	0.723	0.309–1.842	0.471	0.828	0.111–6.252	0.852
Right shoulder height	0.856	0.368–2.175	0.729	0.606	0.062–4.276	0.634
Scapula tilt						
Normal	1	1–1		1	1–1	
Left tilt	0.847	0.381–2.032	0.693	1.207	0.179–8.603	0.441
Right tilt	1.091	0.486–2.637	0.838	1.688	0.268–16.053	0.606
Lumbar concave						
Normal	1	1–1		1	1–1	
Left concave	1.741	0.836–3.737	0.144	2.024	0.809–5.215	0.136
Right concave	0.719	0.358–1.494	0.362	0.572	0.234–1.414	0.221
Pelvic tilt						
Normal	1	1–1		1	1–1	
Left tilt	1.19	0.477-2.7	0.691	1.531	0.473–4.664	0.462
Right tilt	0.922	0.499–1.666	0.791	1.467	0.67–3.23	0.336
Flat back						
Normal	1	1–1		1	1–1	
Abnormal	0.010	0.001–1000	0.983	0.01	0.001–1000	0.995
Hump back						
Normal	1	1–1		1	1–1	
Abnormal	2.341	0.108–24.805	0.490	37.425	0.694–1000	0.091
Lumbar kyphosis						

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Normal	1	1–1		1	1–1	
Abnormal	0.010	0.001–1000	0.985	0.010	0.001–1000	0.992
Rib-hump						
Normal	1	1–1		1	1–1	
Left eminence	2.769	1.209–6.071	0.013	0.408	0.019–3.115	0.448
Right eminence	1.314	0.651–2.534	0.428	1.076	0.208–4.283	0.923
Angle of thoracic rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	3.674	1.509–8.645	0.003	14.725	1.558-347.926	0.036
Right (ATR ≥ 5°)	1.347	0.621–2.734	0.427	1.051	0.224–6.021	0.951
Thoracolumbar eminence						
Normal	1	1–1		1	1–1	
Left eminence	1.139	0.169–4.685	0.871	0.01	0.001–1000	0.997
Right eminence	0.414	0.022–2.19	0.403	0.255	0.012–1.848	0.248
Angle of thoracolumbar rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	1.307	0.192–5.564	0.742	100	0.001–1000	0.992
Right (ATR ≥ 5°)	0.416	0.023–2.198	0.405	0.010	0.001–1000	0.990
Lumbar eminence						
Normal	1	1–1		1	1–1	

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Left eminence	2.440	1.341–4.412	0.003	0.676	0.084–3.366	0.666
Right eminence	1.531	0.578–3.626	0.356	0.497	0.024–3.57	0.549
Angle of lumbar rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	2.856	1.546–5.223	0.002	6.26	1.235–51.57	0.046
Right (ATR ≥ 5°)	2.039	0.704–5.207	0.156	3.457	0.403–76.883	0.313

In the multivariate LR analysis, female sex ($P = 0.006$), left thoracic ATR ≥ 5° ($P = 0.036$), and left lumbar ATR ≥ 5° ($P = 0.046$) were identified as independent predictors of curve progression (Table 6). Additionally, Risser grade 1 demonstrated a significant protective effect against curve progression ($P = 0.027$). None of the other variables showed statistical significance in the multivariate model (all $P > 0.05$).

Comparison of back physical signs between progressive and stable lumbar-curve AIS

In the lumbar-curve subgroup, sex, age, distribution of the Cobb angle, and Risser grade did not differ significantly between the progressive and stable groups (all $P > 0.05$, Table 7). The angle of thoracic rotation differed significantly between the two groups ($P = 0.007$), with left thoracic ATR ≥ 5° being more prevalent in the progressive than in the stable group. Lumbar eminence also differed significantly between the groups ($P = 0.005$), with the left lumbar eminence being markedly more frequent in the progressive group. The angle of lumbar rotation showed the most notable difference between the groups ($P < 0.001$), with left ATR ≥ 5° being considerably more prevalent in the progressive than in the stable group. No other physical signs differed significantly between the groups (all $P > 0.05$).

Table 7
Comparison of back physical signs between progressive and stable groups with lumbar adolescent idiopathic scoliosis

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Gender					
Male	9(14.75%)	65(10.67%)	74(18.78%)	0.768	0.381
Female	52(85.25%)	268(89.33%)	320(81.22%)		
Age (year)					
6–10	10(16.39%)	37(11.11%)	47(11.93%)	1.637	0.441
11–15	49(80.33%)	279(83.78%)	328(83.25%)		
16–18	2(3.28%)	17(5.11%)	19(4.82%)		
Distribution of Cobb angle					
10–19°	46(75.41%)	239(71.77%)	285(72.34%)	0.382	0.826
20–39°	14(22.95%)	89(26.73%)	103(26.14%)		
>40°	1(1.64%)	5(1.50%)	6(1.52%)		
Risser sign					
0	26(42.62%)	103(30.93%)	129(32.74%)	6.026	0.304
1	3(4.92%)	18(5.41%)	21(5.33%)		
2	7(11.48%)	31(9.31%)	38(9.64%)		
3	11(18.03%)	64(19.22%)	75(19.04%)		
4	14(22.95%)	104(31.23%)	118(29.95%)		
5	0(0%)	13(3.90%)	13(3.3%)		
Shoulder-height difference					
Normal	7(11.48%)	34(10.21%)	41(10.40%)	0.089	0.957
Left shoulder height	26(42.62%)	144(43.24%)	170(43.15%)		
Right shoulder height	28(45.90%)	155(46.55%)	183(46.45%)		
Scapula tilt					

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Normal	10(16.40%)	35(10.51%)	45(11.42%)	1.771	0.413
Left tilt	25(40.98%)	148(44.44%)	173(43.91%)		
Right tilt	26(42.62%)	150(45.05%)	176(44.67%)		
Lumbar concave					
Normal	11(18.03%)	88(26.42%)	99(25.13%)	1.932	0.381
Left concave	17(27.87%)	84(25.23%)	101(25.63%)		
Right concave	33(54.10%)	161(48.35%)	194(49.24%)		
Pelvic tilt					
Normal	33(54.10%)	179(53.76%)	212(53.81%)	0.004	0.998
Left tilt	9(14.75%)	49(14.71%)	58(14.72%)		
Right tilt	19(31.15%)	105(31.53%)	124(31.47%)		
Flat back					
Normal	60(98.36%)	330(99.10%)	390(98.98%)	0.28	0.597
Abnormal	1(1.64%)	3(0.90%)	4(1.02%)		
Hump back					
Normal	59(96.72%)	328(98.50%)	387(98.22%)	0.933	0.334
Abnormal	2(3.28%)	5(1.50%)	7(1.78%)		
Lumbar lordosis					
Normal	59(96.72%)	331(99.40%)	390(98.98%)	3.68	0.055
Abnormal	2(3.28%)	2(0.60%)	4(1.02%)		
Lumbar kyphosis					
Normal	60(98.36%)	331(99.40%)	391(99.24%)	0.736	0.391
Abnormal	1(1.64%)	2(0.60%)	3(0.76%)		
Rib-hump					
Normal	36(59.01%)	246(73.87%)	282(71.57%)	5.600	0.061
Left eminence	7(11.48%)	25(7.51%)	32(8.12%)		

Variables	Progression of the major curve		Total	χ2	*P*
	Progression Group n (%)	Stable Group n (%)			
Right eminence	18(29.51%)	62(18.62%)	80(20.31%)		
Angle of thoracic rotation					
Normal (ATR 0–4°)	39(84.78%)	270(81.08%)	309(78.42%)	9.928	0.007
Left (ATR ≥ 5°)	6(13.04%)	12(3.60%)	18(4.57%)		
Right (ATR ≥ 5°)	16(2.17%)	51(15.32%)	67(17.01%)		
Thoracolumbar eminence					
Normal	59(96.72%)	312(93.69%)	371(94.16%)	2.078	0.354
Left eminence	0(0%)	11(3.30%)	11(2.79%)		
Right eminence	2(3.28%)	10(3.01%)	12(3.05%)		
Angle of thoracolumbar rotation					
Normal (ATR 0–4°)	59(96.72%)	313(93.99%)	372(94.42%)	2.117	0.347
Left (ATR ≥ 5°)	0(0%)	11(3.30%)	11(2.79%)		
Right (ATR ≥ 5°)	2(3.28%)	9(2.71%)	11(2.79%)		
Lumbar eminence					
Normal	24(39.35%)	199(59.76%)	223(56.6%)	10.471	0.005
Left eminence	28(45.90%)	88(26.43%)	116(29.44%)		
Right eminence	9(14.75%)	46(13.81%)	55(13.96%)		
Angle of lumbar rotation					
Normal (ATR 0–4°)	26(42.62%)	224(67.27%)	250(63.45%)	15.318	0.000
Left (ATR ≥ 5°)	27(44.26%)	73(21.92%)	100(25.38%)		
Right (ATR ≥ 5°)	8(13.12%)	36(10.81%)	44(11.17%)		

LR analysis of the risk of lumbar-curve progression

In the lumbar subgroup, univariate LR analysis identified right rib-hump eminence ($P = 0.033$), both left and right ATR ≥ 5° ($P = 0.019$; $P = 0.020$, respectively), and left lumbar eminence ($P = 0.002$) as significantly associated with curve progression (Table 8). No other variables reached statistical significance in the univariate analysis (all $P > 0.05$, Table 8).

Table 8
Results of logistic regression analysis to identify the risk factors of lumbar-curve progression in adolescent idiopathic scoliosis

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Gender						
Boys	1	1–1		1	1–1	
Girls	1.401	0.686–3.173	0.383	1.935	0.826–5.025	0.149
Age (year)						
5–10	1	1–1		1	1–1	
11–15	0.650	0.313–1.457	0.267	0.569	0.225–1.49	0.238
16–19	0.435	0.062–1.886	0.315	0.424	0.046–2.837	0.402
Distribution of Cobb angle						
10–19°	1	1–1		1	1–1	
20–39	0.817	0.415–1.524	0.540	0.735	0.337–1.531	0.422
>40°	1.039	0.054–6.641	0.972	1.888	0.092–14.017	0.586
Risser sign						
0	1	1–1		1	1–1	
1	0.660	0.147–2.140	0.530	0.933	0.182–3.666	0.926
2	0.895	0.332–2.168	0.814	1.012	0.323–2.866	0.983
3	0.681	0.304–1.441	0.328	0.6	0.232–1.481	0.277
4	0.533	0.258–1.064	0.080	0.588	0.238–1.408	0.238
5	0.010	0.001–1000	0.982	0.010	0.001–1000	0.987
Shoulder-height difference						
Norma	1	1–1		1	1–1	
Left shoulder height	0.877	0.367–2.340	0.778	4.91	0.973–27.958	0.062
Right shoulder height	0.877	0.370–2.329	0.778	5.201	0.837–33.621	0.078
Scapula tilt						
Normal	1	1–1		1	1–1	

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Left tilt	0.591	0.266–1.393	0.209	0.23	0.051–1.031	0.055
Right tilt	0.607	0.274–1.424	0.230	0.154	0.028–0.885	0.032
Lumbar concave						
Normal	1	1–1		1	1–1	
Left concave	1.619	0.724–3.754	0.247	2.551	0.956–7.196	0.067
Right concave	1.640	0.812–3.544	0.184	2.644	1.104–6.796	0.035
Pelvic tilt						
Normal	1	1–1		1	1–1	
Left tilt	0.996	0.424–2.146	0.993	0.755	0.266–1.998	0.582
Right tilt	0.982	0.523–1.797	0.953	0.877	0.401–1.888	0.740
Flat back						
Normal	1	1–1		1	1–1	
Abnormal	1.833	0.09-14.589	0.602	2.984	0.106–49.471	0.449
Hump back						
Normal	1	1–1		1	1–1	
Abnormal	2.224	0.313–10.584	0.346	2.784	0.116–49.471	0.459
Lumbar lordosis						
Norma	1	1–1		1	1–1	
Abnormal	5.610	0.663–47.503	0.088	5.456	0.542–56.907	0.130
Lumbar kyphosis						
Normal	1	1–1		1	1–1	
Abnormal	2.758	0.127–29.233	0.41	3.775	0.114–66.199	0.390
Rib-hump						
Normal	1	1–1		1	1–1	
Left eminence	1.913	0.721–4.547	0.161	0.444	0.021–3.069	0.486

Variables	Univariate logistic regression Analysis			Multivariate logistic regression Analysis		
	OR	95% CI	P	OR	95% CI	P
Right eminence	1.984	1.039–3.691	0.033	1.484	0.200-7.135	0.651
Angle of thoracic rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	3.462	1.15–9.469	0.019	8.851	0.973-210.546	0.087
Right (ATR ≥ 5°)	2.172	1.106–4.124	0.020	1.615	0.312–12.53	0.597
Thoracolumbar eminence						
Normal	1	1–1		1	1–1	
Left eminence	0.010	0.001–1000	0.984	0.010	0.001–1000	0.989
Right eminence	1.058	0.16–4.143	0.943	0.010	0.001–1000	0.997
Angle of thoracolumbar rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	0.010	0.001–1000	0.984	100	0.001–1000	0.997
Right (ATR ≥ 5°)	1.179	0.177–4.719	0.836	4.499	0.539–25.807	0.150
Lumbar eminence						
Normal	1	1–1		1	1–1	
Left eminence	2.638	1.45–4.839	0.002	0.435	0.022–2.591	0.449
Right eminence	1.622	0.675–3.619	0.254	0.277	0.012–2.141	0.295
Angle of lumbar rotation						
Normal (ATR 0–4°)	1	1–1		1	1–1	
Left (ATR ≥ 5°)	3.187	1.748–5.83	0.155	8.095	1.382-156.132	0.056
Right (ATR ≥ 5°)	1.915	0.761–4.402	0.142	6.298	0.721-151.176	0.148

In multivariate LR analysis, right lumbar concavity was identified as an independent risk factor for curve progression ($P = 0.035$), whereas right scapula tilt exhibited a statistically significant protective effect ($P = 0.032$). No other variables were statistically significant in the multivariate model (all $P > 0.05$).

Discussion

While previous studies established that back physical signs, particularly ATR, represent clinically actionable noninvasive biomarkers within the SSS [5, 11, 14], few large-cohort studies have systematically evaluated the subtype-specific prognostic performance of back physical signs for predicting curve progression. In this study, we stratified patients with AIS into thoracic, thoracolumbar, and lumbar subgroups and assessed their demographic features and multidimensional back physical signs to identify progression-related risk markers in each subtype. Left lumbar concavity predicted thoracic-curve progression. Female sex, left thoracic ATR ≥ 5°, and left lumbar ATR ≥ 5° were risk factors for thoracolumbar-curve progression, whereas Risser grade 1 was protective. Right lumbar concavity conferred elevated risk, while right-tilted scapula exerted a statistically protective effect in lumbar-curve AIS.

Sex and skeletal maturity influenced the progression risk differently across curve patterns. Female sex was an independent risk factor exclusively for thoracolumbar-curve AIS, consistent with previous studies linking female pubertal growth potential to a higher deformity-worsening susceptibility [6, 15]. Risser grade 1 exerted an independent protective effect in the thoracolumbar group. This may be explained by the diminished residual spinal growth in Risser grade 1 patients as compared with Risser grade 0 patients [9]. Although the Risser grade showed no independent effect in the thoracic and lumbar subgroups, Risser grade 0 skeletal immaturity was overrepresented in all progressive groups, confirming that adolescents with skeletal immaturity require intensified follow-up, regardless of the curve subtype [9, 16]. Clinically, female adolescents with thoracolumbar-curve AIS, even Risser grade 1, require more intense risk surveillance [17]. These subtype-specific associations involving female sex and Risser grade 1 may arise from unique biomechanical and pubertal interactions within thoracolumbar deformities. However, such underlying mechanisms cannot be fully established in this retrospective analysis and require validation in prospective cohorts.

Trunk rotational asymmetry, quantified by the ATR, is an important subtype-specific factor associated with AIS curve progression. Among these identified associated factors, left-sided ATR ≥ 5° represented an independent risk factor exclusively for thoracolumbar-curve AIS. Notably, both left thoracic and left lumbar ATR ≥ 5° predicted higher progression risk within this subgroup, although the wide CI for left thoracic ATR ≥ 5° suggests limited precision of its effect estimate. This left-sided rotational predominance aligns with the anatomical features of the common right-thoracic–left-lumbar Lenke type 1 curves [18]. Biomechanically, the Stokes vicious-cycle hypothesis provides a plausible mechanistic explanation: rotational vertebral deformity creates asymmetric spinal loading, which may further amplify curve deterioration [10, 19]. Clinically, our findings suggest that ATR ≥ 5°, an easily obtained screening metric, may warrant heightened clinical vigilance in adolescents presenting with thoracolumbar-pattern AIS.

Associations of the lumbar concavity direction differed substantially across the AIS curve subtypes. For the thoracic-curve AIS, left lumbar concavity was associated with curve progression. In patients with a

primary thoracic curve, lateral lumbar deviation frequently develops as a compensatory mechanism to center the trunk over the pelvic base [18, 20]. While this lumbar shift partially offsets the coronal trunk imbalance caused by thoracic deformities, it can disrupt the overall spinopelvic balance. This secondary lumbar malalignment may introduce additional asymmetric mechanical loading onto the spinal column, thereby predisposing patients to subsequent curve deterioration [21]. In contrast, right lumbar concavity independently increased the risk of lumbar-curve AIS progression. In this subgroup, lumbar concavity directly coincided with the concave side of the primary lumbar curve [22]. This side of a scoliotic curve sustains greater compressive stress on the vertebral growth plates; chronically elevated compression may inhibit local vertebral growth, which in turn facilitates further aggravation of the primary lumbar deformity [19, 23]. Clinically, assessment of the lumbar concavity direction may offer rapid, radiation-free clues regarding the underlying spinopelvic biomechanical status.

The right-tilted scapula represents a statistically identified, rare, subtype-specific, protective back physical sign exclusively in lumbar-curve AIS in the present cohort. Scapular positioning reflects the postural equilibrium of the shoulder girdle and the upper trunk. In patients with lumbar-curve AIS, a right-tilted scapula might reflect a compensatory upper-trunk postural adaptation that could partially counteract the coronal imbalance and asymmetric mechanical loading induced by the primary lumbar curve, potentially conferring relative spinal stability [24]. Notably, such a protective association was not observed in the thoracic or thoracolumbar subgroups. This finding suggests that shoulder–trunk postural profiles may serve as auxiliary clinical indicators for risk stratification, specifically within lumbar-curve AIS. However, the exact posture-related mechanism remains unclear. This observation requires further prospective validation, given the wide CI of the effect estimate [25].

This study had some limitations. First, this was a single-center, retrospective investigation, which may be prone to selection bias, and the findings require multicenter prospective validation. Second, not all participants were followed-up until skeletal maturity, limiting conclusions regarding full-course, long-term progression. Third, several multivariate predictors showed broad CIs, reflecting reduced statistical precision after subgroup stratification. Fourth, we lacked data on follow-up interventions, such as bracing and rehabilitation, which may have confounded the progression outcomes. Genetic and bone-density variables known to modify the natural history of AIS were also not incorporated into the models.

Conclusion

In this large-sample study, left lumbar concavity was associated with curve progression in thoracic-curve AIS. For thoracolumbar-curve AIS, female sex, left thoracic ATR ≥ 5°, and left lumbar ATR ≥ 5° were associated with higher progression risk, while Risser grade 1 was protective. For lumbar-curve AIS, right lumbar concavity was associated increased progression risk, whereas a right-tilted scapula was protective. Our findings suggest that back physical sign assessment is simple, radiation-free, low-cost, and allows subtype-specific early risk stratification in mass screening. Multidimensional evaluation incorporating ATR, lumbar concavity direction, and scapular alignment may identify progression risk and

guide the timely management of high-risk patients. Future multicenter prospective studies are required to validate these subtype-specific associations.

Abbreviations

AIS Adolescent idiopathic scoliosis

ATR Angle of trunk rotation

LR Logistic regression

SSS School-Based Scoliosis Screening

CSSSP Chinese School-based Scoliosis Screening Program

SYSHC Shenzhen Youth Spine Health Center

FBT Forward Bend Test

OR Odds ratio

CI Confidence interval

Declarations

Ethics approval and consent to participate

The studies involving human participants were reviewed and approved by the Shenzhen Second People's Hospital Institutional Review Board (approval number: 2023-315-02PJ, approval date: 2024-01-08). This study was performed in accordance with the principles of the Declaration of Helsinki. Written or oral informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Consent for publication

All authors have approved the final version of the manuscript and have consented.

Competing interests

The authors declare no competing interests.

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Author Contribution

RL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. RZ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. RT: Formal analysis, Investigation, Methodology. XC: Formal analysis, Investigation, Methodology. WZ: Investigation, Methodology, Project administration. LP: Formal analysis, Investigation, Methodology. LY: Funding acquisition, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. QL: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Data Availability

The original contributions presented in the study are included in the article or Supplementary material, further inquiries can be directed to the corresponding author.

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