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Original Article

Application of high-frequency musculoskeletal ultrasound combined with shear wave elastography in assessing paravertebral muscle morphology in adolescents with idiopathic scoliosis

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Abstract: Objectives: To evaluate the clinical utility of high-frequency musculoskeletal ultrasound combined with shear wave elastography (SWE) in assessing paravertebral muscle asymmetry in adolescents with adolescent idiopathic scoliosis (AIS), and to investigate its relationship with Cobb angle across different body positions. Methods: A total of 100 adolescents with AIS (mean age: 12.81 ± 1.86 years) were included. Ultrasound examinations were performed at the upper, apex, and lower vertebrae in both standing and prone positions using ALOKA ARIETTA 60 and 850 systems. Muscle parameters (transverse diameter, anteroposterior diameter, circumference, and area) and SWE values were measured. Differences between concave and convex sides were analyzed, and correlations with Cobb angle were assessed using SPSS 27.0 and R 4.3.1. Results: Significant asymmetry in paravertebral muscle parameters was observed at all vertebral levels, particularly at the apex ($P<0.05$). SWE demonstrated significantly higher muscle stiffness on the concave side ($P<0.05$). Stronger correlations between muscle asymmetry and Cobb angle were found in the standing position, with area showing the highest correlation coefficients. Compared with the prone position, standing measurements more accurately reflected scoliosis severity. Conclusions: High-frequency musculoskeletal ultrasound combined with SWE is an effective, non-invasive method for evaluating paravertebral muscle asymmetry in AIS. The standing position provides more clinically relevant information, and muscle asymmetry is strongly associated with Cobb angle. This technique may support improved diagnosis, monitoring, and individualized treatment planning in AIS.

Keywords: High-frequency musculoskeletal ultrasound, shear wave elastography, adolescent idiopathic scoliosis, paravertebral muscles, Cobb angle, scoliosis, muscle asymmetry

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity marked by lateral curvature, rotation, and associated vertebral and rib abnormalities [1]. It affects 1.5%-3% of adolescents, with a higher prevalence in females [2]. In severe cases, AIS may lead to postural imbalance, pulmonary dysfunction, and neurologic complications [3]. Its etiology remains incompletely understood and is thought to involve genetic, biomechanical, and environmental factors [4, 5].

Paravertebral muscles, including the multifidus and erector spinae, are essential for spinal stability and segmental control. In AIS, accumulating evidence indicates that asymmetry in these muscles is closely associated with spinal deformity. Differences in cross-sectional area, muscle activity, and stiffness have been reported between the concave and convex sides of the

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curve, reflecting altered mechanical loading [6]. These imbalances may disrupt spinal biomechanics, leading to uneven force distribution and potentially contributing to curve progression [7]. Moreover, morphological changes such as differences in muscle size and fat infiltration have been shown to correlate with Cobb angle and scoliosis severity [8]. Although it remains unclear whether these changes are causal or secondary, paravertebral muscle asymmetry is widely recognized as an important factor in AIS pathophysiology, highlighting the need for quantitative muscle assessment [9].

Radiographic assessment, with the Cobb angle as the reference standard, is routinely used for the diagnosis of AIS [10]. However, repeated radiation exposure, the inability to provide dynamic assessment, and the limited evaluation of muscle structures underscore the need for alternative imaging approaches [11]. Recent technological advances have prompted increasing interest in non-invasive imaging methods for assessing soft-tissue changes in AIS [12, 13].

High-frequency musculoskeletal ultrasound combined with shear wave elastography (SWE) has emerged as a promising approach for evaluating paravertebral muscle morphology in AIS. SWE is a non-invasive technique that quantifies tissue stiffness by measuring the propagation velocity of shear waves within muscle. It enables assessment of muscle stiffness and asymmetry, thereby providing insight into the mechanical properties of muscles involved in spinal stability and postural control [14]. In AIS, SWE has been reported to detect differences in muscle stiffness between the concave and convex sides of the spine, with these differences showing an association with the degree of spinal curvature as measured by the Cobb angle [15]. Ultrasound also offers real-time visualization of muscle structures with high resolution [16]. It can be used to evaluate muscle asymmetry, stiffness, and other morphologic features that may be relevant to the development and progression of scoliosis [17]. Because paravertebral muscles are critical to spinal stability and posture, structural or functional abnormalities in these muscles may aggravate spinal curvature in patients with AIS [18].

Despite these potential advantages, the role of high-frequency musculoskeletal ultrasound and SWE in AIS assessment, particularly across different body positions, remains insufficiently studied. Therefore, this study used ultrasound and SWE to assess paravertebral muscle asymmetry in patients with AIS in both standing and prone positions and to examine its relationship with the Cobb angle. The findings may help refine clinical assessment and inform treatment strategies for AIS.

Methods

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Yuyao Traditional Chinese Medicine Hospital (Approval No. PJ-2023-11). All procedures were conducted in accordance with relevant ethical guidelines and regulations. Written informed consent was obtained from all participants and their legal guardians prior to enrollment in the study.

Study design and participants

A total of 100 adolescents with AIS (mean age: 13.20 ± 2.08 years) were recruited from January 1, 2024, to December 31, 2025, based on specific inclusion and exclusion criteria.

Inclusion criteria: Patients were eligible if they had a diagnosis of AIS based on standard clinical criteria, were aged 10 to 17 years, had a standing full-spine radiograph obtained within the previous 3 months with a documented Cobb angle, and provided written informed consent signed by both the patient and a legal guardian.

Exclusion criteria: Patients were excluded if they had engaged in regular unilateral physical activity (e.g., badminton, tennis, or golf) within the previous 3 months; had a history of abdominal, pelvic, or spinal surgery; had serious underlying cardiovascular, pulmonary, hepatic, renal, hematologic, or psychiatric disease; or had used medications that might affect neuromuscular function within the previous year.

In addition to paravertebral muscle morphological parameters, AIS-related clinical parameters were incorporated into the study design to better characterize the relationship between

Table 1. Patient demographics

	N = 100
Angle	16.93 ± 8.03
Age	12.81 ± 1.86
Height (m)	1.55 ± 0.07
Weight (kg)	53.38 ± 4.84
BMI (Body Mass Index)	22.35 ± 2.22
Direction	
Left	76 (76.00%)
Right	24 (24.00%)
Gender	
Male	55 (55.00%)
Female	45 (45.00%)

muscle asymmetry and scoliosis severity. The Cobb angle, obtained from standing full-spine radiographs within three months prior to ultrasound examination, was used as the primary indicator of scoliosis severity. The curve direction (left/right) and curve location (upper, apex, and lower vertebrae) were also recorded to ensure anatomical correspondence between imaging measurements and spinal deformity. To quantitatively evaluate muscle asymmetry in relation to AIS, the differences between the concave and convex sides for each parameter (transverse diameter, anteroposterior diameter, circumference, area, and shear wave elastography values) were calculated and used for correlation analysis with the Cobb angle.

Instruments and methods

The study used an ALOKA ARIETTA 60 ultrasound system with an L441 probe operating at 2-12 MHz and a LOGIQ E8 ultrasound system with a C1-6 probe operating at 1-6 MHz to perform examinations. Participants were examined in both standing and prone positions. The L441 probe was used to acquire transverse cross-sectional images of the paravertebral muscles at the upper vertebra, apex vertebra, and lower vertebra, which were identified and marked by a clinician. At the apex vertebra, the C1-6 probe was additionally used to perform SWE to measure muscle stiffness.

The upper vertebra was defined as the upper end vertebra of the main scoliotic curve, the apex vertebra as the vertebra with the greatest lateral deviation, and the lower vertebra as the lower end vertebra of the same curve.

For the standing position, participants stood naturally with both arms relaxed at their sides. Transverse ultrasound images were obtained at the marked vertebrae, measuring anteroposterior diameter, transverse diameter, circumference, and area, and SWE measurements were obtained at the apex vertebra using the C1-6 probe. All parameters were measured three times, and the mean value was used for analysis.

For the prone position, participants lay prone with arms relaxed alongside the body. Measurements were performed at the same vertebral levels using the same parameters as in the standing position, with each parameter measured three times and the average used for analysis.

Statistical analysis

All analyses were performed using SPSS version 27.0 and R version 4.3.1. Normality of continuous variables was assessed using the Shapiro-Wilk test, and homogeneity of variance was evaluated using Levene's test. For normally distributed data with homogeneous variances, comparisons between the concave and convex sides were performed using the independent-samples t test. For non-normally distributed data, the Mann-Whitney U test was used. Pearson correlation analysis was performed to assess the association between differences in muscle measurements and the Cobb angle. Data are expressed as means ± standard deviation (SD). A p-value of <0.05 was considered statistically significant.

Results

Patient demographics

A total of 100 patients with AIS were included (mean age, 12.81 ± 1.86 years), including 45 females and 55 males (**Table 1**).

Ultrasound measurement of paravertebral muscle asymmetry and corresponding Cobb angle at the apex vertebra in AIS patients

High-frequency musculoskeletal ultrasound was used to evaluate paravertebral muscle asymmetry at the apex vertebra in AIS. Cross-sectional images were acquired to measure

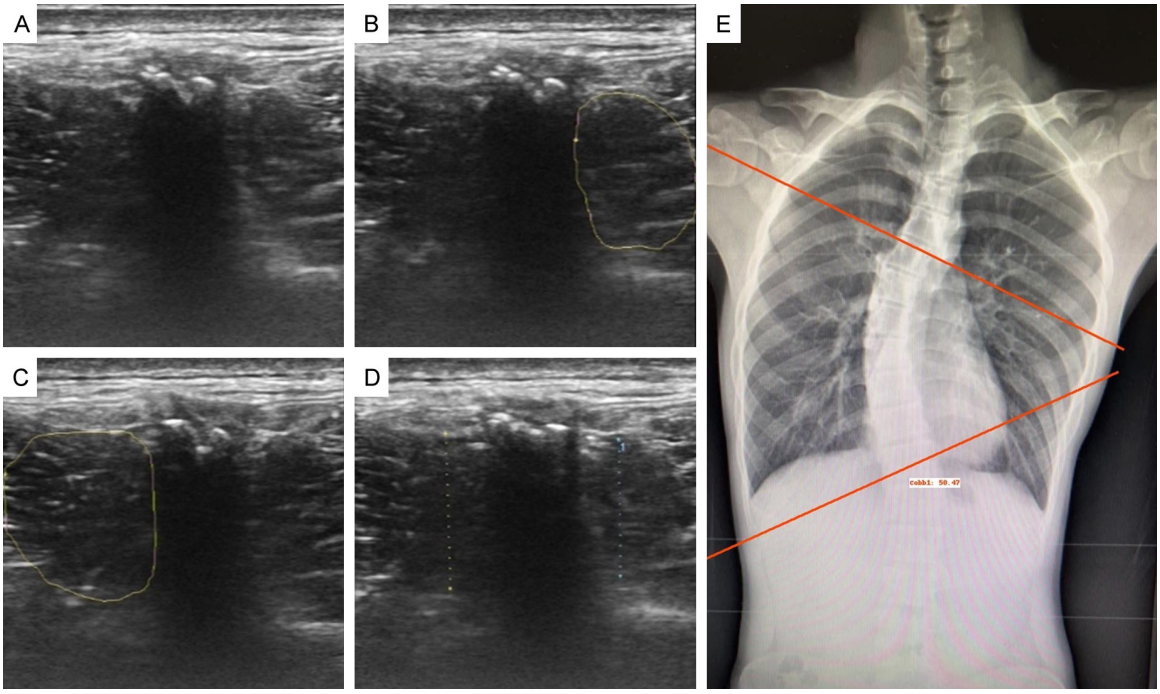

Figure 1. Ultrasound measurements at the apex vertebra in AIS patients. The apex vertebra was defined as the vertebra with the greatest lateral deviation of the main scoliotic curve on standing full-spine radiographs. A. Cross-sectional two-dimensional ultrasound image of the paravertebral muscles at the apex vertebra in a patient with AIS. B. Measurement of circumference and area on the convex side at the apex vertebra. C. Measurement of circumference and area on the concave side at the apex vertebra. D. Measurement of anteroposterior diameter of the paravertebral muscles at the apex vertebra. E. Standing full-spine radiograph showing right convex scoliosis with a Cobb angle of 50.47°.

Table 2. Comparison of paravertebral muscle parameters at the upper vertebra in two positions

		Concave Side (n = 100)	Convex Side (n = 100)	*t*	*P* Value
Standing Position	Transverse Diameter	16.48 ± 2.30	14.65 ± 2.27	2.191	0.035
	Anteroposterior Diameter	14.46 ± 1.80	13.52 ± 1.65	2.043	0.045
	Circumference	53.34 ± 6.28	48.98 ± 5.81	2.162	0.038
	Area	2.02 ± 0.51	1.68 ± 0.41	2.325	0.027
Prone Position	Transverse Diameter	17.07 ± 2.16	15.75 ± 2.25	2.031	0.048
	Anteroposterior Diameter	13.65 ± 1.86	12.94 ± 1.75	1.086	0.066
	Circumference	54.12 ± 6.34	50.85 ± 6.07	1.67	0.115
	Area	2.37 ± 0.53	1.98 ± 0.49	2.163	0.039

circumference, area, and anteroposterior diameter on both the concave and convex sides of the spine (**Figure 1A-D**). The Cobb angle, as an indicator of scoliosis severity, was obtained from standing full-spine radiographs (**Figure 1E**).

Comparison of paravertebral muscle parameters at the upper vertebra in two positions

At the upper vertebra, significant differences between the concave and convex sides were observed in transverse diameter, anteroposterior diameter, circumference, and area in the standing position (all $P<0.05$). In the prone position, significant differences were observed only for transverse diameter and area (both $P<0.05$), whereas differences in anteroposterior diameter and circumference were not statistically significant (both $P>0.05$) (**Table 2**).

Comparison of paravertebral muscle parameters at the apex vertebra in two positions

At the apex vertebra, significant differences between the concave and convex sides were

Table 3. Comparison of paravertebral muscle parameters at the apex vertebra in two positions (n = 100)

		Concave Side (n = 100)	Convex Side (n = 100)	t	*P* Value
Standing Position	Transverse Diameter	20.83 ± 3.49	18.70 ± 2.85	2.241	0.030
	Anteroposterior Diameter	17.09 ± 2.17	15.80 ± 1.78	2.073	0.043
	Circumference	67.05 ± 8.68	65.20 ± 7.31	2.167	0.035
	Area	3.15 ± 0.90	2.25 ± 0.75	2.364	0.023
	Shear Wave Elastography	5.79 ± 0.42	4.20 ± 0.44	2.549	0.016
Prone Position	Transverse Diameter	22.15 ± 3.51	19.91 ± 3.19	2.109	0.040
	Anteroposterior Diameter	16.07 ± 2.27	15.50 ± 2.15	1.863	0.072
	Circumference	67.39 ± 8.37	66.16 ± 8.44	2.046	0.044
	Area	3.47 ± 1.12	2.89 ± 0.74	2.185	0.034
	Shear Wave Elastography	5.25 ± 0.53	4.18 ± 0.49	2.303	0.026

Table 4. Comparison of paravertebral muscle parameters at the lower vertebra in two positions

		Concave Side (n = 100)	Convex Side (n = 100)	t	*P* Value
Standing Position	Transverse Diameter	24.31 ± 3.18	22.15 ± 3.57	2.176	0.034
	Anteroposterior Diameter	19.21 ± 2.52	17.84 ± 1.71	1.636	0.102
	Circumference	77.09 ± 7.66	70.99 ± 8.26	2.014	0.048
	Area	4.13 ± 0.86	3.53 ± 0.84	2.235	0.031
Prone Position	Transverse Diameter	24.85 ± 3.27	23.13 ± 4.01	2.062	0.044
	Anteroposterior Diameter	18.55 ± 2.55	17.24 ± 1.87	1.492	0.135
	Circumference	79.32 ± 7.34	73.16 ± 8.39	1.928	0.055
	Area	4.52 ± 0.65	4.03 ± 0.74	2.102	0.039

observed for transverse diameter, circumference, and area in both standing and prone positions (all P<0.05). In the prone position, no significant difference was observed for anteroposterior diameter (P>0.05). SWE values also differed significantly between the 2 sides (P<0.05) (**Table 3**).

Comparison of paravertebral muscle parameters at the lower vertebra in two positions

At the lower vertebra, significant differences between the concave and convex sides were observed for transverse diameter, circumference, and area in the standing position (all P<0.05), whereas the difference in anteroposterior diameter was not statistically significant (P>0.05). In the prone position, significant differences were observed for transverse diameter and area (both P<0.05), whereas differences in anteroposterior diameter and circumference were not statistically significant (both P>0.05) (**Table 4**).

Pearson correlation analysis between the differences in paravertebral muscle parameters and Cobb angle at the apex vertebra in two positions

In both the standing position (**Figure 2**) and the prone position (**Figure 3**), differences in paravertebral muscle parameters at the apex vertebra were positively correlated with the Cobb angle. In the standing position, the Pearson correlation coefficients and slope coefficients for transverse diameter, anteroposterior diameter, circumference, and area were higher than those in the prone position (0.795/0.473 vs. 0.720/0.387, 0.841/0.298 vs. 0.785/0.186, 0.930/1.457 vs. 0.675/1.247, and 0.910/3.137 vs. 0.900/2.627, respectively).

Discussion

AIS is a common spinal deformity of unclear etiology, and the paravertebral muscles play an important role in spinal stability and postural control. In this study, high-frequency ultrasound

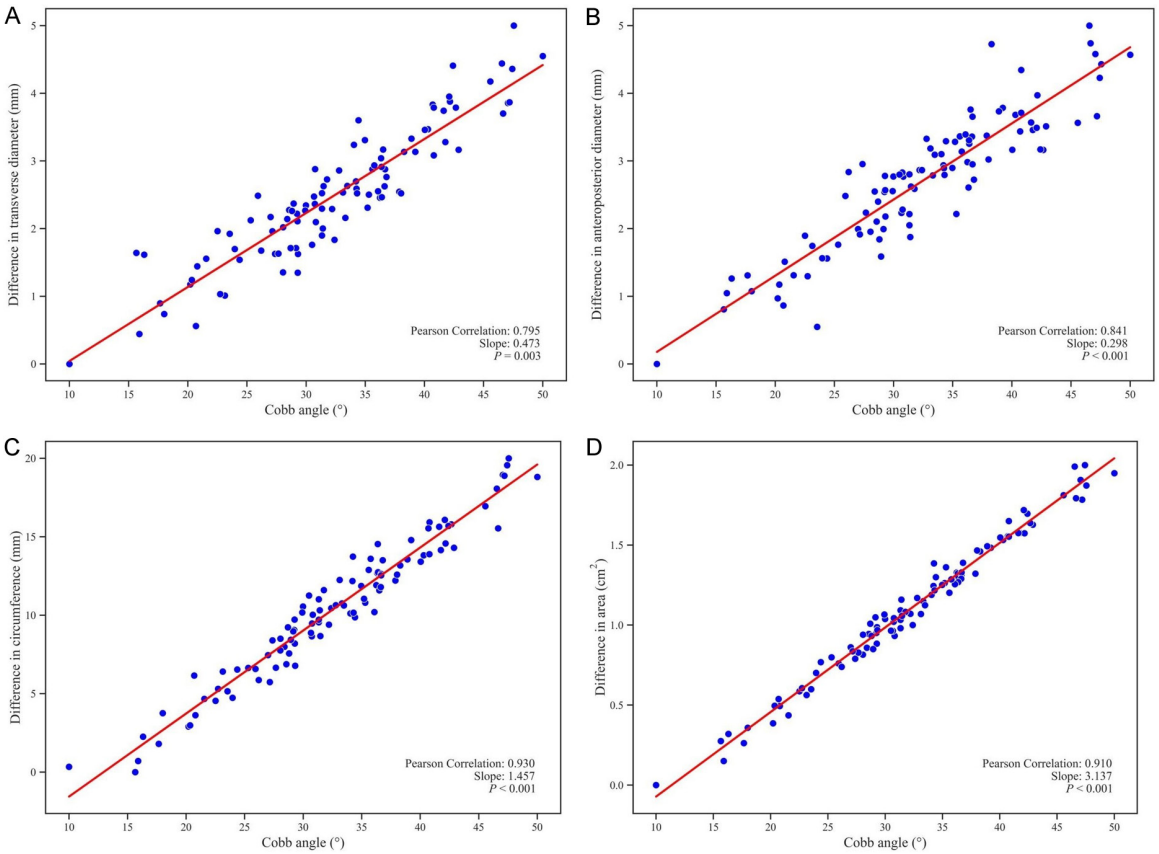

Figure 2. Pearson correlation analysis between differences in paravertebral muscle parameters at the apex vertebra and Cobb angle in the standing position. A. Correlation between Cobb angle and the difference in transverse diameter. B. Correlation between Cobb angle and the difference in anteroposterior diameter. C. Correlation between Cobb angle and the difference in circumference. D. Correlation between Cobb angle and the difference in area. Statistical analysis was conducted with SPSS 27.0 using Pearson correlation and slope coefficients, with $P<0.05$ considered significant.

was used to assess paravertebral muscle characteristics in the standing and prone positions to identify the position that may provide the most informative measurements for AIS evaluation.

These findings are consistent with previous reports showing asymmetric paraspinal muscle morphology in AIS, particularly compensatory hypertrophy on the concave side [19, 20], as well as MRI-based evidence of structural differences [16].

We observed significant differences in transverse diameter, anteroposterior diameter, circumference, and area at the upper and apex vertebrae, with the most pronounced differences at the apex. At the lower vertebra, significant differences were observed only for transverse diameter and area. In the prone position, significant differences at the apex were found for transverse diameter, circumference, and area, and SWE also demonstrated significant side-to-side differences at the apex vertebra. Collectively, these findings suggest that the standing position may be more sensitive for detecting muscle asymmetry, with stronger correlations with the Cobb angle than those observed in the prone position. This may be explained by the standing position reflecting physiological spinal loading, which has been emphasized in previous imaging studies [11].

The greatest differences in muscle-related measurements were observed at the apex vertebra, supporting the relevance of this level for AIS assessment. Transverse diameter and area were significantly different between sides at all vertebral levels, suggesting that these parameters may be particularly informative. By con-

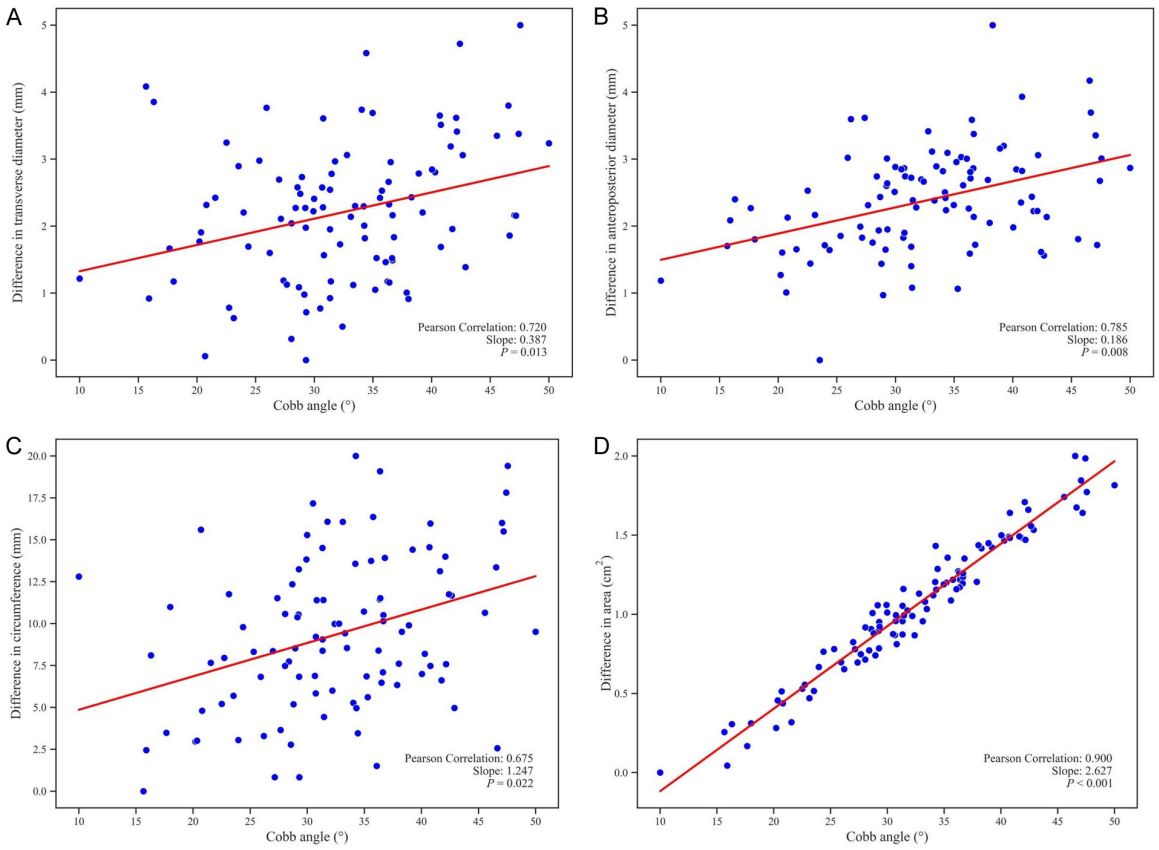

Figure 3. Pearson correlation analysis between differences in paravertebral muscle parameters at the apex vertebra and Cobb angle in the prone position. A. Correlation between Cobb angle and the difference in transverse diameter. B. Correlation between Cobb angle and the difference in anteroposterior diameter. C. Correlation between Cobb angle and the difference in circumference. D. Correlation between Cobb angle and the difference in area. Statistical analysis was conducted with SPSS 27.0 using Pearson correlation and slope coefficients, with P<0.05 considered significant.

trast, anteroposterior diameter showed less consistent statistical significance. The greater stability and discriminatory capacity of transverse diameter may make it especially useful in the evaluation of AIS.

Significant differences in muscle stiffness between the concave and convex sides were also observed, particularly at the apex vertebra, with higher SWE values on the concave side. This finding is in keeping with the hypothesis that the larger muscles on the concave side may represent an adaptive response to increased mechanical loading [19, 20]. The observed association between muscle asymmetry and the Cobb angle suggests that paravertebral muscle abnormalities are related to scoliosis severity, although the direction of this relationship cannot be determined from the present cross-sectional data. Similar increases in muscle stiffness have been reported in elastography studies [21], supporting the role of altered mechanical properties in AIS.

The relationship between paravertebral muscle changes and AIS remains incompletely understood. One view is that muscle changes are secondary to spinal deformity [22], whereas another proposes that muscle abnormalities, particularly on the concave side, may contribute to scoliosis development [23]. Regardless of causality, characterization of muscle dysfunction may be clinically relevant in AIS. High-frequency ultrasound combined with SWE provides information on both muscle morphology and stiffness and may therefore assist clinical assessment and monitoring.

The observed association between muscle asymmetry and Cobb angle further under-

scores the potential relevance of paravertebral muscle abnormalities in AIS. SWE findings also suggest that muscle stiffness may be associated with curvature severity, thereby adding potentially useful information beyond conventional morphologic assessment [24].

This study has several limitations, including its single-center design, limited sample size, cross-sectional nature, and lack of reliability assessment. In addition, SWE measurements may be affected by technical factors. Future studies should involve multicenter and longitudinal designs, integrate multimodal imaging, and explore the role of ultrasound and SWE in monitoring treatment response and guiding personalized management.

Conclusion

In this study, measurements on the concave side were greater than those on the convex side, particularly at the apex vertebra, and these differences were more apparent in the standing position. Paravertebral muscle asymmetry was associated with the Cobb angle in AIS. High-frequency musculoskeletal ultrasound combined with SWE may provide a useful non-invasive approach for evaluating muscle morphology, asymmetry, and stiffness, with potential applications in diagnosis, follow-up, and individualized treatment planning.

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Disclosure of conflict of interest

None.

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