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Sensory integration and spinal structure in AIS: is there a functional–structural association?

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Abstract

Background Adolescent idiopathic scoliosis (AIS) is characterized by three-dimensional spinal deformities and often co-occurs with balance impairments. However, it remains unclear whether postural deficits in AIS are statistically associated with spinal morphology, or instead reflect independent alterations in sensorimotor integration.

Objective This study aimed to examine whether postural control performance under sensory challenge is statistically associated with three-dimensional spinal morphology in adolescents with AIS.

Methods A total of 64 young adults (35 with AIS, Cobb angle 10°–39°; and 29 healthy controls) were assessed using a cross-sectional design. Postural control was evaluated via the modified Clinical Test of Sensory Interaction and Balance (mCTSIB), which included four standard sensory conditions and an additional vestibular-challenging task involving rhythmic head movements. Spinal morphology was measured using the DIERS 4D Formetric system. Between-group differences were analyzed using Mann–Whitney U tests. Within-group correlations were tested via Spearman's coefficients, and intergroup differences in correlation strength were evaluated using Fisher Z-transformation with false discovery rate (FDR) correction.

Results AIS participants exhibited significantly greater postural instability in two sway parameters—mediolateral (ML) average velocity and path length—but only under the most challenging vestibular condition (FoEC-HDM; $p < 0.01$). Five spinal parameters also differed significantly between groups ($p < 0.05$). However, no significant correlations were observed between postural control and spinal morphology within either group. No intergroup differences in correlation strength were identified after FDR correction.

Conclusion In yong adults with mild to moderate AIS (Cobb angle 10°–39°), postural instability and structural spinal deformities appear to be coexisting but statistically independent. No significant associations were found between spinal morphology and postural control under sensory challenge. These findings suggest that balance impairments may reflect central sensorimotor alterations rather than curve severity.Future studies should examine whether such independence persists across broader severity ranges or curve types in AIS.

Keywords Adolescent idiopathic scoliosis, Postural control, Sensory integration, Spinal morphology, mCTSIB

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Introduction

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional (3D) spinal deformity that typically develops during puberty and affects approximately 2–4% of the adolescent population [1]. Despite extensive research, the pathogenesis of AIS remains incompletely understood. Beyond the evident biomechanical changes in spinal curvature, emerging evidence suggests that neurophysiological dysfunctions—especially in sensory integration, which plays a central role in postural control—may contribute to the development and clinical presentation of scoliosis [2, 3, 4].These dysfunctions may represent early manifestations of altered sensorimotor control that interact with spinal asymmetry during early stages of curve development [5]. Although prior studies such as Haumont et al. [5] examined patients with Cobb angles starting at 15°, their findings suggest that postural instability may emerge before spinal curvature becomes severe, raising questions about early sensorimotor involvement in AIS.

Sensory integration refers to the central nervous system's ability to process and synthesize multisensory inputs—including visual, proprioceptive, and vestibular information—to maintain upright posture and dynamic balance. Numerous studies have shown that individuals with AIS demonstrate increased postural sway and instability, particularly under challenging sensory conditions [2, 6]. These observations suggest that sensorimotor impairments may not merely result from spinal asymmetry, but could reflect intrinsic deficits in se nsory processing and motor adaptation [4, 5].

However, the nature of the relationship between postural control and spinal structure in AIS remains poorly defined. While several studies have reported the coexistence of postural instability and spinal deformity in adolescents with AIS [3, 6], few have directly examined whether the severity of postural sway is statistically associated with specific three-dimensional spinal parameters [7]. Clarifying whether these functional and structural features covary may provide valuable insight into the sensorimotor profile of AIS. Despite its clinical relevance, this question remains insufficiently explored.

Recent advances in assessment tools now enable precise quantification of both sensory integration and spinal morphology. The modified Clinical Test of Sensory Interaction and Balance (mCTSIB) systematically evaluates postural performance under progressively challenging sensory conditions, including vestibular perturbation [8]. Meanwhile, the DIERS 4D Formetric system provides reliable, non-invasive three-dimensional measurements of spinal alignment and axial rotation [9, 10].

The present study aimed to examine whether sensory integration performance is statistically associated with three-dimensional spinal morphology in adolescents with idiopathic scoliosis. Specifically, we sought to (1) compare sensory integration and spinal morphology parameters between AIS participants and healthy controls, (2) evaluate within-group correlations between structural and functional measures, and (3) test group differences in correlation strength using Fisher Z-transformation. By addressing the presence or absence of such associations, this study contributes to a more nuanced understanding of sensorimotor function in AIS.

Methods

Study design

This was a cross-sectional study designed to investigate the potential functional–structural coupling between sensory integration performance and 3D spinal morphology in adolescents with idiopathic scoliosis. This study was approved by the ethics committees of Wuhan Sports University and Xiangtan Central Hospital and registered in the Chinese Clinical Trial Registry with the registration number ChiCTR2300075371.

Participants recruitment

Participants were recruited from a local college between September and October 2023. The AIS group included young adults who were flagged as potentially having idiopathic scoliosis during routine college health screening. These individuals were referred to a collaborating hospital for further radiographic evaluation. All AIS participants underwent standing full-spine X-ray imaging, and Cobb angles were measured by experienced orthopedic specialists. Final diagnoses and group assignment were based on these radiographic findings, using a standard diagnostic threshold of 10°for AIS. The detailed distribution of radiographic Cobb angles (range: 10°–39°) is presented in Table 2.

The control group consisted of age- and sex-matched healthy individuals with no history of scoliosis, postural abnormalities, or diagnosed balance disorders.

Inclusion criteria included: (1) for AIS, radiographically confirmed Cobb angle between 10° and 45°; and (2) the ability to complete all planned assessments, including mCTSIB and DIERS 4D Formetric evaluations.

Exclusion criteria for both groups comprised: a history of neurological, musculoskeletal, or neurodevelopmental conditions affecting balance (e.g., cerebral palsy, vestibular disorders), prior spinal surgery, limb-length discrepancy > 2.5 cm, or lower limb injuries in the past 3 months. Individuals on medications known to affect postural control (e.g., vestibular suppressants, antiepileptics) were also excluded.

To screen for vestibular or sensory integration disorders, all participants completed a structured questionnaire addressing sensory sensitivities, motor coordination, dizziness, vertigo, and motion intolerance.

Sensory integration assessment: mCTSIB protocol

Sensory integration and postural stability were assessed using the modified Clinical Test of Sensory Interaction and Balance (mCTSIB), administered on the Pro-Kin 252 balance system (Tecnobody, Italy). Each participant was evaluated under five sequential sensory conditions, designed to progressively challenge the visual, somatosensory, and vestibular systems: The mCTSIB is a widely used protocol with demonstrated reliability and validity in assessing sensory integration and balance performance [7, 8].

Firm surface, eyes open (FiEO): Provides full sensory input, allowing assessment of baseline multisensory integration.

Firm surface, eyes closed (FiEC): Eliminates visual input to evaluate somatosensory and vestibular contributions.

Foam surface, eyes open (FoEO): Disrupts somatosensory input, emphasizing reliance on visual and vestibular cues.

Foam surface, eyes closed (FoEC): Removes visual and distorts somatosensory feedback, thereby challenging vestibular function.

Foam surface, eyes closed with head movements (FoEC-HDM): Further challenges vestibular integration by adding rhythmic head motion. Participants performed 15 s of anterior–posterior (AP) and 15 s of mediolateral (ML) head movements, guided by a metronome set at 60 beats per minute (15 repetitions per direction).

Prior to testing, participants were instructed to remove their shoes and stand barefoot on the force plate. All assessments were conducted by two licensed physical therapists who were blinded to participant group allocation (AIS or control) to minimize observer bias.Basic biometric data—including height, weight, and body mass index (BMI)—were collected and recorded. To standardize posture across conditions, participants adopted a feet-together stance with arms crossed over the chest.

Each sensory condition lasted for 30 s and was performed across three consecutive trials, with a five-second rest interval between trials. During each trial, sway metrics were continuously recorded, including the standard deviation of anteroposterior sway (AP SD), standard deviation of mediolateral sway (ML SD), average velocity, path length, and ellipse area. The mean value for each parameter across the three trials was calculated and used for subsequent analysis.

Spinal morphology assessment: DIERS 4D formetric system

3D spinal morphology was evaluated using the DIERS Formetric 4D analysis system (DIERS International GmbH, Germany), a non-invasive surface topography device that provides real-time, marker-free measurements of spinal alignment and posture in three dimensions.

Prior to scanning, participants were instructed to remove upper body garments to allow clear visualization of anatomical landmarks on the back. Each participant stood in a relaxed, natural upright posture with arms hanging loosely at the sides and feet positioned hip-width apart on the designated platform. The scanner captured images over a few seconds while the participant maintained a stable stance.

The DIERS system computes standard spinal metrics based on specific anatomical landmarks. Key abbreviations used to define segmental angles and alignment include:

VP– vertebra prominens (typically C7);

DM– midpoint between the bilateral dimples of Venus (posterior superior iliac spines);

ICT– cervico-thoracic inflection point;

ITL– thoraco-lumbar inflection point;

ILS– lumbo-sacral inflection point.

Angular parameters (e.g., kyphotic angle, lordotic angle) are calculated between these anatomical reference points, while spatial parameters (e.g., sagittal/coronal imbalance, apical deviation) reflect deviations of the spine or pelvis relative to these landmarks.

The spinal parameters were categorized into three domains:

Global alignment indicators: sagittal imbalance (VP–DM), coronal imbalance (VP–DM), and pelvic obliquity (tilt).

Sagittal profile parameters: kyphotic angle (ICT–ITL, max) and lordotic angle (ITL–ILS, max).

Scoliotic deformation metrics: scoliosis angle, vertebral rotation (maximum and root mean square [RMS]), apical deviation (positive and negative maxima), and pelvis rotation.

Each measurement was performed once under standardized conditions. All data were automatically calculated by the DIERS software and exported for statistical analysis.

Data collection procedure

All assessments were conducted in a controlled laboratory environment. Participants first completed the mCTSIB protocol, followed by the DIERS spinal scan, with a rest period between tests. All procedures were performed on the same day to minimize temporal variability.

All assessments were administered by two licensed physical therapists who were formally trained in operating both the mCTSIB and DIERS systems. To minimize analytical bias, the investigator responsible for data analysis was blinded to participants' group allocation.

Table 1 Participants demographics and physical characteristics

Variables	AIS group			Control group			*P* value
	Male	Female	Total	Male	Female	Total	
Participants	8	27	35	8	21	29	
Age (year)(min-max)	19.4 ± 0.9 (18.0–20.0)	18.9 ± 0.9 (18.0–21.0)	19.0 ± 0.9 (18.0–21.0)	19.3 ± 0.7 (18.0–20.0)	18.9 ± 0.8 (18.0–20.0)	19.0 ± 0.8 (18.0–20.0)	0.73
Height (cm)	174.8 ± 6.1	160.3 ± 5.8	163.6 ± 8.4	168.5 ± 7.9	161.4 ± 6.5	163.3 ± 7.5	0.93
Body weight (kg)	59.5 ± 6.4	51.1 ± 7.4	53.8 ± 7.8	60.9 ± 11.6	54.8 ± 7.2	56.5 ± 8.9	0.33
BMI (kg/m2)	19.5 ± 1.9	20.3 ± 2.7	20.1 ± 2.5	21.3 ± 2.5	21.0 ± 2.5	21.1 ± 2.5	0.14

*Variables are presented as mean ± SD. P-values were calculated using the independent samples t-test

Table 2 Cobb angle distribution among AIS participants ($n = 35$)

Cobb angle category (°)	Classification	Number of participants (*n*)	Percentage (%)
10°-20°	Mild AIS	22	62.9%
21°-39°	Moderate AIS	13	37.1%
Total	—	35	100%

*Mean (SD) Cobb angle: 19.5°± 8.5, Min–Max Range: 10°– 39°

Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics for Windows 26.0 (IBM Corp., Armonk, NY), JASP (version 0.19.3), and Python (version 3.11). The normality of continuous variables was evaluated using the Shapiro–Wilk test. For between-group comparisons, independent-samples t-tests were used for normally distributed data, while the Mann–Whitney U test was applied for non-normally distributed variables. Similarly, Pearson's correlation was used for normally distributed variables, and Spearman's rank correlation (ρ) was employed otherwise.

Effect sizes were calculated using Cliff's delta (δ), with values interpreted as negligible ($|\delta| < 0.147$), small ($0.147 \le |\delta| < 0.33$), moderate ($0.33 \le |\delta| < 0.474$), and large ($|\delta| \ge 0.474$). In addition, Bayes factors (BF_{10}) were computed to quantify the strength of evidence for group differences. Between-group differences in correlation strength were evaluated using Fisher's Z transformation. Multiple comparisons were corrected using the Benjamini–Hochberg false discovery rate (FDR) method.

Statistical significance was set at $p < 0.05$ for uncorrected comparisons and $q < 0.05$ for FDR-adjusted results.

Results

Participants characteristics

A total of 64 participants were enrolled in the study, including 35 young adults with idiopathic scoliosis and 29 healthy controls. No significant differences were found between the two groups in terms of age, height, weight, or BMI (all $P > 0.05$; see Table 1 for details).

Radiographic assessment using standing full-spine X-rays confirmed AIS diagnoses and served as the basis for group classification. The distribution of radiographic Cobb angles in the AIS group ranged from 10°to 39°, as presented in Table 2. These X-ray–derived values were interpreted by orthopedic specialists and used exclusively for diagnostic decision-making and participant grouping.

Spinal morphology parameters used in the statistical analysis—including scoliosis angle, vertebral rotation, coronal imbalance, and apical deviation—were subsequently obtained through surface topography using the DIERS 4D Formetric system. While minor discrepancies between surface topography and radiographic Cobb angles are expected, radiographic values alone informed the inclusion criteria. Any overlap cases near the diagnostic threshold were rare and did not materially influence group-level comparisons.

In the control group, DIERS-based assessments occasionally identified spinal curvatures under 10°, which are considered within the range of normal physiological variation and did not meet clinical criteria for scoliosis.

Group differences in sensory integration and spinal parameters

Among the five mCTSIB conditions, no significant group differences were observed under the first four states. However, under the fifth and most challenging condition—foam surface, eyes closed with head movements (FoEC-HDM)—all six balance-related parameters showed higher values in the AIS group. After false discovery rate (FDR) correction, two of these parameters—ML average velocity and path length—remained significantly different ($q < 0.05$), while the remaining variables approached significance ($q = 0.08$–0.10). These findings were accompanied by moderate effect sizes($0.33 \le |\delta| < 0.474$) and Bayes Factor support ranging from anecdotal to strong ($BF_{10} = 1.53$–13.33), as shown in Table 3.

Regarding spinal morphology, five out of the eleven 3D parameters assessed via DIERS showed significant group differences even after FDR correction. These included scoliosis angle, vertebral rotation (+ max and RMS), apical deviation (+ max), and coronal imbalance. The scoliosis angle exhibited the largest effect size ($\delta = 0.78$), with BF_{10} >100,000, indicating decisive evidence in favor of a group difference. These results, detailed in Table 4, confirm structural spinal asymmetries in the AIS group.

Table 3 Group comparison of mCTSIB parameters

Variables	AIS group (Median, IQR) (*n* = 35)	Control group (Median, IQR) (*n* = 29)	*P* value	q value (FDR-adjusted *p*)	Cliff's δ	BF_{10}
FoEC-HDM						
AP SD	16.0(14.7 ~ 17.7)	14.7(12.7 ~ 16.5)	**0.01***	0.08	-0.38	7.23
ML SD	15.0(13.0 ~ 18.0)	13.9(12.3 ~ 15.3)	**0.02***	0.10	-0.34	3.76
AP average velocity	44.7(38.3 ~ 65.0)	39.0(35.0 ~ 47.2)	**0.02***	0.10	-0.35	2.29
ML average velocity	48.0(38.3 ~ 55.3)	38.3(34.5 ~ 43.7)	**0.00***	**0.00 ***	-0.45	13.33
ellipse area	4828.3(3595.7 ~ 5543.0)	4077.0(2842.7 ~ 4692.7)	**0.01***	0.08	-0.38	1.53
path length	2090.3(1782.3 ~ 2684.0)	1792.0(1601.3 ~ 1970.0)	**0.00***	**0.00***	-0.43	9.67

*Values are shown as median (IQR); p-values from Mann–Whitney U tests. Effect sizes are reported as Cliff's delta (δ); Bayes Factors (BF_{10}) quantify evidence for group differences. FDR correction for multiple comparisons was applied using the Benjamini–Hochberg method, with statistical significance set at q < 0.05. Only parameters with significant between-group differences are shown. Full results for all variables are available in Supplementary Table S1. FoEC HDM: AP and ML head movement on a foam surface, eyes closed. AP: anterior-posterior; ML: medial-lateral; SD: standard deviation; AP SD: average sway amplitude of the COP in the AP direction; ML SD: average sway amplitude of COP in the ML direction; AP average velocity: average COP sway velocity in the AP direction; ML average velocity: average COP sway velocity in the ML direction; ellipse area: maximum COP displacement area; path length: total COP displacement length

Table 4 Group comparison of spinal morphology parameters

Variables	AIS group (Median, IQR) (*n* = 35)	Control group (Median, IQR) (*n* = 29)	*P* value	q value (FDR-adjusted *p*)	Cliff's δ	BF_{10}
Scolosis Angle	19.0(12.0 ~ 24.0)	7.0(5.5 ~ 9.5)	**0.00***	**0.00***	-0.78	486612.56
Sagittal imbalance VP-DM	20.0(12.0 ~ 26.0)	19.0(6.0 ~ 37.5)	0.95	0.95	-0.01	0.26
Coronal Imbalance VP-DM	14.0(6.0 ~ 20.0)	6.0(3.0 ~ 10.0)	**0.01***	**0.02***	-0.41	14.31
Kyphotic Angle ICT-ITL(max)	37.0(34.0 ~ 42.0)	40.0(33.0 ~ 43.0)	0.50	0.61	-0.10	0.30
Lordotic Angle ITL-ILS(max)	35.0(29.0 ~ 43.0)	31.0(27.5 ~ 38.0)	0.17	0.27	-0.20	0.53
Vertebral Rotation(+ max)	4.0(1.0 ~ 10.0)	1.0(0.5 ~ 2.0)	**0.00***	**0.00***	-0.45	108.71
Vertebral Rotation(rms)	5.0(4.0 ~ 8.0)	2.0(1.5 ~ 3.0)	**0.00***	**0.00***	-0.74	13980.59
Apical Deviation VP-DM(+ max)	12.0(5.0 ~ 25.0)	4.0(1.5 ~ 7.0)	**0.00***	**0.00***	-0.57	1178.05
Apical Deviation VP-DM(-max)	4.0(1.0 ~ 10.0)	3.0(1.0 ~ 6.5)	0.21	0.29	-0.18	1.06
pelvis rotation	3.0(1.0 ~ 5.0)	2.0(0.0 ~ 4.0)	0.10	0.18	-0.23	0.52
Plevic Obliquity(tilt)	3.0(3.0 ~ 6.0)	4.0(2.0 ~ 6.0)	0.84	0.92	-0.03	0.26

*Values are shown as median (IQR); p-values from Mann–Whitney U tests. Effect sizes are reported as Cliff's delta (δ); Bayes Factors (BF_{10}) quantify evidence for group differences. FDR correction for multiple comparisons was applied using the Benjamini–Hochberg method, with statistical significance set at q < 0.05

Table 5 Within-group correlations between postural and spinal parameters in the AIS group

mCTSIB Parameter	Spinal Parameter	ρ (AIS)	*p* (AIS)
ML average velocity	Scoliosis Angle	-0.24	0.17
path length	Scoliosis Angle	-0.22	0.21
ML average velocity	Coronal Imbalance	0.14	0.43
path length	Coronal Imbalance	0.11	0.52
ML average velocity	Vertebral Rotation (+ max)	-0.06	0.75
path length	Vertebral Rotation (+ max)	-0.15	0.40
ML average velocity	Vertebral Rotation (rms)	0.02	0.93
path length	Vertebral Rotation (rms)	0.00	0.99
ML average velocity	Apical Deviation	-0.25	0.14
path length	Apical Deviation	-0.21	0.23

*Spearman's rank correlation coefficients (ρ) are presented for each combination of the two mCTSIB parameters and five spinal morphology parameters. Statistical significance thresholds are denoted as follows: $**p < 0.01$, $*p < 0.05$, † $0.05 < p < 0.10$. No correlation reached statistical significance. Full correlation matrices (30 × 11) for group are provided in Supplementary Table S2

Within-Group correlation between sensory integration and structural metrics

Correlation analyses were conducted between all 30 mCTSIB parameters (six balance metrics across five sensory conditions) and 11 spinal parameters. The primary results focused on variables that showed significant group differences after FDR correction, presented in Tables 5 and 6. The full set of correlations for all parameters in both groups is available in Supplementary Table S1 for exploratory completeness.

In the AIS group, no significant associations were observed between the two mCTSIB parameters (ML average velocity and path length) and the five spinal morphology parameters included in the analysis. All Spearman's correlation coefficients were weak (|ρ| < 0.30), and none reached statistical significance or trend-level relevance (all $p > 0.10$), multiple comparison correction was not applied, as shown in Table 5.

In contrast, the control group exhibited a trend-level association between path length and vertebral rotation (RMS), with a negative correlation (ρ= −0.32, $p = 0.09$).

Table 6 Within-group correlations between postural and spinal parameters in the control group

mCTSIB Parameter	Spinal Parameter	ρ (Control)	*p* (Control)
ML average velocity	Scoliosis Angle	0.06	0.77
path length	Scoliosis Angle	-0.10	0.63
ML average velocity	Coronal Imbalance	0.11	0.57
path length	Coronal Imbalance	-0.03	0.90
ML average velocity	Vertebral Rotation (+ max)	0.27	0.16
path length	Vertebral Rotation (+ max)	0.16	0.41
ML average velocity	Vertebral Rotation (rms)	-0.16	0.42
path length	**Vertebral Rotation (rms)**	**-0.32**	**0.09†**
ML average velocity	Apical Deviation	0.20	0.29
path length	Apical Deviation	0.07	0.73

*Spearman's rank correlation coefficients (ρ) are presented for each combination of the two mCTSIB parameters and five spinal morphology parameters. Statistical significance thresholds are denoted as follows: ***p* < 0.01, **p* < 0.05, † 0.05 < *p* < 0.10. No correlation reached statistical significance. Full correlation matrices (30 × 11) for group are provided in Supplementary Table S3

Although this may seem counterintuitive, it may reflect physiological compensation mechanisms in healthy young adults, whereby minor spinal asymmetries are effectively integrated into stable postural strategies through intact sensorimotor pathways.No other parameter pairs reached statistical significance or trend-level relevance ($p > 0.10$), and multiple comparison correction was not applied. The results are presented in Table 6.

Group differences in correlation strength

To further examine group-level differences in postural–spinal coupling, Fisher Z-transformation was applied to compare Spearman's correlation coefficients between the AIS and control groups across 10 variable pairs. The results are summarized in Table 7 and visualized in Fig. 1, ranked by the absolute magnitude of Z values.

Most comparisons yielded negative Z values, indicating that correlations between postural parameters and spinal morphology were generally stronger in the control group than in the AIS group. However, none of these between-group differences in correlation strength reached statistical significance, as determined by the Benjamini–Hochberg false discovery rate (FDR) correction (all q > 0.05), suggesting that, while no definitive dissociation was observed in AIS, the overall pattern reflects relatively weaker coupling in this group compared to healthy controls.

The bar plot displays Fisher Z values comparing correlation strengths between AIS and control groups across 10 postural–spinal parameter pairs. Each pair reflects the relationship between one mCTSIB variable (ML average velocity or path length) and a spinal morphology parameter. Negative Z values indicate stronger correlations in the control group, while positive values favor AIS. Red bars highlight the top five pairs with the largest absolute Z values. Although none reached statistical significance after FDR correction, the consistent directionality suggests weaker coupling in AIS.

Discussion

This study investigated whether postural control performance under sensory challenge is statistically associated with spinal morphology in young adults with idiopathic scoliosis. Compared to controls, AIS participants (Cobb angle 10°-39°) showed significantly greater postural instability under the most challenging vestibular condition (FoEC-HDM) of the mCTSIB. Structural parameters such as scoliosis angle, coronal imbalance, vertebral rotation, and apical deviation also differed significantly between groups.

Our results do not indicate a statistically significant association between postural control and spinal morphology in young adults with mild to moderate AIS

Table 7 Between-group differences in postural–spinal coupling based on fisher Z transformation

mCTSIB Parameter	Spinal Parameter	ρ(AIS)	ρ(Control)	Z value	*P* value	q value (FDR-adjusted *p*)	Significance
ML average velocity	Apical Deviation VP-DM(+ max)	-0.25	0.20	-1.76	0.08	0.49	ns
path length	Vertebral Rotation(rms)	0.00	-0.32	1.26	0.21	0.49	ns
ML average velocity	Vertebral Rotation(+ max)	-0.06	0.27	-1.25	0.21	0.49	ns
path length	Vertebral Rotation(+ max)	-0.15	0.16	-1.16	0.25	0.49	ns
ML average velocity	Scolosis Angle	-0.24	0.06	-1.13	0.26	0.49	ns
path length	Apical Deviation VP-DM(+ max)	-0.21	0.07	-1.05	0.29	0.49	ns
ML average velocity	Vertebral Rotation(rms)	0.02	-0.16	0.66	0.51	0.71	ns
path length	Coronal Imbalance VP-DM	0.11	-0.03	0.52	0.60	0.71	ns
path length	Scolosis Angle	-0.22	-0.10	-0.47	0.64	0.71	ns
ML average velocity	Coronal Imbalance VP-DM	0.14	0.11	0.12	0.91	0.91	ns

*ρ = Spearman's correlation coefficient. Z = Fisher Z transformation of between-group difference in correlation strength. P values represent uncorrected two-tailed significance from Fisher Z comparisons of correlation coefficients derived from within-group Spearman correlation analyses. q-values were calculated using the Benjamini–Hochberg False Discovery Rate (FDR) correction method. Statistical significance was set at q < 0.05. ns = non-significant.Full results are available in Supplementary Table S4

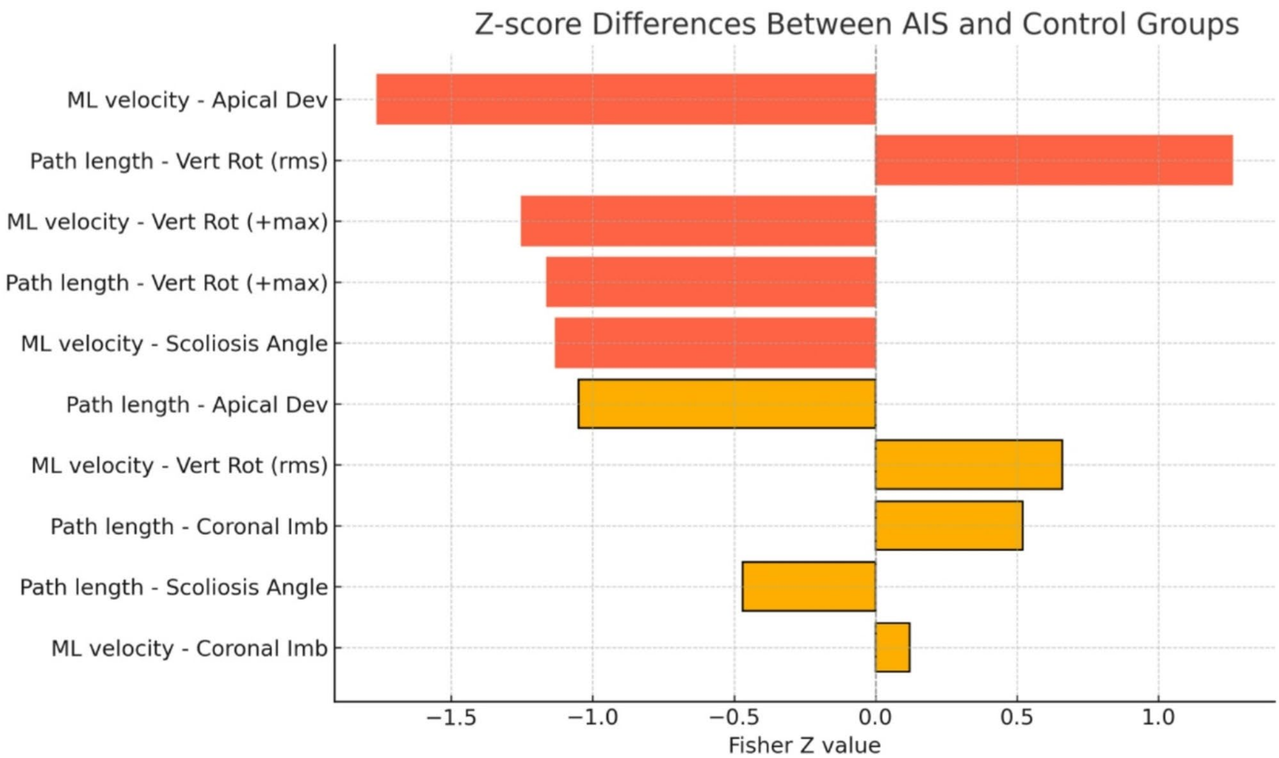

Fig. 1 between-group differences in postural–spinal correlations based on Fisher Z transformation

(Cobb angle 10°-39°). Although previous studies, such as Haumont et al. [5], have reported greater postural instability in individuals with Cobb angles above 15°, our findings suggest that postural impairments do not increase linearly with curve severity within this range. This interpretation is consistent with previous meta-analytic evidence suggesting only moderate or inconsistent associations between spinal curvature and postural performance under varying task demands [11]. It is important to note that our cohort did not include participants with Cobb angles above 40°, and we did not directly assess central neural or vestibular function. Thus, the underlying neurophysiological basis for balance impairments remains speculative. Future studies incorporating longitudinal tracking, neuroimaging, or vestibular testing are needed to clarify the extent to which these deficits reflect structural deformity, altered central integration, or both.

To better understand the sensory conditions under which postural instability becomes apparent, we examined balance performance across all mCTSIB test conditions. Notably, significant group differences were found only in the most challenging state—Foam surface with eyes closed and head movement (FoEC-HDM)—which selectively stresses the vestibular system by removing visual cues, reducing proprioceptive input, and introducing dynamic head motion [12]. Under this high sensory conflict condition, AIS participants exhibited significantly increased mediolateral (ML) sway velocity and path length, indicating greater postural instability. These findings suggest that young adults with AIS may have difficulties adapting to increased vestibular demands, possibly reflecting impairments in sensory reweighting and integration under vestibular challenge [13].

These findings support the possibility that individuals with AIS may exhibit vestibular-related impairments, which become evident only under conditions of reduced visual and proprioceptive input. Previous studies have identified abnormalities in vestibular function in AIS, including delayed vestibulo-ocular reflexes, otolith asymmetry, and atypical vestibular evoked potentials [14–17, 16]. Our results extend this literature by demonstrating that such impairments may manifest behaviorally during tasks involving high sensory conflict, such as FoEC-HDM. Nevertheless, as vestibular function was not directly measured in this study, the physiological basis of the observed instability remains speculative and requires confirmation through future neurophysiological or imaging-based assessments.

Another key finding is that postural control impairments under multisensory challenge were not significantly associated with spinal morphology in our AIS sample. Although participants with AIS exhibited pronounced structural deviations—including higher Cobb angles, greater vertebral rotation, and increased apical deviation—none of these measures were significantly correlated with postural sway metrics. These structural differences were statistically robust and clinically meaningful, as indicated by moderate to large effect sizes. However, their lack of correspondence with functional outcomes suggests that, in young adults with mild to moderate scoliosis, postural instability may arise from mechanisms beyond spinal curvature severity. These results argue against a simple linear model in which increasing deformity directly leads to poorer postural control.

While AIS is characterized by coronal and axial deviations of the spine [18, 19], the lack of significant correlations between these structural parameters and postural control performance in our study suggests that non-biomechanical factors may play a key role. Specifically, our findings do not support a direct linear relationship in which greater deformity leads to greater postural instability. Instead, they underscore the need for multidimensional models that account for the possibility that functional and structural characteristics may develop along partially independent pathways. Previous literature has highlighted that sensorimotor integration deficits in AIS may stem from atypical central processing mechanisms [2, 11], such as abnormal proprioceptive weighting or vestibular integration [2]. Importantly, these impairments can be present even in individuals with relatively mild spinal curvature [5], indicating that structural severity alone may not fully explain sensorimotor dysfunction in AIS.

Furthermore, the post-pubertal status of our participants may help explain the apparent dissociation between spinal morphology and postural control. At this stage of development, the central nervous system is more mature and may possess greater adaptive plasticity, potentially enabling the formation of compensatory mechanisms that stabilize posture despite structural asymmetries. Such neural adaptation could dampen or mask statistical associations between spinal deformity and postural performance, particularly in cases with mild to moderate curvature severity. Future research should investigate how these compensatory processes evolve across different developmental stages, ideally using longitudinal designs or neurophysiological techniques such as EEG or fMRI.

One plausible explanation for our findings is that postural instability in AIS reflects deficits in central sensorimotor integration—particularly involving brain regions responsible for vestibular and proprioceptive processing, such as the parietal cortex, cerebellum, and brainstem nuclei [20, 21]. In contrast, spinal deformities may result from biomechanical asymmetries, asymmetric growth trajectories, or underlying hormonal and genetic influences, which follow a distinct developmental course [22—24]. While these structural changes may accumulate over time, they might not correspond directly to an individual's moment-to-moment postural control capabilities. This interpretation is supported by neuroimaging studies showing altered activation in sensory and motor cortical areas in individuals with AIS—even in cases without clear curve progression [21, 25, 26].

Although our study did not identify significant correlations between spinal morphology and postural control variables, existing literature presents a more nuanced picture. Some studies have reported moderate associations between postural instability and radiographic severity [11], whereas others have found weak or inconsistent relationships, often depending on task-specific demands or curve magnitude [6, 7]. Our results align more closely with the latter—particularly under high sensory challenge conditions—but we acknowledge that structural–functional associations may still exist in other subpopulations or under different testing conditions.

Interestingly, our control group exhibited a trend-level inverse correlation between sway path length and vertebral rotation (RMS), potentially reflecting a normative functional relationship in which mild structural asymmetries are actively compensated through effective sensory integration. In contrast, this pattern was not observed in the AIS group, suggesting a disruption in adaptive postural mechanisms. This functional–structural dissociation may reflect a broader neurodevelopmental alteration in AIS, consistent with previous findings on proprioceptive reweighting and vestibular integration deficits [2, 5, 13]. Alternatively, it may indicate a form of compensatory neural adaptation, where the central nervous system deprioritizes unreliable proprioceptive input from a deformed spine to maintain balance [27]. These hypotheses warrant further validation through longitudinal designs incorporating neurophysiological and imaging techniques.

Collectively, these findings contribute to a more nuanced understanding of the sensorimotor pathophysiology in AIS. The observed postural instability—occurring without significant correlation to spinal morphology—suggests that structural correction alone may be insufficient to address the functional deficits, especially those rooted in central sensory integration mechanisms.From a clinical perspective, these insights underscore the value of complementing structural management with interventions targeting sensory integration and balance function [28]. Specifically, programs that include dynamic postural control tasks (e.g., unstable surface training, dual-task balance exercises) and vestibular-focused exercises (e.g., gaze stabilization, rhythmic head movements) may improve functional outcomes in AIS—even in early stages of spinal curvature.

Early identification of discrepancies between spinal structure and sensory integration performance may help classify AIS patients into distinct sensorimotor subtypes, enabling more tailored and functionally oriented interventions. In this context, the mCTSIB protocol represents a simple and feasible assessment tool with established reliability [7, 8]. Its ability to detect postural instability under sensory challenge supports its integration into routine scoliosis evaluations. Nevertheless, further validation is needed to confirm its sensitivity and specificity in AIS populations and to establish normative benchmarks and clinically actionable thresholds.

Several limitations must be acknowledged. The modest sample size may have reduced the statistical power to detect weaker structure–function associations. Vestibular function was inferred from behavioral performance but not directly measured, limiting physiological interpretation. Furthermore, the DIERS surface topography system, while non-invasive and practical, may not fully capture deeper osseous deformities. Lastly, the study did not stratify participants by curve type or location, such as thoracic versus lumbar patterns, which could influence postural control mechanisms.Additionally, the known measurement error of approximately ± 5°in Cobb angle assessment may have introduced minor diagnostic overlap between the AIS and control groups around the 10°threshold. Although our group allocation was based on specialist-confirmed radiographs, future studies may improve clarity by adopting stricter stratification criteria or conducting sensitivity analyses around borderline cases.

Future longitudinal studies incorporating neuroimaging and direct vestibular testing are warranted to elucidate the temporal and causal dynamics between sensorimotor dysfunction and spinal deformity progression in AIS [29, 30]. Such work will be critical for clarifying whether postural instability is a precursor, consequence, or parallel feature of spinal asymmetry.

Conclusion

This cross-sectional study found no significant association between postural control under sensory challenge and spinal morphology in young adults with idiopathic scoliosis. These findings suggest that postural instability in mild to moderate AIS (Cobb angle 10°–39°) may arise independently of spinal curvature severity, potentially reflecting altered central sensorimotor integration. Recognizing such functional impairments may inform early interventions focused on balance, vestibular stimulation, or sensory integration training alongside conventional structural management strategies.

Supplementary Information

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Supplementary Material 1

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Author contributions

Dan Wang and Song Wang designed the experiments. Dan Wang, Qing Li and Feng Chen conducted the experiments. Dan Wang and Raymond Tsang analysed the data and wrote the article. Rajkumar Krishnan Vasanthi and Vinosh Kumar Purushothaman provided feedback on the article. All the authors have read and approved the current version of the article.

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Data availability

The datasets used and analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the ethics committees of Wuhan Sports University and Xiangtan Central Hospital and registered in the Chinese Clinical Trial Registry (https://www.chictr.org.cn) with the registration number ChiCTR2300075371 (Date: 03/09/2023).

Competing interests

The authors declare no competing interests.

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