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RESEARCH

Oxygen dynamics in paraspinal muscles during isometric loading measured using near-infrared spectroscopy in adolescents with idiopathic scoliosis: SOSORT 2025 award winner

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Abstract

Purpose Paraspinal muscle imbalances in teenagers with adolescent idiopathic scoliosis (AIS) are well-documented, but their metabolic characteristics remain unclear. This study assessed oxygen recovery asymmetry (TrAsy) in paraspinal muscles during isometric trunk extension in teenagers with and without AIS and explored its correlation with spinal curvature.

Methods Fifty-one AIS participants with primary right thoracic curves (40 females; 13.5 ± 1.7 years; thoracic Cobb angles: 22.9°±6.8°; 28 mild [Cobb angles 10°–24°], 23 moderate-to-severe [≥25°]) and 51 non-AIS controls (33 females; 13.2 ± 1.7 years) performed prone isometric trunk extensions. Bilateral paraspinal oxygen recovery times (Tr) at T9 and L3 were measured using near-infrared spectroscopy. TrAsy (between-side Tr difference) was analyzed using mixed-design ANOVA with group (AIS vs. controls) and side (convex vs. concave) factors; Welch's ANOVAs assessed TrAsy differences by curve severity and location. The association between thoracic Cobb angles and TrAsy was evaluated using multiple linear regression, adjusting for covariates.

Results AIS cases (Cobb angles: 22.9°±6.8°) showed significantly longer Tr on the concave side at T9 (74.6s ± 10.1s vs. 50.1s ± 16.8s; $p < 0.001$), with no significant between-side difference at L3 in both groups analyzed collectively ($p = 0.31$). Tr was longer at T9 than L3 ($p < 0.001$) Single curves exhibited greater TrAsy than double curves at T9 (mean difference: 25.0s ± 8.60s; $p = 0.004$), with moderate-severe AIS showing larger concave-side Tr. The regression model showed that greater TrAsy was associated with larger thoracic Cobb angles ($R^2 = 0.46$, $p < 0.001$).

Conclusion Teenagers with AIS showed greater TrAsy at T9, predominantly on the concave side, which correlated with curve severity. Further research should investigate causal relation between metabolic response and curvature progression.

Keywords Scoliosis · Muscle oxygenation · Near-infrared light spectroscopy · Paraspinal muscle · Oxygen dynamics asymmetry

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Introduction

Adolescent idiopathic scoliosis (AIS), affecting 1.5–3% of adolescents globally [1], is characterized by a lateral spinal curvature exceeding 10°, vertebral rotation, and trunk asymmetry [2]. Beyond cosmetic concerns, AIS can cause back pain [3], reduced pulmonary function [4], and diminished quality of life [5]. Paraspinal muscle dysfunction is increasingly recognized as related to curve progression, with surface electromyography (sEMG) and magnetic resonance imaging (MRI) associating muscle imbalances with AIS severity. sEMG shows heightened muscle activity on the convex side [6], while MRI demonstrates convex-side hypertrophy and increased fatty infiltration on the concave side [7]. These differences suggest potential muscle-driven biomechanical feedback loops [8], although the underlying metabolic mechanisms remain unclear.

Muscle metabolism, as reflected in oxygen dynamics, is critical for prolonged muscle activity with minimal fatigue. In AIS, oxygenation asymmetry may indicate localized hypoxia or compensatory perfusion, which can challenge postural stability [9]. Near-infrared spectroscopy (NIRS) measures muscle oxygenation, providing real-time insight into metabolic demand and microvascular responses [10]. Key metrics include oxygenation recovery time (Tr), which is the time required for muscle reoxygenation post-exertion. Between-side differences in recovery times (TrAsy) reflects localized metabolic demand and compensatory adaptations [11]. Despite its potential, NIRS has never been used for paraspinal muscle assessments in teenagers with AIS, leaving a unique opportunity for using NIRS to monitor real-time oxygenation dynamics to understand metabolic mechanisms, such as hypoxia and compensatory perfusion, in their paraspinal muscles.

This study used NIRS to: (1) compare paraspinal TrAsy during isometric trunk extension in teenagers with AIS versus non-AIS controls; (2) assess correlations between TrAsy at T9 level and thoracic Cobb angles; and (3) evaluate differences in TrAsy across AIS curve types and severity. We hypothesized that teenagers with AIS would exhibit greater TrAsy (prolonged concave Tr) than controls. We anticipated positive correlations between TrAsy and thoracic Cobb angles, and distinct TrAsy patterns among different curve types.

Methods

This cross-sectional study was approved by the Institutional Review Board of The Hong Kong Polytechnic University (HSEARS20231115002) and conducted in accordance with the Declaration of Helsinki.

Participants

Teenagers with AIS were recruited consecutively from the scoliosis clinic at the Duchess of Kent Children's Hospital, private healthcare facilities, and primary and secondary schools in Hong Kong between 1 st May 2024 and 31 st December 2024. Inclusion criteria were a primary right major thoracic curve (Cobb angles > 10°, Risser stages 0–4), ages 10–16 years, and proficiency in written and spoken Chinese. Standing posteroanterior and lateral spinal radiographs were used to confirm the diagnosis, classify curve patterns, and measure Cobb angles. For those with double curves, only participants with a primary right thoracic structural curve were included. Exclusion criteria were a history of spinal surgery, untreated comorbidities, skinfold thickness > 15 mm at T9 and L3 levels, and known scoliosis etiologies, such as neuromuscular or congenital conditions. Non-AIS controls were recruited by purposive sampling from primary and secondary schools during the same period, matched to the AIS cohort by age and height (with a 5-cm difference). However, due to recruitment constraints, the control group included a relatively higher proportion of males.

Procedures

After obtaining written informed consent from participants and their guardians, demographic information (age, sex, height, weight, physical activity) and clinical history (menarche, scoliosis treatments) were collected. Physical activity levels were assessed using the Chinese version of the International Physical Activity Questionnaire (IPAQ-C) [12]. A registered physiotherapist conducted bilateral NIRS assessments of paraspinal muscle oxygenation at T9 and L3 levels to ensure precision and consistency.

Oxygenation dynamics assessments

Bilateral paraspinal muscle oxygenation (SmO_2) was measured using a validated NIRS device (Moxy muscle sensor, Fortiori Design LLC, Minneapolis, Minnesota, USA) [13]. Four sensors were attached bilaterally to 2 cm lateral to the spinous processes of T9 and L3 (Figs. 1 and 2). These levels were chosen for their critical role in spinal alignment: T9 often aligns with the apex of common thoracic curves, while L3 corresponds to thoracolumbar/lumbar curve regions [14]. Importantly, while all participants had a primary right major thoracic curve, the presence of a structural lumbar curve (i.e., double major curves) could influence regional muscle activation and hemodynamics. Sensor placements at T9 and L3 allowed for measurement in these critical regions regardless of curve pattern. Participants rested in a

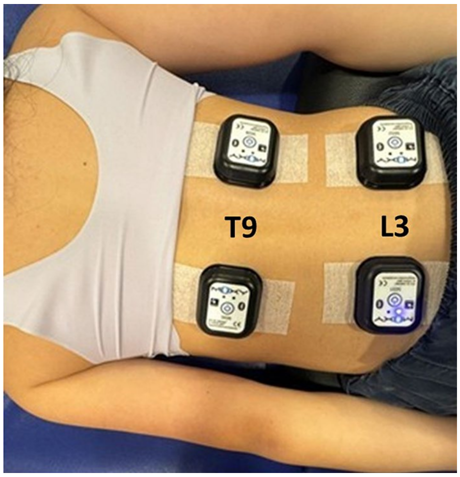

Fig. 1 A near-infrared spectroscopy device, Moxy muscle monitor (Fortiori Design LLC, Minneapolis, Minnesota, USA)

neutral prone lying position for 2 min to establish baseline muscle oxygenation (SmO_2), with the final 60 s used as the baseline value for normalizing NIRS-derived SmO_2 during trunk extension. Participants then performed isometric trunk extensions [15] by lifting their upper body off a padded table (with 10-cm foam support under the lower abdomen), while their legs were secured by straps (Fig. 2). After a familiarization trial and a 2-minute break, three experimental trials (each lasting 1-minute) were then recorded, with 2-minute rest between trials.

NIRS measures SmO_2 by detecting the differential absorption of near-infrared light by oxygenated and deoxygenated hemoglobin, with signals sampled at 0.5 Hz. SmO_2, reflects the balance between oxygen delivery and utilization. Signals were smoothed using a 5-sample moving average filter (low-pass equivalent, cutoff frequency: 0.5 Hz) [16] and normalized to the baseline resting signal. Tr values were averaged across three trials. Test-retest reliability was excellent, as evidenced by between-day ICCs (2, 1) from 15 healthy teenagers who repeated the procedure after 7 days: 0.78–0.86 at T9 and 0.81–0.89 at L3 (standard errors of measurement of 2.0–3.5 s).

After isometric exertion, SmO_2 recovery curves (Fig. 3) were analyzed to derive two metrics: (1) Tr (recovery time), calculated using the exponential equation:

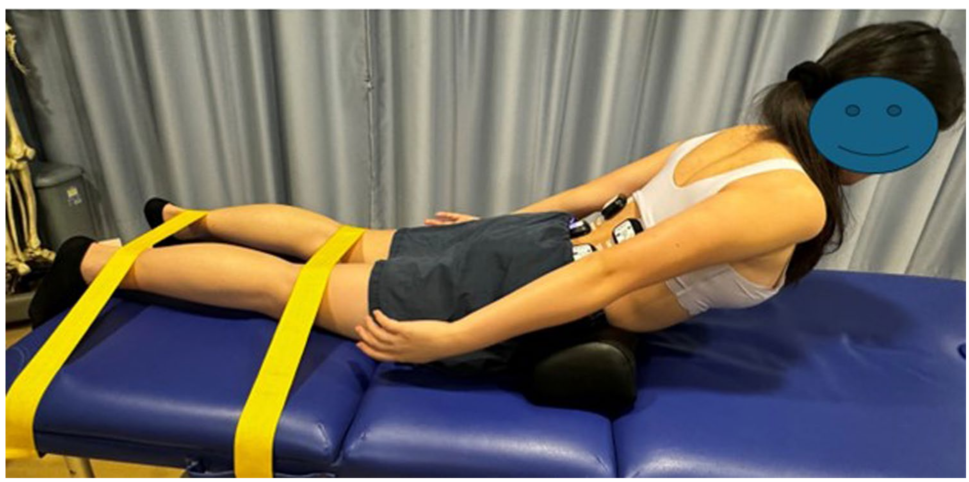

Fig. 2 Participant performing an isometric trunk extension against gravity

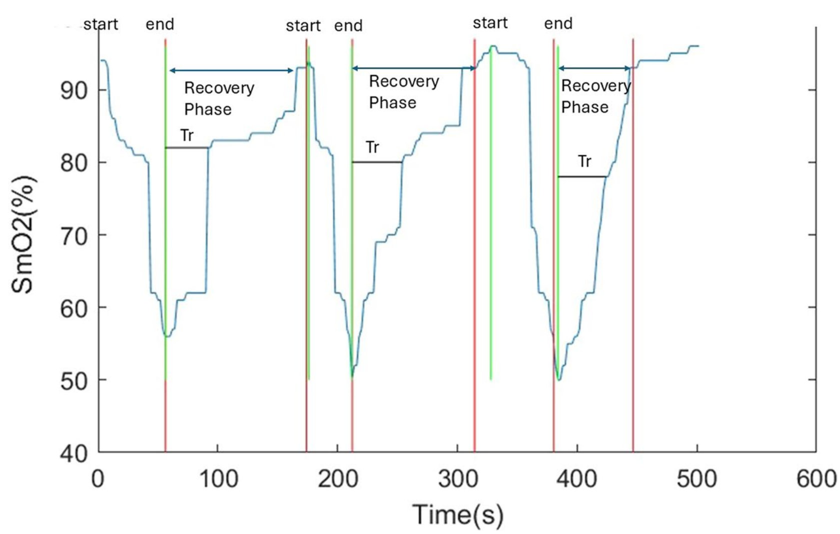

Fig. 3 Representative Moxy NIRS output during the isometric loading test. Percentage of muscle oxygenation (SmO_2) (blue line) against time in second. The real-time muscle oxygenation SmO_2 recovery time (Tr) was defined as the duration to reach 63.2% of baseline SmO_2 (black horizontal line). SmO_2 = muscle oxygenation, s = seconds

$y(t) = A \cdot (1 - e^{-t/\tau}) + B$, where y(t) represents SmO_2 at time t, A denotes the recoverable SmO_2 (baseline minus post-exertion SmO_2), B is the initial SmO_2 level immediately post-exertion, and τ (tau) represents the time constant for SmO_2 to reach 63% of its baseline level, reflecting reoxygenation efficacy [17]; and (2) TrAsy, the difference in Tr between bilateral paraspinal muscles. For participants with AIS, TrAsy was calculated as Tr (concave side) minus Tr (convex side); for controls, it was Tr (left) minus Tr (right). Larger TrAsy values indicate greater asymmetry in metabolic recovery, with prolonged Tr on the concave side suggesting localized hypoxia or impaired perfusion [18]. Thoracic Cobb angles and skeletal maturity (Risser stage) [19] were measured from EOS biplanar X-rays for AIS participants.

Data analysis

Statistical analyses were performed using SPSS Statistics (Version 29.0, IBM Corporation, New York). Average Tr values in paraspinal muscles at T9 and L3 after isometric tests were calculated for participants with and without AIS. Normality was assessed using Shapiro-Wilk tests. Paired t-tests with Bonferroni correction were employed to compare bilateral side differences in participants with AIS at T9 and L3 levels. A mixed-design ANOVA assessed interactions between group (AIS vs. control) and side (concave-convex for AIS; left-right for controls) for Tr at T9 and L3, with post-hoc Tukey and Bonferroni correction applied. To investigate the association between thoracic curvature severity and muscle oxygenation dynamics, participants with AIS were dichotomized into two subgroups based on thoracic Cobb angles: mild (11° to 24°) and moderate-to-severe (≥25°). Welch's ANOVA with Games-Howell post-hoc tests compared TrAsy among mild AIS, moderate-to-severe AIS, and control subgroups at T9 and L3 levels. TrAsy between single thoracic curves, double thoracic curve, and double major curves were evaluated using mixed two-way ANOVA at T9 and L3. Hierarchical multiple linear regression assessed the association between TrAsy and Cobb angle severity, considering covariates including demographics (age, sex, Risser stage), and physical activity levels (IPAQ-C) [12]. The significance level was set at 0.05.

Results

Participants' characteristics

Fifty-one participants with AIS (40 females; average age 13.5 ± 1.7 years; primary thoracic Cobb angles 22.9°±6.8°) and 51 non-AIS controls (33 females; age 13.2 ± 1.7 years) were recruited (Table 1). The AIS group comprised primary

Table 1 Demographic and physical data of the adolescent idiopathic scoliosis (AIS) and Non-AIS control groups

Variable	AIS (*n* = 51)	Mild thoracic AIS subgroup (*n* = 28)	Moderate-to-severe thoracic AIS subgroup (*n* = 23)	Controls (*n* = 51)
Sex (n, %)				
Male	11 (21.57%)	10 (35.71%)	1 (4.35%)	18 (35.29%)
Female	40 (78.43%)	18 (64.29%)	22 (95.65%)	33 (64.71%)
Age (years)	13.5 ± 1.7	13.9 ± 1.8	12.9 ± 1.4	13.2 ± 1.7
Height (m)	1.6 ± 0.1	1.6 ± 0.1	1.6 ± 0.1	1.6 ± 0.1
Weight (kg)	47.1 ± 7.6	49.0 ± 8.7	44.7 ± 5.09	49.8 ± 5.2
BMI (kg/m^2)	18.9 ± 2.0	19.4 ± 2.4	18.4 ± 1.3	20.3 ± 2.0
Exercise regularly (IPAQ-C) (MET-min/week)	2,787.4 ± 3,490.5	3,267.1 ± 4,018.9	2,203.4 ± 2,686.8	2,927.0 ± 3,430.7
Thoracic Cobb angle (T9) (°)	22.9 ± 6.8	18.0 ± 3.7	28.9 ± 4.4	NA
Lumbar Cobb angle (L3) (°)*	16.2 ± 4.1(*n* = 14)	15.8 ± 3.9 (*n* = 10)	17.2 ± 4.5 (*n* = 4)	NA
Type of major curve (thoracic: thoracolumbar)	43:8	23:5	20:3	NA
Curve pattern (single: double)	9:42	1:27	8:15	NA
Curve type (main thoracic: double thoracic: double major)	9:28:14	1:17:10	8:11:4	NA
Risser stage (n, %)				
1	7 (13.73%)	2 (7.14%)	3 (13.04%)	NA
2	23 (45.10%)	12 (42.86%)	12 (52.17%)	NA
3	21 (41.18%)	14 (50.0%)	8 (34.78%)	NA

*Lumbar Cobb angle (L3) applies only to double major curve cases (n = 14; 10 mild thoracic curve, 4 moderate-to-severe curve) with structural lumbar curves (Cobb ≥10°). Data are mean ± Standard deviation or Count (percentages) depending on data type

AIS: Adolescent Idiopathic Scoliosis, BMI: Body Mass Index, IPAQ-C: the Chinese version of the International Physical Activity Questionnaire right-thoracic curves ($n = 27$) and primary right thoracolumbar curves ($n = 24$), with the primary curvature apex most commonly at T8 (41.2%). Among those with double curves ($n = 14$), the mean Cobb angle of the secondary lumbar curve was 16.2°±4.1°.

The AIS and control groups significantly differed in sex distribution, with a higher percentage of females in the AIS group (78.4%) compared to controls (64.8%). Age, height and physical activity levels were comparable between the two groups (Table 1). Within the AIS group, significant differences in thoracic Cobb angles were found between the mild AIS subgroup ($n = 28$, mean 18.0°± 3.7°, range: 10°–22°) and the moderate-to-severe AIS subgroup ($n = 23$, mean 28.9°± 4.4°, range: 25°–41°) (Table 1).

Muscle oxygen dynamics

A mixed-design ANOVA revealed a significant two-way interaction between spinal level and side was found ($p < 0.001$), but no significant three-way interaction among groups, sides, and spinal levels ($p = 1.00$) (Table 2). Post-hoc simple effects analyses of the interaction between spinal level and side, conducted across both cohorts, showed significant side asymmetry at the T9 level: the concave/left side exhibited significantly longer Tr than the convex/right side (mean difference = 12.1s, 95% CI [8.3,15.9], $p < 0.001$, Cohen's $d = 0.67$). No significant between-side difference was observed at the L3 level (mean difference = 4.1s, 95% CI [−0.2, 8.4], $p = 0.31$, Cohen's $d = 0.19$).

This pattern was consistent across groups (AIS and controls) as indicated by the non-significant three-way interaction, with larger side asymmetry pattern at T9 in adolescents with AIS (concave: 74.6s ± 10.1s versus convex: 50.1s ± 16.8s) than controls (left: 65.7 ± 19.0s versus right: 66.0 ± 24.3s). At the L3 level, controls exhibited a longer Tr on the left side compared to the right (57.1 ± 15.1s versus 49.5 ± 14.6s; mean difference = 7.5s, $p = 0.01$, Cohen's $d = 0.51$), whereas AIS participants showed no asymmetry (concave versus convex: 54.8s ± 15.1s versus 54.0s ± 21.1s). However, these group-specific patterns were not statistically different given the non-significant three-way interaction (Table 3; Fig. 4).

Muscle oxygen dynamics asymmetry across subgroups

Welch's ANOVA revealed significant differences in TrAsy at T9 among mild AIS, moderate-to-severe AIS, and

Table 2 Results of mixed-designed ANOVA and Bonferroni-adjusted pairwise comparisons for oxygen recovery time (Tr)

Mixed-Model ANOVA						
Effect	F (df)		Mean difference (sec)	95% CI	*p*-value	Partial η^2
Spinal levels (T9 vs. L3)	F (1,100) = 67.4		13.6	[10.3, 16.9]	**< 0.001**	0.40
Sides (left/concave vs. right/convex)	F (1,100) = 80.5		12.7	[9.9, 15.5]	**< 0.001**	0.45
Group (AIS vs. Control)	F (1,100) = 2.5		-1.1	[-5.2, 2.9]	0.58	0.12
Spinal levels X sides	F (1,100) = 13.0		–	–	**< 0.001**	0.12
Group X spinal levels	F (1,100) = 1.8		–	–	0.08	0.02
Group X sides	F (1,100) = 3.2		–	–	0.08	0.03
Group X spinal levels X sides	F (1,100) = 1.8		–	–	1.00	0.00
Pairwise comparisons for spinal levels X sides interaction (Bonferroni-adjusted; overall sample)						
Spinal level comparison (measurement 1 vs. measurement 2)	**Tr (sec) (measurement 1)**	**Tr (sec) (measurement 2)**	**Mean difference (sec)**	**t (df)**	**Adjusted p-value**	**Cohen's d**
At T9 level						
Side A vs. Side B	70.2 ± 16.5	58.1 ± 16.5	12.1 ± 18.2	t(100) = -6.21	**< 0.001**	0.67
At L3 level						
Side A vs. Side B	55.9 ± 15.3	51.8 ± 18.9	4.1 ± 21.7	t(100) = 1.89	0.31	0.19
Cross-level comparisons						
Comparison	**Tr (sec) (measurement 1)**	**Tr (sec) (measurement 2)**	**Mean difference (sec)**	**t (df)**	**Adjusted p-value**	**Cohen's d**
T9 vs. L3 (main effect)	64.2 ± 19.8	53.9 ± 117.5	10.3 ± 12.6	t(100) = -8.21	**< 0.001**	0.82
T9 Concave vs. L3 Convex	74.6 ± 10.1	54.0 ± 21.1	20.9 ± 23.1	t(50) = 4.56	**< 0.001**	0.64
T9 Convex vs. L3 Convex	50.1 ± 16.8	54.0 ± 21.1	-3.9 ± 18.5	t(50) = 7.15	**< 0.001**	1.00

Adjusted significance threshold: $\alpha = 0.00625$. Significant values are in bold, Data are mean ± Standard deviation. No pairwise comparisons related to group, side and spinal level interaction were included, as the three-way interaction was not significant. Side A = concave side (AIS)/ left (controls), Side B = convex side (AIS)/ right side (controls)

AIS: Adolescent Idiopathic Scoliosis, CI: confidence intervals, Partial η^2: partial eta squared, sec: seconds, Sig.: significant values, sec: seconds Tr: oxygen recovery time

Table 3 Physical data of the adolescent idiopathic scoliosis (AIS) and Non-AIS control groups

Variable	AIS ($n=51$)	Mild thoracic AIS subgroup ($n=28$)	Moderate-to-severe thoracic AIS subgroup ($n=23$)	Controls ($n=51$)
Tr (sec) concave or left				
at T9 level	74.6±10.1	43.9±23.5	79.9±23.6	65.7±19.0
at L3 level	54.8±15.1	50.7±12.9	59.8±16.3	57.1±15.1
Tr (sec) convex or right				
at T9 level	50.1±16.8	50.1±11.6	50.1±16.4	66.0±24.3
at L3 level	54.0±21.1	53.2±18.9	65.2±13.9	49.5±14.6
TrAsy (sec)				
at T9 level	24.5±18.1	−6.2±16.4	29.8±16.6	−0.3±24.0
at L3 level	0.8±24.9	−2.5±26.7	−5.4±23.0	7.5±18.8

Tr: recovery time for oxygenation; TrAsy: Between-side differences in recovery times for oxygenation. N/A: not applicable. sec: seconds

Negative TrAsy values indicate longer recovery on the thoracic or lumbar convex side. Data are mean ± SD or Count (percentages) depending on data type

non-AIS control subgroups (F [2, 58.35]=32.75, $p<0.001$, partial $\eta^2=0.53$). Post-hoc analyses showed moderate-to-severe AIS cases had a 36.0s longer Tr on the concave side than mild AIS (95% CI [24.7, 47.2], $p<0.001$) and significantly greater TrAsy than controls (mean difference=30.1s, 95% CI [18.5, 41.7], $p<0.001$) (Table 4; Fig. 5). At the L3 level, no statistically significant differences in TrAsy were observed among subgroups (Table 4; Fig. 6).

Muscle oxygen dynamics asymmetry at T9 and L3 between curve types

A mixed ANOVA analysis of comparing TrAsy at T9 and L3 revealed a significant interaction between curve types and spinal levels (F (1,49)=5.63, $p=0.02$, partial $\eta^2=0.10$). Post hoc analyses showed that participants with a single curve had significantly greater TrAsy at T9 (30.6s±20.9s) compared to those with double curves (5.6s±22.9s; mean difference=25.0s±8.3s, $p=0.004$, Cohen's d=0.85) (Fig. 7). No significant between-group difference in TrAsy was observed at the L3 level (Fig. 7).

Association between curvature severity and muscle oxygen dynamics

A multiple linear regression revealed a significant association between TrAsy at T9 and thoracic Cobb angles (β=0.62, R^2=0.46, $p<0.001$), after adjusting for TrAsy at L3, age, sex, IPAQ-C scores, and Risser stage (Table 5; Fig. 8). None of the covariates were significantly related to thoracic Cobb angles.

Discussion

This study is the first to investigate paraspinal muscle oxygen dynamics in adolescents with AIS using NIRS. It reveals significant TrAsy at the T9 level in both AIS and control cohorts combined (mean difference=12.1s, $p<0.001$), with the effect being particularly pronounced in AIS participants with right thoracic curves. This T9 asymmetry was correlated with thoracic Cobb angles, providing new insights into

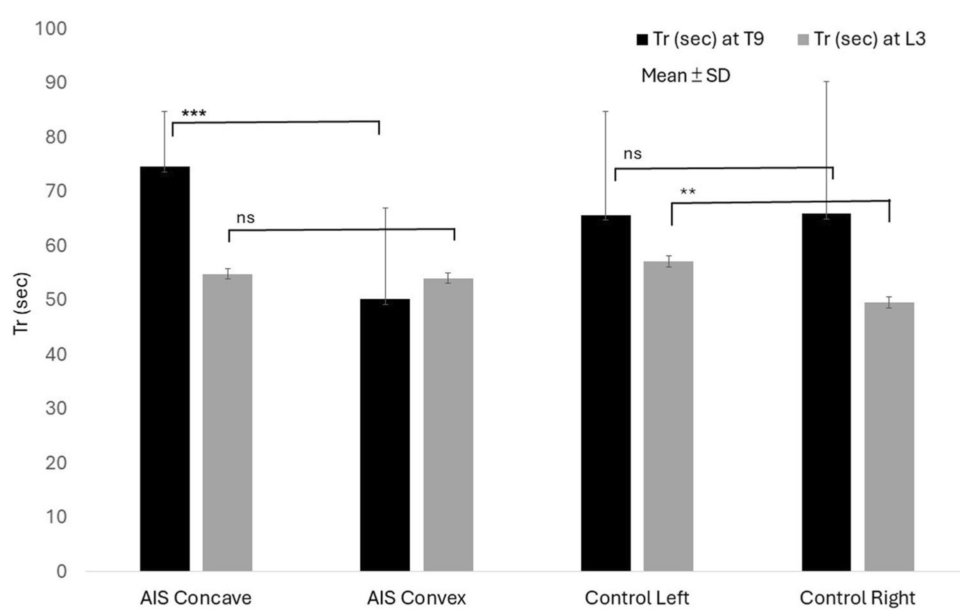

Fig. 4 Oxygen recovery time (Tr) at thoracic (T9) and lumbar (L3) levels in participants with AIS (concave/convex) and controls (left/right). AIS participants exhibited significantly longer Tr on the concave side at T9 (****p* < 0.001), with no asymmetry at L3 (ns). In contrast, controls showed no significant side differences at T9, but they showed longer Tr on the left of L3 (***p* = 0.01). AIS: Adolescent Idiopathic Scoliosis, Tr: oxygen recovery time, Significant values are marked by asterisks, Error bars=±1 standard deviation; ns = not significant, sec = seconds

Table 4 Post-Hoc comparisons of between-side asymmetry in oxygen recovery time (TrAsy) at T9 and L3 by curve severity subgroup (Mild vs. Moderate-Severe vs. Controls)

Subgroup	Mean (sec) ± SD (subgroup)	Comparison group	Mean (sec) ± SD (comparison group	Mean difference (sec)	95% CI	Sig.
T9 level						
Mild AIS	−6.2 ± 16.4	Controls	−0.3 ± 24.0	−5.9	[−16.8, 5.1]	0.41
Moderate-to-severe AIS	29.8 ± 16.6	Controls	−0.3 ± 24.0	30.1	[18.5, 41.7]	**< 0.001**
Moderate-to-severe AIS	29.8 ± 16.6	Mild AIS	−6.2 ± 16.4	36.0	[24.7, 47.2]	**< 0.001**
L3 level						
Mild AIS	−2.5 ± 26.7	Controls	7.5 ± 18.8	−10.0	[−23.8, 3.9]	0.20
Moderate-to-severe AIS	−5.4 ± 23.0	Controls	7.5 ± 18.8	−12.9	[−26.3, 0.5]	0.06
Moderate-to-severe AIS	−5.4 ± 23.0	Mild AIS	−2.5 ± 26.7	−2.94	[−19.8, 13.9]	0.91

CI: confidence intervals, Sig: significant values, sec: seconds, TrAsy: Between-side differences in recovery times for oxygen

Negative TrAsy values indicate longer recovery on the thoracic or lumbar convex side. Significant values are in bold. Data are mean ± Standard deviation

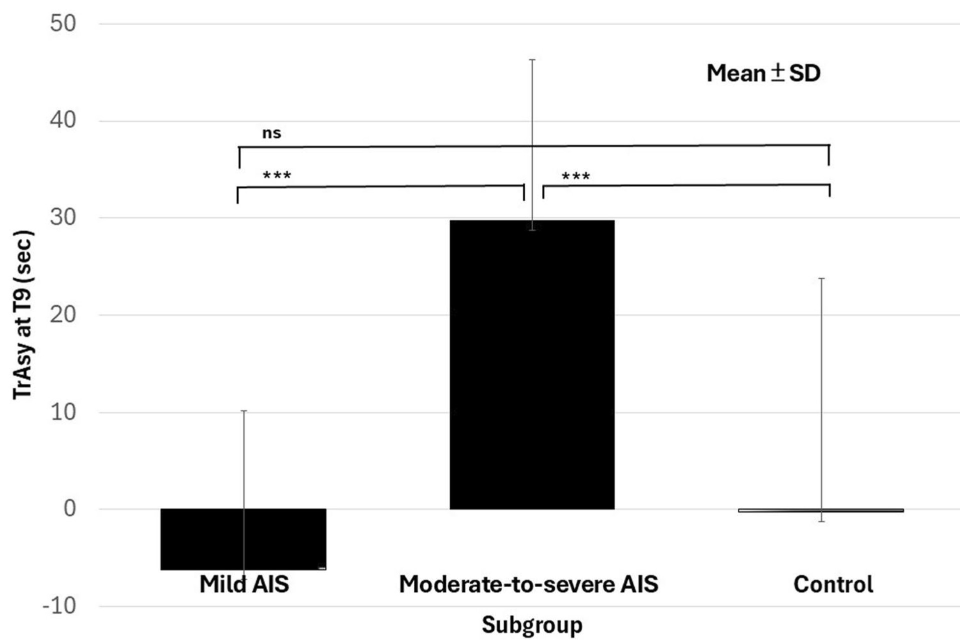

Fig. 5 Between-side differences in oxygen recovery times (TrAsy) at T9 (thoracic level) across subgroups. Moderate-to-severe AIS subgroup exhibited significantly greater concave-side dominance compared to controls (***$p < 0.001$) and mild AIS (***$p < 0.001$). TrAsy: Between-side differences in oxygen recovery times (concave-side recovery time − convex-side recovery time). Negative TrAsy values indicate longer recovery on the thoracic or lumbar convex side. Significant values are marked by stars. Error bars = ± 1 standard deviation; ns = not significant, sec = seconds

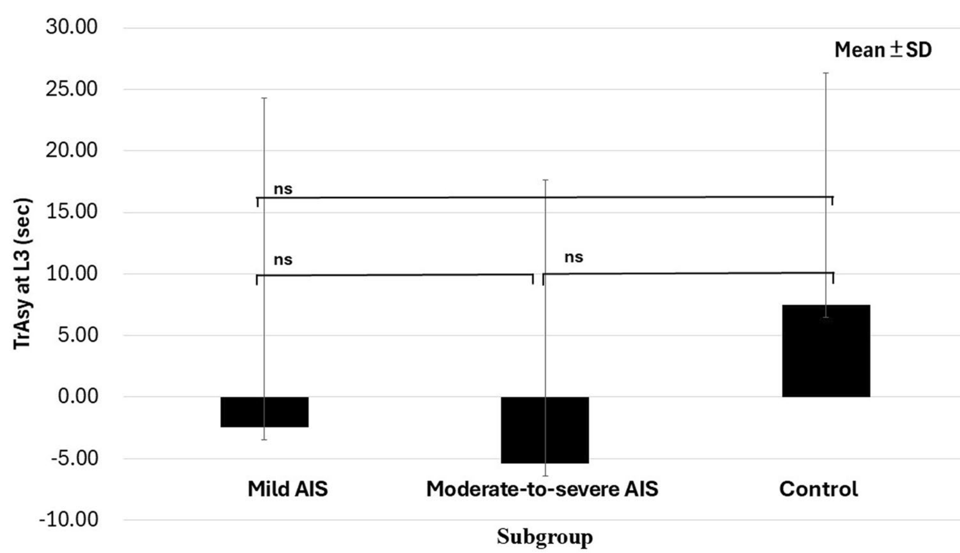

Fig. 6 Between-side differences in oxygen recovery times (TrAsy) at L3 (lumbar level) across subgroups. Greater TrAsy in convex side than concave side (negative TrAsy) at L3 in moderate-to-severe AIS, contrasting with controls. (moderate-to-severe vs. controls, trend reversal) (ns, $p = 0.06$). TrAsy: Between-side differences in oxygen recovery times (concave-side recovery time − convex-side recovery time). Negative TrAsy values indicate longer recovery on the thoracic or lumbar convex side. Significant values are marked by stars. Error bars = ± 1 standard deviation; ns = not significant, sec = seconds.

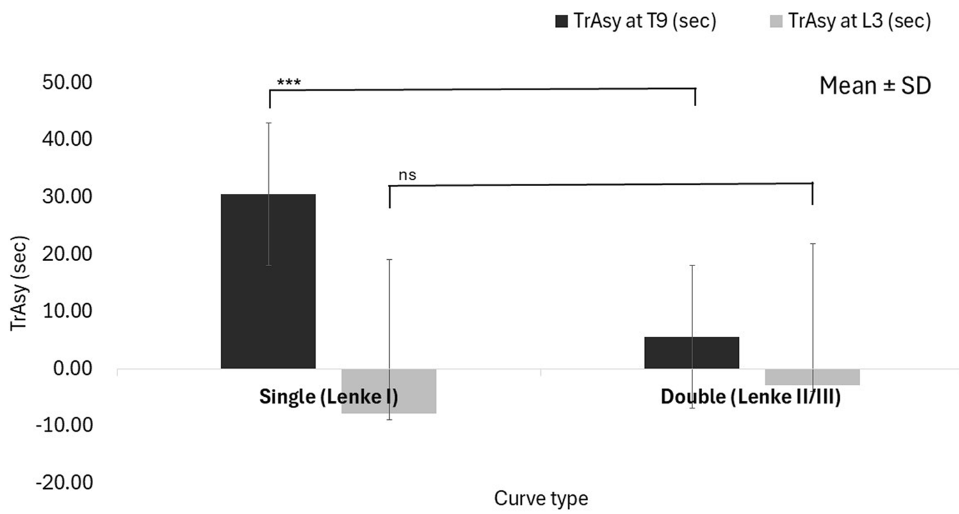

Fig. 7 Between-side differences in oxygen recovery time (TrAsy) at thoracic (T9) and lumbar (L3) levels between single and double curves. A mixed two-way ANOVA revealed a significant spinal level × curve type interaction (F (1,49) = 5.63, p = 0.02). Post hoc Bonferroni comparisons showed significantly greater TrAsy at T9 in single curves compared to double curves (mean difference = 25.0 ± 8.3s, t (49) = 3.01, p = 0.004, Cohen's d = 0.85). No significant difference was observed at L3 (p = 0.60, d = 0.28). Error bars = ± 1 standard deviation; TrAsy = concave-side recovery time − convex-side recovery time. Negative TrAsy values indicate longer recovery on the thoracic or lumbar convex side. AIS: Adolescent Idiopathic Scoliosis; Significant values are marked by stars. ns = not significant, sec = seconds.

Table 5 A multiple regression analysis predicting thoracic scoliotic curvature severity using muscle oxygenation discrepancies, controlling for confounding variables

Predictor variable	Unstandardized coefficients		Standardized coefficients	t	Sig.	R^2	F(Sig.)
	Beta	SE	Beta				
(Constant)	25.42	7.29		3.49	**0.001**	0.46	5.97(**<0.001**)
TrAsy atT9 (sec)	0.17	0.03	0.62	5.35	**<0.001**		
TrAsy at L3 (sec)	0.03	0.03	0.10	0.83	0.41		
Age (year)	−0.39	0.53	−0.10	−0.73	0.47		
Male Sex	0.82	1.96	0.05	0.42	0.68		
IPAQ-C (MET-min/week)	0.00	0.00	−0.12	−1.07	0.29		
Risser stage/0–5	0.44	1.33	0.04	0.34	0.74		

IPAQ-C: the Chinese version of the International Physical Activity Questionnaire, SE: standard error, Sig.: significance p-values, TrAsy: Between-side differences in oxygen recovery times in seconds. Dependent variable: Thoracic Cobb angle

The model included TrAsy at T9, TrAsy at L3, age, sex, IPAQ-C and Risser sign as predictors of thoracic scoliotic curvature severity. Significant values are bold

the association between muscle oxygen dynamics and spinal curvature.

Prolonged Tr on the concave side at T9 may indicate chronic biomechanical strain and ischemia, though histological validation is needed. In AIS, this overload may result in type I fibers atrophy, reduced capillary density, and impaired perfusion on the concave side, slowing oxygen recovery [20]. Histological findings of fast-twitch fibers dominance on the concave-side [21] align with slower metabolic clearance. This concurs with sEMG findings of convex-side hyperactivity [22] and MRI evidence of convex hypertrophy [7]. Moderate-to-severe AIS subgroups exhibited significantly greater TrAsy at T9 than mild cases, consistent with histopathological evidence of mitochondrial dysfunction and fatty infiltration on the concave side increasing with curve severity [23]. As muscle imbalance grows, asymmetrical biomechanical loading on paraspinal muscles during trunk extension intensifies, resulting in greater TrAsy disparity between subgroups.

While TrAsy at T9 correlates with thoracic Cobb angles, its clinical utility as a biomarker warrants further investigation. TrAsy may reflect compensatory adaptations rather than causing curve progression. Larger curves impose greater biomechanical strain, potentially increasing TrAsy and progression risk independently. Given the unclear causation, exploring TrAsy as metabolic biomarker for predicting curve progression or rehabilitation responsiveness is crucial.

Participants with single major thoracic curve exhibited significantly greater thoracic TrAsy than those with

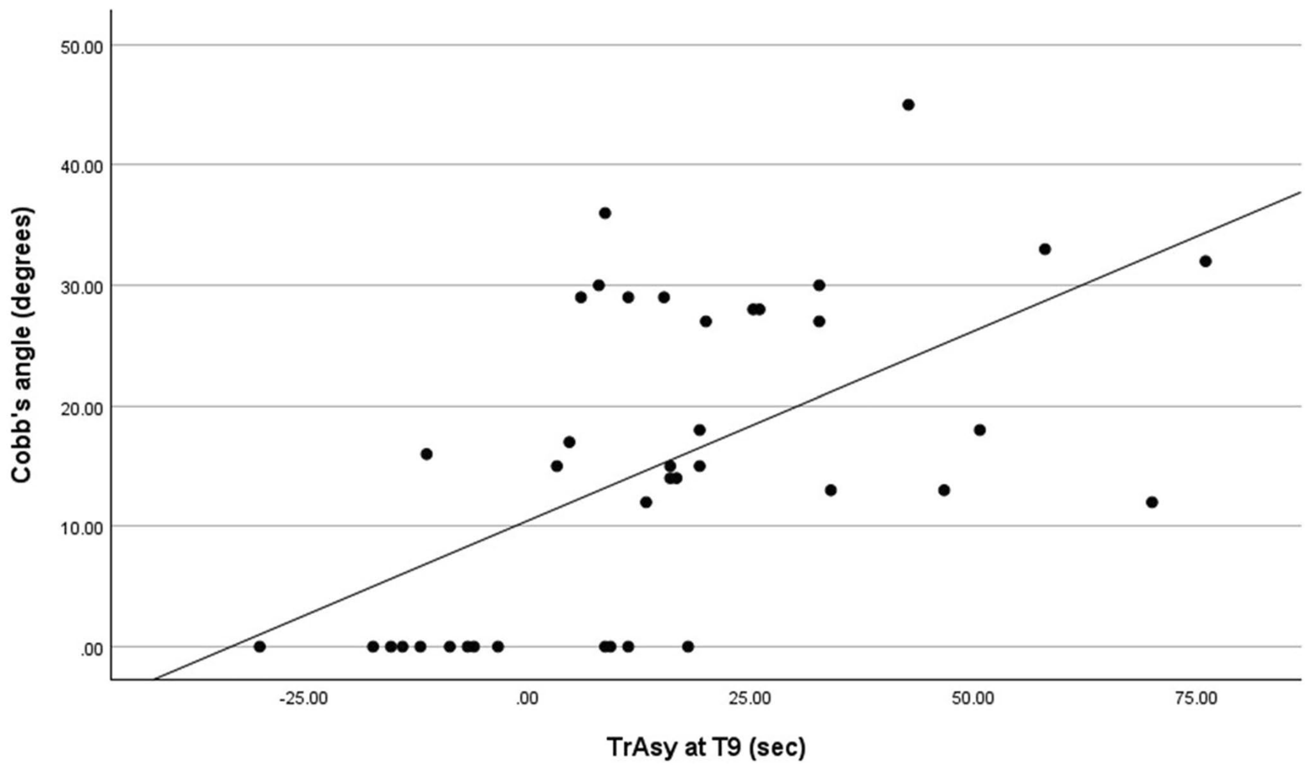

Fig. 8 Association between thoracic Cobb angles and between-side differences in recovery times for oxygenation (TrAsy) at T9 after adjusting for covariates. The regression line corresponds to the adjusted relationship from the multiple regression model. (β = 0.62, $p < 0.001$). The model was statistically significant ($F = 5.97$, $R^2 = 0.46$, $p < 0.001$). Covariates included TrAsy at the L3 level, age, sex, physical activity level in term of IPAQ-C, and Risser stage. TrAsy indicates the between-side differences in oxygenation recovery times in seconds(sec). sec = seconds

double curves (major thoracic curve with a secondary lumbar curve). This difference may result from uncompensated biomechanical strain in single curves, where the lack of a secondary lumbar curve concentrates hypoxia on the concave thoracic side. Conversely, double curves redistribute load through compensatory lumbar curvature, mitigating concave-side perfusion deficits. This aligns with MRI evidence of more pronounced convex-side hypertrophy in single curves [7] and EMG findings of increased neuromuscular activation on the convex side of single curves [24]. This compensatory mechanism could explain the larger thoracic TrAsy in single curve cases.

Clinical implications and future research

The significant correlation between thoracic TrAsy and Cobb angles suggests that paraspinal metabolic strain could be a biomarker for biomechanical load in AIS. Although the cross-sectional study cannot establish causality, interventions like concave-side endurance training may improve oxidative capacity. This approach aligns with a NIRS-guided protocol in a 12-week walking program that improved muscle metabolism in peripheral arterial disease [25], supporting the exploration of similar regimens in AIS. It is noteworthy that while TrAsy can indicate asymmetric demand, it should not be considered a treatment target until its connection to curve progression is established.

Future prospective studies are needed to determine whether reducing TrAsy is feasible and can slow progression. Combining NIRS with MRI or sEMG could provide a comprehensive evaluation of muscle function. Future research should explore the metabolic mechanisms of concave-side hypoxia and validate findings in larger, diverse cohorts. Randomized controlled trials are warranted to assess the efficacy of targeted interventions in reducing oxygen recovery asymmetry and improving clinical outcomes.

Limitations

This study has several limitations. First, the cross-sectional design cannot establish causality between TrAsy and curvature development. Prospective studies are needed to explore this relationship further. Second, while the sample size was adequate for analysis, larger cohorts may be required for subgroup comparisons (e.g., single versus double curves).

Third, excluding lumbar major curves restrict generalizability to thoracolumbar or lumbar AIS.

Conclusions

This study identifies distinct oxygen recovery asymmetries in the paraspinal muscles of AIS, at the thoracic level in major thoracic curves. The association between TrAsy at T9 and thoracic curve severity suggests localized metabolic dysfunction in scoliosis. These findings lay a foundation for future research into the causal mechanisms of muscle oxygenation asymmetry and its therapeutic implications, possibly paving the way for personalized interventions to mitigate curve progression in AIS.

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Author contributions W.C is the principal researcher and author of the manuscript. A.W., E.S., S.F., Y.Z., J.C., and E.P. assisted in drafting and editing the manuscript. W.C., A.W. and E.S. conceptualized the study design. W.C. and E.S. performed the analysis. All authors read and approved of the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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