Accepted Article

J Musculoskelet Neuronal Interact 2026

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Comparative Analysis of Erector Spinae Muscle Activation during Three Spinal Corrective Exercises in Adolescents with Idiopathic Scoliosis

Shin-A. Choi[1], Sang-Gil Lee[2], Jin-Ho Yoon[1], Jae-Keun Oh[1], Han-Soo Park[1]

[1]Sports Medicine Laboratory, Korean National Sport University, 1239, Yangjae-daero, Songpa-gu, Seoul, Republic of Korea;
[2]K-Schroth, 192, Seohyeon-ro, Bundang-gu, Seongnam-si, Gyeonggi-do, Republic of Korea

Abstract

Objectives: We aimed to determine how the effects of the bird dog exercise (BDE), muscle cylinder exercise (MCE), and superman exercise (SE) differ in terms of side-specific paraspinal muscle activation in individuals with adolescent idiopathic scoliosis (AIS). **Methods**: During this randomized within-subject crossover design, 51 individuals with AIS performed three corrective exercises (BDE, MCE, and SE). Surface electromyography recorded erector spinae activity bilaterally at the apex and lower end vertebrae (LEV) of the primary curve. The symmetry index (SI) was calculated as the raw convex-to-concave root mean square (RMS) ratio at each measurement position (starting and exercise positions), and differences in SI between positions were analyzed using a two-way repeated-measures analysis of variance. **Results**: Significant exercise × position interactions were observed at both the apex and LEV (both $p<0.001$). During the exercise position, the MCE produced concave-dominant activation patterns (apex SI=0.29; LEV SI=0.43), whereas the BDE and SE produced convex-dominant activation patterns. **Conclusion**: The specific MCE protocol tested in this study produced a marked concave-dominant SI shift, whereas the BDE and SE protocols tested produced convex-dominant SI values. Different corrective exercises induce distinct acute neuromuscular activation patterns in adolescents with AIS; however, long-term clinical implications remain unclear.

Keywords: Adolescent Idiopathic Scoliosis, Core Stabilization, Corrective Exercise, Electromyography, Muscle Symmetry

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity involving lateral curvature, vertebral rotation, and sagittal profile alteration[1]. Although bracing and surgery are standard treatments for moderate-to-severe cases, the application of core stabilization exercises (CSEs) and scoliosis-specific exercises as conservative options for mild-to-moderate AIS is increasing[2,3,4].

Muscular imbalance and the asymmetrical activation of the paraspinal muscles are key biomechanical features that contribute to curve progression in AIS. In particular, the disproportionate activation of the convex and concave sides of the spine may lead to uneven spinal loading, compromised postural control, and structural asymmetry[5,6]. Surface electromyography (sEMG) studies have consistently demonstrated greater muscle activation on the convex side of the curvature, particularly in the erector spinae (ES)[7,8]. This persistent asymmetry in neuromuscular activation not only reflects underlying functional instability but may also reinforce abnormal movement patterns, thereby perpetuating the progression

The authors have no conflict of interest.

Corresponding authors:
Han-Soo Park, PhD, Sports Medicine Laboratory, Korean National Sport University, 1239, Yangjae-daero, Songpa-gu, Seoul, Republic of Korea
E-mail: 302673@knsu.ac.kr
ORCID: 0000-0003-0651-2130

Jae-Keun Oh, OMD, PhD, Sports Medicine Laboratory, Korean National Sport University, 1239, Yangjae-daero, Songpa-gu, Seoul, Republic of Korea
E-mail: sportsomd@knsu.ac.kr
ORCID: 0000-0003-1303-2661

Edited by: G. Lyritis
Accepted 8 June 2026

of spinal deformities over time[9].

CSEs are widely applied as conservative interventions for AIS[10]. Li et al.[11] reported that CSEs effectively reduce the Cobb angle and improve the quality of life without adverse effects, supporting their use as a favorable non-surgical approach. Compared with traditional methods, such as breathing, postural, flexibility, and stretching exercises, CSEs are superior for reducing pain and correcting vertebral rotation, particularly in moderate scoliosis[2]. Furthermore, CSEs enhance the recruitment efficiency of deep stabilizing muscles surrounding the spine, thereby improving the muscular capacity to support and maintain optimal spinal alignment[12].

The Schroth method is a widely adopted, evidence-based, physiotherapeutic scoliosis-specific exercise approach for AIS. As the Schroth method has been extensively studied, evidence of its efficacy for AIS has accumulated[13]. Developed by Katharina Schroth in the 1920s, the Schroth method applies three-dimensional correction through the following five core principles: auto-elongation, deflection, derotation, rotational breathing, and stabilization[14,15]. A previous study has reported improvements in paraspinal strength and pulmonary function, attenuation of curve progression, and Cobb angle reduction[16]. Collectively, these findings position the Schroth method as a structured mechanism-based exercise approach that complements CSEs for conservative AIS management.

Although the therapeutic benefits of CSEs and the Schroth method for AIS are well-established, few studies have directly compared the neuromuscular responses to different corrective exercises. In particular, asymmetrical ES activation, a key biomechanical factor in curve progression, has been rarely examined across exercises using objective measures, such as sEMG. Therefore, understanding how different corrective exercises influence side-specific paraspinal activation may provide important insights for optimizing exercise selection based on acute neuromuscular responses during scoliosis rehabilitation.

This study compared bilateral ES activation during three corrective exercises—the bird dog exercise (BDE), muscle cylinder exercise (MCE), and superman exercise (SE)—in individuals with AIS. As the BDE and MCE involve asymmetrical limb loading and trunk rotation, we hypothesized that the tested BDE and MCE protocols would enhance concave-side recruitment and reduce convex dominance, whereas the bilateral SE would induce a less asymmetrical but less specific activation pattern.

Materials and Methods

Study design

This study used a randomized within-subject crossover design to compare bilateral ES activation during three spinal corrective exercises (Figure 1). All participants attended a familiarization session 1 week before the first measurement to ensure the consistent and accurate execution of each exercise. Following familiarization, each participant performed the BDE, MCE, and SE on separate days. The order of these exercises was randomized and counterbalanced to control for order effects. To minimize fatigue and carryover effects associated with acute neuromuscular responses, a 72-h washout period was implemented between sessions. Exercise order was assigned using sealed opaque envelopes prepared by an investigator not involved in data collection. Participants were allocated to one of the approximately counterbalanced exercise sequences prior to testing to minimize potential order effects. All participants completed all exercise conditions.

During each exercise trial, sEMG was used to record ES activity bilaterally at the apex and lower end vertebrae (LEV) of the primary scoliotic curve while participants performed the three exercises. Measurements were performed at the starting and exercise positions of each exercise. The study protocol was approved by the Institutional Review Board of Korea National Sport University (approval number: 20240613-064). Written informed assent was obtained from all participants, and written informed consent was obtained from their legal guardians before participation.

Participants

Participants aged 10–18 years with a clinical diagnosis of AIS were recruited from local scoliosis rehabilitation clinics and community referrals in Seoul, Republic of Korea. Participant recruitment and data collection were conducted between July 2024 and December 2024. Those who previously underwent spinal surgery and those with exercise contraindications, congenital deformities, or any recent (≤6 months) trauma, neurological, musculoskeletal, or psychiatric disorders were excluded[16].

All participants in this study were minors. Prior to participation, the study purpose, procedures, potential risks, and benefits were fully explained to both the participants and their legal guardians. Written informed assent was obtained from all participants, and written informed consent was obtained from their legal guardians before data collection, in accordance with institutional and national ethical guidelines. This study was not prospectively registered because it was designed as an acute physiological crossover investigation rather than a longitudinal clinical intervention trial.

The sample size was estimated with G*Power 3.1 using the effect size (F=0.28) reported by Batista et al.[17] for trunk sEMG activity. With α=0.05 and power=0.95, 46 participants were required; after accounting for 10% dropout, the final target was 51.

Radiographic examination results were used to classify participants according to the Lenke classification system. Radiographic assessments, including Cobb angle measurements and Lenke classification, were performed using standing posterior–anterior spinal

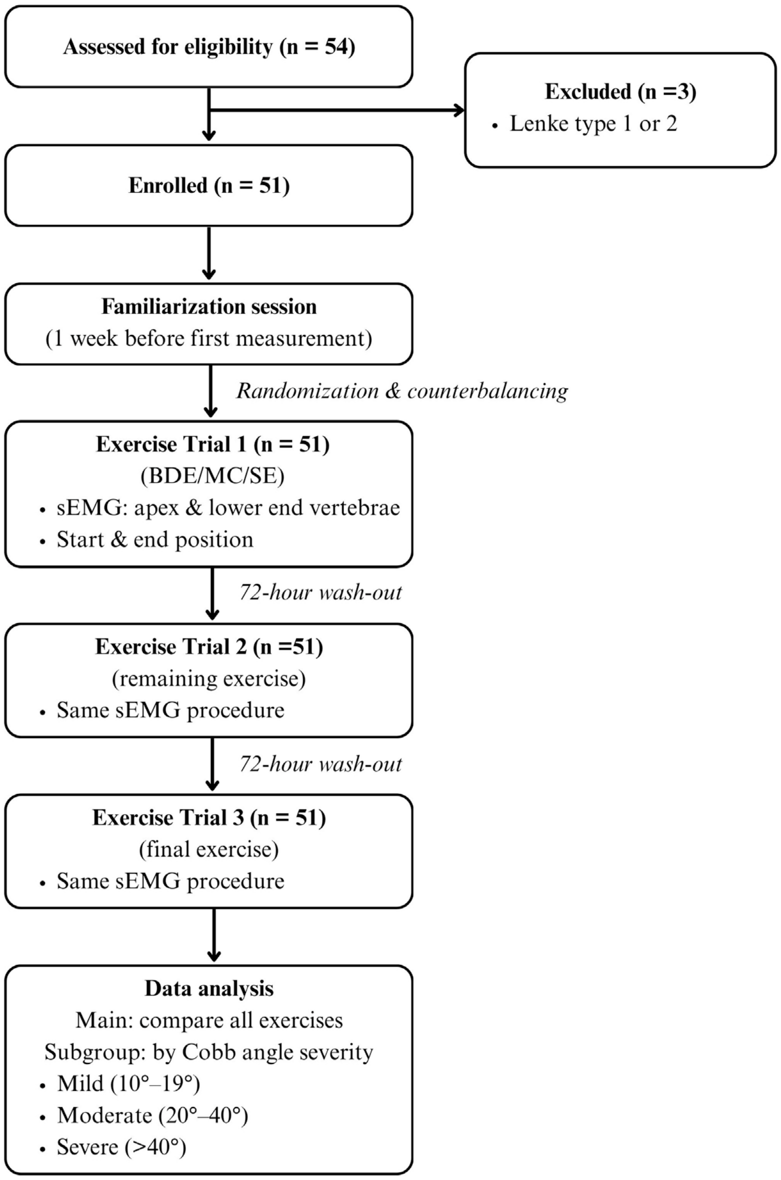

Figure 1. Overall study design and randomized within-subject crossover design procedure. After recruitment, provision of consent, and a familiarization session, participants performed three corrective exercises (bird dog exercise [BDE], muscle cylinder exercise [MCE], and superman exercise [SE]) in a randomized and approximately counterbalanced order across separate trials with 72-hour washout periods. Exercise order was assigned using sealed opaque envelopes. All participants completed all exercise conditions. Surface electromyography (sEMG) was recorded bilaterally at the apex and lower end vertebrae during the starting and exercise positions of each exercise. The data analysis included main comparisons across all exercises and subgroup analyses according to the Cobb angle severity (mild: 10°–19°; moderate: 20°–40°; severe: >40°).

radiographs obtained within 3 months prior to enrollment. All radiographic classifications were independently determined by a board-certified orthopedic specialist who was not involved in the study procedures. Only those with structural curves in the thoracolumbar or lumbar regions corresponding to Lenke types 3 to 6 were included[18]. Based on Cobb angle measurements, participants were further categorized into the following three severity subgroups (n=17 in each group) for analysis: mild AIS group (MG; 10°–<20°); moderate AIS group (MOG; 20°–≤40°; n=17); and severe AIS group (SG, >40°)[19]. Participant recruitment, eligibility screening, enrollment, and crossover completion are summarized in Figure 1.

Measurements

Familiarization session

During familiarization, participants were informed of the purpose and correct technique of each exercise. Correct performance of the BDE, MCE, and SE involved the following respective actions: maintaining horizontal alignment of the trunk, head, and raised limbs; maintaining the head and trunk in a straight line; and sustaining approximately 20° of lumbar extension with fully extended legs. Deviations, such as trunk rotation >5°, knee flexion, or excessive lumbar extension, were considered compensatory. Each participant practiced two to three supervised trials until they were able to maintain the target alignment for ≥10 s, as confirmed independently by two researchers. During testing, two experienced researchers independently monitored posture and compensatory movements to ensure consistent execution of each exercise. All verbal instructions, corrective cues, and postural feedback were standardized across participants throughout familiarization and testing sessions.

sEMG measurements

ES muscle activity was recorded using a wireless sEMG system (FREEEMG 1000; BTS Bioengineering, Garbagnate Milanese, Italy) with four channels at a sampling rate of 1,000 Hz and 16-bit resolution. Pairs of Ag/AgCl electrodes were placed bilaterally over the ES at the apex and LEV of the primary curve[7]. Vellus hair was shaved if necessary and the skin was cleansed with alcohol to reduce impedance. According to SENIAM recommendations[20], electrodes were positioned 20 mm lateral to the spinous process and aligned parallel to muscle fibers. Electrode placement was verified through palpation of the ES muscle belly during resisted trunk extension to ensure accurate positioning despite potential surface asymmetry associated with scoliosis.

sEMG signals were collected during the starting and exercise positions of the BDE, MCE, and SE. Each posture was maintained for 10 s and RMS values were calculated from the middle 5 s (i.e., seconds 3–8) using a 100-ms moving window. Each exercise position was measured three times and only trials with Cronbach's α≥0.80 were included. All signals were visually inspected to exclude trials with motion artifacts. Cronbach's α was used as an index of within-session signal consistency across repeated trials to ensure stable electromyographic measurements. No participants or trials were excluded based on this criterion.

Raw data were processed using EMG Analyzer (version 2.10.44; BTS Bioengineering) and bandpass-filtered between 20 and 500 Hz. After filtering, mean RMS values from the three accepted trials were calculated separately for the convex and concave sides and used to compute the symmetry index (SI). The muscle activation SI was calculated as the raw convex-to-concave RMS ratio (SI = RMSconvex / RMSconcave) at both the starting position (SP) and exercise position (EP) of each exercise. Normalization to maximal voluntary isometric contraction (MVIC) was not applied because obtaining reliable MVIC values can be challenging in adolescents with structural spinal deformities. Accordingly, the SP SI reflects each participant's pre-existing baseline neuromuscular asymmetry and is not constrained to 1.0. Values >1.0 indicate convex-dominant activation, whereas values <1.0 indicate concave-dominant activation[20].

Bird dog exercise

The BDE is an asymmetrical, evidence-based CSE that targets paraspinal and multifidus activation in AIS[3]. A previous sEMG analysis of six CSEs showed that contralateral arm–leg extension in the quadruped position elicits the greatest thoracic ES activity on the elevated arm side, whereas unilateral leg extension primarily activates the lumbar ES ipsilaterally[21]. Therefore, the BDE was modified according to the curve location. For thoracic or double curves, the convex-side leg and concave-side arm were extended simultaneously to promote more balanced paraspinal recruitment (Figure 2a). For lumbar curves, only the concave-side leg was extended to activate the weaker paraspinal region (Figure 2b). Based on the applied exercise protocol, 16 participants with thoracic or double-curve patterns performed the thoracic/double-curve BDE variant, whereas 35 participants with thoracolumbar or lumbar curve patterns performed the lumbar-curve BDE variant.

Each contraction was maintained for 10 s while minimizing lumbar extension and pelvic rotation. Three trials were performed for the prescribed exercise condition and a 60-s rest period between trials was allowed to prevent fatigue. Trials with compensatory movements were repeated after adequate rest.

Muscle cylinder exercise

The MCE is a Schroth-based corrective exercise emphasizing high-intensity spinal strengthening through active correction, rotational breathing, and stabilization[22]. Initially, participants placed the foot on the convex side of the thoracic curve on a wall bar and leaned laterally until the trunk and leg were aligned. One hand supported the convex lumbar region and the other rested on the convex shoulder with the elbow directed outward. During active correction, the movement pattern was adjusted by curve location. For thoracic curves, the concave-side elbow was extended outward to induce overcorrection (Figure 2c). For lumbar or double curves, downward pressure through the convex-side foot lowered the pelvis while maintaining thoracic correction (Figure 2d). During rotational breathing, participants maintained the corrected posture and inhaled toward the concave side of the thoracic or lumbar region to counter-rotate the deformed ribs. The inhalation phase was divided into three segments to facilitate targeted rib

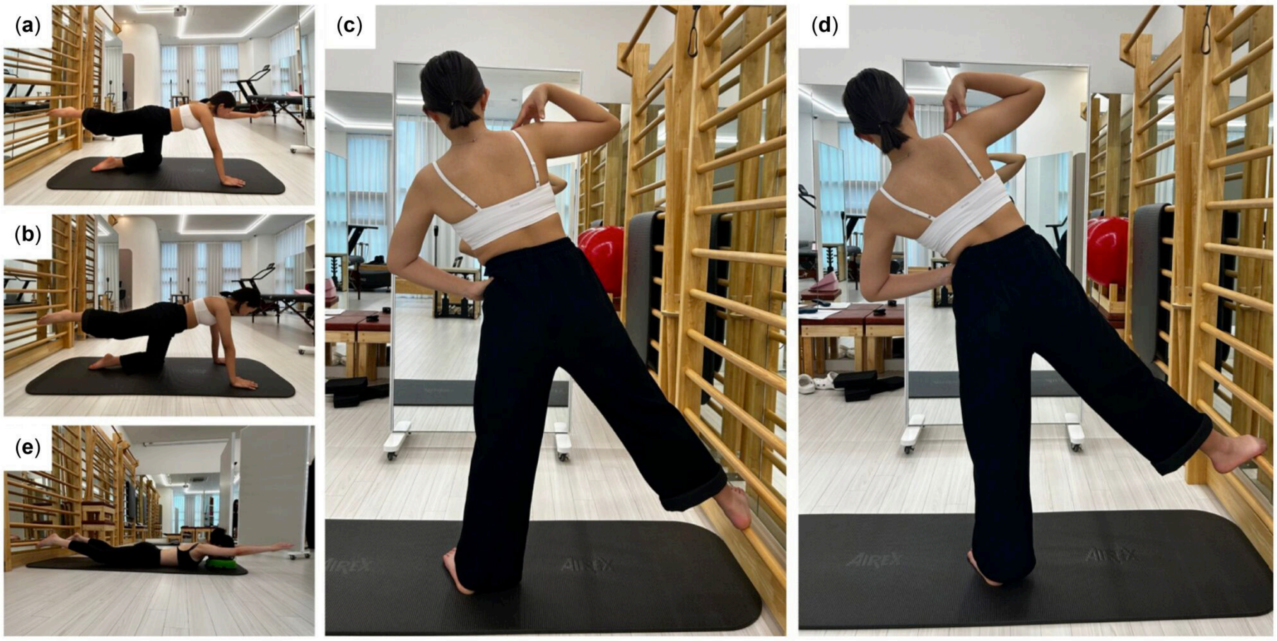

Figure 2. Corrective exercises performed during the electromyographic assessment of adolescents with idiopathic scoliosis. (a) Bird dog exercise (BDE) for thoracic or double curvature with extension of the concave-side arm and convex-side leg. (b) BDE for lumbar curvature with unilateral leg extension on the concave side. (c) Muscle cylinder exercise (MCE) for thoracic curvature emphasizing concave-side overcorrection. (d) MCE for lumbar or double curvature applying downward pressure through the convex-side foot during stabilization. (e) Superman exercise (SE) involving symmetrical trunk extension of approximately 20° to activate bilateral erector spinae.

expansion. During the stabilization stage, participants sustained trunk and pelvic correction while performing strong exhalation for 10 s, producing an "S" sound. sEMG recordings of the ES were obtained during the stabilization phase. Based on the applied exercise protocol, 10 participants with thoracic curve patterns performed the thoracic-curve MCE variant, whereas 41 participants with lumbar or double-curve patterns performed the lumbar/double-curve MCE variant.

Superman exercise

The SE, a symmetrical CSE designed to activate the paraspinal muscles, can elicit higher activation levels in the superficial fibers, including the longissimus and iliocostalis, and deep fibers, including the multifidus, than traditional CSEs, such as the abdominal bridge, bridge, and side bridge[20]. To assume the starting position, participants maintained the neutral curvature of the spine while prone. Throughout the exercise, the elbows and knees were fully extended and approximately 20° of lumbar extension was maintained (Figure 2e). Each trial was performed for 10 s; during that time, ES activation was recorded[23].

Statistical Analysis

All statistical analyses were performed using SPSS version 30.0 (IBM Corp., Armonk, NY, USA). The primary outcome was the symmetry index (SI) of erector spinae activation, calculated as the convex-to-concave RMS ratio. A value of 1 indicated equal bilateral activation, whereas values >1.0 and <1.0 indicated convex- and concave-dominant activation, respectively.

A two-way repeated-measures analysis of variance (ANOVA) with exercise (BDE, MCE, and SE) and position (starting position and exercise position) was conducted. When significant main or interaction effects were found, simple main effects and Bonferroni-adjusted pairwise comparisons were performed. Effect sizes were quantified using partial eta squared (η^2). Subgroup analyses were performed according to scoliosis severity (mild, moderate, or severe based on the Cobb angle). Within each group, a two-way repeated-measures ANOVA assessed exercise effects on muscle activation symmetry.

Prior to analysis, the assumptions of repeated-measures ANOVA were verified. Normality was assessed using the Shapiro–Wilk test, and sphericity was evaluated

Table 1. Baseline characteristics of the study participants (N=51).

Variable	Mean±SD	95% CI	p-value[a]
Age (years)	14.75±2.60	14.01–15.48	<0.001
MG (n=17)[b]	13.59±2.57	12.87–14.31	
MOG (n=17)[b]	14.47±2.30	13.82–15.12	
SG (n=17)[b]	16.18±2.20	15.56–16.79	
Weight (kg)	48.85±12.99	45.20–52.50	0.583
MG (n=17)[b]	49.48±15.01	41.76–57.19	
MOG (n=17)[b]	50.82±12.57	44.36–57.29	
SG (n=17)[b]	46.25±11.48	40.35–52.16	
Height (cm)	160.68±11.59	157.42–163.94	0.709
MG (n=17)[b]	158.77±13.63	151.76–165.78	
MOG (n=17)[b]	161.36±13.08	154.63–168.08	
SG (n=17)[b]	161.91±7.52	158.05–165.78	
BMI (kg/m^2)	18.67±3.32	17.74–19.60	0.212
MG (n=17)[b]	19.26±3.48	17.47–21.04	
MOG (n=17)[b]	19.24±2.75	17.83–20.66	
SG (n=17)[b]	17.51±3.55	15.68–19.33	
Cobb angle	32.63±14.66	28.50–36.75	<0.001
MG (n=17)[b]	16.35±3.12	14.75–17.96	
MOG (n=17)[b]	32.82±3.05	31.26–34.39	
SG (n=17)[b]	48.71±9.83	43.65–53.76	

Values are presented as means (SDs) with 95% CIs. BMI, body mass index; CI, confidence interval; MG, mild adolescent idiopathic scoliosis group; MOG: moderate adolescent idiopathic scoliosis group; SD, standard deviation; SG, severe adolescent idiopathic scoliosis group. [a]One-way analysis of variance. [b]Subgroup analysis.

using Mauchly's test of sphericity. No violations of normality were detected, and sphericity was satisfied for all effects; therefore, no correction was applied. Statistical significance was set at p<0.05.

Results

Fifty-one participants with AIS completed the protocol (40 female [78.4%] and 11 male [21.6%] adolescents). No participant withdrawals, period-specific exclusions, or dropouts occurred after enrollment. Sex distributions did not differ across Cobb angle severity subgroups. The MG, MOG, and SG comprised 13 female and four male adolescents, 14 female and three male adolescents, and 13 female and four male adolescents, respectively (p=0.891).

Regarding the curve pattern, Lenke type 5 predominated (n=35; 68.6%), followed by type 3 (n=10; 19.6%) and type 6 (n=6; 11.8%). Distributions of Lenke types did not differ among severity subgroups (p=0.183). Lenke type 3 (n=3) and type 5 (n=13) were observed in the MG. Lenke type 3 (n=2), type 5 (n=14), and type 6 (n=1) were observed in the MOG. Lenke type 3 (n=5), type 5 (n=8), and type 6 (n=4) were observed in the SG. No adverse events or exercise-related complications were reported during the study. Baseline characteristics are summarized in Table 1.

Main Analysis

At the apex of the primary curve, a significant main effect of position (F[1, 50]=15.317, p<0.001; partial η^2=0.093) and significant interaction effect (F[2, 100]=50.924, p<0.001; partial η^2=0.404) were observed. From the starting position to the exercise position, the SI increased to >1.0 with the BDE and SE; however, it decreased to <1.0 with the MCE. In the exercise position, the SI was lowest, intermediate, and highest with the MCE, SE, and BDE, respectively (Table 2, Figure 3a). These findings indicated that the MCE produced lower SI values indicative of concave-dominant activation, whereas the BDE and SE produced higher SI values indicative of convex-dominant activation.

At the LEV, the main effect of position was not significant (F[1, 50]=0.548, p=0.460; partial η^2=0.004); however, the interaction effect remained significant

Table 2. Outcomes of the curve apex and lower end vertebrae across exercise groups.

Outcome	BDE			MCE			SE		
	SP	EP	ΔEP–SP (95% CI)	SP	EP	ΔEP–SP (95% CI)	SP	EP	ΔEP–SP (95% CI)
Apex	1.04 (0.13)	2.96[b,c] (0.19)	1.92 (1.51–2.33)	1.33 (0.13)	0.29[a,c] (0.19)	-1.04 (-1.45–-0.63)	1.05 (0.13)	1.58[a,b] (0.19)	0.53 (0.12–0.94)
MG	0.95 (0.17)	2.54[b,c] (0.28)	1.59 (0.92–2.26)	1.23 (0.17)	0.29[a,c] (0.28)	-0.94 (-1.61–-0.27)	1.12 (0.17)	1.35[a,b] (0.28)	0.22 (-0.45–0.89)
MOG	1.11 (0.26)	3.28[b,c] (0.36)	2.18 (1.43–2.92)	1.44 (0.26)	0.31[a] (0.36)	-1.13 (-1.87–-0.38)	0.97 (0.26)	1.55[a] (0.36)	0.59 (-0.16–1.33)
SG	1.06 (0.23)	3.04[b,c] (0.33)	1.98 (1.21–2.75)	1.32 (0.23)	0.27[a,c] (0.33)	-1.06 (-1.83–-0.28)	1.05 (0.23)	1.84[a,b] (0.33)	0.78 (0.01–1.56)
LEV	1.37 (0.18)	2.24[b] (0.27)	0.87 (0.20–1.53)	1.39 (0.18)	0.43[a,c] (0.27)	-0.96 (-1.62–-0.29)	1.41 (0.18)	1.93[b] (0.27)	0.52 (-0.14–1.19)
MG	1.06 (0.14)	1.64[b] (0.17)	0.58 (0.14–1.03)	0.98 (0.14)	0.43[a,c] (0.17)	-0.55 (-1.00–-0.10)	1.37 (0.14)	1.27[b] (0.17)	-0.10 (-0.54–0.35)
MOG	1.06 (0.33)	2.85[b,c] (0.34)	1.79 (0.83–2.75)	1.86 (0.33)	0.50[a] (0.34)	-1.35 (-2.31–-0.38)	1.34 (0.33)	1.52[a] (0.34)	0.18 (-0.78–1.14)
SG	2.00 (0.39)	2.23 (0.71)	0.23 (-1.47–1.94)	1.33 (0.39)	0.34 (0.71)	-0.98 (-2.69–0.72)	1.53 (0.39)	3.01 (0.71)	1.48 (-0.22–3.19)

Values are estimated marginal means (EMMs) with standard errors. SP values of SI reflect pre-existing baseline neuromuscular asymmetry and are not normalized to 1.0; values >1.0 indicate convex-dominant activation at the starting position, whereas values <1.0 indicate concave dominance. ΔEP−SP, change from the SP to the EP; BDE, bird dog exercise; CI, confidence interval; EP, exercise position; LEV, lower end vertebra; MCE, muscle cylinder exercise; MG, mild adolescent idiopathic scoliosis group; MOG, moderate adolescent idiopathic scoliosis group; SE, superman exercise; SG, severe adolescent idiopathic scoliosis group; SEM, standard error of the mean; SP, starting position. The following letters indicate significant pairwise post hoc differences at p<0.05 (Bonferroni-adjusted): [a]differs from the BDE; [b]differs from the MCE; and [c]differs from the SE.

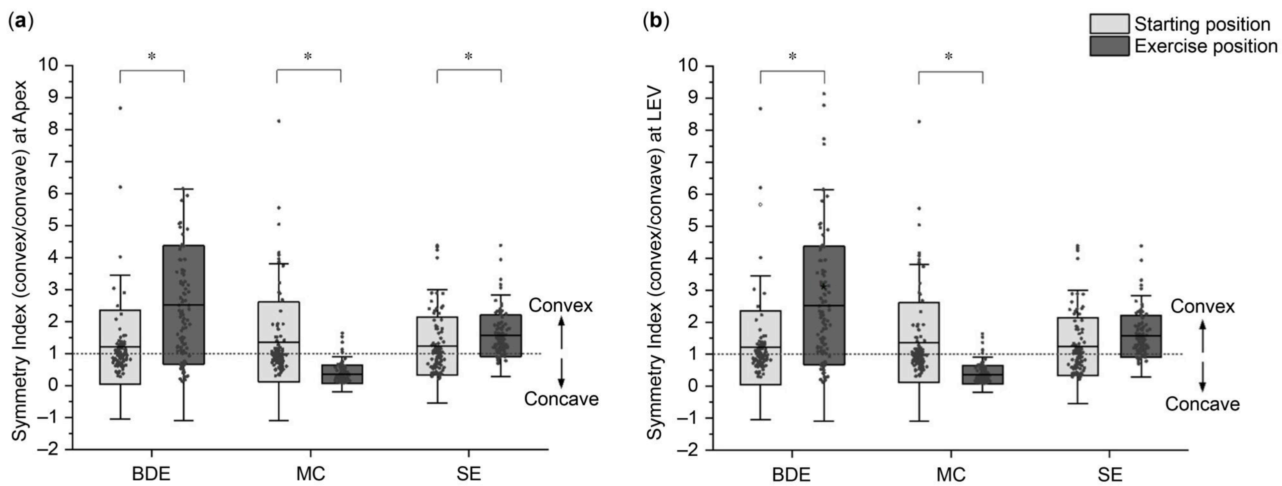

Figure 3. Symmetry index (convex/concave) at the apex (a) and lower end vertebra (LEV) (b). The center line represents the mean, the box represents mean ± standard deviation (SD), the whiskers represent ±1.96 × SD, and the individual points represent participant-level data. The dashed line at 1.0 denotes perfect bilateral symmetry between the convex and concave sides. Values >1.0 indicate convex-dominant activation, whereas values <1.0 indicate concave-dominant activation. *p<0.05 for within-exercise comparisons (starting and exercise positions). BDE, bird dog exercise; MCE, muscle cylinder exercise; SE, superman exercise.

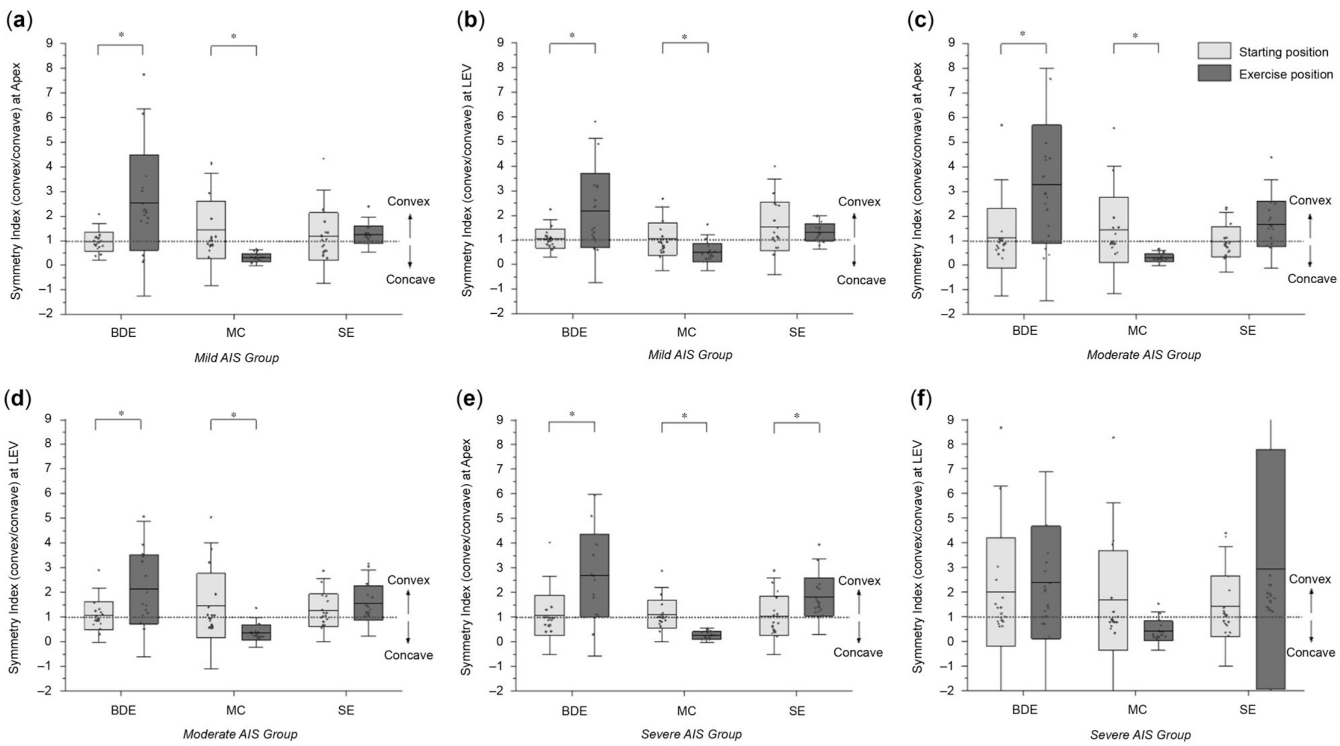

Figure 4. Symmetry index (convex/concave) of the mild, moderate, and severe adolescent idiopathic scoliosis (AIS) groups at the apex and lower end vertebrae (LEV). (a, c, e) Apex measurements of the mild, moderate, and severe AIS groups, respectively. (b, d, f) Lower end vertebra (LEV) measurements of the mild, moderate, and severe AIS groups, respectively. The center line represents the mean, the box represents mean ± standard deviation (SD), the whiskers represent ±1.96 × SD, and the individual points represent participant-level data. The dashed line at 1.0 denotes perfect bilateral symmetry between the convex and concave sides. Values >1.0 indicate convex-dominant activation, whereas values <1.0 indicate concave-dominant activation. *p<0.05 for within-exercise comparisons (starting and exercise positions). BDE, bird dog exercise; MCE, muscle cylinder exercise; SE, superman exercise.

(F[2, 100]=8.334, p<0.001; partial η^2=0.100). From the starting position to the exercise position, the SI decreased to <1.0 with the MCE, increased with the BDE, and showed minimal change with the SE. In the exercise position, the pattern mirrored the apex; the SI was lowest, intermediate, and highest with the MCE, SE, and BDE, respectively (Table 2, Figure 3b). This pattern confirmed that the MCE consistently produced lower SI values across spinal levels, whereas the BDE and SE produced higher SI values indicative of convex-dominant recruitment.

Subgroup Analyses

At the apex, the MG showed no significant main effect of position (F[1, 16]=2.228, p=0.137; partial η^2=0.046); however, it demonstrated a significant interaction effect (F[2, 32]=14.509, p<0.001; partial η^2=0.377). From the starting position to the exercise position, the SI increased to >1.0 with the BDE and SE; however, it decreased to <1.0 with the MCE, indicating concave-dominant activation. In the exercise position, the SI was lowest, intermediate, and highest with the MCE, SE, and BDE, respectively.

The MOG exhibited significant main (F[1, 16]=6.523, p=0.014; partial η^2=0.120) and interaction effects (F[2, 32]=19.884, *p*<0.001; partial η^2=0.453), showing a similar trend. Moreover, the SG showed a significant main effect of position (F[1, 16]=6.572, p=0.014; partial η^2=0.120) and significant interaction effect (F[2, 32]=15.838, p<0.001; partial η^2=0.398). Despite differences in statistical significance among subgroups, the overall activation trend remained consistent. The MCE produced lower SI values indicative of concave-dominant recruitment, whereas the BDE and SE produced higher SI values indicative of convex-dominant recruitment (Table 2, Figure 4a, c, and e).

At the LEV, the MG showed no significant main effect of position (F[1, 16]=0.025, p=0.874; partial η^2=0.001); however, it did show a significant interaction effect (F[2, 32]=6.632, p=0.003; partial η^2=0.216). In the MOG, the main effect of position (F[1, 16]=0.569, p=0.454; partial

η^2=0.012) was not significant; however, the interaction (F[2, 32]=10.762, p<0.001; partial η^2=0.310) was significant. In the SG, neither the main effect of position (F[1, 16]=0.247, p=0.621; partial η^2=0.005) nor the interaction (F[2, 32]=2.113, p=0.132; partial η^2=0.081) reached significance (Figure 4b, d, and f).

Discussion

This study examined side-specific paraspinal activation during three corrective exercises in adolescents with AIS. The specific MCE protocol tested in this study produced a marked concave-dominant SI shift (apex: 0.29; LEV: 0.43). These values substantially below 1.0 reflect temporary overcorrection during active correction rather than bilateral symmetry and may reflect a temporary overcorrection strategy used in some Schroth-based corrective approaches. In contrast, the specific BDE and SE protocols tested increased convex-dominant activity, reinforcing the asymmetrical recruitment typical of AIS. Contrary to our initial hypothesis, the BDE did not facilitate concave-side recruitment but instead increased convex-dominant activation patterns. This pattern may reflect the mechanical demands of quadruped limb elevation and trunk stabilization, which could preferentially recruit dominant extensor chains during asymmetrical loading tasks. These results suggest that the specific MCE protocol tested in this study produced lower SI values indicative of concave-dominant recruitment, whereas the specific BDE and SE protocols tested produced higher SI values indicative of convex-dominant recruitment. Deep stabilizing muscles, such as the multifidus, contribute to segmental spinal stability and are often implicated in the neuromuscular control of spinal alignment in AIS. Although the present study focused on superficial ES activation, interactions between deep stabilizers and global extensors may partly explain the asymmetric recruitment patterns observed during corrective exercises.

Subgroup analyses revealed that the overall activation trend was consistent across all severity subgroups, with the MCE producing concave-dominant SI values and the BDE and SE producing convex-dominant SI values in each group. In the severe AIS subgroup, the interaction effect at the LEV did not reach statistical significance, which may reflect greater interindividual variability and larger standard errors within this subgroup. These subgroup findings are descriptive and should be interpreted within each severity group independently, as no formal severity-by-exercise interaction test was conducted. Collectively, these results suggest that the specific MCE protocol tested in this study produced lower SI values indicative of concave-dominant recruitment, whereas the specific BDE and SE protocols tested produced higher SI values indicative of convex-dominant recruitment. Whether these acute neuromuscular activation patterns translate into long-term structural correction, progression prevention, or functional benefits requires further longitudinal investigation.

Asymmetrical activation of the paraspinal muscles in AIS has been consistently reported. Furthermore, higher EMG activity on the convex side than on the concave side has been observed. For example, Schmid et al. reported that asymmetrical exercises, such as the front press at the lumbar level and bent-over row at the thoracic level, increase the EMG amplitude on the concave side of the curve, suggesting that targeted asymmetrical loading helps modify asymmetrical muscle activation patterns[24]. More recent studies that applied the Schroth method have examined paraspinal muscle activity before, during, and after corrective exercises in AIS. For instance, He et al. reported that some Schroth corrective positions enhance concave-side activation and reduce the paraspinal muscle SI, indicating improved bilateral balance[25]. Similar findings were presented by Liang et al., who found that Schroth-based positions that emphasize overcorrection modify paraspinal activation patterns toward greater symmetry[26]. Wang et al. compared paraspinal muscle activity in different postural conditions and noted that corrective positions that emphasize alignment and overcorrection produce stronger muscle activation and more balanced recruitment than relaxed postures[27].

This study extended previous research by directly comparing three functional corrective exercises performed by adolescents with AIS. By analyzing EMG activity at both the apex and LEV, regional activation differences related to curve magnitude were identified. Unlike previous studies focused on static postures, this investigation examined dynamic corrective movements commonly applied in rehabilitation. In particular, the MCE emphasizes stabilization with active spinal alignment and controlled breathing, distinguishing it from extension-based tasks, such as the BDE and SE.

These findings advance the understanding of paraspinal activation asymmetry in AIS. Although previous work suggested that Schroth-based postures improve muscle balance, this study provides quantitative evidence indicating that distinct corrective exercises induce different neuromuscular patterns. The specific MCE protocol tested in this study produced a concave-dominant SI shift, whereas the specific BDE and SE protocols tested produced higher SI values indicative of convex-dominant recruitment. These results underscore the need to select exercises tailored to therapeutic goals and distinguish between interventions that modify acute paraspinal activation patterns and those targeting overall trunk strength.

This study had some limitations. First, sEMG primarily reflects the activity of superficial paraspinal muscles and cannot capture the response of deep stabilizers such as the multifidus. Second, this study focused on acute activation patterns. Long-term adaptations to repeated exercise sessions have not yet been established. Third, the SI was computed as a raw convex-to-concave RMS ratio without prior normalization of individual-channel values, meaning that SP SI values reflect pre-existing neuromuscular asymmetry rather than a common baseline of 1.0. While this approach preserves clinically relevant baseline information specific to each participant's scoliotic posture, it differs from designs that normalize to MVIC, and direct comparison of absolute SI values across studies should be made with caution. In addition, because each exercise involved a different starting posture, baseline neuromuscular activation patterns may have differed across exercises, which should be considered when interpreting between-exercise SI comparisons. Additionally, side-specific convex and concave RMS values were not separately reported, as the primary analytical focus was on relative asymmetry captured by the SI; future studies should examine absolute side-specific activation to better characterize the direction of neuromuscular changes. Future studies should incorporate imaging or fine-wire EMG to examine deeper musculature and longitudinal designs to assess functional outcomes. Fourth, most participants exhibited Lenke type 5 curves, representing thoracolumbar or lumbar patterns. Therefore, the findings may primarily reflect activation characteristics of the lumbar paraspinal region and should be interpreted cautiously when generalized to primary thoracic curves. In addition, age differed significantly across scoliosis severity subgroups, which may have influenced neuromuscular performance and contributed to variability in subgroup responses. Fifth, the exercise protocols were not fully standardized across participants. Both the BDE and MCE were modified according to curve location and therapeutic objectives, and the MCE additionally incorporated rotational breathing and controlled exhalation during sEMG acquisition. Therefore, differences in electromyographic activity may partly reflect exercise-specific breathing demands, posture, or movement strategies rather than isolated corrective muscle activation alone. These findings should therefore be interpreted as responses to the complete exercise protocols tested in this study rather than to isolated exercise categories. In addition, information regarding brace use, ongoing physiotherapy, prior Schroth exercise experience, and recent exercise exposure was not systematically collected, which may have contributed to inter-individual variability in neuromuscular responses. Formal statistical assessment of period or carryover effects was not performed. However, because the present study examined acute neuromuscular responses during isolated exercise sessions separated by a minimum 72-h washout period, substantial carryover effects were considered unlikely.

In conclusion, the specific MCE protocol tested in this study produced a marked concave-dominant SI shift. In contrast, the specific BDE and SE protocols tested produced convex-dominant SI values. These findings suggest that corrective exercises may induce distinct acute neuromuscular activation responses in adolescents with AIS. However, because the present study examined only acute activation patterns, the long-term clinical implications for spinal alignment, curve progression, or functional outcomes remain to be established.

Ethics Approval

The study protocol was approved by the Institutional Review Board of Korea National Sport University (IRB no. 20240613-064).

Consent to Participate

As all participants were minors, written informed assent was obtained from all participants, and written informed consent was obtained from their legal guardians prior to enrollment.

Authors' Contributions

Shin-A. Choi: Writing – original draft, Conceptualization, Methodology. Sang-Gil Lee: Investigation, Formal analysis, Methodology. Jin-Ho Yoon: Methodology, Data curation. Jae-Keun Oh: Supervision, Writing – review and editing. Han-Soo Park: Writing – review and editing, Methodology, Conceptualization. All authors read and approved the final version of the manuscript.

Acknowledgments

The authors would like to express their sincere gratitude to all the research staff and colleagues at the Sports Medicine Laboratory of Korea National Sport University for their valuable support and assistance.

References

1. Borysov M, Nan X, Weiss H-R, Turnbull D, Kleban A. Reliability of the original Lehnert-Schroth (LS) scoliosis classification in physiotherapy practice. J Phys Ther Sci 2020;32(10):647–52.
2. Kocaman H, Bek N, Kaya MH, Büyükturan B, Yetiş M, Büyükturan Ö. The effectiveness of two different exercise approaches in adolescent idiopathic scoliosis: a single-blind, randomized-controlled trial. PLOS One 2021;16(4):e0249492.
3. Negrini S, Donzelli S, Aulisa AG, Czaprowski D, Schreiber S, de Mauroy JC, et al. 2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth. Scoliosis Spinal Disord 2018;13:3.
4. Kaya MH, Erbahçeci F, Alkan H, Kocaman H, Büyükturan B, Canlı M, et al. Factors influencing quality of life in adolescent idiopathic scoliosis. Musculoskelet Sci Pract 2022;62:102628.
5. Becker L, Li Z, Wang Z, Pumberger M, Pumberger M, Schömig F. Adolescent idiopathic scoliosis is associated with muscle area asymmetries in the lumbar spine. Eur Spine J 2023;32(11):3979–86.
6. Martínez-Llorens J, Ramírez M, Colomina MJ, Bagó J, Molina A, Cáceres E, et al. Muscle dysfunction and exercise limitation in adolescent idiopathic scoliosis. Eur Respir J 2010;36(2):393–400.
7. Chan WWY, Fu S-N, Chong T-F, Singh G, Tsai DSJ, Wong MCY, et al. Associations between paraspinal muscle

characteristics and spinal curvature in conservatively treated adolescent idiopathic scoliosis: a systematic review. Spine J 2024;24(4):692–720.
8. Cheung J, Halbertsma JPK, Veldhuizen AG, Sluiter WJ, Maurits NM, Cool JC, et al. A preliminary study on electromyographic analysis of the paraspinal musculature in idiopathic scoliosis. Eur Spine J 2005;14(2):130–7.
9. Xu J-J, Zhu X-L, Li T, Lin Y, Luo X, Wu YS, et al. Assessment of the cross-sectional areas of the psoas major in patients with adolescent idiopathic scoliosis before skeletal maturity. Acta Radiol 2021;62(5):639–45.
10. Yetiş M, Yildiz NT, Canli M, Kocaman H, Yildirim H, Alkan H, et al. Determination of predictors associated with pain in non-surgically treated adults with idiopathic scoliosis. J Orthop Surg Res 2024;19(1):406.
11. Li X, Shen J, Liang J, Zhou X, Yang Y, Wang D, et al. Effect of core-based exercise in people with scoliosis: a systematic review and meta-analysis. Clin Rehabil 2021;35:669–80.
12. Gür G, Ayhan C, Yakut Y. The effectiveness of core stabilization exercise in adolescent idiopathic scoliosis: a randomized controlled trial. Prosthet Orthot Int 2017;41:303–10.
13. Schreiber S, Parent EC, Khodayari Moez E, Hedden DM, Hill DL, Moreau M, et al. Schroth physiotherapeutic scoliosis-specific exercises added to the standard of care lead to better Cobb angle outcomes in adolescents with idiopathic scoliosis—an assessor and statistician blinded randomized controlled trial. PLOS One 2016;11(12):e0168746.
14. Chwała W, Koziana A, Kasperczyk T, Walaszek R, Płaszewski M. Electromyographic assessment of functional symmetry of paraspinal muscles during static exercises in adolescents with idiopathic scoliosis. BioMed Res Int 2014;2014:573276.
15. Berdishevsky H, Lebel VA, Bettany-Saltikov J, Rigo M, Lebel A, Hennes A, et al. Physiotherapy scoliosis-specific exercises—a comprehensive review of seven major schools. Scoliosis Spinal Disord 2016;11:20.
16. Schreiber S, Parent EC, Moez EK, Hedden DM, Hill D, Moreau MJ, et al. The effect of Schroth exercises added to the standard of care on the quality of life and muscle endurance in adolescents with idiopathic scoliosis-an assessor and statistician blinded randomized controlled trial: "SOSORT 2015 Award Winner". Scoliosis 2015;10:24.
17. Batista G de A, Beltrán SP, dos Passos MHPD, Calixtre LB, Santos LRH, de Araújo RC. Comparison of the electromyography activity during exercises with stable and unstable surfaces: a systematic review and meta-analysis. Sports (Basel) 2024;12(4):111.
18. Lenke LG, Betz RR, Harms J, Bridwell KH, Clements DH, Lowe TG, et al. Adolescent idiopathic scoliosis: a new classification to determine extent of spinal arthrodesis. J Bone Joint Surg Am 2001;83(8):1169–81.
19. Zhu F, Hong Q, Guo X, Wang D, Chen J, Zhu Q, et al. A comparison of foot posture and walking performance in patients with mild, moderate, and severe adolescent idiopathic scoliosis. PLOS One 2021;16(5):e0251592.
20. Behm DG, Leonard AM, Young WB, Bonsey WA, MacKinnon SN. Trunk muscle electromyographic activity with unstable and unilateral exercises. J Strength Cond Res 2005;19(1):193–201.
21. Kavcic N, Grenier S, McGill SM. Quantifying tissue loads and spine stability while performing commonly prescribed low back stabilization exercises. Spine 2004;29(20):2319–29.
22. Akçay B, Kuru Çolak T, Apti A, Çolak İ. The immediate effect of hanging exercise and muscle cylinder exercise on the angle of trunk rotation in adolescent idiopathic scoliosis. Healthcare 2024;12(3):305.
23. Carvalheiro Reiser F, Gonçalves Durante B, Cordeiro de Souza W, Mascarenhas LPG, Bonuzzi GMG. Paraspinal muscle activity during unstable superman and bodyweight squat exercises. J Funct Morphol Kinesiol 2017;2(1):9.
24. Schmid AB, Dyer L, Böni T, Held U, Brunner F. Paraspinal muscle activity during symmetrical and asymmetrical weight training in idiopathic scoliosis. J Sport Rehabil 2010;19(3):315–27.
25. He C, Yang J-T, Zheng Q, Mei Z, Ma CZ. How do paraspinal muscles contract during the Schroth exercise treatment in patients with adolescent idiopathic scoliosis (AIS)? Bioengineering (Basel) 2022;9(6):234.
26. Liang R, Yip J, Fan Y, Cheung JPY, To KM. Electromyographic analysis of paraspinal muscles of scoliosis patients using machine learning approaches. Int J Environ Res Public Health 2022;19(3):1177.
27. Wang Y, Wang S, Gu M, Xu J, Huang X, Xie L. Paraspinal muscles activities in S-shaped adolescent idiopathic scoliosis during physiotherapeutic scoliosis specific exercise: a case-control study. BMC Musculoskelet Disord 2025;26(1):167.