



Effects of proprioceptive neuromuscular facilitation and core stabilization on physical and functional parameters in adolescents with idiopathic scoliosis: a randomized controlled trial

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Abstract

Background Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional spinal deformity that negatively affects postural alignment, functional capacity, and quality of life. Exercise-based interventions such as Proprioceptive Neuromuscular Facilitation (PNF) and Core Stabilization (CS) are increasingly utilized to improve structural and functional outcomes in AIS, yet comparative evidence remains limited.

Objective To evaluate and compare the isolated effects of Proprioceptive Neuromuscular Facilitation (PNF) and Core Stabilization (CS) exercises on spinal curvature, trunk rotation, physical function, and health-related quality of life in adolescents with Adolescent Idiopathic Scoliosis (AIS), with the aim of informing evidence-based conservative treatment strategies.

Methods This randomized controlled trial included 52 adolescents aged 10–18 years diagnosed with AIS. Participants were randomly assigned to either a PNF group ($n=26$) or a CS group ($n=26$). Both groups underwent supervised exercise interventions three times per week for 10 weeks. The primary outcome was the Cobb angle. Secondary outcomes included Angle of Trunk Rotation (ATR), Scoliosis Research Society-22 (SRS-22) questionnaire scores, and physical function tests (six-minute walk test, sit-to-stand test). Assessments were conducted by blinded evaluators.

Results Both groups demonstrated significant improvements in Cobb angle, ATR, SRS-22 scores, and physical function ($p<0.05$). The PNF group showed a greater reduction in Cobb angle ($6.8^\circ \pm 1.2^\circ$) compared to the CS group ($5.4^\circ \pm 1.1^\circ$, $p<0.05$), as well as superior improvements in ATR. Quality of life and physical performance improved significantly in both groups, with no statistically significant differences between groups in SRS-22 scores.

Conclusion Both PNF and CS exercises are effective in improving spinal alignment, trunk symmetry, and physical function in adolescents with AIS. PNF appears to offer greater structural benefits, while both interventions are equally effective in enhancing quality of life. These findings support the integration of exercise-based rehabilitation into conservative management protocols for AIS.

Highlights

- Both PNF and CS exercises significantly improved Cobb angle, trunk rotation, functional capacity, and quality of life in AIS.
- Improvements in 6-minute walk distance and sit-to-stand test performance paralleled structural changes, indicating that postural correction may also enhance aerobic capacity and physical endurance.
- Both interventions were effective not only in radiographic correction but also in improving psychosocial well-being, including perceived appearance and overall quality of life.

Keywords Adolescent idiopathic scoliosis · Core stabilization · Proprioceptive neuromuscular facilitation · Cobb angle · Angle of trunk rotation · SRS-22 · Randomized controlled trial

Introduction

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional spinal deformity, typically defined by a lateral spinal curvature greater than 10°, accompanied by vertebral rotation and often reduced thoracic kyphosis [1, 2]. It affects an estimated 1 to 4% of adolescents aged 10 to 18, with a higher incidence reported in females [3]. Beyond structural abnormalities, AIS often involves neuromuscular control deficits and postural asymmetry, which may contribute to curve progression, particularly during growth spurts [4]. While its exact cause remains unclear, AIS is widely considered a multifactorial condition involving genetic, hormonal, biomechanical, and environmental factors [5]. Recent research has identified genetic and epigenetic alterations potentially influencing spinal development, though these mechanisms are not yet fully understood [6]. Early detection—preferably before or during a growth spurt—is critical for preventing long-term complications such as chronic discomfort, structural deformities, respiratory dysfunction, and psychosocial difficulties [7]. To prevent curve progression and reduce long-term impact, conservative treatments are typically recommended. These include bracing, scoliosis-specific physiotherapy, and targeted exercise programs designed to improve spinal alignment and motor control [8, 9]. Exercise-based interventions are popular due to their non-invasive nature and ease of implementation. Some studies suggest combining exercise with bracing produces better outcomes than bracing alone [10]. However, inconsistencies across studies—likely due to variations in protocols and therapist experience—highlight the need for more standardized, evidence-based approaches.

Several scoliosis-specific exercise methods, including the Schroth and Lyon techniques, have been explored for their potential to improve spinal alignment and function in AIS. However, their reliance on highly trained practitioners and consistent patient commitment may limit their practicality in routine settings [11].

Core stabilization (CS) exercises are another widely applied strategy. These target deep trunk muscles such as the transversus abdominis and multifidus to help maintain spinal control during movement. Studies indicate that CS exercises can improve balance, posture, and trunk endurance in adolescents with AIS, and its adaptability makes it a practical choice for long-term use [12]. The hypothesized mechanisms underlying these interventions differ: PNF enhances neuromuscular re-education, proprioceptive input, and dynamic postural control, whereas CS primarily targets deep stabilizing muscles (e.g., transversus abdominis, multifidus) to improve trunk endurance and lumbopelvic stability.

Proprioceptive Neuromuscular Facilitation (PNF) uses spiral and diagonal movement patterns along with rhythmic stabilization to enhance joint mobility and neuromuscular coordination. In AIS, PNF has been associated with improved trunk symmetry and posture and reduced mechanical load on the spine. Structured PNF programs may also reduce pain and improve respiratory function, Cobb angle, and trunk rotation [13].

Although scoliosis-specific exercises are increasingly used, few high-quality studies have directly compared the individual effects of core stabilization and PNF in adolescents with AIS. In a recent systematic review, only two of the 24 included studies involved PNF, underscoring the limited comparative evidence between these two methods [14]. Nevertheless, several systematic reviews and meta-analyses have reported inconsistent or even negligible effects of exercise-based interventions in AIS, highlighting the need for cautious interpretation [15].

A clearer understanding of their respective impacts on structural and functional outcomes could support more personalized and effective rehabilitation strategies. This study was designed with that goal in mind—to compare the effects of core stabilization and PNF on Cobb angle, ATR, and health-related quality of life (HRQoL) in AIS. However, contradictory findings also exist regarding exercise-based approaches; while some studies report meaningful benefits, others have shown limited or no effects. Therefore, more standardized protocols and high-quality trials are needed [10, 15].

By evaluating these two commonly used interventions side by side, the present study aims to provide practical insight to guide clinical decision-making and enhance conservative management strategies for AIS.

Materials and methods

This study was a single-center, two-arm, parallel-group randomized controlled trial (RCT) conducted at the (removed for blinded review), between January and December 2022. The study adhered to the Consolidated Standards of Reporting Trials (CONSORT) guidelines to ensure transparency and reproducibility. Ethical approval was obtained from the (removed for blinded review) University Institutional Ethics Committee (Approval No: removed for blinded review), and written informed consent was secured from all participants and their legal guardians in accordance with the Declaration of Helsinki. The study was registered at ClinicalTrials.gov (removed for blinded review).

Participants

Participants were recruited from the outpatient scoliosis clinic at (removed for blinded review). Inclusion criteria comprised adolescents aged 10–18 years with a first-time diagnosis of AIS, a Cobb angle between 10° and 30°, a Risser sign of 0–3, and a Sanders stage of 0–6. Only individuals with Lenke Type 1–1 A curves were included. At baseline, only skeletally immature patients (Risser sign 0–3, Sanders 0–6) were included to ensure that participants had remaining growth potential, which is a critical factor in AIS progression and treatment response. Exclusion criteria were prior scoliosis treatment, spinal surgery, brace use, non-idiopathic scoliosis (e.g., congenital or neuromuscular), and medical contraindications to exercise (e.g., cardiovascular or pulmonary conditions). To enhance transparency, these criteria were selected a priori to minimize confounding from skeletal maturity and curve-pattern heterogeneity: skeletally

immature adolescents (Risser 0–3; Sanders 0–6), Lenke type 1/1A, and mild-to-moderate curves (10°–30°). Exclusion criteria were explicitly defined to avoid prior or concurrent treatments and comorbidities that could bias outcomes (previous bracing or spinal surgery, non-idiopathic scoliosis, and cardiopulmonary contraindications to exercise).

Fifty-two eligible participants were randomized into two intervention groups—PNF or Core Stabilization—using a computer-generated stratified randomization process. Stratification was based on gender, age (10–14 vs. 15–18 years), and initial Cobb angle (10–20° vs. 21–30°). A physiotherapist blinded to group assignment conducted all baseline and post-intervention assessments.

Interventions Both groups participated in a 10-week structured exercise program, including three supervised physiotherapy sessions per week and a daily home exercise component. Each supervised session lasted approximately 90 min and included a standardized warm-up, cool-down, and group-specific scoliosis intervention.

General Exercise Protocol All participants completed a common warm-up (10 min) and cool-down (10 min) during each session. This general program included:

- Pectoral muscle stretching.
- Spinal mobility exercises.
- Postural education.
- Diaphragmatic and thoracic breathing exercises.

PNF Group Participants in the PNF group engaged in Proprioceptive Neuromuscular Facilitation exercises aimed at enhancing neuromuscular coordination, spinal alignment, and strength. Key components included:

- Diagonal and spiral movement patterns (D1/D2).
- Rhythmic stabilization for trunk control.
- Contract-relax and hold-relax techniques.
- Repeated contractions for muscular endurance.

TrA and multifidus activation was encouraged through tactile cueing and breathing control. Exercises progressed from supine to upright functional positions, utilizing Theraband® and Swiss balls to increase difficulty (Table 1).

Core Stabilization Group The CS group followed a progressive exercise regimen targeting deep core musculature. The protocol was divided into three phases:

1. Beginner (Weeks 1–3): TrA activation, lumbopelvic control, and isometric trunk stabilization.
2. Intermediate (Weeks 4–6): Dynamic tasks including heel slides, bridging on unstable surfaces, and ball exercises.

Table 1 PNF Exercise Program

Exercise	Description	Frequency	Intensity	Duration
Diagonal Pattern 1	Diagonal flexion-abduction-external rotation pattern	3 sets of 10 reps	Moderate	30 min
Diagonal Pattern 2	Diagonal extension-adduction-internal rotation pattern	3 sets of 10 reps	Moderate	30 min
Rhythmic Stabilization	Isometric contraction against manual resistance in various positions	3 sets of 10 reps	Moderate	30 min
Contract-Relax	Isotonic contraction of the antagonist followed by passive stretch	3 sets of 10 reps	Moderate	30 min
Hold-Relax	Isometric contraction of the agonist followed by passive stretch	3 sets of 10 reps	Moderate	30 min
Repeated Contractions	Repetitive isotonic contractions against manual resistance	3 sets of 10 reps	Moderate	30 min

PNF=Proprioceptive Neuromuscular Facilitation; reps=repetitions

Table 2 Core Stabilization Exercises Program

Level	Exercise	Description	Frequency	Intensity	Duration
Beginner	TrA muscle activation training	Activating the transverse abdominis muscle	3 sets of 10 reps	Moderate	30 min
	Neutral lumbopelvic control	Maintaining neutral lumbopelvic position	3 sets of 10 reps	Moderate	30 min
	Warm-up exercises	General warm-up exercises	3 sets of 10 reps	Moderate	30 min
	Supine hip flexion	Hip flexion exercises	3 sets of 10 reps	Moderate	30 min
	Supine straight leg raise	Straight leg raise exercises	3 sets of 10 reps	Moderate	30 min
Intermediate	TrA muscle activation training	Activating the transverse abdominis muscle	3 sets of 10 reps	Moderate	30 min
	Active TrA with heel slide	Heel slide exercises with active TrA	3 sets of 10 reps	Moderate	30 min
	Supine ball rolling	Rolling exercises with a ball	3 sets of 10 reps	Moderate	30 min
	Bridge on Pilates ball with knee extension	Bridging exercises on a Pilates ball	3 sets of 10 reps	Moderate	30 min
Advanced	Side bridge with knee flexion	Side bridging exercises	3 sets of 10 reps	Moderate	30 min
	Warm-up exercises	General warm-up exercises	3 sets of 10 reps	Moderate	30 min
	Bridge on ball with knee flexion	Bridging exercises on a ball	3 sets of 10 reps	Moderate	30 min
	Rolling with abdominal muscles	Rolling exercises using abdominal muscles	3 sets of 10 reps	Moderate	30 min
	Bridging in prone position	Bridging exercises in a prone position	3 sets of 10 reps	Moderate	30 min
	Side bridge with knee extension	Side bridging exercises	3 sets of 10 reps	Moderate	30 min

Abbreviations: TrA = Transversus Abdominis; reps = repetitions

- Advanced (Weeks 7–10): Multi-planar tasks focusing on balance and coordination.

Progressions were individualized based on motor control and symptom tolerance (Table 2).

Common Protocol Elements Both intervention groups adhered to the following principles:

- Gradual progression in intensity and complexity.
- Real-time postural correction feedback.
- Avoidance of the Valsalva maneuver.
- Daily home-based reinforcement exercises (15–20 min).

Outcome Measures

Primary Outcome

- Cobb Angle (CA): Measured using standardized standing anteroposterior radiographs. Calculations followed the end-vertebra method by a blinded radiologist.

Secondary Outcomes

- Angle of Trunk Rotation (ATR): Assessed with a Bunnell scoliometer during Adam's forward bend test.
- Quality of Life: Measured using the Turkish version of the Scoliosis Research Society-22 (SRS-22) questionnaire [16].
- Perceived Trunk Appearance: Evaluated using the Walter Reed Visual Assessment Scale (WRVAS).
- Functional Performance:
 - Six-Minute Walk Test (6MWT): Submaximal aerobic capacity.
 - Sit-to-Stand Test (STS): Lower limb strength and mobility.

The 6MWT has been validated in pediatric and adolescent populations, including those with scoliosis, as a reliable measure of submaximal aerobic capacity and functional performance [17].

Exploratory: Manual muscle testing (MMT) of trunk/lower extremities was performed according to the standardized Kendall and Kendall protocol, using a 0–5 ordinal grading scale to assess trunk flexors, extensors, and major lower extremity muscle groups. All assessments were conducted by the same experienced physiotherapist to ensure consistency and reproducibility.

Sample size calculation

Sample size was determined using G*Power software (version 3.1.9.4; Heinrich-Heine-Universität Düsseldorf, Germany). A medium effect size ($f = 0.30$) was assumed based on prior randomized controlled trials investigating exercise-based interventions in adolescents with idiopathic scoliosis [18, 19]. Power was set at 80% ($1-\beta = 0.80$) with an alpha level of 0.05, considering two measurement time points (pre- and post-intervention) for a mixed-design repeated-measures ANOVA. The minimum sample size required was calculated as 44 participants (22 per group). To accommodate potential dropouts of up to 15%, a total of 52 participants were recruited.

Randomization and blinding

Stratified randomization was implemented based on age (10–14 vs. 15–18 years), gender, and baseline Cobb angle (10° – 20° vs. 21° – 30°) to ensure comparability between groups. Allocation was concealed using sealed opaque envelopes prepared by an independent researcher not involved in assessments or interventions. The outcome assessor was blinded to allocation and trained in scoliosis-specific evaluation. Statistical Analysis Data analysis was performed with IBM SPSS Statistics (v24.0). Descriptive statistics (mean $\pm$ SD, frequencies) were calculated. Normality was assessed with the Shapiro–Wilk test. Paired t-tests and Wilcoxon tests were used for within-group comparisons, while independent t-tests and Mann–Whitney U tests were applied for between-group analyses. A two-way mixed-design repeated-measures ANOVA evaluated group, time, and interaction effects. Significant findings were followed by Bonferroni-adjusted post hoc tests. Effect sizes were reported as partial eta squared (η^2p) and Cohen's d . Statistical significance was set at $p < 0.05$.

Results

A total of 52 participants were enrolled and randomly assigned to either the PNF ($n = 26$) or CS group ($n = 26$). All participants completed the 10-week intervention program. There were no reported adverse events during the study period. During the 10-week intervention and subsequent assessments, no participants demonstrated curve progression, and none required additional treatment such as bracing or surgery. Participant flow throughout the trial is presented in Fig. 1, illustrating the number of individuals screened, randomized, and completing follow-up.

Baseline Characteristics Table 3 summarizes the baseline demographic and clinical characteristics of participants in

each group. There were no statistically significant differences between the groups in terms of age, sex distribution, BMI, or Cobb angle ($p > 0.05$ for all). In addition, the distribution of Risser stages (0–3) was comparable between groups ($p > 0.05$), confirming that skeletal maturity was balanced at baseline.

Changes in Physical Function Table 4 presents the functional outcomes assessed by the 6-Minute Walk Test (6MWT) and Sit-to-Stand Test (STS). Both groups showed significant within-group improvements in 6MWT and STS performance after the intervention ($p < 0.001$). However, between-group differences in functional gains were not statistically significant.

At baseline, there were no statistically significant differences between the CS and PNF groups in any of the SRS-22 subscales, including pain, function, body image, mental health, satisfaction with treatment, and total score ($p > 0.05$ for all). This indicates that the two groups were comparable in terms of their pre-intervention quality of life and perceptions related to scoliosis (Table 5).

Pearson correlation coefficients (r) and significance values (p) are presented to describe the relationship between changes in Cobb angle and improvements in functional parameters, including six-minute walk test (6MWT) distance and sit-to-stand (STS) repetitions, in both the PNF and CS groups. Negative correlation coefficients indicate that as the Cobb angle decreases, functional outcomes improve (Table 6).

Comprehensive Analysis of Clinical Outcomes To provide a detailed comparison between the groups over time, Table 7 summarizes the main effects, group-by-time interaction effects, and between-group differences for the Cobb angle, Angle of Trunk Rotation (ATR), SRS-22 scores, and Walter Reed Visual Assessment Scale (WRVAS) scores. The analysis revealed significant time and interaction effects for all outcomes, with the PNF group generally demonstrating greater improvements, particularly in Cobb angle and ATR. While SRS-22 and WRVAS also improved significantly, the between-group differences for these were less pronounced.

Discussion

This randomized controlled trial demonstrated that both PNF and CS exercises resulted in significant improvements in key structural parameters in AIS. Following the 10-week intervention, reductions were observed in both Cobb angle and trunk rotation across groups, indicating the positive impact of conservative exercise-based treatment. Notably, the PNF group demonstrated greater reductions in spinal curvature, which may indicate a potentially stronger effect on postural realignment. These findings suggest the potential

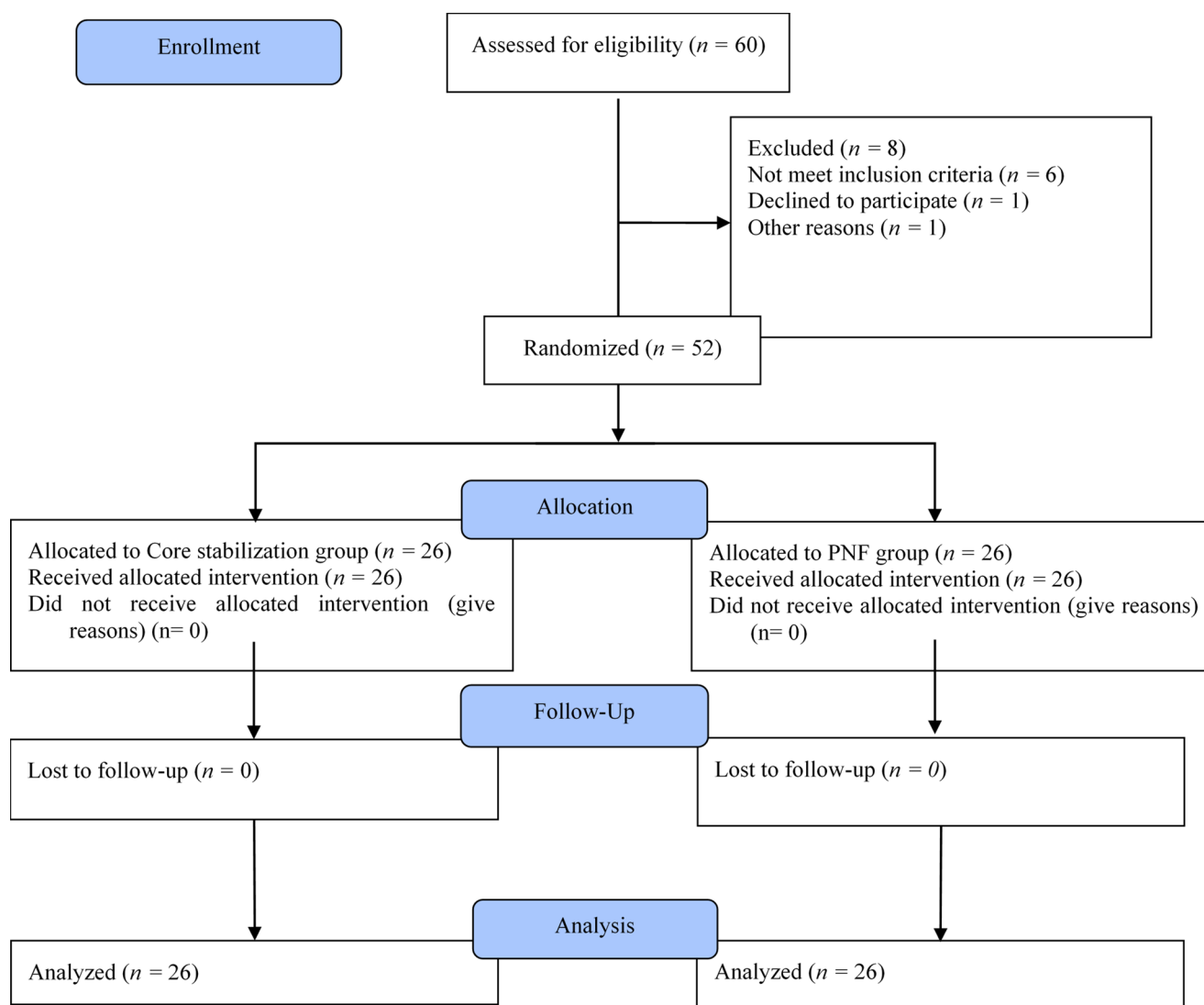


Fig. 1 CONSORT flow diagram of participant flow throughout the study

Table 3 Baseline Demographic and Clinical Characteristics

Characteristic	PNF Group (n=26)	Core Stabilization Group (n=26)	p-value
Age (years)	14.50±1.80	14.30±1.60	0.38
BMI (kg/m ²)	22.10±2.60	21.60±2.80	0.71
Cobb Angle (°)	25.40±4.60	24.80±3.90	0.59
Gender (Female/Male)	18 / 8	17 / 9	0.77
Risser stage (0/1/2/3)	8 / 7 / 6 / 5	7 / 8 / 5 / 6	0.84

BMI=Body Mass Index; PNF=Proprioceptive Neuromuscular Facilitation

clinical relevance of PNF and CS approaches in non-invasive scoliosis management and indicate that targeted physiotherapeutic strategies may contribute to improving spinal alignment during adolescence.

Spinal curvature and trunk rotation are critical clinical indicators of scoliosis progression in AIS, with a reduction

of at least 4° in Cobb angle commonly accepted as clinically significant [20, 21]. In this study, both intervention groups exhibited statistically significant improvements in Cobb angle and trunk rotation following treatment, reflecting the effectiveness of conservative exercise approaches reported in the literature [21]. Although radiographic measurement error for the Cobb angle has been estimated at approximately 3°–5° [22], the magnitude of change observed in both groups exceeded this range. Mean reductions were 6.8° in the PNF group and 5.4° in the CS group.

Therefore, the observed improvements are unlikely to reflect measurement variability alone and may suggest potentially meaningful structural improvement. However, the clinical significance of these short-term radiographic changes should be interpreted with caution in the absence of long-term follow-up data. The PNF group demonstrated a more pronounced reduction in Cobb angle. This effect may

Table 4 Physical Function Outcomes (6MWT and STS) Before and After Intervention

Parameter	PNF Group (n=26)	CS Group (n=26)	p-value (within group)	Between- Group p-value
6MWT – Baseline (m)	462.40±34.20	464.80±33.90	—	—
6MWT – Post-intervention (m)	507.60±32.10	503.50±31.70	<0.001	—
6MWT – Mean Change (m)	45.20±15.30	38.70±13.90	—	0.278
STS – Baseline (reps)	12.40±2.50	12.80±2.40	—	—
STS – Post-intervention (reps)	16.0±2.10	15.90±2.20	<0.001	—
STS – Mean Change (reps)	3.60±1.10	3.10±1.0	—	0.195

6MWT=Six-Minute Walk Test; STS=Sit-to-Stand Test; PNF=Proprioceptive Neuromuscular Facilitation; CS=Core Stabilization; m=meters; reps=repetitions

Table 5 Comparison of Pre-Treatment SRS-22 Scores Between the Two Groups

SRS-22	CS Group (n=26) Mean±SD	PNF Group (n=26) Mean±SD	p-value
Pain	3.54±0.36	3.51±0.42	0.791
Function	4.36±0.20	4.48±0.35	0.278
Body Image	2.86±0.31	2.99±0.33	0.381
Mental Health	3.29±0.25	3.08±0.39	0.119
Satisfaction with Treatment	2.78±0.32	2.69±0.41	0.714
Total Score	3.36±0.14	3.35±0.28	0.903

Table 6 Correlation Between Changes in Cobb Angle and Functional Outcomes (6MWT and STS) in PNF and CS Groups

Correlation Between Variables	Group	Angle Change (Mean±SD)	Functional Change (Mean±SD)	r value	p value
Cobb ↔ 6MWT	PNF	6.80° ± 1.20	45.20 m ± 15.3	−0.54	<0.001
Cobb ↔ 6MWT	CS	5.40° ± 1.10	38.70 m ± 13.9	−0.48	<0.001
Cobb ↔ STS	PNF	6.80° ± 1.20	3.60 reps ± 1.1	−0.61	<0.001
Cobb ↔ STS	CS	5.40° ± 1.10	3.10 reps ± 1.0	−0.49	<0.001

6MWT=Six-Minute Walk Test; STS=Sit-to-Stand Test; PNF=Proprioceptive Neuromuscular Facilitation; CS=Core Stabilization; m=meters; reps=repetitions

be attributed to the technique's emphasis on neuromuscular re-education, proprioceptive stimulation, and dynamic motor control. These effects likely contributed to enhanced spinal alignment and segmental mobility, as supported by previous PNF-based trials [23, 24].

Beyond radiographic improvements, addressing the perceptual and psychosocial dimensions of scoliosis is essential, particularly during adolescence when body image concerns are heightened. In line with this, both groups showed significant reductions in perceived trunk asymmetry, as measured by the Walter Reed Visual Assessment Scale (WRVAS), a tool validated for its sensitivity to cosmetic changes in scoliosis [25, 26]. While improvements were observed in both groups, the CS group exhibited slightly greater reductions in WRVAS scores, which may be linked to their more substantial structural changes. These perceptual improvements may translate into enhanced self-image and reduced psychosocial distress. Similar associations between structural correction and body image have been reported in previous studies [27, 28].

Quality of life (QoL), assessed using the scoliosis-specific SRS-22 questionnaire, improved significantly in both groups post-intervention, with gains observed in physical function, self-image, and treatment satisfaction domains [29]. Notably, the CS group demonstrated greater overall improvement in SRS-22 scores compared to the PNF group, particularly in the subdomains of function, body image, and satisfaction. This pattern suggests that the CS intervention may foster improvements in daily functioning and perceived appearance. These effects may be related to targeted activation of deep stabilizing musculature. Furthermore, the consistent alignment between WRVAS and SRS-22 outcomes supports the notion that structural improvements play a pivotal role in enhancing psychosocial well-being in AIS [30]. The differential effects observed between PNF and CS may be attributed to their underlying mechanisms. PNF emphasizes diagonal and spiral movement patterns combined with rhythmic stabilization. These features enhance neuromuscular re-education, proprioceptive input, and dynamic postural control. Such mechanisms may explain the superior improvements observed in structural parameters such as Cobb angle and ATR. In contrast, CS specifically targets the deep stabilizing musculature, including the transversus abdominis and multifidus, which are essential for trunk endurance and lumbopelvic stability. Activation and strengthening of these muscles likely contributed to greater functional and strength-related gains observed in the CS group. Together, these method-specific adaptations highlight the complementary roles of PNF and CS in addressing different aspects of AIS rehabilitation.

Emerging evidence highlights a negative correlation between scoliosis severity and physical performance, with

Table 7 Baseline, Post-treatment, and Change Values for Cobb, ATR, SRS-22, and WRVAS Parameters

		PNFG (<i>n</i> = 26)		CSG (<i>n</i> = 26)		Main Effect (Time)	Main Effect (Group)	Group*Time (Interaction)	Between Group Differ- ences in Change Scores Mean (95% CI)
		<i>X</i>	<i>SD</i>	<i>X</i>	<i>SD</i>	<i>p1</i>	<i>p2</i>	<i>F</i> / <i>p</i> value	
CA (°)	Baseline	25.40	4.60	24.80	3.90	<0.001	<0.001	103.1 / <0.001	1.40 (0.9, 1.9)
	Post-treatment	18.60	4.40	19.40	4.0				
SRS-22 (score/ total score)	Baseline	3.4 / 5	0.5	3.3 / 5	0.6	<0.001	<0.05	15.7 / <0.001	0.20 (0.1, 0.3)
	Post-treatment	4.2 / 5	0.6	3.9 / 5	0.5				
ATR (°)	Baseline	10.40	1.60	10.20	1.50	<0.001	<0.001	64.1 / <0.001	0.50(0.2, 0.8)
	Post-treatment	7.90	1.30	8.20	1.40				
WRVAS (score/ total score)	Baseline	17.60/35	2.40	17.2/35	2.10	<0.001	<0.001	169.5 / <0.001	0.60 (0.4, 0.8)
	Post-treatment	12.40/35	2.50	12.6/35	2.30				

CA: Cobb angle, SRS-22: Scoliosis Research Society-22, ATR: Angle of Trunk Rotation, WRVAS: Walter Reed Visual Assessment Scale, *SD*: Standard Deviation, *p1*: Within Group Comparison (Time), *p2*: Group Comparison (Group), CI: Confidence interval, PNFG: PNF group, CSG: CS group

greater spinal deformity associated with reduced exercise tolerance. In a recent study, increasing Cobb angles were linked to declines in cardiopulmonary capacity, as assessed by 6-minute walk distance (6MWD) and peak VO_2 , suggesting that spinal misalignment can limit thoracic mobility and respiratory efficiency [17]. Our findings are consistent with this relationship: following a 10-week intervention, both the PNF and CS groups exhibited significant reductions in Cobb angle, paralleled by notable improvements in 6MWT distance and STS performance. These gains suggest that improvements in spinal alignment may contribute to better functional and aerobic performance in adolescents with AIS. In addition, improved alignment may support better functional and aerobic performance. Particularly, the enhancement in 6MWD suggests improved submaximal exercise capacity, further supporting the clinical value of conservative physiotherapy interventions in addressing both postural asymmetry and physical deconditioning in scoliosis populations.

While this study offers valuable insights into the structural, functional, and psychosocial benefits of PNF and CS exercises in AIS, certain limitations should be acknowledged. Although the 10-week intervention period was sufficient to elicit significant clinical improvements, it may not capture the long-term sustainability of these outcomes across skeletal maturation. In untreated AIS populations, the expected annual progression in Cobb angle has been reported to range between 0.5° and 2° depending on growth potential and curve severity [5, 20]. Therefore, while our findings demonstrate significant short-term improvements, future long-term follow-up is essential to determine whether these benefits exceed the natural course of curve progression.

Additionally, while the 6MWT and STS tests provided practical and clinically relevant assessments of functional capacity, the absence of more comprehensive cardiopulmonary evaluations—such as CPET—limits the precision

of physiological interpretations. Future research should focus on long-term follow-up to examine whether these benefits persist or evolve over time, and incorporate more objective measures of cardiopulmonary function and exercise adherence. Expanding sample diversity and exploring subgroup-specific responses may also contribute to more individualized and evidence-based rehabilitation strategies for AIS. Another important limitation of this study is the absence of a non-exercise or usual-care control group. Because both study arms consisted of active exercise interventions, it is difficult to fully distinguish the specific effects of the interventions from potential natural variation, placebo responses, or growth-related changes. Future trials incorporating a usual-care or observation-only group would help to strengthen causal inference and clarify the specific contribution of exercise-based interventions. An important limitation of the present trial is that only skeletally immature patients (Risser 0–3, Sanders 0–6) were included. While this approach minimized confounding related to skeletal maturity, the findings may not be generalizable to patients at higher maturity stages (Risser 4–5). Treatment responsiveness may differ once growth potential is limited. Therefore, future studies should examine whether the efficacy of PNF and CS varies according to skeletal maturity. Treatment responsiveness may also vary depending on participants' age and baseline curve severity; future studies should examine subgroup differences to clarify these effects. Although manual muscle testing (MMT) was planned as an exploratory outcome, detailed strength data were not systematically reported. Therefore, conclusions regarding muscle strength should be interpreted with caution. Future studies should incorporate objective and standardized muscle strength assessments. Another limitation of this study is that only participants with Lenke type 1–1 A curves were included. As the effectiveness of PNF and CS may vary depending on curve location and classification, the findings cannot be generalized to patients with other Lenke

types (e.g., thoracolumbar or double curves). Future studies should investigate whether the outcomes of these exercise approaches differ across a broader range of curve patterns.

Conclusion

This randomized controlled trial demonstrated that both PNF and CS exercises are effective conservative interventions for AIS. Both modalities led to significant improvements in spinal alignment, trunk symmetry, functional performance, and quality of life. While the PNF group showed greater reductions in Cobb angle, the CS group demonstrated superior gains in functional performance and patient-reported outcomes. These findings underscore the multifaceted benefits of structured physiotherapy in managing AIS and highlight the potential of exercise-based approaches to address not only structural deformity but also functional and psychosocial domains. Integrating tailored exercise programs into routine clinical care may enhance rehabilitation outcomes and support long-term physical and emotional well-being in this population.

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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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