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Article

Unraveling the Muscle Activation Equation: 3D Scoliosis-Specific Exercises and Muscle Response in Adolescent Idiopathic Scoliosis

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Abstract: This study aimed to analyze both thoracic and lumbar erector spinae muscle activations during three different types of 3-dimensional elongation exercises in individuals with adolescent idiopathic scoliosis (AIS). Participants included 24 adolescents with AIS with a double curve (S type scoliosis), meeting specific criteria, such as a Cobb angle between 10° and 20° and not having undergone surgical or brace treatments. Electromyography (EMG) data were collected to evaluate muscle activation. Three-dimensional scoliosis-specific exercises were applied as 3 different exercise types with TheraBand resistance, manual stimulation, and breathing inducement from convex side to concave side until a symmetric position was maintained with self-correction. Different exercise types significantly affected muscle activity, with the highest activations in TheraBand resistance, followed by manual and just breathing inducement conditions for the convex and concave sides of the thoracic and lumbar regions. This suggests that exercise type significantly impacts muscle engagement in AIS patients, providing valuable insights for targeted exercise program design. Specially, the muscle activation of TheraBand resistive exercise can be an alternative with more muscle activation and motivational effects during a 3D scoliosis-specific exercise program.

Keywords: adolescent idiopathic scoliosis; EMG (electromyography); erector spinae; 3D elongation exercises; cobb angle

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1. Introduction

Scoliosis is a 3-dimensional deformity caused by lateral curvature and rotation of the spine [1]. The etiology of most scoliosis patients is unclear [2]. The most commonly diagnosed type is adolescent idiopathic scoliosis (AIS), which usually occurs during adolescence [3]. The worldwide prevalence of AIS varies between 0.93% and 12%, and the incidence and severity of spinal curvature are higher in girls than in boys [4]. Currently, two different approaches are generally adopted for the treatment of scoliosis. According to the degree of Cobb angle, surgery is recommended for patients with a Cobb angle greater than 40°, while conservative treatment, including orthosis or exercise therapy, is recommended for patients with a Cobb angle less than 40° [5].

Previous studies in individuals with scoliosis have reported an asymmetry in the activation of paraspinal muscles on the concave and convex sides of the curve [6]. In individuals with AIS, higher electromyographic (EMG) muscle activity was found on the convex side of the curve compared to the concave side [7–9]. Although it has not been fully confirmed whether the asymmetry in muscle activity is a cause or a consequence of spinal curvature, the current literature suggests that muscle asymmetry in the erector spinae plays an important role in the progression of scoliosis in individuals with AIS [10,11]. Therefore, posture training and scoliosis-specific exercises to improve symmetry in paraspinal muscle activity in AIS may reduce the risk of curve progression [12].

Scoliosis-specific exercises are designed to bring patients' asymmetrical posture into alignment and restore a correct upright position. It also includes sensorimotor and breathing exercises aimed at static/dynamic postural control, spinal stability, and recalibration of breathing patterns [13]. In a study examining the EMG activations of the paraspinal muscles during scoliosis exercises, it was observed that the EMG activity in the paraspinal muscle during exercise was higher than in the relaxed standing position. At the same time, EMG signals were found to be higher on the convex side of the curve during asymmetric exercise and on the concave side during symmetric exercise [9,14–16]. However, the effect of different forms of stimulation on these muscle activations during exercise is not available in the literature.

The aim of this study was to compare thoracic and lumbar erector spinae muscle activations during 3D elongation exercises given in three different ways in individuals with adolescent idiopathic scoliosis. The hypotheses of this study were: (1) the three different variations of the 3D elongation exercise will lead to significantly different activation levels in both thoracic and lumbar erector spinae muscles in individuals with AIS, (2) there will be a significant interaction effect between the type of 3D elongation exercise and the activation of thoracic and lumbar erector spinae muscles, and (3) there will be a significant difference in activation between thoracic and lumbar erector spinae muscles in all three exercise variations in individuals with AIS.

2. Materials and Methods

2.1. Study Design and Participants

This study employed a prospective cohort design conducted at a single center. Twenty-four (15 females and 9 males) adolescents with idiopathic scoliosis (AIS) with a mean age of 14.5 $\pm$ 2.3 years were included in the study. The criteria for inclusion in this study were specifically defined as follows: Firstly, participants must conform to the diagnostic criteria for scoliosis as set by the International Society of Spine Surgery [17]. Secondly, they should have double curvature (S type scoliosis) and a Cobb angle ranging between 10° and 20°. Thirdly, individuals included in the study should not have undergone surgical treatment for scoliosis nor should they have plans to undergo brace treatment in the foreseeable future. Additionally, they must not have any motor organ diseases. Finally, participants must provide informed consent for this study, willingly participate, and sign the consent form. On the other hand, the exclusion criteria for this study were as follows: individuals with non-idiopathic scoliosis were excluded. Participants with growth and developmental disorders, or a history of nerve, muscle, and bone infections, psychological issues, etc., were also not included. Furthermore, individuals with obvious deformities of the lower limbs and feet, or those who had undergone major surgery in the past were not eligible for this study. The R package "pwr" was used to estimate the sample size (Franz Faul, University of Kiel, Kiel, Germany) for a two within-factor repeated measures design. The effect sizes for the side effect (η^2partial = 0.095) and the interaction effect (η^2partial = 0.032) were too small, so the sample size was calculated based on exercise type (η^2partial = 0.734, f = 1.081). According to the pilot study based on five subjects' values, the minimum sample size was obtained as 17 subjects with a power of 0.80, an alpha level of 0.05, and an effect size of f = 0.6 > 0.40 as large. The study was completed with a total of 24 subjects, and all subjects gave informed consent.

2.2. EMG Recording and Data Analysis

EMG data were collected using a Noraxon Ultium EMG sensor system (Noraxon USA, Inc., Scottsdale, AZ, USA) sampling frequency of 4000 Hz. per channel; gain: 1000 (signal to noise ratio; 1 μV RMS); common mode rejection rate (CMRR): −100 dB; input impedance >100 mΩ). Any hair on the skin was first removed, and then the area was cleansed with an alcohol swab before electrodes were connected to detect EMG signals. The electrodes were positioned bilaterally on the iliocostalis lumborum pars lumborum (convex side ICL and concave ICL) at the L3 level, midway between the lateral-most palpable border of the erector spinae and a vertical line through the posterosuperior iliac spine; on the longissimus thoracis (convex LT and concave LT) at the T9 level, midway between a line through the spinous process and a vertical line through the posterosuperior iliac spine, located approximately 5 cm laterally; and on the iliocostalis lumborum pars thoracis (convex ICT and concave ICT) at the T10 level, midway between the lateral-most palpable border of the erector spinae and a vertical line through the posterosuperior iliac spine [18]. The sample rate was set to 2000 Hz. Two filters were applied, including a band-pass filtered from 10 to 500 Hz using a first-order high-pass and fourth-order low-pass Butterworth filter to remove unacceptable artifacts and a notch filter (60 Hz) to eliminate noise. A moving 100-ms window was used to calculate the root mean square (RMS) values. The Noraxon MyoResearch XP program was used to process the data (version 3.16; Noraxon Inc., Scottsdale, AZ, USA). The data for each trial were expressed as a percentage of the calculated mean RMS of the MVIC (%MVIC), and the mean %MVIC of 3 trials was used for analysis [19].

2.3. Evaluation Protocol

To standardize the electromyographic (EMG) data, each muscle underwent maximal voluntary isometric contraction (MVIC). We recorded the EMG signal amplitude during these contractions. While the test postures mirrored those found in standard physical therapy manuals for muscle testing, we applied additional manual resistance to the back muscles. This progressive manual pressure was gradually increased to a maximum and held for five seconds. With a 30-s rest period between each repetition, each muscle was tested three times. Additionally, we checked the accuracy of electrode placement by scrutinizing the EMG amplitudes during these tests. Specifically, to assess the erector spinae muscles, we stabilized the participant's lower limbs while they performed maximal prone trunk extension, with resistance applied to the upper thoracic region [8,20]. Furthermore, the placement of the EMG electrodes was performed according to the guidelines provided by the SENIAM [21].

The exercises were performed in a controlled environment with adequate space and a non-slip surface. Each participant underwent an initial assessment to tailor the exercise to their specific scoliosis curve. The participant was seated with the spine in a neutral position. Participants then started the exercise by extending their spines. This involves lengthening the torso, focusing on creating space between the vertebrae. During the extension phase, the correct breathing technique is emphasized with inhalation from the convex side to the concave side following the corrective symmetric body position. The participant performs specific movements aimed at spinal de-rotation, side shifting in central position, and keeping neutral kypholordosis. This included lateral shifting, rotational movements or shoulder and pelvic adjustments until a symmetric body position was maintained. Throughout the exercise, the participant practiced scoliosis-specific 3-dimensional exercise-specific breathing and correction techniques. All three exercise types included elongation from caudal to cranial with neutral lumbar lordosis, thoracic kyphosis and fixed neck chin in position, breathing and self-correction directed from the convex side to the concave side of the body to facilitate de-rotation against the gibbosity side in the transverse plane. The side shifted from the convex side to the concave side in the frontal plane, and neutral and relaxed thoracic kyphosis and lumbar lordosis was maintained in the sagittal plane. All of this 3D protocol was then applied with manual resistance using hand rhythmic stimulation on the concave side (Figure 1A) and with self-resistance from the concave side to the convex side on participants with a TheraBand. In this position, the participant tries to pull himself into a symmetric position against resistance from a TheraBand (Figure 1B), with the TheraBand chosen based on OMNI-RES scores for each participant [22], and the other group used just breathing and self-correction (Figure 1C). To eliminate the learning effect and ensure randomization, each participant performed the exercises in a random order. In order to lessen the effects of tiredness, rest intervals of 30 s were permitted between each exercise repeat, and a minute-long break was provided between workouts.

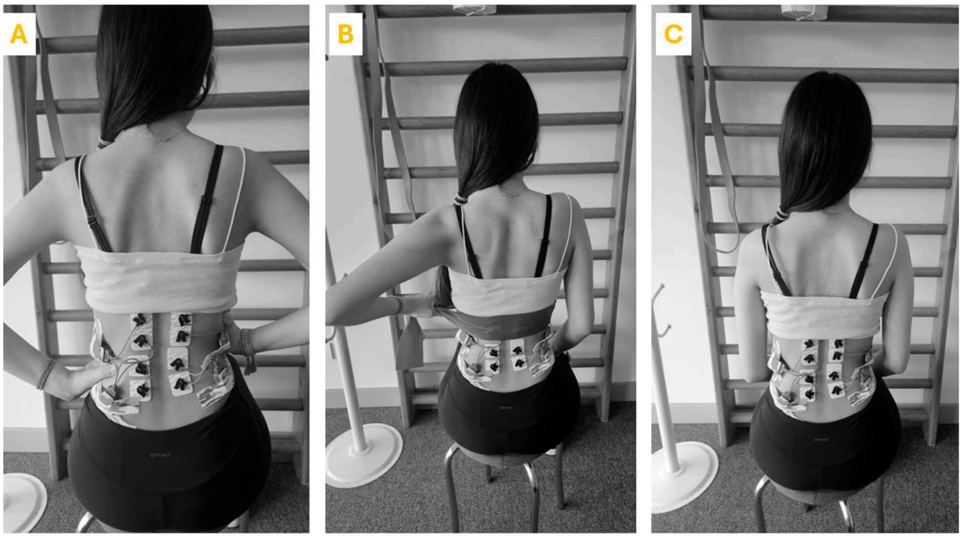

Figure 1. The 3D elongation self-correction exercises: (**A**) preferred manual resistance, (**B**) with TheraBand, and (**C**) without self-breathing.

2.4. Statistical Analyses

The data were summarized as frequency (percentage), mean ± standard deviation, and median (quartile 1–quartile 3) based on the type of variable. The two-way repeated measures design and two-way mixed design were used to evaluate the main (exercise, side, Cobb angle) and interaction effects (exercise side, exercise cobb angle). The main effects were examined when the interaction effect was not statistically significant. The Bonferroni-adjusted p-values were interpreted for all multiple comparisons. The effect size (f) was interpreted as follows: ≥0.40: large, 0.25–0.39: medium, 0.10–0.24: small effect size. The statistical analysis was conducted using R language (R Core Team, 2021) in R Studio 2022.02.3 and SPSS Version 21.0 (Armonk, NY, USA: IBM Corp.). The following R packages were used: "ggplot2" and "ggpubr".

3. Results

Descriptive characteristics of the participants are shown in Table 1.

Table 1. The descriptive statistics.

Variables	Frequency (%)	Mean ± SD	Median (Q1–Q3)
Age		14.5 ± 2.3	15 (13.3; 16)
Gender			
Girl	15 (62.5)		
Boy	9 (37.5)		
BMI		18.9 ± 3.1	18.2 (16.5; 20.6)
Menarche		13.1 ±1.4	13 (12; 15)
Exercise time		11.2 ± 8.3	7 (4.3; 21)
Corset	7 (29.2)		
Risser		2.3 ± 1.5	3 (1; 3)
Place of thoracic curvature			
Right	13 (54.2)		
Left	11 (45.8)		
Thoracic cobb angle		12.6 ± 2.2	13.5 (10.5; 16)

Table 1. *Cont.*

Variables	Frequency (%)	Mean ± SD	Median (Q1–Q3)
Thoracic gibosity angle		4.1 ± 3.6	4 (1; 6.8)
Lumbal direction			
Right	13 (54.2)		
Left	11 (45.8)		
Lumbar cobb angle		14.6 ± 13.6	18.6 (10; 20)
Lumbar gibosity angle		3.4 ± 5.2	2 (0; 4)
R-TESMVC		272.3 ± 149.9	247 (154.5; 329)
L-TESMVC		296.6 ± 171.4	257.5 (192.8; 326.8)
R-LESMVC		196.6 ± 94.2	178 (133.8; 242.3)
L-LESMVC		236.8 ± 151.6	231.5 (124.3; 273)

Data were summarized as frequency(percentage), mean ± standard deviation, median Quartile 1–Quartile 3. BMI: body mass index; R: right, L: left, TESMVC: Thoracic erector spina maximal voluntary isometric contraction; LESMVC: Lumbar erector spina maximal voluntary isometric contraction.

The interaction effects for both TES and LES were not significant (Figures 2 and 3 and Table 2). Therefore, the main effects were analyzed. The main effects for exercise and side are also reported in Table 2. For TES, all exercises were significantly different from each other. For LES, all exercises were significantly different from each other, and the sides were also significantly different.

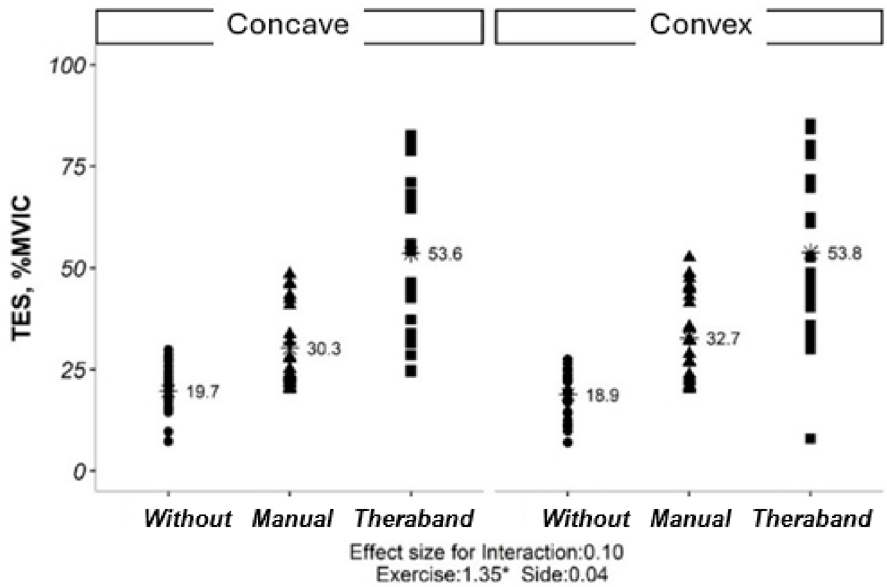

Figure 2. The values of TES muscle activity during the Without, Manual, and TheraBand self-correction exercises on concave and convex sides. TES: Thoracic erector spinae, %MVIC: the percentage of Maximal voluntary isometric contraction. The effect sizes for the interaction and main effects are presented. To indicate a statistically significant p-value ($p < 0.05$), the * icon was used. The p-values for the interaction, exercise, and side main effect were obtained as 0.097, <0.001, and 0.347; respectively.

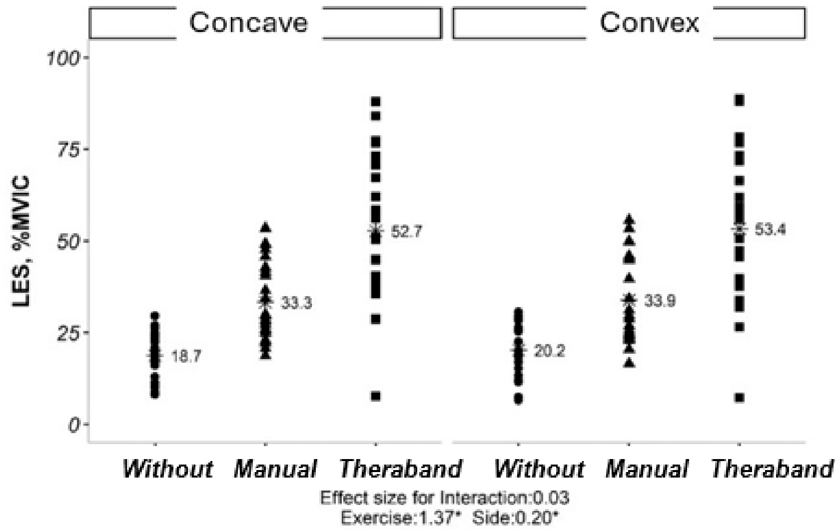

Figure 3. The values of LES muscle activity during the Without, Manual, and TheraBand self-correction exercises on concave and convex sides. LES: Lumbal erector spinae, %MVIC: the percentage of maximal voluntary isometric contraction. The effect sizes for the interaction and main effects are presented. To indicate a statistically significant *p*-value ($p < 0.05$), the * icon was used. The *p*-values for the interaction, exercise, and side main effect were obtained as 0.480, <0.001, and 0.026; respectively.

The multiple comparisons of the main effects for the measurements are summarized in Table 2.

Table 2. The mean difference for multiple comparisons of [3] %MVIC *.

	Exercise				Side	
	Without Manuel	**Without TheraBand**	**Manuel TheraBand**	***p*-Value**	**Concave /Convex**	***p*-Value**
TES [1]	−12.24	−34.41	−22.17	<0.001 for all	−0.60	0.347
LES [2]	−14.10	−33.56	−19.45		−0.89	0.026

[1] TES: Thoracic erector spinae, [2] LES: Lumbar erector spinae, [3] %MVIC: the percentage of Maximal voluntary isometric contraction. * All multiple comparison results based on the Bonferroni adjustment were statistically significant at the 0.05 level.

4. Discussion

The purpose of this study was to investigate the effects of three different exercise types on the electromyographic activity of both the thoracic and lumbar erector spinae muscles on the convex and concave sides of individuals with AIS. The results of this study showed that there were no significant interaction effects between exercise type and concave and convex sides for either the TES or LES muscles. This indicates that the effects of exercise on muscle activity were increased ($p < 0.001$) but not significantly different between the concave and convex sides. Previous studies have highlighted that EMG activity tends to be higher on the convex side of scoliotic curves, suggesting a potential link between this overactivation of paraspinal muscles and Adolescent Idiopathic Scoliosis (AIS) [9,14–16]. On the contrary, de Oliveira et al. (2011) found no significant differences in the electromyographic amplitudes of the erector spinae muscles between the convex and concave sides [23]. Similarly, Shiba et al. (2020) reported that there were no differences in multifidus and erector spinae muscle activation between the convex and concave sides of individuals with mild AIS and the control sides of healthy individuals [20]. Furthermore, there is research that demonstrates an increase in muscle activation while utilizing elastic bands during different exercises [24]. This discrepancy in findings may stem from methodological variances, such as differences in patient selection, a focus on specific types of scoliotic curves without adequate justification, or a failure to control for factors such as improper posture [25]. Considering these conflicting results, our study demonstrates that 3D exercises with corrective movements result in muscle activation on both the convex and concave sides. This finding indicates that isolated muscle activation cannot be achieved. When scoliosis-specific exercises are applied, muscle activation occurs concentrically on the convex side, while it occurs eccentrically on the concave side. This underscores the complexity of targeting muscle activation in scoliosis interventions, necessitating a holistic approach that accounts for both sides of the curvature. We specifically focused on dissecting the relationship between paraspinal muscle asymmetry and various types of scoliotic curves. This was done in response to previous studies that did not provide clear descriptions of curve classifications and recording levels, which could be crucial in understanding this relationship.

However, there was a significant main effect of exercise on both the TES and LES muscles. This means that the three different exercise types had different effects on muscle activity. The pairwise comparisons showed that all three exercise types were significantly different from each other for both the TES and LES muscles. The highest values were obtained for the TheraBand exercise, followed by the manual exercise, and finally, the without exercise condition. Marchese et al. [26] demonstrated that specific exercises tailored to individual curve patterns in scoliosis led to greater improvements in trunk muscle strength and endurance compared to generic exercises. This aligns with the present study's finding that different exercise types elicit different responses. Bialek et al. [27] found TheraBand exercises effective in increasing paraspinal muscle activity in individuals with scoliosis, supporting the present study's observation of higher activation with a TheraBand. They propose that the elastic resistance of TheraBand provides progressive overload, potentially explaining its effectiveness. This result supported our research in which participants tried to pull the concave side until they aligned and maintained a central position against the continuous resistance of a TheraBand. After concentric contraction, they had to maintain control with eccentric contraction until the end of the exercises. Fan et al. [28] highlighted the importance of exercise specificity and dosage in scoliosis management. They emphasized the need for individualized programs considering curve type, severity, and muscle imbalances. The present study reinforces this, suggesting varying activation patterns across exercises. This paragraph showcases the study's key finding: exercise type plays a crucial role in muscle activation for individuals with scoliosis. The specific exercise chosen can significantly impact the level of engagement, with the TheraBand option proving the most effective in this study. This information can be valuable for healthcare professionals designing targeted exercise programs to address specific muscle activation needs in individuals with scoliosis.

There was also no significant interaction effect between exercise type and convex concave side for either the TES or LES muscles. This indicates that the effects of exercise on muscle activity were not significantly different between individuals with thoracic and lumbar regions on the convex and concave sides. The pathological underpinnings of scoliosis extend far beyond the simple quantification of the Cobb angle. Recent research highlights the multifactorial nature of the condition, encompassing not just curvature severity but also neuromuscular control deficits and biomechanical imbalances [29]. This inherent complexity might explain the observed consistency in exercise-induced muscle activation across varying Cobb angles. Importantly, this study prioritizes assessing muscle activation itself, distinct from directly targeting Cobb angle correction. While Cebellos-Laita et al. [30] suggest specific exercises can influence Cobb angle, others, Mohamed et al. [31] emphasize the disassociation between muscle activation and curvature correction. This underscores the crucial need for research that delves into both aspects separately. Furthermore, the present study focuses on the short-term dynamics of muscle activation, excluding the long-term trajectory of Cobb angle progression. Long-term studies hint at the potential of exercise to prevent curve progression, but further exploration is necessary to elucidate the nuanced effects of specific exercise types on different Cobb angle presentations [32].

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These results suggest that all three exercise types can be effective in increasing muscle activity in individuals with scoliosis. However, the TheraBand exercise appears to be the most effective, followed by the manual exercise, and finally, the without exercise condition. These findings may have implications for the design of exercise programs for individuals with scoliosis. However, according to this research, we found that short-term muscle activation initially and long-term Cobb angle progression require further study in this area.

This study had several limitations. First, the sample size was relatively small. Future studies with larger sample sizes are needed to confirm these findings. Second, the study included only individuals with mild to moderate scoliosis. Future studies should investigate the effects of exercise on individuals with more severe scoliosis. The study focused on short-term exercise effects, suggesting that future research should explore long-term effects on muscle activity and Cobb angle in individuals with scoliosis, also using superfacial electrodes for muscle activation, and analyzing deep muscle activation could be helpful.

5. Conclusions

The results of this study suggest that all three exercise types can be effective in increasing muscle activity in the thoracic and lumbar regions in convex and concave side individuals with scoliosis. However, the TheraBand exercise appears to be the most effective, followed by the manual exercise, and finally, the without exercise condition. These findings may have implications for the design of exercise programs for individuals with scoliosis.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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