Spine Deformity
https://doi.org/10.1007/s43390-025-01075-2

AIS

Trunk endurance differences between female adolescents with and without idiopathic scoliosis

Hanh Thi Nguyen[1] · Thanh-Van Le[2,4] · Tan Minh Pham[1] · Hieu Kim Huynh[5] · Philippe Mahaudens[6] · Ngoc-Minh Nguyen[2,3]

Received: 21 December 2024 / Accepted: 28 February 2025
© The Author(s), under exclusive licence to Scoliosis Research Society 2025

Abstract

Purpose This study compared trunk muscle endurance between female adolescents with idiopathic scoliosis (AIS) and non-AIS groups.

Methods This cross-sectional study included 91 females. Trunk muscle endurance was assessed using the Ito-Shirado and Biering-Sørensen tests. Anthropometric and radiographic data were collected. The Mann–Whitney *U* test compared endurance and abdominal-to-paraspinal endurance ratio between groups. Spearman's correlation assessed relationships between endurance and participant characteristics.

Results The AIS group's performance on the Ito-Shirado and Biering-Sørensen tests was 57% and 68% of the non-AIS group's test durations, respectively ($p = 0.001$). However, there was no significant difference in the abdominal-to-paraspinal endurance ratio between the two groups ($p = 0.7$). Additionally, a low negative correlation was observed between paraspinal muscle endurance and both weight (rho = − 0.29, $p = 0.006$)) and BMI (rho = − 0.3, $p = 0.005$) in the AIS group, while abdominal endurance correlated negatively with height (rho = − 0.25, $p = 001$).

Discussion Females with AIS exhibit significantly reduced endurance in both paraspinal and abdominal muscles compared to healthy controls, despite maintaining a similar abdominal-to-paraspinal endurance ratio. The findings suggest the need for trunk muscle endurance evaluation and training in rehabilitation programs for individuals with AIS.

Keywords Adolescent idiopathic scoliosis · Trunk endurance · Ito-Shirado · Biering-Sørensen · Abdominal-To-Paraspinal endurance ratio

Hanh Thi Nguyen and Thanh-Van Le shared the role of co-first authors for this work.

✉ Ngoc-Minh Nguyen
minhngpt@ump.edu.vn

Hanh Thi Nguyen
nthihanh@dhktyduocdn.edu.vn

Thanh-Van Le
lethanhvan@ump.edu.vn

Tan Minh Pham
pmtan@dhktyduocdn.edu.vn

Hieu Kim Huynh
hkhieu@ctump.edu.vn

Philippe Mahaudens
philippe.mahaudens@saintluc.uclouvain.be

[1] Faculty of Rehabilitation, Da Nang University of Medical Technology and Pharmacy, Da Nang, Vietnam

[2] Department of Rehabilitation, Faculty of Nursing and Medical Technology, University of Medicine and Pharmacy at Ho Chi Minh City, 72713 Ho Chi Minh, Vietnam

[3] Institut de Recherche Experimental Et Clinique (IREC), Pneumology, ENT and Dermatology Pole (LUNS), Université Catholique de Louvain (UCLouvain), Brussels, Belgium

[4] Institute of Neuroscience, Université Catholique de Louvain, Louvain-La-Neuve, Belgium

[5] Department of Orthopedics, Can Tho University of Medicine and Pharmacy, Can Tho, Vietnam

[6] Institut de Recherche Experimentale Et Clinique (IREC), Neuromusculoskeletal Pole (NMSK), Université Catholique de Louvain (UCLouvain), Brussels, Belgium

Published online: 21 March 2025

Introduction

Idiopathic scoliosis is a complex and debilitating spinal deformity that affects around 3% of adolescents worldwide [1]. This condition, with no known underlying cause, can lead to a visible and progressively worsening curvature of the spine during the critical developmental period of children [2]. Almost 10% of those with idiopathic scoliosis require more intensive treatments, such as bracing or surgery, to prevent the curvature from continuing to worsen and potentially causing further serious complications [3]. Adolescent idiopathic scoliosis (AIS) can cause significant discomfort during basic activities, psychological difficulties [4], a decreased range of motion [1], and lead to abnormal ventilation patterns [5]. The progression of spinal curvature is more common in adolescent girls and can eventually lead to severe pain, decreased mobility, and other serious health issues [3, 4]. Patients with a Cobb angle of 20° have a 10% risk of progression, which steeply increases to a staggering 70% in children with curves greater than 20° and skeletal immaturity [6]. The progression of spinal curvature in scoliosis has been attributed to numerous complex and interrelated factors, including diminished muscle strength and endurance, as well as skeletal immaturity, vertebral rotation, and asymmetrical growth patterns [6]. Among these multifaceted contributors, impairments in trunk muscle performance are thought to play a particularly critical role in the progression of this debilitating condition, potentially exacerbating the spinal deformity, and related symptoms [7].

Several studies have suggested the important role of paraspinal muscles in idiopathic scoliosis development [8]. While some evidence indicates that the paraspinal muscles are directly involved in the onset of this condition, another has observed structural changes in these muscles as the disease progresses [9]. However, there is no consensus on whether the paraspinal muscles directly influence the onset and progression of scoliosis or if the changes in muscle fibers, strength, and electromyographic activity are secondary effects of the disease. Regarding the abdominal muscles, this muscle group is considered to have a role in stabilizing the trunk and minimizing compressive force on the lumbar spine [10]. Maintaining good abdominal muscle strength helps stabilize the trunk and protect the lumbar spine and related structures from damage when bearing loads [11]. While the deficit in trunk muscle strength among patients with AIS has been well investigated, leading to better interventions [12], trunk muscle endurance has not yet received the same level of attention. Additionally, despite the reported trunk imbalance [13], there is a lack of evidence clarifying the relationship between the abdominal and paraspinal muscles. Therefore, this study aimed to investigate the differences in muscle endurance and abdominal-paraspinal endurance ratio between adolescents with and without idiopathic scoliosis. The secondary aim of this study was to investigate the correlation between trunk muscle endurance and demographic characteristics in the AIS group.

Methods

Ethnic statement

This cross-sectional study was approved by the Ethics Committee in Biomedical Research of the University of Medicine and Pharmacy at Ho Chi Minh City, with approval number 233/HĐĐĐ-ĐHYD dated February 28, 2022. All participants and their parents or legal guardians provided informed consent to participate in the study.

Participants

The sample size required for each group was calculated to be 38, based on the specified criteria of detecting a minimum difference of 5 s between the means of two samples, with a 95% confidence interval and 80% statistical power, and a population variance of 60 [14]. To account for an estimated 10% dropout rate, the sample size for each group was increased to 42 participants. The study included two groups: an AIS group and a control group without AIS. The CONSORT report guidelines were used to report the study's participant selection and allocation.

The study included female participants aged 10 to 18 years who had been diagnosed with AIS by orthopedists at public or private clinics in Ho Chi Minh City and Da Nang City.

The inclusion criteria were children with a Cobb angle greater than 10 degrees accompanied by vertebral rotation observed on standing full spine X-ray [15]. The Risser sign on the X-ray was ≤ 4 [16]. The exclusion criteria for this group were children with neurological disorders, previous spinal surgery, or those indicated for surgery, as well as those who had received exercise treatment for 2 months or more.

The non-AIS group consisted of female volunteers aged 10 to under 18 years, randomly selected from the community, with a scoliometer measurement of less than 5 degrees on Adam's forward bending test [17]. The exclusion criteria for this group were children with previous spinal disorders, trauma such as spinal fractures, tumors, infections, or signs of cauda equina syndrome.

Protocol

The demographic characteristics data, including age, height, weight, and body mass index were collected for all participants. Cobb angle was radiologically obtained in the AIS group only. Then, the Ito-Shirado [18] and Biering-Sørensen [19] tests were used to assess the endurance of the trunk flexor and extensor muscles, respectively in both groups. Before the experimental trials, subjects underwent a familiarization phase comprising practice trials to assimilate the procedural protocols. An inter-trial rest period of 5 min was allocated between each practice trial to ensure optimal recuperation of the subjects for the subsequent test. The termination criteria for the tests included the subject's inability to maintain the required static position, manifestation of pain, or the onset of excessive fatigue precluding continuation of the exercise. To minimize potential performance bias, the experimenter refrained from providing any verbal encouragement throughout the tests.

The Ito-Shirado test

For the Ito-Shirado test [18], participants were positioned supine with their trunk supported on the table and their hips and knees flexed at 90 degrees. During the pre-test phase, the examiner manually stabilized the participants' distal lower extremities to ensure standardized positioning. To assess abdominal muscle endurance, the participants were instructed to maintain the trunk in a 30-degree flexed position relative to the table surface for as long as possible. The duration of this hold was recorded. The test area was covered with a soft mat to ensure participant comfort and safety.

The Biering-Sørensen test

For the Biering-Sørensen test [19], the participants were positioned in a prone orientation on the examination table, with the superior border of their iliac crests aligned with the table's edge, allowing the unsupported portion of the trunk to extend beyond this point. The lower extremities were immobilized on the table surface using standardized strapping techniques. An auxiliary table was positioned anteriorly to the participants, providing a support mechanism for pre-test stabilization and test termination. To assess back extensor muscle endurance, participants were instructed to maintain the trunk in a horizontal position, parallel to the floor, for the maximum duration possible. The time to task failure was recorded as the primary outcome measure. Assessors remained in close proximity to the participants to ensure safety throughout the procedure. All assessments were conducted by investigators involved in this study to maintain methodological consistency.

Data analysis

The data analysis was conducted using STATA 14. The Shapiro–Wilk test was used to assess the normality of the participants' data distribution. Patient demographic variables were compared between the AIS and non-AIS groups using the Student's *t*-test. The duration of the Ito-Shirado and Biering-Sørensen tests was compared between the two groups using either Student's *t*-test or the Mann–Whitney *U* test, depending on the data distribution. The abdominal-to-paraspinal endurance ratio was calculated by dividing the Ito-Shirado test duration by the Biering-Sørensen test duration and this ratio was also compared between the two groups using either the Student's *t*-test or the Mann–Whitney *U* test. The correlation between the Ito-Shirado and Biering-Sørensen tests with demographic characteristics in the AIS group was checked with Pearson's or Spearman's correlation coefficients. The correlation is typically classified as low when $r < 0.5$, moderate when between 0.5 and 0.69, and high when 0.7 or greater [20]. A *p*-value less than 0.05 was considered statistically significant.

Results

Demographic

The study included 91 female participants, 45 in the AIS group and 46 in the non-AIS group (Fig. 1). The two groups differed significantly in age (0.8 years) and height (4 cm), but their weight and body mass index were similar, with most participants in both groups having a normal BMI (Table 1).

The difference in trunk endurance between the two groups

The Mann–Whitney *U* test revealed significantly shorter durations in the Ito-Shirado and Biering-Sørensen tests for the AIS group compared to the non-AIS group (Table 2). The Ito-Shirado and Biering-Sørensen test durations in the AIS group were 57% and 68% of the non-AIS group, respectively (Fig. 2). No significant difference in the abdominal-to-paraspinal endurance ratio between the two groups was observed (Table 2).

Correlations

In the AIS group, Spearman's rho correlation analysis found a low negative correlation between paraspinal muscle

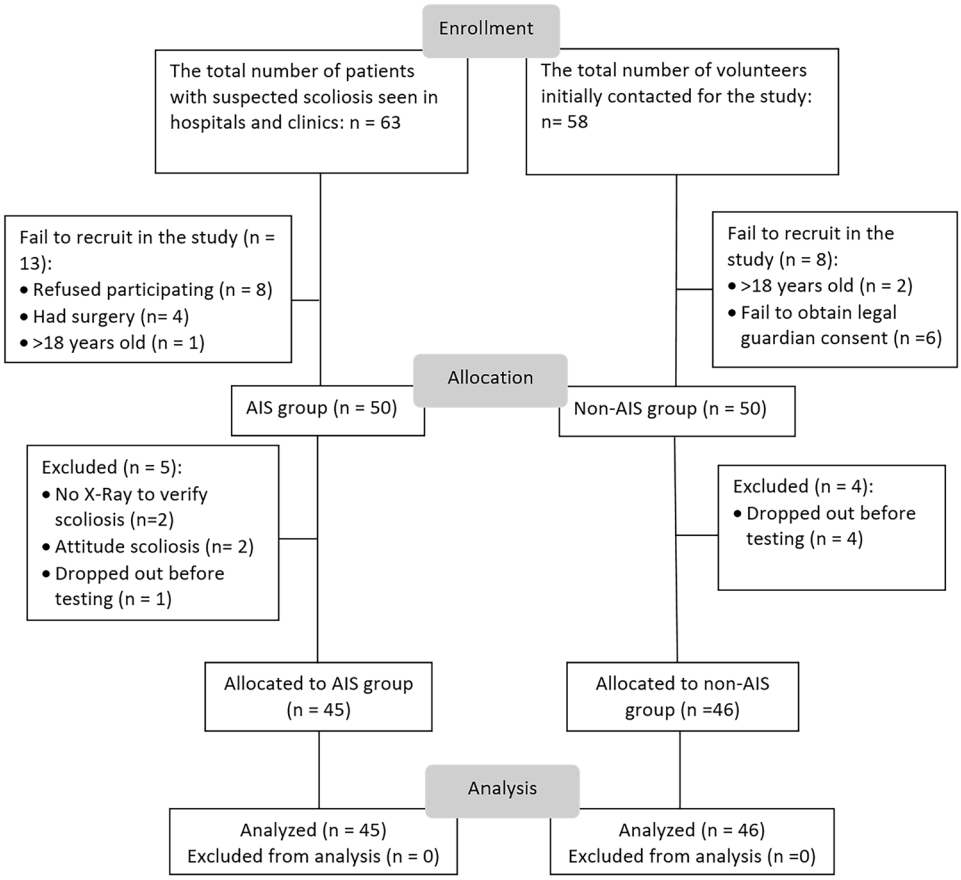


Fig. 1 The CONSORT diaphragm of participants' selection and allocation. AIS: adolescents with idiopathic scoliosis

Table 1 The anthropometric and radiographic characteristics of all participants

		AIS ($n=45$)	Non-AIS ($n=46$)	p*
Age (year)		13.3 ± 1.87■	12.4 ± 1.75■	0.02
Height (m)		1.54 ± 0.08■	1.50 ± 0.07■	0.01
Weight (kg)		43.5 ± 7.63■	40.4 ± 7.71■	0.05
BMI		18.2 ± 2.52■	17.9 ± 3.13■	0.60
BMI range (%)	Underweight	13.3	13.0	–
	Normal weight	73.3	67.4	–
	Overweight	13.3	15.2	–
	Obesity	0	4.4	–
Cobb angle (degree)		23.6 (10–45)◆	–	–
Cobb angle groups (%)	Cobb ≤ 20°	51.1	–	–
	20° < Cobb < 40°	37.8	–	–
	Cobb ≥ 40°	11.1	–	–
Risser (%)	Stage 0	22.2	–	–
	Stage 1	11.1	–	–
	Stage 2	20.0	–	–
	Stage 3	28.9	–	–
	Stage 4	17.8	–	–

■: The data with normal distribution was demonstrated in Mean ± S.D

◆: The data without normal distribution was demonstrated in median (min–max)

AIS adolescents with idiopathic scoliosis, *BMI* body mass index

*: p value of Student's t-test

Table 2 Median and range values for Biering–Sørensen test and Ito-Shirado test for two groups

	AIS ($n=45$)	Non-AIS ($n=46$)	p*
Biering–Sørensen's test (sec)	82 (26–170)	121 (37–240)	0.001
Ito–Shirado's test (sec)	34 (7–114)	60 (24–240)	0.001
Ito–Shirado's test/ Biering–Sørensen's test	0.52 (0.13–1.79)	0.53 (0.24–1.46)	0.7

The data was demonstrated in Median (min–max)

AIS adolescents with idiopathic scoliosis

*: p value of Mann–Whitney U Test

endurance and weight as well as BMI. In contrast, abdominal muscle endurance, measured by the Ito-Shirado test, only negatively correlated with height (Table 3).

Discussion

This study demonstrated that individuals with AIS exhibited significantly lower trunk muscle endurance than their healthy, non-AIS peers. The result indicated lower endurance in both abdominal and paraspinal muscles in the AIS group. Notably, despite the AIS group in our study being significantly older than the non-AIS group, they exhibited poorer trunk endurance, which contrasts with the typical increase in muscle endurance observed during adolescence [21]. The reduced trunk muscle endurance in AIS may be due to their lower body mass, long limbs [22], and delayed puberty [23]. These features can impair muscle development compared to non-AIS peers. Furthermore, a previous study has shown that children with AIS exhibit altered paraspinal muscle morphology and composition, likely reducing these muscles' capacity for prolonged activation and endurance [9].

The spinal deformity in AIS may also cause asymmetrical loading and biomechanical changes, leading to imbalanced muscle activation and endurance [24, 25]. Additionally, AIS patients often experience impaired proprioception, and poor postural control, which may contribute to their reduced trunk muscle endurance [26]. For instance, a previous study has shown that impaired proprioception and central integration can lead to poor motor response in children with AIS [27]. Structural changes in the paraspinal muscles may result in compensatory adaptations in other trunk muscles, as the body attempts to maintain stability. Previous studies have shown that reduced lumbar muscle endurance can lead to compensatory recruitment of abdominal muscles to stabilize the trunk, as seen in young adults with chronic low back pain

Table 3 Correlation between trunk muscle endurance and participant characteristics in the AIS group

	Biering–Sørensen's test		Ito–Shirado's test	
	rho	p	rho	p
Age	0.08	0.44	− 0.15	0.15
Height	− 0.10	0.34	− 0.25	**0.02**
Weight	− 0.29	**0.006**	− 0.19	0.07
BMI	− 0.30	**0.005**	− 0.08	0.46
Cobb angle	0.11	0.50	− 0.02	0.92
Ito-Shirado's test	0.54	**0.001**	1	–
Biering – Sørensen's test	1	–	0.54	**0.001**

Bold: $p < 0.05$

AIS adolescents with idiopathic scoliosis

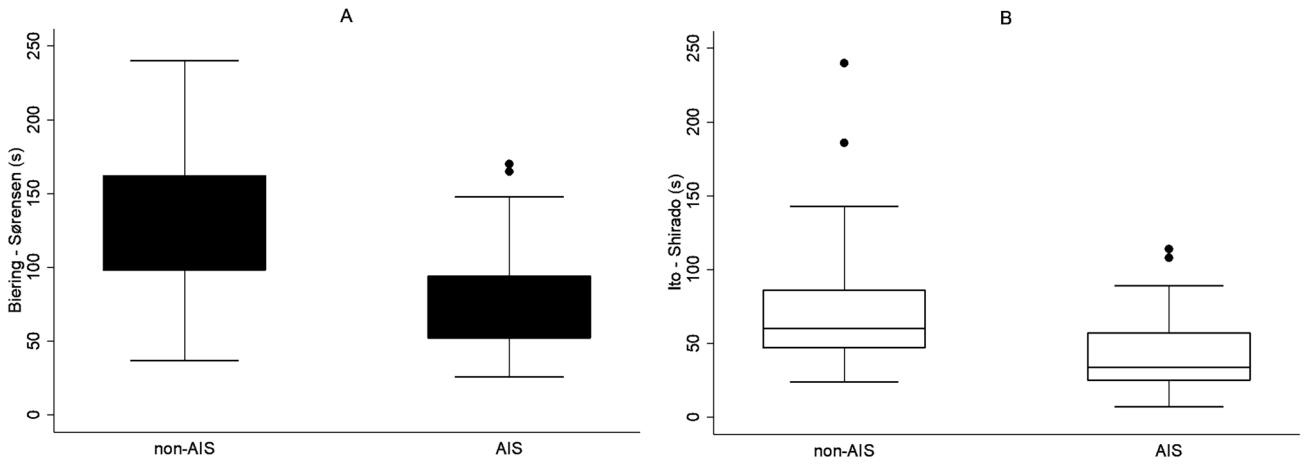


Fig. 2 Differences in paraspinal and abdominal muscle endurance in the AIS and non-AIS groups by the Biering-Sørensen (**A**) and Ito-Shirado (**B**) tests. AIS: adolescents with idiopathic scoliosis

[28]. This compensatory mechanism may place additional demands on abdominal muscles, partially explaining the generalized impairment in trunk endurance observed in AIS and supporting the need for comprehensive endurance training that addresses both paraspinal and abdominal stability.

This study observed that the difference in abdominal muscle endurance was greater than in paraspinal muscle endurance between the two groups. However, the difference may not be significant, as this study observed a similar abdominal-to-paraspinal endurance ratio between the two groups, suggesting that the reduced trunk muscle endurance in AIS is not limited to a specific muscle group, but rather a more generalized impairment. This finding was similar to a previous study examining the abdominal-to-paraspinal muscle strength ratio in children with AIS [12]. This indicates that both the abdominal and paraspinal muscle groups can be affected, potentially due to the three-dimensional nature of the spinal deformity in AIS [29]. The moderate correlation observed between abdominal and paraspinal muscle endurance in this study further supports the finding of a generalized impairment in trunk muscle endurance among individuals with AIS. Therefore, the results of this study support the idea of comprehensive muscle training without emphasizing any single muscle group in the AIS population [30]. Besides, the poorer trunk muscle endurance seen in this study suggests the need for endurance evaluation and training in rehabilitation for AIS.

The negative correlation between paraspinal muscle endurance and weight/BMI in the AIS group suggests that excess body weight may influence back extensor performance. Higher BMI has been shown to increase localized muscle fatigue, particularly in back extensors, as it places an additional load on these muscles [31]. In contrast, abdominal muscle endurance was only correlated with height. However, these findings may not be clinically significant due to the low correlations and the relatively small range of height variation and normal body weights among participants. The findings of this study did not show a correlation between the Cobb angle and trunk endurance, contradicting prior research that found a relationship between the Cobb angle and trunk muscle strength [32]. However, the findings aligned with a recent study that reported no correlation between the severity of spinal curvatures and the electromyographic activity of the bilateral paraspinal muscles [33]. This discrepancy may be due to the distinction in neuromuscular adaptations between endurance and strength [34] or the limited number of participants with severe AIS (Cobb angle > 40°) in our study, which may have restricted the ability to detect significant correlations. To our knowledge, this is the first study to investigate the trunk endurance deficit in adolescents with AIS, leading to a lack of comparative studies. Therefore, this study suggests evaluating the endurance of the trunk muscles for potential training.

This study has several limitations. Due to the design of this study, we cannot confirm whether poor trunk muscle endurance influences the curve progression in AIS. Additionally, including participants with Risser grade 4, indicating the cessation of spinal growth, may limit the confidence in the observed differences in muscle endurance between the AIS and non-AIS groups during the earlier developmental stages, where muscle adaptation to curvature might differ. Future studies should include a broader range of growth stages to understand better endurance patterns in developing AIS populations. Another limitation of this study is the lack of data on participants' physical activity levels, which could influence trunk muscle performance, despite the current evidence on this topic being debatable [35, 36]. Another potential limitation is that the employed tests alone do not allow for the separate evaluation of muscles on each side of the spine, instead providing only a global assessment of endurance issues.

Conclusion

This study reported that females with AIS, exhibit significantly lower paraspinal and abdominal muscle endurance compared to their healthy, non-AIS peers. However, the similar abdominal-to-paraspinal endurance ratio between the two groups suggests a generalized endurance impairment rather than a muscle-specific deficit. While this study did not establish a direct link between curve severity and endurance deficits, the limited number of participants with severe scoliosis (Cobb angle > 40°) highlights the need for further research. These findings suggest the need for comprehensive trunk muscle endurance training in the rehabilitation of patients with AIS.

Author contributions Conceptualization: Philippe Mahaudens, Thanh-Van Le, Ngoc-Minh Nguyen, Hanh Thi Nguyen; methodology: Thanh-Van Le, Ngoc-Minh Nguyen, Hanh Thi Nguyen; formal analysis and investigation: Ngoc-Minh Nguyen, Hanh Thi Nguyen, Hieu Kim Huynh, Tan Minh Pham; writing—original draft preparation: Thanh-Van Le, Ngoc-Minh Nguyen; writing—review and editing: Philippe Mahaudens, Thanh-Van Le, Ngoc-Minh Nguyen, Hanh Thi Nguyen, Tan Minh Pham, Hieu Kim Huynh; Supervision: Tan Minh Pham, Hieu Kim Huynh.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Conflict of interest The authors have no conflicts of interest to declare and that they have no financial interests.

Ethical approval This cross-sectional study was approved by the Ethics Committee in Biomedical Research of the University of Medicine and Pharmacy at Ho Chi Minh City, with approval number 233/HĐĐĐ-

ÐHYD dated February 28, 2022. All participants and their parents or legal guardians provided informed consent to participate in the study.

References

1. Weinstein SL (2019) The natural history of adolescent idiopathic scoliosis. J Pediatr Orthop 39:S44–S46. https://doi.org/10.1097/BPO.0000000000001350
2. Tan KJ, Moe MM, Vaithinathan R et al (2009) Curve progression in idiopathic scoliosis: follow-up study to skeletal maturity. Spine (Phila Pa 1976) 34:697–700. https://doi.org/10.1097/BRS.0b013e31819c9431
3. El-Hawary R, Chukwunyerenwa C (2014) Update on evaluation and treatment of scoliosis. Pediatr Clin North Am 61:1223–1241. https://doi.org/10.1016/j.pcl.2014.08.007
4. Gallant JN, Morgan CD, Stoklosa JB et al (2018) Psychosocial difficulties in adolescent idiopathic scoliosis: body image, eating behaviors, and mood disorders. World Neurosurg 116(421–432):e421. https://doi.org/10.1016/j.wneu.2018.05.104
5. Martinez-Llorens J, Ramirez M, Colomina MJ et al (2010) Muscle dysfunction and exercise limitation in adolescent idiopathic scoliosis. Eur Respir J 36:393–400. https://doi.org/10.1183/09031936.00025509
6. Peterson L-E, Nachemson AL (1995) Prediction of progression of the curve in girls who have adolescent idiopathic scoliosis of moderate severity. Logistic regression analysis based on data from The Brace Study of the Scoliosis Research Society. JBJS 77:823–827. https://doi.org/10.2106/00004623-199506000-00002
7. He Y, Dong H, Lei M et al (2024) The role of the paraspinal muscles in the development of adolescent idiopathic scoliosis based on surface electromyography and radiographic analysis. BMC Musculoskelet Disord 25:263. https://doi.org/10.1186/s12891-024-07329-w
8. Weinstein SL, Dolan LA, Cheng JC et al (2008) Adolescent idiopathic scoliosis. Lancet 371:1527–1537. https://doi.org/10.1016/S0140-6736(08)60658-3
9. Shahidi B, Yoo A, Farnsworth C et al (2021) Paraspinal muscle morphology and composition in adolescent idiopathic scoliosis: a histological analysis. JOR Spine 4:e1169. https://doi.org/10.1002/jsp2.1169
10. Richardson C, Toppenberg R, Jull G (1990) An initial evaluation of eight abdominal exercises for their ability to provide stabilisation for the lumbar spine. Aust J Physiother 36:6–11. https://doi.org/10.1016/S0004-9514(14)60514-6
11. Gur G, Ayhan C, Yakut Y (2017) The effectiveness of core stabilization exercise in adolescent idiopathic scoliosis: a randomized controlled trial. Prosthet Orthot Int 41:303–310. https://doi.org/10.1177/0309364616664151
12. Minjollet L, Abelin-Genevois K, De Chelle G et al (2021) Are trunk muscles weaker in adolescent females with adolescent idiopathic scoliosis compared with their healthy counterparts? Isokinet Exerc Sci 29:419–427. https://doi.org/10.3390/jcm13030653
13. Fortin C, Grunstein E, Labelle H et al (2016) Trunk imbalance in adolescent idiopathic scoliosis. Spine J 16:687–693. https://doi.org/10.1016/j.spinee.2016.02.033
14. Del Águila MR, González-Ramírez A (2014) Sample size calculation. Allergol Immunopathol (Madr) 42:485–492. https://doi.org/10.1016/j.aller.2013.03.008
15. Reamy BV, Slakey JB. Adolescent idiopathic scoliosis: review and current concepts. Am Fam Physician 2001; 64:111–116. https://www.ncbi.nlm.nih.gov/pubmed/11456428
16. Zaoussis AL, James JI (1958) The iliac apophysis and the evolution of curves in scoliosis. J Bone Joint Surg Br 40-B:442–453. https://doi.org/10.1302/0301-620X.40B3.442
17. Roach JW (1999) Adolescent idiopathic scoliosis. Orthop Clin North Am 30:353–365. https://doi.org/10.1016/s0030-5898(05)70092-4
18. Ito T, Shirado O, Suzuki H et al (1996) Lumbar trunk muscle endurance testing: an inexpensive alternative to a machine for evaluation. Arch Phys Med Rehabil 77:75–79. https://doi.org/10.1016/s0003-9993(96)90224-5
19. Biering-Sørensen F (1984) Physical measurements as risk indicators for low-back trouble over a one-year period. Spine (Phila Pa 1976) 9:106–119. https://doi.org/10.1097/00007632-198403000-00002
20. Mukaka MM. Statistics corner: A guide to appropriate use of correlation coefficient in medical research. Malawi Med J 2012;24:69–71. https://www.ncbi.nlm.nih.gov/pubmed/23638278
21. Parreira RB, de Oliveira MR, Amorim CF et al (2014) Older adults present better back endurance than young adults during a dynamic trunk extension exercise. J Back Musculoskelet Rehabil 27:153–159. https://doi.org/10.3233/BMR-130430
22. Cheung CSK, Lee WTK, Tse YK et al (2003) Abnormal peripubertal anthropometric measurements and growth pattern in adolescent idiopathic scoliosis: a study of 598 patients. Spine (Phila Pa 1976) 28:2152–2157. https://doi.org/10.1097/01.BRS.0000084265.15201.D5
23. Mao S-h, Jiang J, Sun X et al (2011) Timing of menarche in Chinese girls with and without adolescent idiopathic scoliosis: current results and review of the literature. Eur Spine J 20:260–265. https://doi.org/10.1007/s00586-010-1649-6
24. Schlager B, Krump F, Boettinger J et al (2018) Characteristic morphological patterns within adolescent idiopathic scoliosis may be explained by mechanical loading. Eur Spine J 27:2184–2191. https://doi.org/10.1007/s00586-018-5622-0
25. Gonzalez-Ruiz JM, Perez-Nunez MI, Garcia-Alfaro MD et al (2021) Geometric morphometrics of adolescent idiopathic scoliosis: a prospective observational study. Eur Spine J 30:612–619. https://doi.org/10.1007/s00586-020-06583-5
26. Smania N, Picelli A, Romano M et al (2008) Neurophysiological basis of rehabilitation of adolescent idiopathic scoliosis. Disabil Rehabil 30:763–771. https://doi.org/10.1080/17483100801921311
27. Le Berre M, Guyot M-A, Agnani O et al (2017) Clinical balance tests, proprioceptive system and adolescent idiopathic scoliosis. Eur Spine J 26:1638–1644. https://doi.org/10.1007/s00586-016-4802-z
28. Wang H, Zheng J, Fan Z et al (2022) Impaired static postural control correlates to the contraction ability of trunk muscle in young adults with chronic non-specific low back pain: a cross-sectional study. Gait Posture 92:44–50. https://doi.org/10.1016/j.gaitpost.2021.11.021
29. Stokes IA. Three-dimensional terminology of spinal deformity. A report presented to the Scoliosis Research Society by the Scoliosis Research Society Working Group on 3-D terminology of spinal deformity. Spine (Phila Pa 1976) 1994;19:236–248. https://www.ncbi.nlm.nih.gov/pubmed/8153835
30. Kelly JJ, Shah NV, Freetly TJ et al (2018) Treatment of adolescent idiopathic scoliosis and evaluation of the adolescent patient. Curr Orthop Pract 29:424–429
31. Mehta RK, Cavuoto LA (2017) Relationship between BMI and fatigability is task dependent. Hum Factors 59:722–733. https://doi.org/10.1177/0018720817695194
32. Minehisa K, Nara I, Endoh T (2003) Muscle strength and electromyography of paraspinal muscles during isokinetic exercise in adolescent idiopathic scoliosis. J Phys Ther Sci 15:105–111

33. Mahaudens P, Dalemans F, Banse X et al (2018) Gait in patients with adolescent idiopathic scoliosis. Effect of surgery at 10 years of follow-up. Gait Posture 61:141–148. https://doi.org/10.1016/j.gaitpost.2018.01.007
34. Eklund D, Pulverenti T, Bankers S et al (2015) Neuromuscular adaptations to different modes of combined strength and endurance training. Int J Sports Med 36:120–129. https://doi.org/10.1055/s-0034-1385883
35. Šidlauskienė A, Strukcinskiene B, Raistenskis J et al (2019) The association between the level of physical activity with spinal posture and physical fitness parameters in early adolescence. Vojnosanit Pregl 76:1209–1216. https://doi.org/10.2298/VSP170517098S
36. Bayraktar D, Özyürek S, Genç A (2015) The relationship between isometric trunk muscle endurance and physical activity related energy expenditure in healthy young adults. J Back Musculoskelet Rehabil 28:859–864. https://doi.org/10.3233/BMR-150618

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.