



OPEN Hyperlaxity and low bone mass predispose young female gymnasts to develop scoliosis suspected status

Gali Dar^{1,2✉}, Liav Elbaz^{1,3}, Tamar Vilnai⁴, Danny Ben-Zvi^{4,5}, Mor Grinstein⁶ & Nili Steinberg³

This study aimed to examine the association between scoliosis and musculoskeletal characteristics in young female gymnasts and to develop a model for predicting scoliosis. The study included 274 female gymnasts: 154 rhythmic, 60 acrobatic, and 60 artistic, aged 10–16 years. Participants were assessed for age, height, weight, and pubertal stage. Each participant was identified for scoliosis suspected status (Adam's test and scoliometer) and examined for muscle strength, joint range of motion, hyperlaxity, bone strength, and skeletal age. Hours of training/week and years of training were recorded. The results revealed that 79/274 (28.8%) gymnasts had scoliosis suspected status without a significant difference between gymnast disciplines ($p = 0.09$). The scoliosis suspected status was associated with hyperlaxity (Brighton scale), smaller bone strength, higher training volume, and older age. No differences between gymnasts with and without scoliosis suspected status were found in range of motion and muscle strength. A logistic regression model for the prediction of scoliosis suspected status in gymnasts using age, bone strength, and hyperlaxity had a high predictive value ($AUC = 0.87$). The scoliosis suspected status was highly prevalent in young female gymnasts. Hyperlaxity, older age, high training load, and low bone strength are associated with scoliosis suspected status, while menarche and pubertal development are not. Predicting scoliosis development in young gymnasts can be important in preventing its pathogenesis.

Keywords Athletes, Prediction, Risk factors, Spinal deformity, Scoliosis

Scoliosis is a three-dimensional spinal deformity characterized by a lateral deviation of at least 10 degrees, accompanied by vertebra rotation¹. In 80% of cases, scoliosis is idiopathic, occurring at pubescence without a definitive cause. Adolescent idiopathic scoliosis (AIS) is the most common type, and its prevalence in the population is 0.47–5.2%. The prevalence and severity are higher in girls than in boys^{1–3}. In young athletes, the prevalence of scoliosis is higher than in the general population, with an estimated prevalence of 27%. The prevalence of scoliosis reported in gymnasts is 12%⁴ and 35% in ballet dancers⁵.

Several hypotheses have been proposed to explain the etiology of scoliosis, including hormonal disorders, biomechanical factors, deficits in neurosensory mechanisms, abnormal vestibular and proprioceptive systems, genetic components, and lack of synchronization in the maturation of the skeleton and nervous system⁶.

During puberty, there is a significant change in body proportion, body composition, increase in bone mass and density, rapid skeletal growth, hormonal changes, and development of secondary sex characteristics^{7–11}. These changes also include growth in muscle mass and fatty tissue, and especially an increment in lower limb muscle mass¹². During peak growth velocity which usually occurs around 11–13 years of skeletal age in girls and 13–15 years for boys, the spinal growth rate increases¹³ and the skeleton grows faster than the supporting muscles¹². This lack of synchronization between the development of the skeleton and the development of muscles

¹Department of Physical Therapy, Faculty of Social Welfare & Health Sciences, University of Haifa, Haifa, Israel.

²Physical Therapy Clinic, The Ribstein Center for Sport Medicine Sciences and Research, Wingate Institute, Netanya, Israel. ³The Academic college Levinsky-Wingate at the Wingate Institute, Netanya, Israel. ⁴Department of Developmental Biology and Cancer Research, The Institute for Medical Research Israel-Canada, The Faculty of Medicine, The Hebrew University of Jerusalem, Jerusalem, Israel. ⁵Center for Computational Medicine, The Hebrew University of Jerusalem, Jerusalem, Israel. ⁶Renal division, Department of Medicine, Brigham and Women's Hospital, Harvard Medical School, Longwood, MA, USA. ✉email: gdar@univ.haifa.ac.il; galidar@yahoo.com

further causes an imbalance between growth and strength. In addition, during this period, growth plates become more fragile and less able to resist forces¹⁴. This rapid and imbalanced growth and skeleton fragility is considered to be associated with the development and progression of scoliotic curves and increases the risk of injury¹⁴. Accordingly, it was found that girls with scoliosis were taller than healthy girls suggesting that rapid growth is a risk factor for scoliosis development^{15,16}.

The changes that occur during adolescent growth combined with a high repetitive training load further increase the risk of injury and scoliosis development¹⁴. Gymnasts are subjected to high and repetitive loads during training and competitions^{17,18}. All three types of gymnastics (rhythmic, acrobatic and artistic) entail intensive physical activity, including the repetition of extreme movements that apply force to the lower limbs and spine^{19,20}. The extreme balance, strength, and flexibility required in these sports expose young gymnasts to loads and strains that exert high pressure on the immature spine and may increase the risk of scoliosis^{14,21}.

This study aimed to examine the associations between scoliosis suspected status (measured via clinical tests) and anthropomorphic data, gymnastics discipline (rhythmic, acrobatic, artistic), and musculoskeletal characteristics in young (pre- and post-pubertal) female gymnasts, and to develop a model for the prediction of scoliosis to identify populations at risk. We hypothesized that gymnasts with scoliosis would have a greater ROM, hyperlaxity, and lower bone and muscle strength.

Materials and methods

Design

This cross-sectional observational study was approved by the Ethical Review Board of Adi-Negev Hospital (ADINEGEV-102_2022). All procedures were performed in accordance with relevant guidelines and regulations. All participants and their parents signed an informed consent form prior to participation. The study was registered prospectively on a public clinical trial database. Clinical trial registration no: NCT06318325 (clinicalTrials.gov).

Participants

The study included 274 Caucasian female gymnasts (154 rhythmic, 60 acrobatic, 60 artistic) aged 10–16 (mean age, 11.8 ± 1.9 years). Inclusion criteria were training at least four times/week, for a minimum of 16 h/week, at a competitive level. The gymnasts exercised fully three months before the beginning of the study and had not been absent for more than three days from training due to pain, discomfort, or injury. The exclusion criteria were the presence of injury causing pain or missing training.

Research procedure

Gymnasts were recruited by contacting sports associations and coaches. The gymnasts were asked about anthropomorphic details (age, height, weight) and training intensity (age at onset of training, total h/week of practice). Body composition parameters were assessed using the TANITA- BC-545 N device (Tanita Corp., Tokyo, Japan). The TANITA is a bioelectrical impedance analysis device that accurately measures fat-free mass and total body water. It is validated for assessing body composition in both adults and younger populations^{22–24}.

Pediatric physicians assessed pubertal signs as the time of first menarche and Tanner's pubertal stage (breast development and pubic hair development) (< 3 , ≥ 3)²⁵.

Each gymnast was screened once by an experienced physical therapist for the following:

Scoliosis suspected status

To determine the scoliosis suspected status, first, the Magee skyline view assessment was performed for posture assessment. The examiner assessed the gymnast's posture while standing in an anatomical position and examined any deviation or asymmetry from the normal posture (e.g. head position, symmetry of: levels of shoulders, levels of iliac crest, waist angles, carrying angles, sternum and ribs, knees, arches of the feet)^{26,27}. Secondly, the Adams forward-bend test was utilized. Scoliosis was indicated if trunk asymmetry was observed during forward flexion of the spine from a standing position²⁸. The Adams test is considered the best non-invasive clinical test for scoliosis screening with a sensitivity of 50.8%, and high specificity of 94.4% with a positive predictive value of 79%²⁹. Combining a few diagnostic methods ensures accurate scoliosis detection. These two clinical tests have been previously applied in a screening study on a large number of dancers by the researchers in the current study²⁶.

When a positive Adam's test was detected, the scoliosis was measured using a scoliometer. The scoliometer is an inclinometer that measures the asymmetries between the sides of the trunk in axial rotation degrees³⁰. The scoliometer was found to have high intra and inter-rater reliability, with a good correlation between the scoliometer measurements and radiograph analyses of Cobb angle ($r = 0.7$, $p < 0.05$). and high sensitivity value of 87% for a trunk rotation of 5° ³⁰. Measurements were performed at the levels of the vertebrae T4, T7 and T12. The presence of scoliosis was defined as scoliosis $> 5^\circ$, as measured by the scoliometer at any level measured³¹.

Since we did not use radiographic imaging to assess scoliosis, we can characterize our methods as indicating a suspected status of scoliosis.

All examinations to assess the scoliosis suspected status were performed by the same physical therapist, who is experienced in evaluating posture and treating scoliosis.

Joint range of motion (ROM)

Joint ROM measurements were performed following previously described techniques, adjusted for gymnasts using a goniometer. The following angles were measured: (1) ankle plantar-flexion and dorsi-flexion in the supine position (the angle between the tibia bone to the first metatarsophalangeal joint)^{32,33} (2) anterior and posterior split (the angle between the two femur bones while one leg is in flexion and the other in extension),

and (3) hip abduction with side turnout and extension in standing position (the angle between the two femur bones)^{33,34}.

Lower extremity muscle strength

The following muscles were measured using a portable handheld dynamometer (MicroFET2TM, Hoggan Scientific LLC., Salt Lake City, UT). The test positions were chosen according to the instrument manual and previous studies^{35–37} as follows: hip abduction/adduction in a side-lying position, hip extension-prone position-long Lever, Hip flexion-sitting position, knee extension in sitting, knee flexion in prone position, and ankle plantar/dorsi flexion in a supine position. The “make” test was used in which the examiner gives an isometric contraction for a few seconds³⁸.

Each movement was performed three times with a 30-second rest interval between each effort within the test condition and a 2-minute rest interval between the different movements. The average of the three measurements was used for the final analysis.

Hyperlaxity

Was assessed using the Beighton 9-Point Hypermobility Test. Beighton’s test consisted of five items, of which four were conducted bilaterally. The items included first-finger opposition, fifth-finger extension, elbow extension, knee extension, and back forward bending. The minimum total score is 0 and the maximum of 9 points represents hyperlaxity³⁹. Hyperlaxity was determined if the gymnast had a score ≥ 6 ⁴⁰. Beighton scale is the most common and reliable tool to identify general hypermobility and demonstrated substantial to excellent inter- and intra-rater reliability^{40,41}.

Bone strength

Was assessed using a quantitative ultrasound (QUS) Sunlight MiniOmni Ultrasound Bone Sonometer (Sunlight Medical, Somerset, NJ). The QUS is designed to measure the speed of sound (SOS) in various skeletal areas⁴². The QUS was found to be a valid tool for assessing bone status, and bone measurements were found to correlate significantly with bone mineral density measurements by Dual Energy X-ray Absorption (DXA) in both adults and children^{43,44}. Measurements were conducted on the nondominant side at the distal one-third of the radius and the midshaft of the tibia⁴².

Skeletal age

Was measured using the BAUSportTM instrument, a portable ultrasound device, and a Sonometer (SonicBone, Rishon Lezion, Israel). Measurements were performed at three sites on the left hand: (1) the distal radial and ulnar secondary ossification centers of the epiphyses at the wrist, (2) the growth plate of the third metacarpal and the shaft of the adjacent proximal phalanx, and (3) the distal metacarpal epiphysis. Skeletal age was calculated (to the nearest 0.01 years) using an algorithm integrated into the software of BAUSportTM⁴⁵. The validity of the BAUSportTM sonometer for skeletal age assessment is high, with comparable results to other methods^{45,46}.

Data analysis

One-way ANOVA or Student’s t-test were used to compare continuous variables, and Chi-squared to compare categorical variables across groups of gymnasts. P-values were adjusted for multiple hypothesis testing using the Holm-Bonferroni method. The analysis was performed using Python.

Logistic regression with 10-fold cross-validation was used to formulate a classification model for scoliosis based on parameters found to be different between gymnasts with and without scoliosis suspected status. Only variables that contributed significantly to the model were maintained. The model was constructed using the MATLAB software.

Sample size calculation: The expected priori power was estimated using ANOVA with repeated measures. A sample size of 200 participants, $\alpha = 0.05$, and moderate effect size (0.25) generated a power of 0.989.

Results

Background variables

The study included 274 young female gymnasts (mean age, 11.8 ± 1.9 years). Significant differences in age, weight, height, BMI, years of training and hours of training/week were found between the three groups. ($p < 0.05$) (Table 1).

	Rhythmic <i>n</i> = 154 X $\pm$ SD	Acrobatic <i>n</i> = 60 X $\pm$ SD	Artistic <i>n</i> = 60 X $\pm$ SD	Adjusted <i>P</i> -value between groups
Age (years)	11.87 $\pm$ 1.92	12.68 $\pm$ 2.01	11.08 $\pm$ 1.61	<i>P</i> < 0.001*
Height (cm)	144.62 $\pm$ 11.69	147.56 $\pm$ 12.14	139.75 $\pm$ 8.40	<i>P</i> = 0.034*
Weight (kg)	35.93 $\pm$ 9.55	39.12 $\pm$ 10.76	33.84 $\pm$ 6.62	<i>P</i> = 0.025*
BMI	16.84 $\pm$ 2.32	17.53 $\pm$ 2.36	17.21 $\pm$ 1.73	<i>P</i> = 0.012*
Years training (age- reported)	6.76 $\pm$ 2.51	6.64 $\pm$ 2.84	5.22 $\pm$ 1.96	<i>P</i> < 0.001*
Hours training/week	25.61 $\pm$ 10.55	19.13 $\pm$ 8.44	19.37 $\pm$ 7.19	<i>P</i> < 0.001*

Table 1. Anthropometric characteristics of research groups. *Significant difference between groups (ANOVA).

Musculoskeletal features

The discipline effect was found for the ROM of several measured parameters, such as anterior and posterior splits, with higher values among rhythmic gymnasts and lower values among artistic gymnasts. The discipline effect was found in muscle strength for some parameters being higher among acrobatic gymnasts. Bone strength measured at the tibia was found to be the lowest among the artistic gymnasts. No difference in the prevalence of hyperlaxity was observed between groups (Table 2).

Puberty

In the entire sample, 34/274 reached menarche (10.4% among the rhythmic, 25% among the acrobatic, and 5% among the artistic), with a mean of 12.7 years of menarche age ($p < 0.01$). Tanner stage > 3 was found in 48 gymnasts from the entire sample (14.2% of the rhythmic, 35% of the acrobatic, and 8.3% of the artistic) ($p < 0.01$). Muscle strength and bone strength were found to be higher in gymnastics post-menarche ($p < 0.05$) however, ROM was found to be lower or similar post-menarche compared to pre-menarche.

Scoliosis suspected status

From the entire sample (274), 79 had scoliosis suspected status: 51/154 (33%) in the rhythmic, 17/60 (28%) acrobatic, and 11/60 (18.3%) artistic. No statistically significant differences were found in the prevalence of gymnasts with scoliosis suspected status between the different research groups ($p = 0.09$).

Gymnasts with scoliosis suspected status were found to have greater hyperlaxity according to the Beighton scale than gymnasts without (6.6 ± 1.7 vs. 4.4 ± 2.3 respectively) ($p < 0.001$), smaller bone strength according to the SOS examination (3511 ± 99 m/s vs. 3585 ± 125 m/s respectively) ($p < 0.001$) and older age (12.5 ± 2.1 vs. 11.6 ± 1.8 years respectively) ($p < 0.001$). In addition, gymnasts with scoliosis suspected status trained more hours /week than gymnasts without (25.8 ± 10.0 vs. 21.6 ± 9.7 h/week) ($p = 0.0017$). No differences in ROM or muscle strength were found between gymnasts with and without scoliosis suspected status. Menarche age onset for the scoliotic gymnasts and non-scoliotic gymnasts was 12.45 ± 1.31 and 12.83 ± 1.03 respectively ($p > 0.05$).

Scoliosis suspected status was not associated with pubertal development as measured by menarche onset and tanner stage for the entire sample ($p > 0.05$). Scoliosis had a different prevalence when considering pre- and post-menarche and gymnastics disciplines together ($p < 0.01$). Among the Rhythmic, 8/16 (50%) gymnasts who already reached menarche had scoliosis suspected status compared with 4/11 (36%) gymnasts among the acrobatic and 0/3 among the artistic ($p < 0.05$). These results were similar when examining scoliosis suspected status and Tanner stage of > 3 in each discipline. Among the rhythmic, 14/22 (63%) gymnasts who had tanner stage > 3 had scoliosis suspected status compared with 4/21 (19%) gymnasts among the acrobatic and 1/5 among the artistic (20%) ($p < 0.01$) (Table 3).

Predictive model for scoliosis suspected status

We developed a logistic regression model to predict scoliosis using all significant parameters that differ between the groups. Hyperlaxity, bone strength, and age were found to contribute significantly to the model, resulting in an average AUC of the response operating curve (ROC) of 0.87 and an F1-score of 0.63 (Table 4; Fig. 1).

	Rhythmic <i>n</i> = 154 X $\pm$ SD	Acrobatic <i>n</i> = 60 X $\pm$ SD	Artistic <i>n</i> = 60 X $\pm$ SD	Adjusted <i>P</i> -value between groups
Tibia strength	3573.46 $\pm$ 126.32	3595.65 $\pm$ 101.74	3507.3 $\pm$ 116.48	< 0.001*
Muscle strength (kgf)				
Planter flexion	23.03 $\pm$ 6.82	25.34 $\pm$ 8.81	28.00 $\pm$ 8.29	< 0.001*
Dorsi flexion	14.64 $\pm$ 4.45	14.69 $\pm$ 5.05	15.73 $\pm$ 3.89	0.564
Knee flexion	10.53 $\pm$ 3.62	11.13 $\pm$ 4.02	9.5 $\pm$ 2.13	0.126
Knee extension	18.74 $\pm$ 5.57	24.02 $\pm$ 7.50	20.07 $\pm$ 4.98	0.036*
Hip abduction	8.93 $\pm$ 4.41	8.97 $\pm$ 4.25	7.94 $\pm$ 5.70	0.350
Hip extension	10.40 $\pm$ 3.61	11.07 $\pm$ 4.62	9.25 $\pm$ 2.68	0.128
Hip flexion	12.95 $\pm$ 3.65	14.90 $\pm$ 5.44	13.36 $\pm$ 2.97	0.088
ROM (angles)				
Anterior split	196.38 $\pm$ 21.83	193.44 $\pm$ 9.44	183.55 $\pm$ 8.30	< 0.001*
Posterior split	192.17 $\pm$ 14.68	189.61 $\pm$ 8.80	179.42 $\pm$ 7.74	< 0.001*
Side turnout	171.51 $\pm$ 20.44	170.73 $\pm$ 28.79	161.27 $\pm$ 22.63	0.153
Hip extension	71.07 $\pm$ 19.39	75.81 $\pm$ 19.54	53.28 $\pm$ 16.27	< 0.001*
Ankle plantar flexion	181.87 $\pm$ 7.22	183.79 $\pm$ 7.07	179.06 $\pm$ 4.68	0.142
Ankle dorsi flexion	91.69 $\pm$ 3.43	91.73 $\pm$ 3.76	90.34 $\pm$ 1.43	0.136
Hyperlaxity (total ≥ 6)	5.36 $\pm$ 2.30	4.78 $\pm$ 2.97	4.92 $\pm$ 2.10	0.289

Table 2. Range of motion, muscle strength and bone strength in research groups (right and left sides combined). *Significant difference between groups ($p < 0.05$), Hyperlaxity—was determined if the gymnast had a score ≥ 6 in Beighton score, kgf —kilogram-force.

	No scoliosis				Scoliosis suspected status				Total all	P value between gymnasts' groups
	Rhythmic	Acro	Artistic	Total	Rhythmic	Acro	Artistic	Total		
Menarche										
No	95	32	46	173	43	13	11	67	240	0.006*
Yes	8	11	3	22	8	4	0	12	34	
Total	103	43	49		51	17	11		274	
Tanner stage										
< 3	95	26	45	166	37	13	10	60	226	< 0.0001*
≥ 3	8	17	4	29	14	4	1	19	48	
Total	103	43	49		51	17	11		274	

Table 3. Research groups and scoliosis suspected status according to menarche and Tanner stage. *Significant difference between groups ($p < 0.05$).

	Estimate	Standard error	Adjusted p -value
Intercept	23.36	5.65	4×10^{-5}
Age	0.62	0.12	2×10^{-7}
Average tibia strength	− 0.0092	0.0018	4×10^{-7}
Hyperlaxity (1 = yes, 0 = no)	2.44	0.39	1×10^{-9}

Table 4. Parameters for model development.

Discussion

This study examined the associations between scoliosis suspected status and anthropomorphic data, gymnastics discipline (rhythmic, acrobatic, artistic), and musculoskeletal characteristics in young (pre- and post-pubertal) female gymnasts. The results of the study show that 79/274 (28.8%) gymnasts were identified as having the scoliosis suspected status, without significant difference between gymnast disciplines (rhythmic, acrobatic, artistic). Scoliosis suspected status was associated with hyperlaxity, smaller bone strength, higher training volume, and older age.

The high prevalence of scoliosis suspected status in our study is much higher than the general population of girls (0.47–5.2%)⁴⁷ and the previously reported value of 12% for gymnasts⁴. A high prevalence of scoliosis has been previously observed in the athlete population, estimated at 27%, with a higher incidence among females and dancers (20–35%)^{5,21,48}. Tanchev et al.⁴ studied 100 rhythmic gymnastics conducting radiographs diagnosis for all the gymnasts with suspected scoliosis. They found that 12% of gymnasts have scoliosis, compared to 1.1% of normal girls not involved in sports, according to a nationwide statistical survey.

Although most studies agree that the prevalence of scoliosis is higher among athletic populations, particularly in sports that demand flexibility and intensive training such as gymnastics and dance^{4,5,21}, prevalence rates slightly vary between studies. These differences may largely be attributed to the diagnostic methods used. While radiographic imaging is considered the gold standard for diagnosing scoliosis, it is often impractical and ethically challenging to perform routine radiographs on healthy, asymptomatic young athletes due to concerns about unnecessary radiation exposure. In our study, we employed non-invasive clinical assessments—Adam’s forward bend test and a scoliometer—which have been shown in previous research to be valid and reliable tools for scoliosis screening^{26,28,30}. Although these methods may have limitations compared to radiographic confirmation, they offer a feasible and sound approach for evaluating large groups of healthy adolescents in a field-based setting. Since we did not use radiographic imaging to assess scoliosis, we can only characterize our results as indicating a suspected status of scoliosis.

We found an association between the relatively high number of training hours/week and scoliosis suspected status. Gymnasts identified with scoliosis trained for nearly 26 h/week, while those who were not diagnosed trained for less than 22 h/week. Watanabe et al.⁴⁹ found the odds for scoliosis increased as the child’s frequency of training, number of years of experience, and increased duration of training. In contrast, lower levels of physical activity were also found to be associated with a higher incidence of adolescent idiopathic scoliosis⁵⁰. According to Kenanidis et al.⁵¹, there is no evidence to suggest that regular exercise is linked to scoliosis, and participation in sports activities does not appear to have any impact on the severity of the primary scoliotic curve.

The current study revealed that gymnasts with scoliosis suspected status exhibited hyperlaxity, lower bone strength, increased training, and were older. The model obtained from these findings displayed an AUC of 0.87 and can identify gymnasts at risk for scoliosis using relatively simple measurements of age, hyperlaxity, and bone strength. While age, pubertal stage, weight and height are all tightly correlated, our model identified only age as a stronger predictor for the development of scoliosis suspected status compared to other age-related parameters. Moreover, menarche and Tanner stage were not associated with scoliosis suspected status after correcting for age. Importantly, age is a more accessible and less intrusive parameter than the Tanner stage and is more clearly defined than menarche or even weight and height, which is important in applying the model in the field.

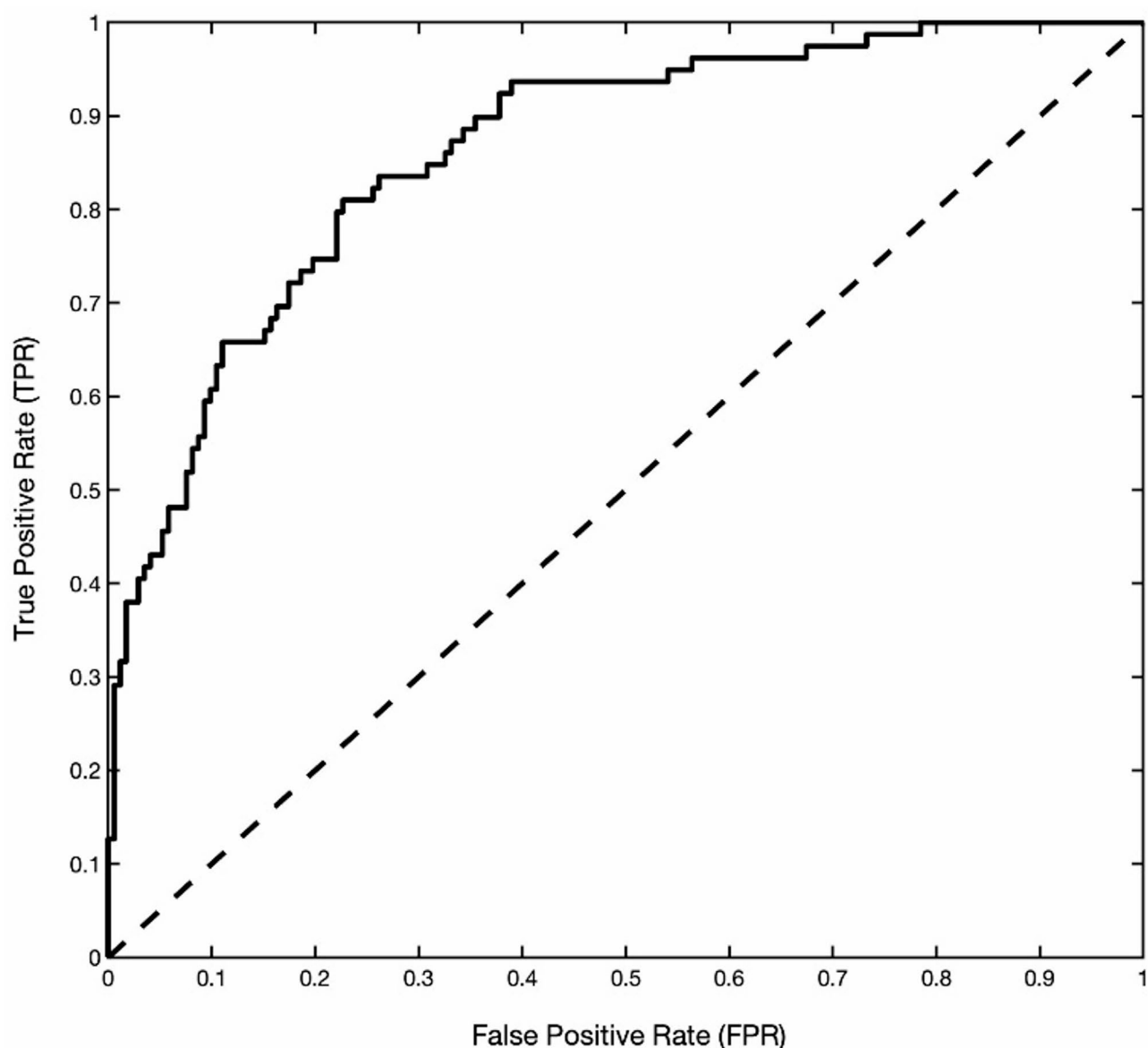


Fig. 1. ROC curve for the logistic regression model. The AUC of the curve is 0.87.

Our study did not reveal an association between scoliosis suspected status and puberty nor any difference in menarche age of onset between gymnasts with and without the presence of scoliosis. This corresponds with several studies^{52,53} however, other studies have indicated an association between the pubertal stage, which is marked by rapid skeletal growth and hormonal changes, with the peak incidence of idiopathic scoliosis. Studies have reported higher prevalence rates of idiopathic scoliosis among post-menarche females, suggesting a hormonal influence on scoliosis development^{13,54}. Age at menarche, representing the initiation of menstrual cycles and estrogen production, is also considered to be related to scoliosis progression during adolescence⁵⁵. Mao et al.⁵⁶ examined a large group of Chinese girls (6376 healthy female adolescents and 2196 scoliotic girls), finding a tendency for delayed onset of menarche among idiopathic scoliotic girls especially for girls with Cobb angle $> 60^\circ$. They also found a higher proportion of girls starting to menstruate after 14 years of age, which was significantly higher in girls with scoliosis compared with normal controls.

These varying findings across studies highlight the complex and contradictory relationship between menarche and adolescent idiopathic scoliosis, indicating that factors beyond hormonal changes may also play a role in the development of scoliosis.

Our study also revealed an association between scoliosis suspected status and hypermobility similar to our previous study of young dancers²¹. During puberty, hormonal fluctuations can affect ligament laxity, which may increase spinal instability and asymmetrical loading on the spine, thus contributing to scoliosis. Studies have reported a higher prevalence of hypermobility among individuals with idiopathic scoliosis than among the general population. Czaprowski et al.⁵⁷ examined 70 subjects with scoliosis (mean age 13.2) and 58 healthy

controls. They found significant differences in hypermobility prevalence between groups being 51.4% among subjects with idiopathic scoliosis compared with 19% in the control.

Another risk factor for the presence of scoliosis found in the current study was low bone strength in gymnasts with scoliosis suspected status compared to those without. High energy-consuming training, coupled with the need to maintain body leanness, may contribute to low energy availability, which in turn leads to changes in hormonal cycles, menstrual disorders, and low bone density⁵⁸. Gymnastics is known to enhance mineral density and bone properties in prepubertal and early pubertal athletes^{59,60}. However, biomechanical studies have also shown that repetitive activities with extreme bone stress and strains may lead to accumulated bone micro-damage and reduced bone properties⁶¹. Lam et al.⁶² examined bone quality with quantitative ultrasound finding that the z-score of bone mineral density at the femoral neck of scoliosis subjects was significantly lower than that of normal controls.

Our findings underscore the multifactorial nature of scoliosis in young female gymnasts, and suggest that both mechanical and biological factors contribute to the development of scoliosis in this athletic population. Identifying gymnasts at risk for scoliosis during puberty early allows for timely implementation of preventive strategies. These may include focusing on strengthening exercises instead of flexibility exercises and conducting regular monitoring, which can help prevent the development and progression of scoliosis.

Study limitations

This study has several limitations. First, it was a cross-sectional study without longitudinal follow-up. Second, it is possible that gymnasts with scoliosis quit earlier or missed training, generating a negative selection bias. Third, the absence of a non-gymnast control group limits our ability to compare the prevalence and associated factors of scoliosis with the general population. However, girls of the same age not engaged in gymnastics would likely differ substantially in terms of daily physical activity, body composition, and musculoskeletal characteristics, introducing multiple confounding variables. Another limitation is the lack of radiographic confirmation for scoliosis. Nonetheless, validated clinical tools such as Adam's forward bend test and scoliometer measurement were used, both of which demonstrated reasonable accuracy in scoliosis screening. Finally, the study sample, although relatively large for this population, included heterogeneous subgroups of gymnasts with differences in age, skeletal maturity, and sample size across disciplines. We addressed this heterogeneity by including these parameters in our analyses.

Conclusion

This study highlights a high prevalence of scoliosis suspected status in young female gymnasts. Hyperlaxity, older age, high training load, and low bone strength are associated with the presence of scoliosis suspected status. Surprisingly, menarche and pubertal development were not found to be associated with the presence of scoliosis suspected status. A logistic regression model that considers the age of the gymnasts, bone strength, and hyperlaxity can predict scoliosis suspected status well. This prediction model for scoliosis, which can be assessed relatively easily, allowing for the identification of at-risk gymnasts. Further research is needed to validate our prognostic model in other sport types and to develop targeted interventions for scoliosis prevention and management.

Data availability

The data that support the findings of this study are not openly available, and are available from the corresponding author upon reasonable request.

Received: 2 March 2025; Accepted: 4 June 2025

Published online: 02 July 2025

References

1. Choudhry, M. N., Ahmad, Z. & Verma, R. Adolescent idiopathic scoliosis. *Open. Orthop. J.* **10**, 143–154 (2016).
2. Negrini, S. et al. 2011 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth. *Scoliosis.* **7** (1), 3 (2012).
3. Addai, D., Zarkos, J. & Bowey, A. J. Current concepts in the diagnosis and management of adolescent idiopathic scoliosis. *Childs Nerv. Syst.* **36** (6), 1111–1119 (2020).
4. Tanchev, P. I., Dzherov, A. D., Parushev, A. D., Dikov, D. M. & Todorov, M. B. Scoliosis Rhythmic Gymnasts: Spine ;**25**(11):1367–1372. (2000).
5. Mousavi, L., Seidi, F., Minoonejad, H. & Nikouei, F. Prevalence of idiopathic scoliosis in athletes: a systematic review and meta-analysis. *BMJ Open. Sport Exerc. Med.* **8** (3), e001312 (2022).
6. Le Berre, M. et al. Clinical balance tests, proprioceptive system and adolescent idiopathic scoliosis. *Eur. Spine J.* **26** (6), 1638–1644 (2017).
7. Dimeglio, A., Canavese, F. & Charles, Y. P. Growth and adolescent idiopathic scoliosis: when and how much?? *J. Pediatr. Orthop.* **31**, S28–36 (2011).
8. Dimeglio, A. & Canavese, F. The immature spine: growth and idiopathic scoliosis. *Ann. Transl. Med.* **8** (2), 22–22 (2020).
9. Libanati, C., Baylink, D. J., Lois-Wenzel, E., Srinivasan, N. & Mohan, S. Studies on the potential mediators of skeletal changes occurring during puberty in girls¹. *J. Clin. Endocrinol. Metab.* **84** (8), 2807–2814 (1999).
10. Rogol, A. D., Roemmich, J. N. & Clark, P. A. Growth at puberty. *J. Adolesc. Health.* **31** (6), 192–200 (2002).
11. Saggese, G., Baroncelli, G. I. & Bertelloni, S. Puberty and bone development. *Best Pract. Res. Clin. Endocrinol. Metab.* **16** (1), 53–64 (2002).
12. Wild, C. Y., Steele, J. R. & Munro, B. J. Why do girls sustain more anterior cruciate ligament injuries than boys?? A review of the changes in Estrogen and musculoskeletal structure and function during puberty. *Sports Med.* **42** (9), 733–749 (2012).
13. Charles, Y. P., Daures, J. P., De Rosa, V. & Dimeglio, A. Progression risk idiopathic juvenile scoliosis Dur. pubertal growth. *Spine.* **31**(17):1933–1942 (2006).

14. Patel, T. S. et al. Coach awareness, knowledge and practice in relation to growth and maturation and training load in competitive, young gymnasts. *Int. J. Sports Sci. Coach.* **16** (3), 528–543 (2021).
15. Yim, A. P. Y. et al. Abnormal skeletal growth patterns in adolescent idiopathic Scoliosis—A longitudinal study until skeletal maturity. *Spine* **37** (18), E1148–E1154 (2012).
16. Meyer, C. et al. Why do idiopathic scoliosis patients participate more in gymnastics? *Scand. J. Med. Sci. Sports.* **16** (4), 231–236 (2006).
17. Jakše, B., Jakše, B., Čuk, I. & Šajber, D. Body composition, training volume/pattern and injury status of Slovenian adolescent female High-Performance gymnasts. *Int. J. Environ. Res. Public Health.* **18** (4), 2019 (2021).
18. Klentrou, P. Onset of puberty, menstrual frequency, and body fat in elite rhythmic gymnasts compared with normal controls. *Br. J. Sports Med.* **37** (6), 490–494 (2003).
19. Gram, M. C. D., Clarsen, B. & Bø, K. Injuries and illnesses among competitive Norwegian rhythmic gymnasts during preseason: a prospective cohort study of prevalence, incidence and risk factors. *Br. J. Sports Med.* **55** (4), 231–236 (2021).
20. Chandran, A. et al. Epidemiology of injuries in National collegiate athletic association women's gymnastics: 2014–2015 through 2018–2019. *J. Athl. Train.* **56** (7), 688–694 (2021).
21. Steinberg, N. et al. Generalized joint hypermobility, scoliosis, patellofemoral pain, and physical abilities in young dancers. *BMC Musculoskelet. Disord.* **22** (1), 161 (2021).
22. Steinberg, N. et al. Tendon structure, clinical tests, and pain during loading in young female competitive gymnasts. *J. Sports Sci.* **42** (17), 1605–1616 (2024).
23. Chen, K. T. et al. Comparison of standing posture bioelectrical impedance analysis with DXA for body composition in a large, Healthy Chinese Population. Handelsman DJ, editor. *PLoS One.* **11** (7), e0160105 (2016).
24. Ohara, K. et al. Similarities and discrepancies between commercially available bioelectrical impedance analysis system and dual-energy X-ray absorptiometry for body composition assessment in 10–14-year-old children. *Sci. Rep.* **13** (1), 17420 (2023).
25. De Souza, M. J. et al. 2014 Female athlete triad coalition consensus statement on treatment and return to play of the female athlete triad: 1st international conference held in San Francisco, California, May 2012 and 2nd international conference held in Indianapolis, Indiana, May 2013. *Br. J. Sports Med.* **48** (4), 289–289 (2014).
26. Steinberg, N. et al. Morphological characteristics of the young scoliotic dancer. *Phys. Ther. Sport Off J. Assoc. Chart. Physiother. Sports Med.* **14** (4), 213–220 (2013).
27. Magee, D. J. *Orthopedic Physical Assessment*, 6th edn. 1173 (Elsevier, 2014).
28. Côté, P., Kreitz, B. G., Cassidy, J. D., Dzus, A. K. & Martel, J. A study of the diagnostic accuracy and reliability of the scoliometer and adam's forward Bend test. *Spine.* **23** (7), 796–802 (1998).
29. Scaturro, D. et al. Adolescent idiopathic scoliosis screening: could a school-based assessment protocol be useful for an early diagnosis? *J. Back Musculoskelet. Rehabil.* **34** (2), 301–306 (2021).
30. Coelho, D. M., Bonagamba, G. H. & Oliveira, A. S. Scoliometer measurements of patients with idiopathic scoliosis. *Braz. J. Phys. Ther.* **17** (2), 179–184 (2013).
31. Huang, S. C. Cut-off point of the scoliometer in school scoliosis screening. *Spine* **22** (17), 1985–1989 (1997).
32. Steinberg, N. et al. Range of joint movement in female dancers and nondancers aged 8 to 16 years: anatomical and clinical implications. *Am. J. Sports Med.* **34** (5), 814–823 (2006).
33. Steinberg, N. et al. The relationship between physical features and patellofemoral-pain in young female gymnasts. *Phys. Sportsmed.* 1–10 (2025).
34. Irurtia, A., Busquets, A., Carrasco, M., Ferrer, B. & Marina, M. Control de La flexibilidad En Jóvenes gimnastas de competición mediante El Método trigonométrico: Un Año de Seguimiento. *Apunts Med. Esport.* **45** (168), 235–242 (2010).
35. Thorborg, K., Petersen, J., Magnusson, S. P. & Hölmich, P. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand. J. Med. Sci. Sports.* **20** (3), 493–501 (2010).
36. Lu, Y. M. et al. The relative and absolute reliability of leg muscle strength testing by a handheld dynamometer. *J. Strength. Cond. Res.* **25** (4), 1065–1071 (2011).
37. Kelln, B. M., McKeon, P. O., Gontkof, L. M. & Hertel, J. Hand-Held dynamometry: reliability of lower extremity muscle testing in healthy, physically active, young adults. *J. Sport Rehabil.* **17** (2), 160–170 (2008).
38. Stratford, P. W. & Balsor, B. E. A comparison of make and break tests using a hand-held dynamometer and the Kin-Com. *J. Orthop. Sports Phys. Ther.* **19** (1), 28–32 (1994).
39. van der Giessen, L. J. et al. Validation of Beighton score and prevalence of connective tissue signs in 773 Dutch children. *J. Rheumatol.* **28** (12), 2726–2730 (2001).
40. Juul-Kristensen, B., Schmedding, K., Rombaut, L., Lund, H. & Engelbert, R. H. H. Measurement properties of clinical assessment methods for classifying generalized joint hypermobility—A systematic review. *Am. J. Med. Genet. C Semin. Med. Genet.* **175** (1), 116–147 (2017).
41. Bockhorn, L. N. et al. Interrater and intrarater reliability of the Beighton score: A systematic review. *Orthop. J. Sports Med.* **9** (1), 2325967120968099 (2021).
42. Steinberg, N., Sitton, Y., Kramer, S., Levy, Y. & Siev-Ner, I. Patellofemoral pain and musculoskeletal features in young pre- and post-pubertal female dancers. *Res. Sports Med.* **32** (5), 751–766 (2024).
43. Njeh, C. F. et al. Assessment of bone status using speed of sound at multiple anatomical sites. *Ultrasound Med. Biol.* **27** (10), 1337–1345 (2001).
44. Eliakim, A., Nemet, D. & Wolach, B. Quantitative ultrasound measurements of bone strength in obese children and adolescents. *J. Pediatr. Endocrinol. Metab.* **14** (2). <https://www.degruyter.com/document/doi/https://doi.org/10.1515/JPEM.2001.14.2.159/html> (2001).
45. Cumming, S., Pi-Rusñol, R., Rodas, G., Drobnic, F. & Rogol, A. D. The validity of automatic methods for estimating skeletal age in young athletes: a comparison of the BAUSport ultrasound system and BoneXpert with the radiographic method of fels. *Biol. Sport.* **41** (1), 61–67 (2024).
46. Rachmiel, M., Naugoln, L., Mazar-Aronovitch, K., Koren-Morag, N. & Bistrizter, T. Bone age assessments by quantitative ultrasound (SonicBone) and hand X-ray based methods are comparable. *Isr. Med. Assoc. J. IMAJ.* **19** (9), 533–538 (2017).
47. Konieczny, M. R., Senyurt, H. & Krauspe, R. Epidemiology of adolescent idiopathic scoliosis. *J. Child. Orthop.* **7** (1), 3–9 (2013).
48. Longworth, B., Fary, R. & Hopper, D. Prevalence and predictors of adolescent idiopathic scoliosis in adolescent Ballet dancers. *Arch. Phys. Med. Rehabil.* **95** (9), 1725–1730 (2014).
49. Watanabe, K. et al. Physical activities and lifestyle factors related to adolescent idiopathic scoliosis. *J. Bone Jt. Surg.* **99** (4), 284–294 (2017).
50. Qi, X., Peng, C., Fu, P., Zhu, A. & Jiao, W. Correlation between physical activity and adolescent idiopathic scoliosis: a systematic review. *BMC Musculoskelet. Disord.* **24** (1), 978 (2023).
51. Kenanidis, E., Potoupnis, M. E., Papavasiliou, K. A., Sayegh, F. E. & Kapetanios, G. A. Adolescent idiopathic scoliosis and exercising: is there truly a liaison?? *Spine* **33** (20), 2160–2165 (2008).
52. Pjanic, S., Jevtic, N. & Grivas, T. B. Menarche in scoliotic and Non-Scoliotic Balkan girls and the relationship between menarche and the laterality of scoliotic curves. *J. Clin. Med.* **13** (1), 132 (2023).
53. Grivas, T. B., Samelis, P., Pappa, A. S., Stavlas, P. & Polyzois, D. Menarche in scoliotic and nonscoliotic mediterranean girls. Is there any relation between menarche and laterality of scoliotic curves? *Stud. Health Technol. Inf.* **88**, 30–36 (2002).

54. Neal, K. M., Shirley, E. D. & Kiebzak, G. M. Maturity indicators and adolescent idiopathic scoliosis: evaluation of the Sanders maturity scale. *Spine* **43** (7), E406–E412 (2018).
55. Grivas, T. B., Vasiliadis, E., Mouzakis, V., Mihos, C. & Koufopoulos, G. Association between adolescent idiopathic scoliosis prevalence and age at menarche in different geographic latitudes. *Scoliosis* **1** (1), 9 (2006).
56. Mao, S. et al. Timing of menarche in Chinese girls with and without adolescent idiopathic scoliosis: current results and review of the literature. *Eur. Spine J.* **20** (2), 260–265 (2011).
57. Czaprowski, D., Kotwicki, T., Pawłowska, P. & Stoliński, L. Joint hypermobility in children with idiopathic scoliosis: SOSORT award 2011 winner. *Scoliosis* **6** (1), 22 (2011).
58. Weimann, E. Gender-related differences in elite gymnasts: the female athlete triad. *J. Appl. Physiol.* **92** (5), 2146–2152 (2002).
59. Falk, B., Bronshtein, Z., Zigel, L., Constantini, N. W. & Eliakim, A. Quantitative ultrasound of the tibia and radius in prepubertal and Early-Pubertal female athletes. *Arch. Pediatr. Adolesc. Med.* **157** (2), 139 (2003).
60. Burt, L. A., Greene, D. A., Ducher, G. & Naughton, G. A. Skeletal adaptations associated with pre-pubertal gymnastics participation as determined by DXA and pQCT: A systematic review and meta-analysis. *J. Sci. Med. Sport.* **16** (3), 231–239 (2013).
61. Meardon, S. A. et al. Peak and Per-Step tibial bone stress during walking and running in female and male recreational runners. *Am. J. Sports Med.* **49** (8), 2227–2237 (2021).
62. Lam, T. P. et al. Abnormal bone quality in adolescent idiopathic scoliosis: A Case-Control study on 635 subjects and 269 normal controls with bone densitometry and quantitative ultrasound. *Spine* **36** (15), 1211–1217 (2011).

Acknowledgements

We would like to thank all the rhythmic gymnasts and coaches for their participation, collaboration, and finding time for research measurements.

Author contributions

N.S., G.D. and L.A. were responsible for research conceptualization; L.A. utilized data collection; G.D. wrote first manuscript draft, all authors reviewed the manuscript; T.V. and D.B.Z. performed statistical analysis.

Funding

This research received a grant from the Ministry of Innovation, Science and Technology, in collaboration with the Ministry of Culture and Sports 21120407, and The Daniel Howard Foundation.

Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

This study was approved by Adi-Negev hospital ethical review board (ADINEGEV-102_2022).

Additional information

Correspondence and requests for materials should be addressed to G.D.

Reprints and permissions information is available at www.nature.com/reprints.

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

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025