Increased Prevalence of Scoliosis in Female Professional Ballet Performers

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Background: Musculoskeletal abnormalities have been reported among female professional ballet performers due, in part, to intrinsic predispositions related to joint and/or connective tissue laxity and extrinsic effectors such as reduced energy availability, low body mass, and high training volumes that may increase the risk of developing idiopathic scoliosis (IS). The purpose of this investigation was to characterize IS prevalence in this population. We hypothesized that there would be elevated prevalence in female performers and that those with IS would exhibit reduced bone mineral density (BMD), body mass, fat mass, and lean mass.

Methods: A retrospective analysis of whole-body anteroposterior radiographs was performed on 98 professional ballet dancers (49 male performers [mean age, 25 ± 6 years] and 49 female performers [mean age, 27 ± 5 years]) from a single company. Body composition and BMD were assessed via dual x-ray absorptiometry. The criterion for IS was defined as a Cobb angle of >10°. The frequency of IS was plotted against general-population norms. A t test was used to compare demographic characteristics, anthropometrics, and BMD between performers with and without IS and to compare the Cobb angles between sexes. A Fisher exact test was used to compare the IS prevalence between sexes. The Type-I error was set at $\alpha = 0.05$.

Results: Compared with male performers, female performers had greater spinal asymmetry (mean Cobb angle, 7.98° [95% confidence interval (CI) width, 1.76°] for men and 4.02° [95% CI width, 1.00°] for women; p = 0.027). The prevalence of IS among male performers (3 [6.12%] of 49) was comparable with the general-population norms (0.31% to 5.60%). Women had an elevated prevalence of IS compared with men (10 [20.41%] of 49; p = 0.037) and with general-population norms (0.65% to 8.90%). Among women, performers with IS were observed to have a reduced percentage of body fat (p = 0.021) and reduced fat mass (p = 0.040) compared with performers without IS.

Conclusions: Female professional ballet performers demonstrate a heightened prevalence of IS that, in addition to intrinsic predisposition, is associated with modifiable factors such as reduced fat mass commonly associated with reduced energy availability known to impact musculoskeletal health in athletes. Future investigations should seek to determine the prevalence of IS in other young female athlete populations commonly exposed to high degrees of activity and reduced energy availability.

Level of Evidence: Prognostic Level III. See Instructions for Authors for a complete description of levels of evidence.

Professional ballet dancers undergo intense physical activity involving elevated stresses on the musculoskeletal system[1-4], with many beginning training as children before progressing to the professional level[2,5,6]. Because this progression often occurs while performers are still undergoing musculoskeletal maturation, factors such as proper nutrition, training, and sleep are important for optimal performance and injury prevention[2,7-10]. However, overuse injuries are common in this population and are often attributed to overtraining and reduced energy availability, which occurs when there is an

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imbalance between caloric consumption and expenditure, leading to insufficient energy for normal physiological functions[1,11].

Musculoskeletal abnormalities are common in this population. In 2020, Lambert et al.[1] observed that performers from a single company (n = 112) measured under the lowest third percentile for the percentage of body fat (2.92% [95% confidence interval (CI) width, 0.82%] for men and 1.05% [95% CI width, 0.15%] for women), and, although the total body bone mineral density (BMD) was not abnormal, a large proportion of female performers were observed to meet criteria for osteopenia in the pelvis (78%) and the spine (24%). Risk factors for disordered eating were also associated with reduced BMD and a higher stress fracture prevalence[1]. Vahedi et al.[3] observed that, compared with age-matched female professional soccer athletes, female ballet performers had reduced pelvic BMD, lean mass, and fat mass paired with a higher incidence of pelvic-region bone and soft-tissue injuries. Lastly, professional ballet dancers, in addition to intense flexibility training from childhood, often have genetic predispositions to hypermobility and joint laxity[12]. Combined, these factors raise concern about spinal deformity development.

Idiopathic scoliosis (IS) develops most commonly in adolescence (11 to 18 years) and is defined as a spinal curvature (often in the thoracic region) in the coronal plane of >10° (mild, >10°; moderate, >24°; and severe, >45°)[13-15]. The etiologies of IS are multifactorial and are not fully understood but may involve hormonal imbalance, proprioceptive disorders, malnutrition, low body mass, and genetic components[16-19]. These factors impact bone and/or connective tissue health and may affect IS development. Although the prevalence of IS in the general population ranges from 1% to 3%, female athletes tend to be about twice as likely to develop IS relative to men and female non-athletes[20-22]. With regard to ballet, hypothesized risk factors for IS include intrinsic factors such as genetic predispositions to joint laxity paired with extrinsic factors such as high-volume and/or high-impact training before skeletal maturity[23,24], asymmetric loading, family history of IS, and reduced BMD[25-27]. For example, Longworth et al.[27] observed that, compared with aged-matched adolescent controls, ballet performers were more likely to have developed scoliosis between the ages of 9 and 16 years and to have a higher prevalence of hypermobility. Although not established to be causative, such findings remain concerning because young dancers (<15 years of age) presenting with IS have been observed to have a heightened incidence of lumbar, knee, and ankle injuries[28].

To date, IS prevalence in professional ballet remains understudied. If their performers are observed to be at a heightened risk, amateur and professional companies may benefit from regular screening, which may help to identify those who would benefit from early interventions (e.g., bracing, casting, physical therapy) or monitoring strategies[29]. Although the mean age of professional performers is past the optimal age for treatment via bracing, improved screening could be performed for this population at younger ages and would be supported by previous findings in youth populations[30]. Additionally, analysis of demographic and physiologic differences between those with and without IS would provide important information for identifying those most likely to present with the condition. Therefore, the purpose of this study was to perform a retrospective review of yearly physical screening records to determine the prevalence of IS in professional ballet performers relative to general-population norms. We also sought to compare demographic characteristics, anthropometric measures, BMD, and skeletal dimensions between performers with and without criteria for IS. We hypothesized that there would be an elevated prevalence of IS in ballet performers and that the prevalence would be elevated in women compared with men. We also hypothesized that performers with criteria for IS would have reduced BMD, body mass, fat mass, and lean mass compared with those without criteria for IS.

Materials and Methods

All procedures for this investigation were approved by the Houston Methodist Hospital institutional review board for human subject research (Protocol #PRO00032736). Annual screening data collected between 2017 and 2022 during routine physicals for 98 professional ballet dancers (49 male performers [mean age, 25 ± 6 years] and 49 female performers [mean age, 27 ± 5 years]) actively employed by a professional dance company were analyzed. During screening, all company dancers had a single full-body anteroposterior dual x-ray absorptiometry (DXA) (iDXA; GE Healthcare) scan made with the dancer in the supine position. Subject body composition, bone densitometry, demographic, and anthropometric data were also recorded and analyzed. Data gathered via DXA during yearly physicals were collected as part of a yearly comprehensive evaluation for improved athlete monitoring with regard to fracture and/or injury risk, metabolic disturbances, and dietary and overall athlete health.[1]

Although individual training volumes were not collected, the company indicated that performers are contracted for performance or rehearsal for up to 6 hours per day, 5 to 6 days per week, for 43 weeks per year.

DXA Analysis

BMD and body composition were assessed using DXA scans performed by a licensed radiologist. The lean mass index (LMI) and fat mass index were also calculated in kg/m^2. Total and regional Z-scores were calculated for BMD measures: (Z-score = [BMD of interest – mean age, sex, and race-matched general reference population BMD] ÷ general-population standard deviation)[31,32].

Screening for IS

Utilizing the same radiographic images acquired via DXA, Cobb angle assessments were performed using a vertebra-by-vertebra analysis (Surgimap, version 2; Nemaris) by 3 independent orthopaedic physicians (intraclass correlation coefficient [ICC], >0.95). The criteria for IS were defined as a Cobb angle of >10°[33]. The accuracy of segmented regional

analysis via DXA has been previously reported as having a 1% to 6% error and excellent reliability (ICC, 0.99)[34].

Skeletal Dimensions

Skeletal dimensions were assessed from DXA images using ImageJ software (National Institutes of Health) in a manner similar to that of previous investigations[35-37]. Measurements of extremity length, trunk length, shoulder width, and pelvic width were performed.

Statistical Analysis

The frequency of IS was plotted against previously reported general-population norms for adolescents and adults[21,38-43]. An ICC was calculated to assess reliability between observers for Cobb angle assessment and was interpreted as follows: <0.5 = poor, 0.5 to 0.74 = moderate, 0.75 to 0.9 = good, and >0.9 = excellent[44]. A t test was used to compare demographic and anthropometric characteristics and DXA measures between performers with and without criteria for IS. The same analysis was used to compare Cobb angles between men and women. Lastly, a Fisher exact test was used to compare the prevalence of IS between sexes. The Type-I error was set at $\alpha = 0.05$. For all significant comparisons, the effect size was calculated using the Cohen d statistic and was interpreted as follows: <0.1 = negligible (N), 0.1 to 0.29 = small (S), 0.3 to 0.49 = moderate (M), 0.5 to 0.7 = large (L), and >0.7 = very large (VL)[36,45,46].

Results

Prevalence of IS

The comparison of the mean Cobb angle between sexes as well as sex-specific plotting of IS prevalence in our ballet sample population against general-population norms are presented in Figure 1. Cumulatively, women were observed to have an elevated major curve Cobb angle compared with men among all performers ($p = 0.027$) (Fig. 1-A). Cobb angle analysis revealed that the prevalence of IS in men (3 [6.12%] of 49) was comparable with reported sex-matched normative reference ranges (0.31% to 5.60%) (Fig. 1-B). Conversely, female dancers were observed to have an elevated prevalence of IS relative to the male dancers (10 [20.41%] of 49; $p = 0.037$) that was also markedly elevated compared with sex-matched normative population reference ranges (0.65% to 8.90%) (Fig. 1-C). The age range of our data was most closely aligned with that published by Carter and Haynes[38] (25 to 34 years). For performers meeting the criteria for IS (Cobb angle, >10°), the Cobb major curve was observed, on average, between vertebrae T4 and T11, with the apex occurring at T8, and the mean major curve angles were measured to be 29.10° (95% CI width, 3.95°) for women and 26.33° (95% CI width, 9.35°) for men.

Comparison of Physiologic Characteristics Between Performers with and without Criteria for IS

Comparisons of demographic and physiologic characteristics between female dancers with and without criteria for IS are shown in Table I. Performers with criteria for IS were observed to have a lower percentage of body fat and fat mass ($p < 0.05$). Female dancers with criteria for IS had greater upper-extremity (arm) length, trunk length, pelvic width, and shoulder width compared with those without criteria for IS ($p < 0.001$). This resulted in a reduced leg:trunk length ratio in performers with criteria for IS ($p = 0.002$). Data for male dancers are presented in Table II. As only 3 men were observed to meet criteria for IS, the same statistical comparisons were not made within the male cohort.

Discussion

We sought to determine the prevalence of IS in a company of professional ballet performers. In line with our hypothesis, female performers had an elevated prevalence of IS compared with male performers as well as with age-matched, general-population women (Fig. 1). These findings were paired with observations that women meeting the criteria for IS were observed to have a significantly lower percentage of body fat and fat mass compared with those not meeting the criteria for IS (Table I), which may add further insight into musculoskeletal abnormalities often associated with reduced energy availability in female athletes[1,47]. As professional ballet performers often begin their training before adolescence and progress to elite levels before physiologic maturation, further prospective investigations should determine the point in development where IS begins to present and to what degree extrinsic factors such as chronic biomechanical stresses, training, and nutrition may contribute to IS development in combination with potential genetic predispositions. Such identification may provide earlier opportunities for intervention or regular monitoring of deformity progression.

Prevalence of Scoliosis in Ballet Performers

Although the IS prevalence was greater among female performers compared with male performers, we also observed the IS prevalence in the female performers to be markedly elevated above the previously reported reference ranges for general-population women (Fig. 1). Such findings are in line with studies of youth amateur performers[27]. There is also growing debate on whether or not musculoskeletal abnormalities related to ballet represent a product of predisposition or chronic adaptation through training exposure[12]. For example, several studies have shown an increased prevalence of syndromic hypermobility as well as connective-tissue gene variants associated with hypermobility in this population[12,48]. Whether or not these adaptations or predispositions allow ballet performers to achieve a highly competitive professional status remains unknown. Vera et al.[12] recently observed that 89% of performers examined met criteria for hip dysplasia, which mirrored the reporting of a heightened incidence of hip instability in this population[49]. However, it was observed that the incidence of pain associated with hip dysplasia was markedly low compared with that in the general population with the same criteria. Therefore, such a condition may be advantageous for reaching various ranges of motion required for professional performance. On the basis of the present

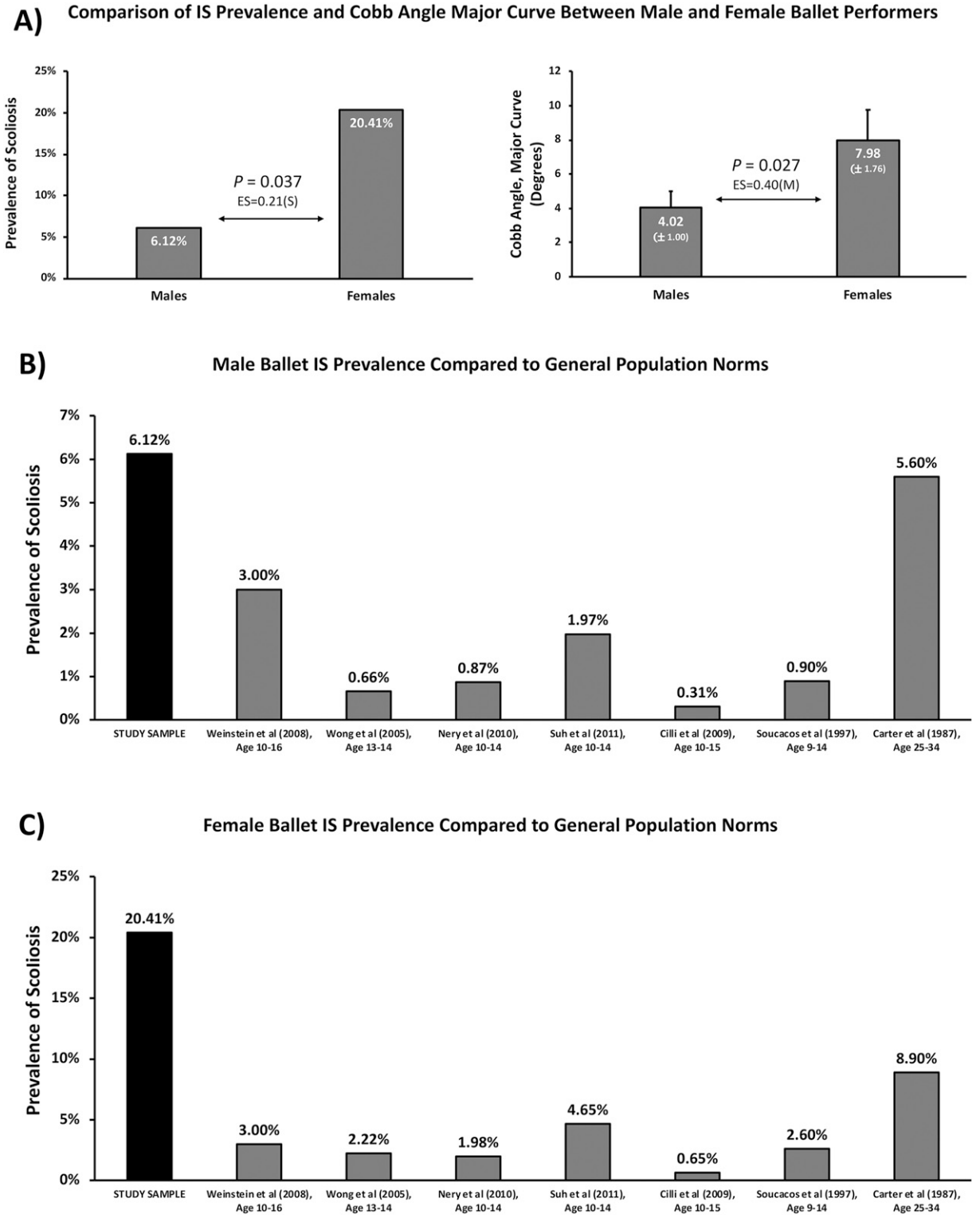

Fig. 1

Prevalence of IS in professional ballet performers. Data are presented as the prevalence of IS (Cobb angle >10°) (**Fig. 1-A**, *left*) and as the mean and the 95% CI width for the Cobb angle major curve (degrees) (**Fig. 1-A**, *right*) for all male and female ballet performers examined. The Type-I error for sex-based comparisons was set at $\alpha = 0.05$. For all significant comparisons, the effect size (ES) was calculated using the Cohen d statistic and was interpreted as follows: <0.1, negligible (N); 0.1 to 0.29, small (S); 0.3 to 0.49, moderate (M); 0.5 to 0.7, large (L); and >0.7, very large (VL). Prevalence data were also plotted against male (**Fig. 1-B**) and female (**Fig. 1-C**) general-population reference norms.

TABLE I Demographic, Anthropometric, and Compositional Comparison Between Female Ballet Dancers with and without Criteria for IS*

	IS† (N = 10)	No IS† (N = 39)	P Value‡	Effect Size§
Demographic characteristics				
Age *(yr)*	27.5 (3.4)	24.5 (5.9)	0.075	
Height *(cm)*	166.6 (3.1)	164.7 (1.5)	0.101	
Weight *(kg)*	53.2 (3.1)	52.3 (1.7)	0.325	
BMI *(kg/m²)*	19.1 (0.6)	19.3 (0.5)	0.394	
Percentage with low body mass, BMI < 20 kg/m²	80.0%	61.5%		
Body composition				
Percentage of body fat	17.7% (3.7%)	21.4% (1.5%)	**0.021**	0.69 (L)#
Fat mass index, FMI *(kg fat mass/m²)*	3.24 (0.75)	3.97 (0.36)	**0.040**	0.62 (L)#
Lean mass index, LMI *(kg lean mass/m²)*	14.85 (0.48)	14.52 (0.62)	0.301	
BMD				
Total BMD *(g/cm²)*	1.154 (0.063)	1.160 (0.031)	0.434	
Total BMD AM Z-score**	0.32 (0.66)	0.34 (0.28)	0.470	
Spine BMD *(g/cm²)*	1.015 (0.091)	1.028 (0.033)	0.381	
Spine BMD AM Z-score**	0.52 (0.80)	0.65 (0.31)	0.367	
Legs BMD *(g/cm²)*	1.180 (0.060)	1.189 (0.031)	0.397	
Legs BMD AM Z-score**	0.31 (0.61)	0.46 (0.44)	0.373	
Skeletal dimensions				
Arm length *(cm)*	54.2 (1.7)	47.8 (0.9)	**<0.001**	2.28 (VL)#
Leg length *(cm)*	89.8 (4.1)	89.7 (1.1)	0.451	
Trunk length *(cm)*	45.4 (0.8)	42.1 (0.9)	**<0.001**	1.51 (VL)#
Leg: trunk ratio	1.98 (0.08)	2.14 (0.05)	**0.002**	1.10 (VL)#
Pelvic width *(cm)*	26.1 (0.6)	23.9 (0.5)	**<0.001**	1.65 (VL)#
Shoulder width *(cm)*	37.1 (1.4)	33.8 (0.5)	**<0.001**	1.75 (VL)#
Pelvic: shoulder width ratio	0.70 (0.03)	0.71 (0.01)	0.438	

*BMI = body mass index. †The values are given as the mean and the 95% CI width for demographic characteristics, body composition, BMD, and skeletal dimensions or as the percentage. ‡Significant values are shown in bold. The Type-I error was set at $\alpha = 0.05$. §For all significant comparisons, the effect size was calculated using the Cohen d statistic and was interpreted as follows: <0.1, negligible (N); 0.1 to 0.29, small (S); 0.3 to 0.49, moderate (M); 0.5 to 0.7, large (L); and >0.7, very large (VL). #Significantly different between groups at $p < 0.05$. **AM Z-score = age-matched Z-score calculated against general-population norms.

findings, similar factors may play a role in spinal deformity observed in this population. Therefore, both early screening before professional participation as well as continued monitoring following retirement may be required to determine if IS observed in this population has long-term negative consequences.

Anthropometrics, Bone Density, and Musculoskeletal Abnormalities in Ballet Performers

Female ballet performers have been observed to have a markedly reduced percentage of body fat compared with the general population and reduced lean mass compared with other athlete populations[1,3,12,49]. In a previous investigation, these findings were also paired with a 26% incidence of oligomenorrhea[1]. Although factors such as overtraining, reduced energy availability, and reduced fat mass have been observed to contribute to a collection of symptoms often referred to as the female athlete triad[36], the findings presented here may be indicative of more chronic exposure to such external and internal stressors. For example, in a similar population of ballet performers, Vahedi et al.[3] reported that female ballet performers were subjected to nearly 3.5 times the yearly training volume of professional female soccer athletes. With regard to musculoskeletal health, the same contributing stressors have been associated with chronically reduced BMD, osteoporosis, skeletal muscle abnormalities, and injury risk[1,3,36,50].

In addition, we observed skeletal structure differences in female performers with the criteria for IS, compared with those without the criteria for IS (Table I), in which those with the criteria for IS were observed to have greater trunk length, longer arms, wider shoulders, and a wider pelvis. This finding is in line with previous observations that longer wing spans and dolichostenomelia (arm-span-to-height ratio, ≥1.05) are common physical examination findings in those with IS[51]. Furthermore, despite similar body masses between those with and without IS in this study, it is possible that load distribution across the spine differs in a manner that contributed to the current findings[52].

TABLE II Demographic, Anthropometric, and Compositional Comparison Between Male Ballet Dancers with and without Criteria for IS*

	IS† (N = 3)	No IS† (N = 46)
Demographic characteristic		
Age *(yr)*	23.7 (5.7)	25.2 (1.7)
Height *(cm)*	188.8 (7.2)	177.5 (1.5)
Weight *(kg)*	82.3 (6.4)	71.3 (2.0)
BMI *(kg/m²)*	23.1 (1.4)	22.6 (0.5)
Percentage with low body mass, BMI < 20 kg/m²	0.0%	0.0%
Body composition		
Percentage of body fat	14.3% (4.1%)	13.8% (1.0%)
Fat mass, FMI *(kg fat mass/m²)*	3.25 (1.05)	3.13 (0.23)
Lean mass, LMI *(kg lean mass/m²)*	18.3 (0.11)	18.6 (0.46)
BMD		
Total BMD *(g/cm²)*	1.407 (0.138)	1.351 (0.034)
Total BMD AM Z-score§	1.30 (1.01)	1.14 (0.26)
Spine BMD *(g/cm²)*	1.250 (0.081)	1.226 (0.035)
Spine BMD AM Z-score§	2.49 (0.53)	2.16 (0.29)
Legs BMD *(g/cm²)*	1.532 (0.222)	1.452 (0.040)
Legs BMD AM Z-score§	1.61 (1.57)	0.90 (0.29)
Skeletal dimensions		
Arm length *(cm)*	54.6 (2.2)	51.2 (0.8)
Leg length *(cm)*	101.8 (1.4)	94.7 (0.9)
Trunk length *(cm)*	43.7 (4.4)	44.9 (0.7)
Leg: trunk ratio	2.34 (0.21)	2.11 (0.04)
Pelvic width *(cm)*	25.7 (3.5)	24.8 (0.5)
Shoulder width *(cm)*	38.9 (4.1)	38.0 (0.5)
Pelvic: shoulder width ratio	0.67 (0.12)	0.65 (0.01)

*BMI = body mass index. †The groups were not sufficiently powered for statistical comparison. The values are given as the mean and the 95% CI width for demographic characteristics, body composition, BMD, and skeletal dimensions or as the percentage. §AM Z-score = age-matched Z-score calculated against general-population norms.

Clinical Considerations and Applications

Importantly, scoliosis prevalence in ballet dancers may exist on a spectrum between idiopathic and syndromic, potentially driven by intrinsic and extrinsic factors. For example, chronic biomechanical stresses combined with a predisposition to hypermobility may make these dancers susceptible to unique spinal challenges. The results of this study show that the greater prevalence of IS in this professional ballet cohort relative to the general population (Fig. 1-C) warrants regular screening, as recommended by several professional societies for girls at ages 10 and 12 years and for boys at age 13 or 14 years[26]. This can allow detection, monitoring, and treatment of scoliosis as indicated and for determination of when symptoms may present. Given the present findings, continued yearly screening past this age range may be of benefit for the identification and monitoring of curve progression. Further investigation will be required to determine whether changes to nutrition, training habits, and other factors at earlier ages may decrease the incidence or progression of IS, thereby reducing the need for more invasive interventions such as bracing or, in some cases, surgery. For example, strength and stability training with an emphasis on symmetry and strength through a range of motion has been observed to reduce orthopaedic pathologies in this population[4]. Whether or not such interventions may influence the development of IS remains to be determined.

Limitations

This investigation was not without limitations. This study was retrospective and had a sample limited to a single ballet company, without age-matched controls. Future investigations related to the prevalence and progression of IS in athlete populations should seek to perform direct age-matched comparisons with non-athlete groups. This will likely provide more insight than current approaches of retrospectively clustering differing athlete groups that are exposed to different physiologic stresses. We were not able to examine the medical history before professional performance or the time in development when their amateur training began. However, a representative of the company utilized in this investigation

indicated that, as an early-specialization sport, all performers within the company had between 8 and 10 years of training before becoming professionals, with training beginning between 7 and 10 years of age as is common[53,54]. Although well-established criteria for IS were used in this investigation, we were only able to include a single frontal plane radiograph with the subject in the supine position and, therefore, we were not able to determine if abnormalities might have been present in other planes. Such information might have allowed for better characterization of spinal deformity. As supine positioning may have reduced the amount of measurable curvature in the spine compared with a standing measurement, the frequency of IS may have been underestimated. Therefore, future prospective studies utilizing gold-standard radiographic assessments are warranted. Lastly, we were unable to gain assessment data on hypermobility, which might have allowed us to better characterize the relationship between hypermobility and IS. Future prospective studies will be needed to further characterize IS prevalence and development in this population; medical history, survey questionnaires, training history information, nutritional status, family history of IS, and further biomechanical analyses may greatly expand on the current findings.

Conclusions

Female professional ballet performers exhibit a higher prevalence of IS that, along with an inherent predisposition, may be linked to modifiable factors such as reduced fat mass resulting from decreased energy availability, which is known to affect musculoskeletal health in this and other elite female athlete populations. Female performers meeting criteria for IS were observed to have longer trunk lengths, a reduced leg: trunk length ratio, wider shoulder and pelvic width measures, and longer arms. Whether or not these factors influence skeletal loading in a manner that may, in turn, influence IS development requires further study. Cumulatively, these results highlight the understudied prevalence of IS as well as the importance of clinical screening and identification of population-specific risk factors for developing IS. As professional ballet performers often begin their training at an early age, further prospective investigations should seek to determine the point in development where IS begins to present. ■

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References

1. Lambert BS, Cain MT, Heimdal T, Harris JD, Jotwani V, Petak S, McCulloch PC. Physiological parameters of bone health in elite ballet dancers. Med Sci Sports Exerc. 2020 Aug;52(8):1668-78.

2. Shaw JW, Mattiussi AM, Brown DD, Springham M, Pedlar CR, Tallent J. The activity demands and physiological responses observed in professional ballet: a systematic review. J Sport Exerc Sci. 2021;5(4):254-69.

3. Vahedi H, Taft CM, Daum JR, Dabash S, McCulloch PC, Lambert BS. Pelvic region bone density, soft tissue mass, and injury frequency in female professional ballet dancers and soccer athletes. Sports Med Health Sci. 2021 Aug 12;3(3):157-64.

4. Vera AM, Barrera BD, Peterson LE, Yetter TR, Dong D, Delgado DA, McCulloch PC, Varner KE, Harris JD. An injury prevention program for professional ballet: a randomized controlled investigation. Orthop J Sports Med. 2020 Jul 28;8(7):2325967120937643.

5. Chatzopoulos D. Effects of ballet training on proprioception, balance, and rhythmic synchronization of young children. J Exerc Physiol Online. 2019;22(2).

6. Shaw JW, Mattiussi AM, Brown DD, Williams S, Springham M, Pedlar CR, Tallent J. Rehearsal and performance volume in professional ballet: a five-season cohort study. J Dance Med Sci. 2023 Mar;27(1):3-12.

7. Clarkson PM. An overview of nutrition for female dancers. J Dance Med Sci. 1998;2(1):32-9.

8. Doyle-Lucas AF, Davy BM. Development and evaluation of an educational intervention program for pre-professional adolescent ballet dancers: nutrition for optimal performance. J Dance Med Sci. 2011 Jun;15(2):65-75.

9. Fietze I, Strauch J, Holzhausen M, Glos M, Theobald C, Lehnkering H, Penzel T. Sleep quality in professional ballet dancers. Chronobiol Int. 2009 Aug;26(6):1249-62.

10. Lim SN, Chai JH, Song JK, Seo MW, Kim HB. Comparison of nutritional intake, body composition, bone mineral density, and isokinetic strength in collegiate female dancers. J Exerc Rehabil. 2015 Dec 31;11(6):356-62.

11. Sobrino FJ, Guillén P. Overuse injuries in professional ballet: influence of age and years of professional practice. Orthop J Sports Med. 2017 Jun 28;5(6):2325967117712704.

12. Vera AM, Peterson LE, Dong D, Haghshenas V, Yetter TR, Delgado DA, McCulloch PC, Varner KE, Harris JD. High prevalence of connective tissue gene variants in professional ballet. Am J Sports Med. 2020 Jan;48(1):222-8.

13. Kuznia AL, Hernandez AK, Lee LU. Adolescent idiopathic scoliosis: common questions and answers. Am Fam Physician. 2020 Jan 1;101(1):19-23.

14. Scholten PJ, Veldhuizen AG. Analysis of Cobb angle measurements in scoliosis. Clin Biomech (Bristol). 1987 Feb;2(1):7-13.

15. Skalli W, Vergari C, Ebermeyer E, Courtois I, Drevelle X, Kohler R, Abelin-Genevois K, Dubousset J. Early detection of progressive adolescent idiopathic scoliosis: a severity index. Spine (Phila Pa 1976). 2017 Jun 1;42(11):823-30.

16. Gorman KF, Julien C, Moreau A. The genetic epidemiology of idiopathic scoliosis. Eur Spine J. 2012 Oct;21(10):1905-19.

17. Liang ZT, Guo CF, Li J, Zhang HQ. The role of endocrine hormones in the pathogenesis of adolescent idiopathic scoliosis. FASEB J. 2021 Sep;35(9):e21839.

18. Normand E, Franco A, Marcil V. Nutrition and physical activity level of adolescents with idiopathic scoliosis: a narrative review. Spine J. 2020 May;20(5):785-99.

19. Ramírez M, Martínez-Llorens J, Sanchez JF, Bagó J, Molina A, Gea J, Cáceres E. Body composition in adolescent idiopathic scoliosis. Eur Spine J. 2013 Feb;22(2):324-9.

20. Parent S, Newton PO, Wenger DR. Adolescent idiopathic scoliosis: etiology, anatomy, natural history, and bracing. Instr Course Lect. 2005;54:529-36.

21. Weinstein SL, Dolan LA, Cheng JC, Danielsson A, Morcuende JA. Adolescent idiopathic scoliosis. Lancet. 2008 May 3;371(9623):1527-37.

22. 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. 2022 Aug 5;8(3):e001312.

23. Hawary RE, Zaaroor-Regev D, Floman Y, Lonner BS, Alkhalife YI, Betz RR. Brace treatment in adolescent idiopathic scoliosis: risk factors for failure-a literature review. Spine J. 2019 Dec;19(12):1917-25.

24. Scaturro D, Costantino C, Terrana P, Vitagliani F, Falco V, Cuntrera D, Sannasardo CE, Vitale F, Letizia Mauro G. Risk factors, lifestyle and prevention among adolescents with idiopathic juvenile scoliosis: a cross sectional study in eleven

first-grade secondary schools of Palermo Province, Italy. Int J Environ Res Public Health. 2021 Nov 24;18(23):12335.

25. Sitoula P, Verma K, Holmes L Jr, Gabos PG, Sanders JO, Yorgova P, Neiss G, Rogers K, Shah SA. Prediction of curve progression in idiopathic scoliosis: validation of the Sanders Skeletal Maturity Staging System. Spine (Phila Pa 1976). 2015 Jul 1; 40(13):1006-13.

26. Sanders JO, Khoury JG, Kishan S, Browne RH, Mooney JF3rd , Arnold KD, McConnell SJ, Bauman JA, Finegold DN. Predicting scoliosis progression from skeletal maturity: a simplified classification during adolescence. J Bone Joint Surg Am. 2008 Mar;90(3):540-53.

27. Longworth B, Fary R, Hopper D. Prevalence and predictors of adolescent idiopathic scoliosis in adolescent ballet dancers. Arch Phys Med Rehabil. 2014 Sep; 95(9):1725-30.

28. Wong AYL, Chan C, Hiller C, Yung PSH, Lau KKL, Samartzis D, Surgenor B. Is scoliosis associated with dance injury in young recreational dancers? A large-scale cross-sectional epidemiological study. J Dance Med Sci. 2022 Mar 15; 26(1):41-9.

29. Weinstein SL, Dolan LA, Wright JG, Dobbs MB. Effects of bracing in adolescents with idiopathic scoliosis. N Engl J Med. 2013 Oct 17;369(16):1512-21.

30. Oetgen ME, Heyer JH, Kelly SM. Scoliosis screening. J Am Acad Orthop Surg. 2021 May 1;29(9):370-9.

31. Looker AC, Borrud LG, Hughes JP, Fan B, Shepherd JA, Sherman M. Total body bone area, bone mineral content, and bone mineral density for individuals aged 8 years and over: United States, 1999-2006. Vital Health Stat 11. 2013 Aug;(253): 1-78.

32. Carey JJ, Delaney MF. T-scores and Z-scores. Clin Rev Bone Miner Metab. 2010; 8:113-21.

33. Horng MH, Kuok CP, Fu MJ, Lin CJ, Sun YN. Cobb angle measurement of spine from X-ray images using convolutional neural network. Comput Math Methods Med. 2019 Feb 19;2019:6357171.

34. Burkhart TA, Arthurs KL, Andrews DM. Manual segmentation of DXA scan images results in reliable upper and lower extremity soft and rigid tissue mass estimates. J Biomech. 2009 May 29;42(8):1138-42.

35. Aflatooni J, Martin S, Edilbi A, Gadangi P, Singer W, Loving R, Domakonda S, Solanki N, McCulloch PC, Lambert B. A novel non-invasive method for predicting bone mineral density and fracture risk using demographic and anthropometric measures. Sports Med Health Sci. 2023 Sep 11;5(4):308-13.

36. Carbuhn AF, Yu D, Magee LM, McCulloch PC, Lambert BS. Anthropometric factors associated with bone stress injuries in collegiate distance runners: new risk metrics and screening tools? Orthop J Sports Med. 2022 Feb 10;10(2): 23259671211070308.

37. Stanelle ST, Crouse SF, Heimdal TR, Riechman SE, Remy AL, Lambert BS. Predicting muscular strength using demographics, skeletal dimensions, and body composition measures. Sports Med Health Sci. 2021 Feb 15;3(1):34-9.

38. Carter OD, Haynes SG. Prevalence rates for scoliosis in US adults: results from the first National Health and Nutrition Examination Survey. Int J Epidemiol. 1987 Dec;16(4):537-44.

39. Cilli K, Tezeren G, Taş T, Bulut O, Oztürk H, Oztemur Z, Unsaldi T. [School screening for scoliosis in Sivas, Turkey]. Acta Orthop Traumatol Turc. 2009 Nov-Dec; 43(5):426-30. Turkish.

40. Nery LS, Halpern R, Nery PC, Nehme KP, Stein AT. Prevalence of scoliosis among school students in a town in southern Brazil. Sao Paulo Med J. 2010;128(2): 69-73.

41. Soucacos PN, Soucacos PK, Zacharis KC, Beris AE, Xenakis TA. School-screening for scoliosis. A prospective epidemiological study in northwestern and central Greece. J Bone Joint Surg Am. 1997 Oct;79(10):1498-503.

42. Suh SW, Modi HN, Yang JH, Hong JY. Idiopathic scoliosis in Korean school-children: a prospective screening study of over 1 million children. Eur Spine J. 2011 Jul;20(7):1087-94.

43. Wong HK, Hui JH, Rajan U, Chia HP. Idiopathic scoliosis in Singapore school-children: a prevalence study 15 years into the screening program. Spine (Phila Pa 1976). 2005 May 15;30(10):1188-96.

44. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med. 2016 Jun;15(2):155-63.

45. Gignac GE, Szodorai ET. Effect size guidelines for individual differences researchers. Personality Ind Diff. 2016;102:74-8.

46. Sawilowsky SS. New effect size rules of thumb. J Mod Appl Stat Methods. 2009; 8(2):26.

47. Márquez S, Molinero O. Energy availability, menstrual dysfunction and bone health in sports; an overview of the female athlete triad. Nutr Hosp. 2013 Jul-Aug; 28(4):1010-7.

48. Chan C, Hopper L, Zhang F, Pacey V, Nicholson LL. The prevalence of generalized and syndromic hypermobility in elite Australian dancers. Phys Ther Sport. 2018 Jul;32:15-21.

49. Vera AM, Nho SJ, Mather RC, Wuerz TH, Harris JD. Hip instability in ballet dancers: a narrative review. J Dance Med Sci. 2021 Sep 15;25(3):176-90.

50. Warren MP, Brooks-Gunn J, Hamilton LH, Warren LF, Hamilton WG. Scoliosis and fractures in young ballet dancers. Relation to delayed menarche and secondary amenorrhea. N Engl J Med. 1986 May 22;314(21):1348-53.

51. Morava E, Lacassie Y, King A, Illes T, Marble M. Scoliosis in velo-cardio-facial syndrome. J Pediatr Orthop. 2002 Nov-Dec;22(6):780-3.

52. Zhang Q, Chon T, Zhang Y, Baker JS, Gu Y. Finite element analysis of the lumbar spine in adolescent idiopathic scoliosis subjected to different loads. Comput Biol Med. 2021 Sep;136:104745.

53. Davenport KL, editor. Dance Medicine, An Issue of Physical Medicine and Rehabilitation Clinics of North America. New York: Elsevier Health Sciences; 2020.

54. Quinn BJ, Scott C, Stracciolini A. Special considerations for growing dancers. Phys Med Rehabil Clin N Am. 2021 Feb;32(1):75-86.