

Quantitative Ultrasound of the Tibia and Radius in Prepubertal and Early-Pubertal Female Athletes

Bareket Falk, PhD; Zohar Bronshtein, BEd; Levana Zigel, BSc; Naama W. Constantini, MD; Alon Eliakim, MD

Background: Physical exercise during childhood has been shown to enhance bone mineral density, thus reducing the risk of osteoporosis.

Objective: To examine bone properties, as measured by quantitative ultrasound, in prepubertal and early-pubertal female athletes engaged in impact and non-impact sports.

Design: Survey.

Setting: General community.

Participants: Twenty-five acrobatic gymnasts, 21 swimmers, and 21 control subjects. Athletes had been training for at least 1½ years.

Main Outcome Measure: Bone speed of sound (bilateral) at the distal radius and the midtibia.

Results: Gymnasts were significantly shorter and lighter than swimmers and control girls ($P < .001$) but had a body

mass index similar to that of swimmers. Adiposity was lower in athletes than in controls. Speed of sound did not correlate with measures of body size. Higher mean \pm SD radial speed of sound values (nondominant side) were observed in gymnasts (3764 ± 104 m/s; $P = .045$) than in swimmers and control girls (3732 ± 99 and 3721 ± 83 m/s, respectively). Mean \pm SD tibial speed of sound values (nondominant side) were similar in gymnasts and swimmers (3629 ± 87 and 3619 ± 78 m/s, respectively) and higher in the athletic groups than in the control group (3516 ± 127 m/s; $P < .001$). In all 3 groups, no differences were observed between dominant and nondominant sides in the radii or tibiae.

Conclusions: Physical exercise, impact and nonimpact, is related to enhanced bone properties, as measured by quantitative ultrasound. Longitudinal studies using various modes of bone evaluation are necessary to determine the long-term effect of various types of exercise on bone properties.

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PHYSICAL EXERCISE during childhood and adolescence is related to increased bone mineral content and enhanced peak bone mass,¹ and therefore may reduce the risk of osteoporosis and osteoporotic fractures later in life.²

Recent prospective studies³⁻⁵ demonstrate that high-impact aerobic and strength-building or weight-bearing exercises can increase bone mineral density (BMD) in prepubertal children. Among adolescents and adults, sports activities that are characterized by heavy loads or impact loading on the skeleton (eg, gymnastics) are associated with higher bone density than sports that generate mechanical loads without additional gravitational loading (eg, swimming). Among prepubertal athletes, 2 studies^{6,7} specifically demonstrate higher BMD in gymnasts than in

swimmers, and several studies^{8,9} show higher BMD in gymnasts than in weight-matched control girls.

All of these studies have examined bone mass using dual-energy x-ray absorptiometry (DXA) technology, which measures bone mineral content in a given area. Although bone mineral content and BMD, as determined by DXA, may be highly correlated with bone strength, the latter depends on other bone properties, such as elasticity, internal architecture, and geometry,¹⁰ which are not reflected in DXA measurements. In addition, BMD, as measured by DXA, is a 2-dimensional measure and is highly influenced by body size.¹¹ Bone mineral density, as measured by quantitative computed tomography, is true density (tridimensional). When volumetric radial BMD was measured using quantitative computed tomography, no differences were reported between gym-

From the Ribstein Center for Sport Medicine Sciences and Research, Wingate Institute, Netanya (Drs Falk, Bronshtein, and Constantini and Ms Zigel), and the Department of Pediatrics, Meir General Hospital, Sapir Medical Center, Kfar Sava (Dr Eliakim), Israel.

nasts and nonathletic girls.⁹ The discrepancy in findings from quantitative computed tomography vs DXA raises the question of whether high-impact exercise among young children truly affects bone mass and density.

Dual-energy x-ray absorptiometry provides an accurate and precise measurement of bone mineral content. However, it is expensive and time-consuming and involves the use of some radiation, although minimal.¹² In recent years, a quantitative ultrasound (QUS) method was developed for bone assessment. The QUS method is portable, is relatively inexpensive, and does not involve any radiation. The QUS values (speed of sound [SOS] and bone ultrasound attenuation) are related to bone density and structure¹³ and to the elastic modulus of bone¹³ but not to cortical thickness.¹⁴ Previous studies¹⁵ have demonstrated that in elderly patients, QUS can predict fracture risk independent of BMD.

The use of SOS in children is gaining rapid support^{13,16} because it is less likely to be affected by bone size compared with DXA. Falk et al¹⁷ recently demonstrated that QUS is sensitive enough to detect changes in tibial SOS in prepubertal boys in an 8-month period.

To date, few studies have used QUS in children. Young gymnasts have been reported^{18,19} to have higher calcaneal and radial ultrasonographic variables than nonathletic controls. We^{20,21} recently reported higher radial SOSs in adolescent volleyball players and adult basketball players than in age- and sex-matched controls. All of these studies have demonstrated a favorable relationship between various sports and bone ultrasound variables. In contrast, Foldes et al²² reported reduced tibial ultrasound velocity in young dancers compared with control girls.

The purpose of this study is to compare bone QUS measures between prepubertal and early-pubertal female athletes (gymnasts and swimmers) and nonathletic girls. A secondary objective is to assess a possible relationship between different types of sports (eg, impact vs nonimpact) and bone SOS at different skeletal sites. Girls were chosen because the older female population seems to experience osteoporosis to a greater extent and, therefore, may have more to gain from exercise during childhood.

METHODS

EXPERIMENTAL PARTICIPANTS

Participants in the study were all healthy girls (25 acrobatic gymnasts and 21 swimmers) who were recruited from regional sports clubs. Only teams who trained year-round were approached. Acrobatic gymnastics is characterized by very high impacts through repeated jumps and body contacts with hard surfaces, whereas swimming is characterized by considerable muscle action but no impact. Training experience for both groups was at least 1½ years. Gymnasts trained a mean ± SD of 4.2 ± 1.7 h/wk, whereas swimmers trained 7.8 ± 3.4 h/wk ($P < .001$). Neither the gymnasts nor the swimmers performed resistance training in addition to their regular training. The control group included 21 healthy girls who volunteered to participate in the study in response to an advertisement posted (for parents) in local social clubs and health clubs. Control subjects did not participate in regular physical activity more than twice per week (as

determined by a questionnaire). All participants were white and premenarcheal. Pubertal stage (stage 1 or 2) was determined by self-assessment, according to pubic hair characteristics.²³ None of the participants had an eating disorder, according to the Eating Attitudes Test–26 questionnaire.²⁴

Each participant who volunteered for the study received an explanation of the purpose of the study, the methods involved, the benefits, and the potential risks or discomforts. The parent or legal guardian signed an informed consent form for participation in the study, in accordance with the Helsinki declaration and the ethics committee and review board (Ribstein Center for Sport Medicine Sciences and Research, Wingate Institute, Israel).

MATERIALS AND METHODS

One parent of each participant filled out a questionnaire regarding his or her daughter's medical history, training history, other physical activities, and calcium intake. The completed questionnaire was checked by one of the investigators (Z.B.) to verify that the information was correct. Each participant was also interviewed regarding the previous day's dietary intake. They were asked to provide as many details as possible. The completed forms were analyzed using a local nutrition analysis program, which contains local products.²⁵

Anthropometric measures, including body weight, height, and skinfold thicknesses, were determined using standard methods. Skinfold thickness was determined at 4 sites (biceps, triceps, suprailiac, and subscapula) in triplicate, and the mean of the 3 measurements was recorded. The sum of 2 skinfold thickness measurements (triceps and subscapula) was used to calculate the percentage of body fat.²⁶ All anthropometric measures were determined by the same investigator (Z.B.).

Bone SOS measurement was performed using the Sunlight Omnisense device (Sunlight Medical Ltd, Tel Aviv, Israel), which consists of a main unit and hand-held probes designed to measure SOS at specific skeletal sites. For a detailed description of the device and technique, see Njeh et al.¹⁴ Briefly, the probe contains a set of 2 transmitters and 2 receivers. The SOS measurement reflects the shortest time that elapses between pulse transmission and the first reception of a signal. The exact path of the signal is determined by using the Snell law²⁷: as the signal enters the bone from the soft tissue, it is refracted through a critical angle, which is a function of the ratio of the SOS in soft tissue and bone. After the sound wave propagates along the bone, it emerges at the same critical angle. The time taken for the signal to travel between the transmitting and receiving transducers is used to infer the SOS in bone.²⁸

Bone SOS was determined bilaterally (dominant and non-dominant sides) at the distal one third of the radius and the midshaft of the tibia. The dominant limb was determined by asking the participant which hand she preferred for writing and which leg she preferred for kicking. All measurements were performed by the same technician (Z.B.) after daily system quality verification, according to a specific method, as follows:

Distal radius: A line was marked midway between the olecranon process of the elbow and the extended third phalanx. The probe was placed parallel to the radius on its medial surface, and a 140° scan from side to side (70° to each side) was performed.

Tibia: A line was marked midway between the apex of the top of the knee and the sole while the participant was in a sitting position. The probe was placed parallel to the bone surface, 3 to 4 cm medial to the tibial crest, and a scan was performed from that point to the crest, repeatedly.

Age and Physical Characteristics of Prepubertal and Early-Pubertal Swimmers, Gymnasts, and Nonathletes*

	Control Subjects (n = 21)	Swimmers (n = 21)	Gymnasts (n = 25)
Age, y	10.1 ± 1.1 ^a	11.0 ± 0.9 ^{a,b}	10.0 ± 0.7 ^b
Height, cm	141 ± 9 ^a	146 ± 8 ^b	135 ± 6 ^{a,b}
Weight, kg	37.8 ± 9.3 ^a	35.3 ± 6.5 ^b	29.4 ± 4.3 ^{a,b}
BMI	18.8 ± 3.3 ^{a,b}	16.6 ± 1.9 ^a	16.2 ± 1.7 ^b
Sum of 4 skinfold measurements, mm	22.7 ± 7.7 ^{a,b}	16.0 ± 3.4 ^a	17.6 ± 4.9 ^b
Body fat, %	20.3 ± 5.7 ^{a,b}	15.3 ± 2.8 ^a	16.6 ± 3.9 ^b
Fat-free mass, kg	29.7 ± 5.7 ^a	29.9 ± 5.1 ^b	24.4 ± 2.8 ^{a,b}

Abbreviation: BMI, body mass index (calculated as weight in kilograms divided by the square of height in meters).

*Data are given as mean ± SD. Like letters represent significant differences between marked groups.

The in vivo precision of tibial and radial measurements was 0.90% and 0.45%, respectively.

STATISTICAL ANALYSIS

Differences between groups in physical characteristics (eg, height and body mass index) were examined using a 1-way (group) analysis of variance. Differences in bone QUS between groups were examined using a general linear model with 2 main effects: (1) impact sport (gymnastics) vs nonimpact sport (swimming) vs nonathlete (between subjects) and (2) dominant vs nondominant side (within subjects). In addition, the interaction between the main effects was also examined. Age, variables of body size, and training volume were checked for covariance. However, no covariates were found to be significant. Therefore, the final analysis was performed without covariates. Post-hoc analysis was performed using the least significant difference procedure. The analysis was performed separately for the radius and tibia. Correlations between variables were tested using the Pearson product moment correlation procedure. Data were analyzed using statistical programs (SPSS; SPSS Inc, Chicago, Ill), and level of significance was set at $P < .05$. Data are given as mean ± SD.

RESULTS

The age and physical characteristics of the participants are given in the **Table**. All participants were prepubertal or early-pubertal (9 gymnasts and 9 control girls were rated as Tanner stage 2; the rest of the girls were at stage 1), although swimmers were significantly older than gymnasts and controls. Gymnasts were significantly shorter and lighter than swimmers and controls. Body mass index was significantly higher in the control group than in gymnasts and swimmers, with no difference between the 2 athletic groups. The percentage of body fat and the sum of 4 skinfold thickness measurements were significantly lower in athletes than in controls. Fat-free mass was significantly lower in gymnasts than in swimmers and controls.

The QUS results in the radii and tibiae are described in **Figure 1** and **Figure 2**, respectively. No differences were observed between the dominant and nondominant sides. A significant group effect was observed for the radii, reflecting a higher SOS in gymnasts than in controls ($P = .03$). Tibial SOS in gymnasts and swim-

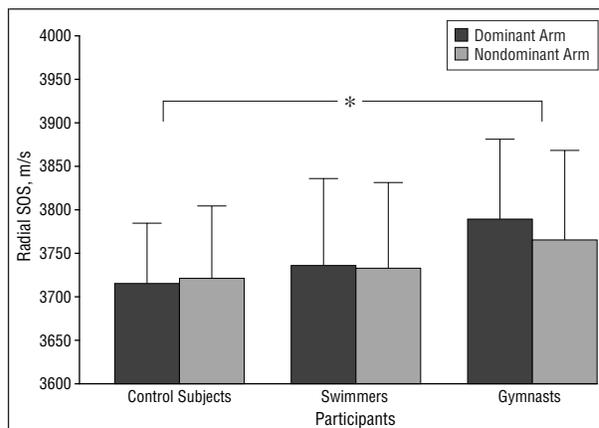


Figure 1. Mean radial speed of sound (SOS) in the dominant and nondominant arms of gymnasts, swimmers, and nonathletic girls. Error bars represent SD. Asterisk indicates a significant difference between groups.

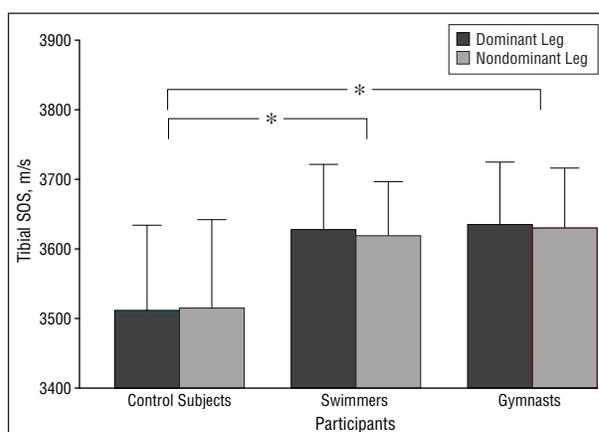


Figure 2. Mean tibial speed of sound (SOS) in the dominant and nondominant legs of gymnasts, swimmers, and nonathletic girls. Error bars represent SD. Asterisk indicates a significant difference between groups.

mers was significantly higher than in controls ($P < .001$ for both). No difference was observed between gymnasts and swimmers.

No differences were observed between groups in calcium intake (gymnasts: 484 ± 229 mg/d; swimmers: 576 ± 206 mg/d; and controls: 463 ± 232 mg/d). Almost all participants consumed far below the recommended daily intake of calcium (1200 mg/d).

High correlation coefficients were observed between the dominant and nondominant sides of the tibiae ($r = 0.88$) and radii ($r = 0.81$). Moderate correlations were observed between the tibia and radius of the respective sides ($r = 0.39-0.53$). In general, neither radial nor tibial SOS results correlated with any of the measures of body size. In the control group only, the nondominant tibial SOS correlated inversely with the percentage of fat ($r = -0.47$) and the sum of skinfold measurements ($r = -0.45$) but not with body mass or fat-free mass.

COMMENT

The results of the present study demonstrate that physical exercise seems to have a favorable effect on the growing skeleton and that this effect can be measured by QUS

as early as the prepubertal years. The main findings of this study are the higher radial and tibial SOS values in gymnasts than in nonathletic girls. In addition, in contrast to previous DXA results, tibial SOS values were higher in swimmers than in nonathletic girls. These results may indicate that quantitative and qualitative properties of bone are enhanced in female gymnasts and swimmers. Although previous studies of gymnasts used DXA technology,^{6,8,9} QUS provides a portable, inexpensive, and radiation-free method for the evaluation of bone properties. Finally, in the present study, no consistent correlation was found between SOS values and measures of body size, suggesting that unlike DXA, QUS variables are not affected by body size in this age group. The possible independence of QUS from body size adds to the attractiveness of this method for the evaluation of bone strength, especially in the growing population.

Previous studies^{18,29} of prepubertal children reported a wide range of SOS results, probably owing to the use of different devices. Nevertheless, regardless of the device used, the results of the present study and these other studies demonstrate higher SOS of cortical bone in the radius¹⁸ and tibia²⁹ in gymnasts, suggesting a positive effect of high-impact training on bone.

Consistent with previous studies, we found higher SOS values in gymnasts than in nonathletic girls. Most previous studies^{2,6,8,9} of prepubertal gymnasts used DXA technology and evaluated bone at typical weight-bearing sites (eg, the femur and the spine). Only 2 previous studies^{2,8} measured BMD in the upper limbs in prepubertal gymnasts, and, consistent with the present study, both found higher BMD in gymnasts than in nonathletic girls.

The SOS values obtained in swimmers are difficult to compare with the literature. To our knowledge, no previous study has used QUS technology to investigate bone properties among swimmers. The similar radial values in swimmers and controls in the present study are in agreement with those in the study by Courteix et al,⁸ who reported similar radial BMD, using DXA, in prepubertal swimmers and control girls. Another study⁶ of prepubertal swimmers reported whole-body BMD only, which was similar in swimmers and control girls, both of which were lower than in the gymnasts. The similar BMD among swimmers and control girls has been explained by the fact that swimming does not exert any impact loading on the skeleton and, therefore, despite the high mechanical loading, is insufficient to affect bone mineral acquisition. Similar BMD measurements were also found in swimmers compared with nonathletic age-matched females.³⁰

The higher tibial SOS values demonstrated in the present study in swimmers than in nonathletic girls are difficult to explain. Because all participants were premenarcheal, this was not a contributing factor to the difference between groups. In addition, chronological age was not a significant covariant in this study, reflecting that the older age of the swimmers was not a factor that contributed to the differences between groups. None of the swimmers engaged in any resistance training. Therefore, this, too, could not have been a contributing factor to the observed difference. Finally, daily calcium intake was similar among groups. A possible explanation for the higher tibial SOS values in swimmers than in nonathletic girls

is that the former may have been more habitually active in daily life. Higher habitual activity in daily living is more likely to affect the lower extremities than the upper extremities.³ This is consistent with the results of other studies³ that demonstrated that even an additional 30 minutes of jumping activity per week can increase bone mineral acquisition in prepubertal children.

The similar tibial SOS values in swimmers and gymnasts, which are in contradiction to previous BMD data,^{6,8} may reflect the fact that swimming may affect bone properties other than density that are detectable by QUS but not by DXA (eg, elasticity and microstructure). This finding is supported by Hart et al,³¹ who recently demonstrated the beneficial effects of swimming in rats on bone structure, turnover, and strength. Further research, using QUS or imaging techniques, could be useful in determining whether the mechanical loads of swimming can indeed be instrumental in affecting bone properties and, ultimately, in reducing the risk of osteoporosis.

In nonathletic girls, tibial SOS was inversely correlated with measures of adiposity (percentage of body fat and sum of skinfold measurements). This is in line with the study by Eliakim et al,³² who demonstrated low QUS values in obese children. Although not specifically measured in the present study, one possible explanation is that girls with higher adiposity may have been less habitually active in their daily life and their higher body mass may not yet have provided the advantage to bone mass often seen in adults.

Finally, a high correlation was observed between the dominant and nondominant sides of both limbs, with no significant differences between sides. This is to be expected in all groups because swimming and gymnastics are symmetrical sports. Previous studies of healthy children and adolescents³³ and of gymnasts, runners, and nonathletic girls¹⁹ reported no significant QUS differences between sides. In contrast, Wu et al³⁴ reported higher BMD in the left hip than in the right hip in adult rhythmic gymnasts. The authors explained this difference by the fact that the left leg is the landing leg and must withstand much higher strains than the takeoff leg. One possible explanation for these apparently inconsistent results is that rhythmic gymnastics is indeed characterized by asymmetry, whereas acrobatic gymnastics is not. In addition, gymnasts in the present study were much younger, and, therefore, the possible differential effect of landing vs takeoff leg may not yet be expressed. Likewise, gymnasts in the present study had a much lower weekly training volume than those in the study by Wu et al.³⁴

In conclusion, consistent with previous studies that used DXA technology, the results of this study indicate that among prepubertal and early-pubertal girls, physical exercise is related to enhanced bone properties, as measured using QUS. The high tibial SOS values among swimmers may suggest that sports that involve high mechanical strain produced by the muscles, and not necessarily by impact, may positively affect bone properties in young athletes and may provide protection against future osteoporosis.

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What This Study Adds

Previous studies have demonstrated, using DXA, higher bone mineral density in young athletes than in nonathletes and the potential beneficial effect that exercise may have on children's bones. DXA is the acceptable method for assessing bone in adults, but its use is problematic in children and athletes because it is affected by body size. In the present study, bone qualities of young athletes were examined using QUS, which is not affected by bone size, is inexpensive, and does not involve any radiation.

The results of this study demonstrate enhanced bone qualities (SOS) in prepubertal and early-pubertal gymnasts (an impact sport), as previously demonstrated by DXA. In addition, higher tibial speed of sound was found in prepubertal and early-pubertal swimmers (a nonimpact sport), implying that swimming, contrary to previous beliefs, may indeed have a beneficial effect on young bones. The results of this study also imply that the quantitative ultrasound technique may be used to evaluate bone in athletes and possibly other populations.

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Corresponding author and reprints: Bareket Falk, PhD, Department of Physiology, Ribstein Center for Sport Medicine Sciences and Research, Wingate Institute, Netanya 42902, Israel (e-mail: bfalk@post.tau.ac.il).

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