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Context: Regular physical activity during puberty improves bone mass acquisition. However, it i unknown whether extreme intense training has the same favorable effect on the skeleton.

Objective: We evaluated the bone mass acquisition in a unique cohort of world-class rhythmic gymnast

Study participants: A total of 133 adolescent girls and young women with a mean age of 18.7 ± 2. (14.4–26.7) years participated in this study: 82 elite rhythmic gymnasts (RGs) and 51 controls (CONs)

Main Outcome Measures: Anthropometric variables and body composition were assessed, and a participants completed questionnaires on their general medical, menstrual, and training historie Broadband ultrasound attenuation (BUA in decibels per megahertz) was determined by quant tative ultrasound at the heel.

Results: RGs presented lower weight (−8.5%, $P < .001$), body mass index (−11.7%, $P < .001$), and bod fat mass (−43%, $P < .001$) and higher muscle mass (6.3%, $P < .01$) and height (+2.8 cm, $P < .01$). RG presented an age of menarche significantly delayed compared with CONs (15.6 ± 1.6 vs 12.7 ± 1.7 year $P < .001$) and a high prevalence of menstrual disorders (64%). BUA values were higher in RGs vs CON (68.6 ± 4.6 and 65.4 ± 3.3 dB/Mhz, respectively; $P < .001$). This difference was exacerbated when BU/ was adjusted for age and body weight. BUA values in RGs were not affected by menstrual or trainin status. Among RGs with menarche, BUA was higher (71.5 ± 4.1 and 67.9 ± 3.5 dB/Mhz) for delaye (14.4 ± 0.8 years) vs severely delayed (17.3 ± 1.4 years) menarcheal age. BUA was positively correlate with body weight and body mass index and tended to be correlated with age.

Conclusion: Conversely to expectations for adolescents and young women with a high prevalence of men strual disorders and/or delayed menarche, intense training in rhythmic gymnastics appeared to have beneficial effect on the bone health of a weight-bearing site. This effect was nevertheless modulated by th age of menarche. The high mechanical loading generated by this activity may counterbalance the negativ effect of menstrual disorders. (*J Clin Endocrinol Metab* **98: 4961–4969, 2013**)

echanical loading is an important determinant of bone mass (1). Weight-bearing activities such as artistic and rhythmic gymnastics are more beneficial for bone mass acquisition in adolescents than no-impact and non–weight-bearing activities such as swimming (2–4). Moreover, our group has recently demonstrated in cross-sectional and longitudinal studies that rhythmic gymnasts (RGs) present higher areal bone mineral density (aBMD) gain throughout the growth period, with differences more marked after menarche (4, 5). The osteogenic effect of training was particularly noted at mechanically loaded bone sites such as the femoral region, whereas no difference was observed at the radius or lumbar spine, 2 less-solicited sites. These studies were mainly conducted in national-level athletes who train about 20 h/wk or less (2, 4, 5), and the bone response in adolescent athletes may vary with the training intensity, as observed in adult athletes (6–8). Although the consequences of very intense training (>40 h/wk) on growth, skeletal maturation, and menarcheal and menstrual status are relatively well described in world-class gymnasts (9, 10), its effects on bone mass acquisition remain questionable. Yet this aspect is fundamental in a population presenting a substantial delay of menarche (>2–3 years) and a high degree of menstrual disorders (9) related to hypoestrogenism, both factors known to have a deleterious effect on bone mass acquisition in untrained girls (11). This impact may be even more deleterious when intense training starts at a young age and continues through adolescence, a key period for bone mass acquisition (5, 12, 13).

The aim of this study was to evaluate the effect of intense training on bone status and body composition in a unique cohort of world-class RGs during the growth period. We also investigated the potential interactions of menstrual disorders, intensity training levels, body composition, and bone status in this privileged population.

Subjects and Methods

Subjects

Ethics approval for the study was obtained by the Ethics Review Committee of Nîmes, France (Commission de Protection des Personnes, Sud Mediterranee III), and permission for the clinical trials was granted by the French Medicine and Health Care Products Regulatory Agency (Agence Française de Securite Sanitaire des Produits de Santé). Moreover, this study was authorized by the International Gymnastics Federation. All participants volunteered for the study, and informed consent was obtained from each athlete and control (CON) or, when needed, from their parents or coaches. All investigations were performed in accordance with article 7 from the medical committee of the International Gymnastics Federation competitions. Over the 9 consecutive days of the September 2011 World Championships

in Montpellier, France, 82 elite RGs from 25 countries were recruited for this study. The CON group (n = 51) consisted of adolescents and young women with ages comparable to those of RGs who performed only leisure physical activities for fewer than 3 h/wk. All the participants were Caucasian.

None had obvious signs of acute or chronic illness known to affect bone health and no long periods of immobilization or fractures within the previous 12 months.

Methods

The study protocol included noninvasive clinical and laboratory investigations and the completion of questionnaires.

Standing height was measured with a stadiometer to the nearest 0.1 cm and recorded as the mean of 2 consecutive measurements. Body weight, body fat mass (percent), and muscle mass were evaluated using a portable bioelectrical impedance weight scale with a precision of 0.1 kg (Tanita BC 601). Body mass index (BMI) was calculated as weight (kilograms) divided by the square of height (meters). Height SD score (SDS) and weight SDS were calculated according to the World Health Organization standard curves. The target height of the participants in cm was calculated with the following equation: target height = ([father's height + mother's height]/2) − 6.5.

Questionnaires

The participants completed a series of questionnaires designed to assess the general medical and menstrual history, with questions about the age of menarche and the pattern of menses, including the menstrual cycle duration and the absence or irregularity of menstruation. Primary amenorrhea (absence of menstruation in girls above 15 years), secondary amenorrhea (absence of menstruation for 3 months in the postmenarche period and in the absence of pregnancy) (14), and oligomenorrhea (menstrual interval of more than 35 days, with 4–9 periods in the past year) (15) were defined as menstrual disorders. The use of oral contraceptive pills (OCPs) was also recorded. Moreover, pubertal onset in family members, included age of the mother's menarche, was also recorded.

Detailed information about the training history was collected, including data on the starting age of intensive training, training hours per week and training months per year as well as a history of the training for each year from the age of starting training until the day of the evaluation.

All the items were translated into French, German, Italian, Spanish, and Russian.

None of the participants used calcium or vitamin D supplements or declared taking any illicit substances.

Quantitative ultrasound measurement

Quantitative ultrasound (QUS) measurements were made with the Osteospace densitometer (Medilink). For this measurement the subject's foot is placed in a dry foot receptacle, and the transducers are acoustically coupled to the heel with a water-based coupling gel. The transducers are positioned automatically, with the aid of a laser beam. The operator positions the laser on the center of the fibular malleolus using the command key panel on the device and a mirror in the foot receptacle. Using the coordinates of the malleolus (where the laser beam is placed) and the subject's foot length, the location of the calcaneus is then determined automatically. The 2 probes then move automatically inward into direct contact with the foot at the determined

location (16). This takes into account anatomical differences among the subjects and ensures that the same relative location will be measured for each subject. The Osteospace measures broadband ultrasound attenuation (BUA in decibels per megahertz). The variables are automatically computed after the ultrasonic wave has transversed the calcaneus. The dominant heel was measured in all subjects. The precision (reproducibility) error for BUA is 1.72% (16).

Statistical analysis

The characteristics of the adolescents and young women in the present study are described with proportions for categorical variables and with means and SD values for continuous variables (age, weight, BUA, etc,). The distributions were tested with the Shapiro-Wilk statistic. The comparisons of means between groups were performed using Student's t test or ANOVA when data distribution was normal, and the Mann-Whitney rank sum test or the Kruskal-Wallis test when the continuous variables were skewed. The comparisons and computation of adjusted BUA means for age and weight were performed using multivariate linear regression analysis. The mean BUA values according to age in both groups were modeled using multivariate linear regression analysis and are expressed graphically with their 95% confidence interval (CI). The family-wise error rate was controlled using Tukey-Kramer multiple-comparison procedures. The relationships between continuous parameters were assessed with the Spearman correlation. Statistical analyses were performed at the conventional two-tailed α level of 0.05 using SAS version 9.1 (SAS Institute).

Results

The anthropometric characteristics and training status of the athletes and CONs are summarized in Table 1. The mean age was 18.3 ± 2.5 (15.3 to 26.7) years for RGs and 19.3 ± 3.0 (14.4 to 26.7) years for CONs. The mean training volume of RGs was 41.4 ± 13.8 h/wk (25–72 hours) with the starting age being 6.2 years. As expected, RGs presented lower weight (-8.5%, $P < .001$), BMI (-11.7%, $P < .001$), and whole-body fat mass (kilograms and percent; -61.7% and -43%, $P < .001$) and higher muscle mass (6.3%, $P < .01$) than CON. When height SDS and weight SDS were calculated according to the French growth-weight curves, RGs presented mean body weight slightly below (-0.1 SD) the population mean and height above the mean ($+0.7$ SD). Moreover, height was greater in RGs ($+2.8$ cm, $P < .01$), in agreement with a tendency toward greater target height ($+1.6$ cm, $P = .07$).

Table 1. Anthropometric and Training Characteristics of Gymnasts and CONs[a]

Parameters	RGs	CONs	P Value
Number of subjects	82	51	
Age, y	18.3 ± 2.5	19.3 ± 3.0	NS
Anthropometric data			
Weight, kg	52.4 ± 4.7	57.3 ± 7.2	<.001
Weight SDS	-0.1 ± 0.7	0.7 ± 1.1	<.001
Height, cm	166.9 ± 5.5	164.1 ± 4.7	<.01
Height SDS	0.8 ± 0.9	0.3 ± 0.8	<.01
BMI, kg/m^2	18.8 ± 1.3	21.3 ± 2.5	<.001
Target height, cm	165.7 ± 4.8	163.9 ± 5.6	.07
Body fat mass, kg	7.2 ± 2.2	18.8 ± 4.7	<.001
Body fat mass, %	13.6 ± 3.4	23.9 ± 6.0	<.001
Muscle mass, kg	44.3 ± 3.7	41.5 ± 4.2	<.01
Training status			
h/wk	41.4 ± 13.8	2.5 ± 1.3	<.001
Age at start of training, y	6.2 ± 1.5		
Gynecological status			
Age of menarche, y	15.6 ± 1.6	12.7 ± 1.3	<.001
Number of athletes with menarche, n (%)	65 (80.2%)	51 (100%)	
Menstrual disorders, n (%)[b]	36 (55%)		
Number of participants taking contraceptive pills, n (%)[b]	5 (7.7%)	27 (52.9%)	
Age of subjects with primary amenorrhea (n = 17)	16.7 ± 0.7		
Age of mother at menarche, y[c]	15.3 ± 1.8 (n = 46)	12.86 ± 2.0 (n = 25)	<.001
Bone status			
BUA, dB/MHz	68.6 ± 4.6	65.4 ± 3.3	<.001
T-score (SD)	0.3 ± 0.8	-0.2 ± 0.6	<.001
Adjusted BUA, dB/Mhz	68.9 ± 0.5	65.0 ± 0.6	<.001

Abbreviation: NS, not significant.

[a] Unless indicated otherwise, values are presented as mean $\pm$ SD. Adjusted BUA values for age and weight are presented as mean $\pm$ SEM.

[b] Menstrual disorders in RGs with menarche.

[c] Mother's age at menarche was evaluated for 46 RGs and 25 CONs. T-score represents theoretical values for a population of same gender at peak bone mass (20 years).
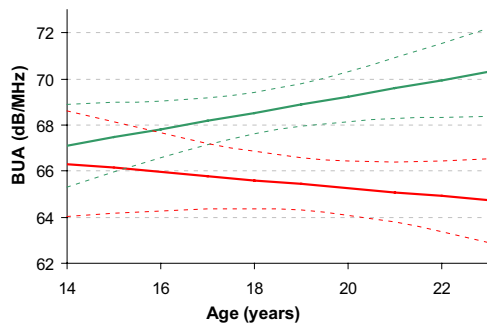
Figure 1. Modeling of BUA gain in RGs (green) and CONs (red). The dashed curves with the same color represent the 95% CI.

The recalled age of menarche was significantly delayed ($P < .001$) in RGs (15.6 ± 1.6 years) compared with CONs (12.7 ± 1.3 years) (Table 1). Moreover, 20.7% (n = 17) of RGs presented primary amenorrhea at a mean age of 16.7 ± 0.7 (15.3–17.9) years, suggesting that the final mean age of menarche for this group would be greater than 16.7 years, whereas all CONs presented a normal age for menarche: 12.7 ± 1.3 years. Among RGs with menarche (n = 65) and no OCP use (n = 5), 36 presented menstrual irregularities (55%). In the CON group, 27 participants (52.9%) used OCPs. The RGs and CONs taking OCPs had presented normal menstrual cycles before starting them, and the OCPs were used only as a contraceptive method and not to treat menstrual irregularities. Last, in a subgroup of participants, maternal menarcheal age was delayed in RGs (n = 46; 15.3 ± 1.8 years) compared with CONs (n = 25; 12.86 ± 2.0 years).

The BUA values were slightly higher ($P < .001$) in RGs (68.6 ± 4.6 dB/Mhz) than CONs (65.4 ± 3.3 dB/Mhz). Moreover, when BUA was expressed as a T-score, gymnasts presented a value of +0.3 SD, suggesting higher values than in the reference population at peak bone mass (age 20 years). When BUA was adjusted for body weight and age, the difference between RGs and CONs was exacerbated (Table 1). Figure 1 shows the modeling of BUA variation in RGs and CONs from 14 to 22 years. The variation in BUA with age was significantly different ($P = .04$) between the 2 groups (0.53 ± 0.27 vs −0.17 ± 0.19 db/Mhz per year for RGs and CONs, respectively). Moreover, the 95% CI indicates significantly higher BUA values in RGs compared with CONs from about 17 years.

To determine the potential negative effect of menstrual disorders on bone acquisition, RGs were subdivided into 2 groups, one with normal menstrual status (n = 29) and the other with menstrual disorders (n = 53) (Table 2). RGs with menstrual disorders were younger and presented lower values for body weight, BMI, and body fat mass (kilograms) than RGs without menstrual disorders, but they had comparable hours of training per week. No difference was observed for adjusted or unadjusted BUA between these 2 groups, and BUA values remained higher in both RG groups than in CONs.

To investigate the role of delayed menarche and menstrual irregularities on bone mass acquisition, we next subdivided the RGs into groups according to primary amenorrhea, secondary amenorrhea or oligomenorrhea, without menstrual irregularities, and OCP use (Table 3). The RGs with delayed menarche were younger and had lower BMI than the other 3 groups. No significant difference was observed between groups for adjusted or unadjusted BUA values. For all RG groups, BUA values were significantly higher or tended to be higher than CON values. Interestingly, when RGs with menarche were dichotomized according to the median age (15 years) into 2 groups of delayed (14.4 ± 0.8 years) and severely delayed (17.3 ± 1.4 years) age of menarche, BUA was significantly higher ($P < .01$) in the delayed group (71.5 ± 4.1 dB/Mhz) vs the severely delayed group (67.9 ± 3.5 dB/Mhz). No

Table 2. Comparison Between RG Groups Without or With Menstrual Disorders[a]

Parameters	RGs Without Menstrual Disorders	RGs With Menstrual Disorders	CONs
Number of subjects	n = 29	N = 53	n = 51
Age, y	19.4 ± 2.9	17.8 ± 2.1[c,f]	19.3 ± 3.0
Weight, kg	54.3 ± 4.8[b]	51.3 ± 4.4[d,e]	57.3 ± 7.2
Height, cm	167.9 ± 6.2[c]	166.4 ± 5.1[b]	164.1 ± 4.7
BMI, kg/m²	19.3 ± 1.3[d]	18.5 ± 1.2[d,e]	21.3 ± 2.5
Body fat mass, kg	7.9 ± 2.2[d]	6.8 ± 2.1[d,e]	13.8 ± 4.7
Body fat mass, %	14.4 ± 3.4[d]	13.1 ± 3.3[d]	23.9 ± 6.0
Muscle mass, kg	44.5 ± 4.1[b]	44.1 ± 3.5[b]	41.5 ± 4.2
Training, h/wk	41.1 ± 15.8	41.7 ± 12.8	
Age at start of training, y	6.0 ± 1.5	6.3 ± 1.6	
BUA, dB/Mhz	68.6 ± 4.5[d]	68.7 ± 4.7[d]	65.4 ± 3.3
Adjusted BUA, dB/Mhz	68.6 ± 0.8[d]	69.0 ± 0.6[d]	65.0 ± 0.6

[a] Values are presented as mean ± SD, except for adjusted BUA values for age and weight, which are presented as mean ± SEM.

[b–d] Significant differences between RGs and CONs: [b] $P < .05$; [c] $P < .01$; [d] $P < .001$.

[e,f] Significant differences between RGs without menstrual disorders and RGs with menstrual disorders: [e] $P < .05$; [f] $P < .01$.

Table 3. Comparison Between RG Groups According to Menarche and Menstrual Cycle Status and Oral Contraceptive Use[a]

Parameters	RGs With Primary Amenorrhea	RGs With Menstrual Irregularities	RGs Taking Contraceptive Pills	RGs Without Menstrual Irregularities	CONs
Number of subjects	n = 17	n = 36	n = 5	n = 24	n = 51
Age, y	16.7 ± 0.7[d]	18.2 ± 2.3	18.9 ± 1.6	19.4 ± 3.1[f]	19.3 ± 3.0
Weight, kg	49.2 ± 3.5[d]	52.3 ± 4.4[d]	54.5 ± 6.7	54.3 ± 4.4[g]	57.3 ± 7.2
BMI, kg/m²	17.8 ± 1.1[d]	18.9 ± 1.1[d,g]	20.4 ± 0.9[g]	19.0 ± 1.2[d,g]	21.3 ± 2.5
Body fat mass, kg	6.1 ± 1.8[d]	7.1 ± 2.1[d]	9.2 ± 3.2[g]	7.6 ± 2.0[d]	13.8 ± 4.6
Body fat mass, %	12.3 ± 2.9[d]	13.5 ± 3.5[d]	16.8 ± 3.7[c]	14.0 ± 3.2[d]	23.9 ± 6.0
Muscle mass, kg	41.3 ± 3.1	44.4 ± 3.4[b]	41.9 ± 3.9	45.3 ± 3.9[b]	41.5 ± 4.2
Training, h/wk	42.6 ± 11.8	41.2 ± 13.3	47.2 ± 14.7	39.7 ± 16.5	
BUA, dB/Mhz	67.9 ± 4.6	69.0 ± 4.7[c]	68.5 ± 4.6	68.6 ± 4.6[b]	65.4 ± 3.3
Adjusted BUA, dB/Mhz	68.6 ± 1.1[b]	68.4 ± 1.8	68.6 ± 0.8[c]	69.3 ± 0.7[d]	65.0 ± 0.6

[a] Values are presented as mean ± SD, except for adjusted BUA values for age and weight, which are presented as mean ± SEM.

[b–d] Significant differences between RGs and CONs: [b] $P < .05$; [c] $P < .01$; [d] $P < .001$.

[e–g] Significant difference with RGs without menarche: [e] $P < .05$; [f] $P < .01$; [g] $P < .01$.

other difference was observed between the 2 groups, and their BUA values remained higher than those of CONs.

When RGs were subdivided according to the median into groups of current relatively intense (30.3 ± 4.8 h/wk) or very intense (51.1 ± 11.7 h/wk) training, the groups were comparable for all parameters, particularly for anthropometric characteristics and BUA (Table 4). In addition, when the duration of training was taken into account according to different age groups (5–8, 9–12, 13–16, and 17–18 years), no relationship was observed between measured BUA and past training at any age.

In the RG group only, simple correlation analysis (Figure 2) demonstrated that BUA was positively correlated with weight ($r = 0.217$, $P = .05$) and BMI ($r = 0.277$, $P < .01$) and showed a tendency with age ($r = 0.193$, $P = .07$). No correlation was observed between BUA and height, whole-body fat mass (kilograms and percent), whole-body muscle mass, age of menarche, or training status (hours per week and age at start of training).

Discussion

Elite RGs are not often investigated for bone status (9, 10, 17) because worldwide they are relatively few in number; it is thus difficult to obtain a representative sample size because they can be recruited only during major events such as the World Championships.

This study evaluated a large series of world-class RGs and shows that very intense training (mean 40.7 h/wk) appeared to have a beneficial effect on the bone health of a weight-bearing site during the growth period, as determined by a QUS device. The favorable effect of training was observed despite a high prevalence of menstrual disorders. World-class RGs are a unique and homogeneous group in that they have been exposed to high-intensity training from childhood through adolescence, a crucial period of life with dramatic hormonal changes associated with accelerated growth, acquisition of peak bone mass, and attainment of reproductive capacity (18). The clinical

Table 4. Comparison Between RG Groups According to Training Status[a]

Parameters	RGs With Intense Training	RGs With Very Intense Training	CONs
Number of subjects	n = 38	N = 44	n = 51
Age, y	18.0 ± 2.3[b]	18.6 ± 2.6	19.3 ± 3.0
Weight, kg	52.4 ± 5.2[d]	52.3 ± 4.4[d]	57.3 ± 7.2
BMI, kg/m²	18.8 ± 1.4[d]	18.7 ± 1.2[d]	21.3 ± 2.5
Body fat mass, kg	7.2 ± 2.5[d]	7.2 ± 1.9[d]	13.8 ± 4.6
Body fat mass, %	13.6 ± 3.8[d]	13.5 ± 3.0[d]	23.8 ± 6.0
Muscle mass, kg	44.1 ± 3.7	44.4 ± 3.8[b]	41.5 ± 4.2
Training, h/wk	30.4 ± 4.8	51.1 ± 11.7[e]	
BUA, dB/Mhz	68.6 ± 4.3[d]	68.6 ± 4.9[d]	65.4 ± 3.3
Adjusted BUA, dB/Mhz	68.9 ± 0.7[d]	68.9 ± 0.6[d]	65.0 ± 0.6

[a] Values are presented as mean ± SD.

[b–d] Significant differences between RGs and CONs: [b] $P < .05$; [c] $P < .01$; [d] $P < .001$.

[e] Significant difference with RGs with intense training at $P < .01$.
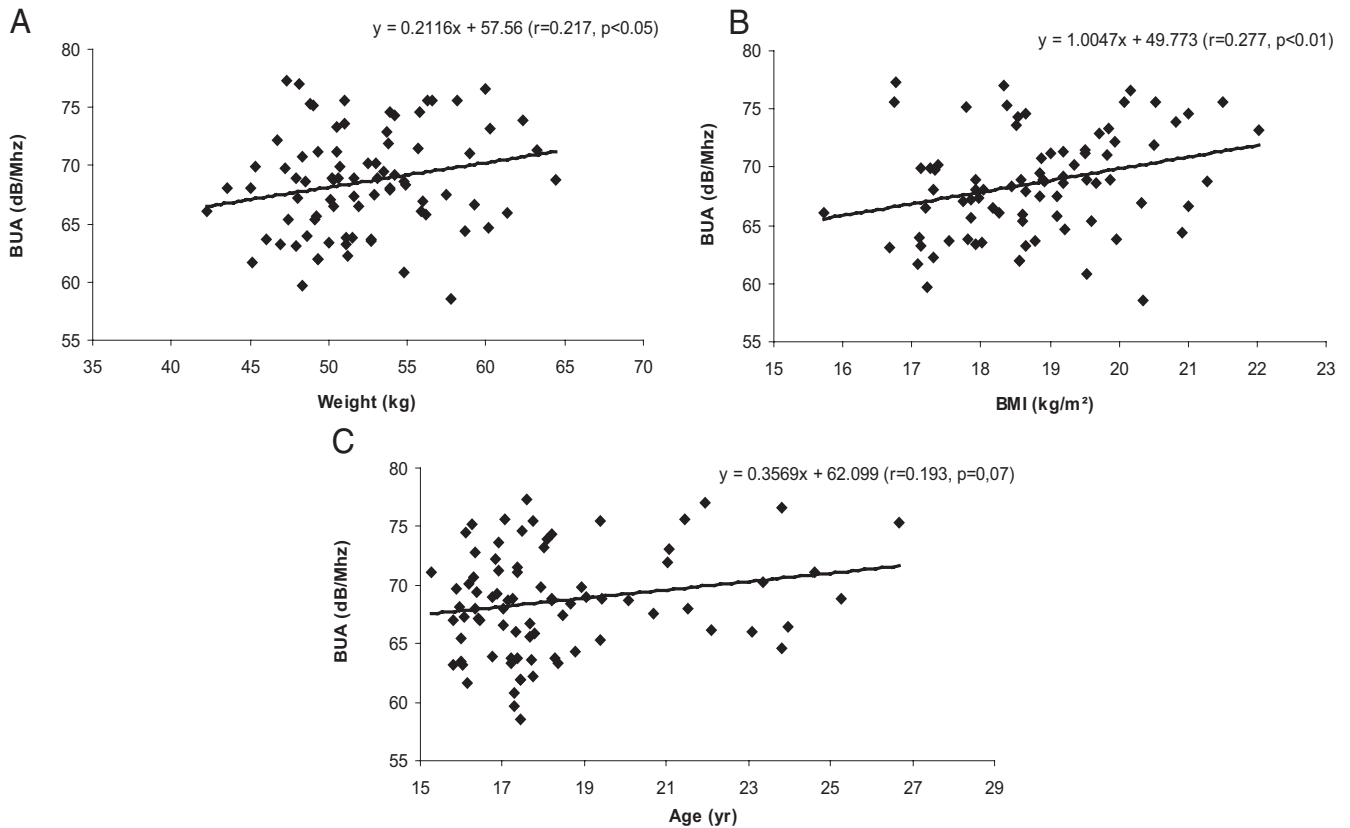
Figure 2. Correlation analysis between BUA and weight (A), BMI (B), and age (C) in RGs.

investigation of these RGs should therefore improve our understanding of the specific effects of intense training and contribute to advances in medical care. Moreover, any alterations during this period may have negative consequences later in life, particularly post career.

This large series confirms the delayed menarche and high prevalence of menstrual irregularities in RGs. The mean age of menarche, as assessed by recall, was 15.6 years, which is similar to previously reported data (9, 17, 19) and more than 3 years later than the normal age observed in the untrained CON group and the general population (20). Approximately 20% of these RGs also presented primary amenorrhea at a mean age of 16.7 years, suggesting that the final mean age of menarche may be much higher than that recorded here. Although genetically determined (21), the age of menarche has been found to be related to body composition (weight and body fat mass) and environmental and lifestyle factors, such as nutrition, physical training, and stress level (22, 23). We demonstrate here in a subgroup of RGs that the age of recalled menarche was not significantly delayed compared with that of their mothers but was higher than that of the CONs. These results may be explained by the observation that RGs are often oriented toward this sport by their mothers, who themselves may have been RGs. However, this hypothesis should be confirmed because a previous

study reported that RGs presented significantly delayed menarche compared with that of their mothers and sisters (9). In addition, more than 60% of the RGs also presented menstrual irregularities, which may be explained by the cofactors associated with intense training (ie, low body fat mass, hypoestrogenism, negative energy balance, and psychological stress) (9). Nevertheless, both experimental and clinical data have indicated that a deficit in energy availability plays the crucial role in the pathogenesis of reproductive function in athletes rather than body weight or exercise stress per se (24–26). Because delayed menarche and menstrual irregularities are known to be major negative factors for bone mass acquisition (11), adolescent RGs should probably be investigated for bone health.

Based on ultrasound evaluations, however, rhythmic gymnastics appeared to have a favorable effect on bone status because BUA values were 5% higher in RGs compared with age-matched CONs. This difference was further accentuated when BUA was adjusted for body weight and age, both parameters known to be strongly correlated with bone mass (27). In this large series of athletes and untrained CONs, we were able to model for the first time the variation in BUA from 14 to 22 years. The model shows that BUA continuously increased in RGs, whereas the values remained relatively stable in the CONs, with RGs presenting significantly higher BUA values than

CONs from 17 to 22 years. BUA parameters reflect not only bone density but also bone structure (connectivity and trabecular orientation), and the higher values in RGs suggest an improvement in bone quality and/or strength (28). We have recently reported higher aBMD and an improvement in bone geometry at the femoral region in national-level RGs compared with untrained girls but comparable values at the radius and lumbar spine (4, 5). Therefore, the osteogenic effect of rhythmic gymnastics seems to be localized in the lower limbs, not only at the femoral region (4, 5) as previously reported but also at the calcaneus, which explains the higher BUA values.

An improvement in BUA was also reported in young male and female gymnasts (29, 30). It is interesting to note that the BUA values reported here are close (68.3 ± 4.9 dB/MHz) to the values (66.72 ± 7.93 dB/MHz) reported by Courteix et al (30) in national-level female RGs (mean age 13.4 years) training approximately 18 h/wk (30). The analysis of our present and previous results suggests an age- and/or training-dependent effect on BUA. However, BUA tended ($P = .07$) to increase only with age in elite RGs, and no relationship was found with age of training start or current training level when absolute values (ie, hours per week) were taken into account. Moreover, when RGs were subdivided according to the median training volume of the current training year to discriminate high and very high training level groups, no difference in bone status or anthropometric characteristics was observed. It is probable that beyond threshold levels that need to be defined, no substantial gain can be expected. Nevertheless, it is also interesting to note that no negative effect of intense training was observed at the heel, which is a weight-bearing bone site. This seems paradoxical because extreme intense training may be detrimental to bone health in children and young adults, as observed in female endurance runners (3, 31, 32). Moreover, in adult women, a negative relationship between training level (kilometers per week) and spine and femoral neck BMD is reported (27). It nevertheless remains difficult to compare the consequences of the 2 physical activities (ie, running and gymnastics) on bone mass, because the mechanical loading applied to bone tissue is different. The forces applied to the limbs is approximately 10 times the body weight for gymnastics (33) and about 1.6 to 3 times body weight for running (34), which is further characterized by numerous successive loadings. According to the Frost theory (35), it is likely that RG induces forces above the minimum threshold needed to improve bone status. Current training volume alone, although it is the easiest to collect, may not be the most relevant parameter because it reflects only a restricted part of the training history. We therefore correlated the current BUA with specific training periods in early life, but no relationship was found.

The final gain in BUA may be higher than the values recorded in this study, because many RGs were still in the growth acceleration period, and we demonstrated with our model that BUA tended to increase with age. In a sedentary population, although the data are not homogeneous (16, 36), the peak value of BUA may be reached beyond 20 years (36). Although it is widely acknowledged that RGs present higher bone mass for the same chronological age as CONs (4, 5), they also present, as recently demonstrated, specific kinetics of bone mass acquisition mainly characterized by a longer period of gain beyond 18 years (5). This is probably related to the late catch-up growth observed in these gymnasts (9, 10). Theoretically, an evaluation in adult RGs (>25 years) would help to confirm this hypothesis; however, world-class athletes in this sport are relatively young, as observed in our population (mean age, 18.3 years; range, 15.3–26.7 years).

As previously noted, RGs present delayed menarche and a high prevalence of menstrual irregularities, two factors known to have a potentially deleterious effect on BMD due to estrogen deficiency (11, 33, 37). Most studies report that late menarche is associated with lower BMD and a deterioration of microstructure in early adulthood (11, 12, 29, 37, 38) and higher fracture risk at several skeletal sites (39). It is probable that the time of exposure to estrogen from prepuberty to peak bone mass is an important factor of bone mass acquisition (40). Interestingly, although we found no direct correlation between the age of menarche and BUA, the RGs with severely delayed menarche presented lower BUA values compared with RGs with delayed menarche but higher values than CONs. This suggests that the age of menarche is an important determinant for BUA in this population and that severely delayed menarche may reduce the favorable effect of training on bone mass acquisition. We next evaluated the potential effect of menstrual disorders on BUA, but no significant difference was observed between groups of RGs with and without primary amenorrhea or with and without menstrual irregularities. Our results are interesting because it is known that estrogens modulate the response of bone to mechanical loading (41, 42) and regular menstrual cycles are necessary for a favorable response to mechanical stimulus (7, 43–45). It is likely that the low estrogen level had a limited negative effect because its action was counterbalanced by high mechanical loading (4, 33). In addition to the well-documented effect of estrogen, it has been suggested that a bone-adipose axis exists and that various adipokines such as leptin may be involved in bone physiology (46). However, our group and others have reported no direct relationship between the low circulating leptin

observed in athletes due to reduced adipose tissue and the bone mass in young RGs and endurance trainers (47–49). It is more likely that leptin is involved as a mechanism in the interaction between the nutritional status and bone metabolism (50, 51).

The main limitation of QUS is the local evaluation at the calcaneus. However, various studies in trained and untrained subjects have reported a strong correlation between ultrasonic and aBMD measurements at the lumbar spine and femur, suggesting that this technique may be particularly useful and reliable for the evaluation of elite athletes during competition (52–54). Moreover, QUS was sufficiently sensitive to discriminate between RGs and CONs and between RG subgroups presenting similar characteristics.

Conclusion

In conclusion, although world-class RGs show a high prevalence of menstrual disorders, they present a paradoxical improvement in bone health at a weight-bearing site. The favorable effect of intense training nevertheless appeared to be modulated by the age of menarche. The high mechanical loading generated by intense training may counterbalance the negative effects of delayed menarche and secondary amenorrhea on bone mass acquisition.

Acknowledgments

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