Categorizing 10 Sports According to Bone and Soft Tissue Profiles in Adolescents

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ABSTRACT

AGOSTINETE, R. R., R. A. FERNANDES, P. H. NARCISO, S. MAILLANE-VANEGAS, A. O. WERNECK, and D. VLACHOPOULOS. Categorizing 10 Sports According to Bone and Soft Tissue Profiles in Adolescents. *Med. Sci. Sports Exerc.*, Vol. 52, No. 12, pp. 2673–2681, 2020. **Purpose:** Considering the different loading and training characteristics of the sports practiced during growth, it is important to specify and categorize the bone and soft tissue adaptations in adolescent athletes. This study aimed to categorize 10 different loading sports and a nonsport group and identify the differences in bone density and soft tissues. **Methods:** The sample included 625 adolescents (10 to 17 yr of age) of 10 sports (soccer, basketball, volleyball, track and field, judo, karate, kung fu, gymnastics, baseball, and swimming) and a nonsport group. Dual-energy x-ray absorptiometry assessed areal bone mineral density (aBMD), bone mineral apparent density (BMAD), and soft tissues (lean soft tissue and fat mass). The results were adjusted for sex, peak height velocity status, lean soft tissue, fat mass, and weekly training volume. **Results:** The comparisons among groups showed that soccer had the highest whole-body aBMD (mean ± SEM: 1.082 ± 0.007 $g{\cdot}cm^{-2}$) and lower limb aBMD (1.302 ± 0.010 $g{\cdot}cm^{-2}$). Gymnastics presented the highest upper limb aBMD (0.868 ± 0.012 $g{\cdot}cm^{-2}$) and whole-body BMAD (0.094 ± 0.001 $g{\cdot}cm^{-3}$). Swimming presented the lowest aBMD values in all skeletal sites (except at the upper limbs) and whole-body BMAD. The soft tissue comparisons showed that soccer players had the highest lean soft tissue (43.8 ± 0.7 kg). The lowest fat mass was found in gymnasts (8.04 ± 1.0 kg). **Conclusion:** The present study investigated and categorized for the first time 10 different sports according to bone density and soft tissue profiles. Soccer and gymnastics sport groups were found to have the highest bone density in most body segments, and both sports were among the groups with the lowest fat mass. **Key Words:** ADOLESCENCE, BONE MINERAL DENSITY, EXERCISE, FAT MASS, LEAN MASS, SPORT PARTICIPATION

Adolescence is a crucial period for accumulation of bone mass with evidence indicating that 33% to 43% of the total bone mineral content (BMC) in adulthood is accumulated during the years surrounding peak height velocity (PHV), depending on the skeletal site (1). These circumpubertal years (−2 to +2 yr from age of PHV) are particularly important for the assessment of somatic maturation (1). Exercise and dietary intake during adolescence play an important role on the accumulation of bone mass during growth (2,3). Also, exercise has the potential to optimize bone health during growth by achieving the full potential of peak bone mass and by reducing the risk of osteoporosis later in life (4), leading to substantial economic and social gains (5).

Participation in sports during growth can have several positive effects on physiological, metabolic, and musculoskeletal health outcomes (6,7). Evidence indicates that the type and characteristics of the sports practiced during growth can have different adaptations on bone mass, and the highest benefits are observed in those who participate in weight-bearing sports (3,8–10). During weight-bearing sport participation, the mechanical forces are applied on the bone matrix directly (ground reaction forces) or indirectly (via the muscle contraction) (10). The muscle contractions and the osteogenic stimulus produced from high external forces during exercise (ground reaction forces), such as jumps, sprints, acceleration, and deceleration, are responsible for the adaptations in bone mineral accrual (10). Most studies in the literature focusing on sports participation and bone health during growth are comparing a specific sport modality or limited number of sports with a control group (8,11). Currently, there are a considerable range of sports with few data available about its osteogenic properties, although they are widely practiced for children and adolescents worldwide, such as martial arts. This background requires a comprehensive investigation about the site-specific skeletal adaptations of the growing skeleton. However, there is no evidence regarding the bone adaptations of the different loading sports practiced during growth and how these are categorized according to the skeletal adaptations.

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Dual-energy x-ray absorptiometry (DXA) is the clinically relevant method to use when assessing bone health during growth, but differences in the size of the children or adolescents can affect the interpretation of areal bone mineral density (aBMD). This is mainly because aBMD is analyzed in grams per square centimeter and does not consider the bone volume (cm^3). Considering that adolescents have evident size differences according to the sports practiced due to the natural selection of each sport modality, the comparisons of aBMD can be affected (12). Therefore, it is important to consider and adjust further for the size differences when comparing BMD of children and adolescents. A more thorough investigation can be provided by using bone mineral apparent density (BMAD), which reduces the confounding role of skeletal size and provide an estimation of volumetric bone density proportional to the true bone volume (13). Previous studies have considered the use of this technique (BMAD) to analyze the impact of some sports, such as gymnastics (14) and cycling (15), on bone density of lumbar spine, femoral neck, and whole-body in adolescents. However, the BMAD has not yet been used in comparisons of bone health among different loading sports within the same study.

In addition to bone differences, previous evidence indicates that depending on the sport practiced, the soft tissues, specifically lean and fat mass, differ according to the movement-specific characteristics of the sport practiced (16). Wilkinson et al. (17) found that adolescent swimmers had higher lean mass when compared with footballers, cyclists, and a control group. In addition, all sports groups (swimmers, footballers, and cyclists) had lower fat mass than an active age-matched control group. Understanding the relations of different sports on lean and fat mass will allow the sports professionals and researchers to identify the body composition status of young athletes and design effective interventions to improve it. However, there is a lack of comprehensive evidence comparing the soft tissue of a large number of sports practiced during adolescence. Considering that the majority of children and adolescents are involved in different types of sports during this period of life (mainly in adolescence when sports participation is the main manifestation of physical exercise), it is crucial to identify their specific impact on bone health and soft tissues during this important period of life.

Thus, the objective of this study was to categorize adolescent athletes from 10 different loading sports (soccer, basketball, volleyball, tennis, track and field, judo, karate, kung fu, gymnastics, baseball, and swimming) and a nonsport group according to bone and soft tissue profiles as well as to quantify the differences in bone density and soft tissues by controlling for important confounders.

METHODS

Population. The data of this cross-sectional study were collected as part of two studies from the Laboratory of Investigation in Exercise (LIVE) that was conducted in the city of Presidente Prudente, São Paulo, Brazil, from October 2013 to May 2018. After authorization of the local authorities, researchers contacted and invited the nonsport group adolescents by inviting schools of the Secretary of Education and in one Philanthropic Institution. The sport groups were recruited from sport clubs (public and private) of the metropolitan area of Presidente Prudente. The initial number of adolescents recruited was 678, and after exclusions (see inclusion criteria), the sample was composed of 625 adolescents (184 females), with a mean age of 14.1 yr (13.9 to 14.2 yr).

The inclusion criteria were as follows: 1) chronological age between 10 and 17 yr of age, 2) a minimum of 6 months of participation in the specific sport (sport groups), and 3) a minimum engagement of three or more hours per week (sport groups). The exclusion criteria were as follows: 1) currently taking medication that could affect bone metabolism, 2) organized involvement in other sports on top of the specialized sport (sport groups), and 3) organized involvement in sports (presence of coach, training routine, and competitions) (nonsport group).

The sample size estimation was performed using an equation previously used in other studies (9,18,19), a bilateral Student *t*-test considering the difference between two dependent means of cyclists (1.133 units [SD = 0.217] in the reference group and 1.002 units [SD = 0.093] in the experimental group) of whole-body BMD (15). Taking into account a power of 90% and an alpha of 5%, the sample size was estimated as a minimum of nine adolescents per group.

The sport group composed of 453 adolescents of 10 different sports: judo (n = 54 [females n = 18]), karate (n = 41 [females n = 21]), kung fu (n = 39 [females n = 10]), swimming (n = 67 [females n = 22]), basketball (n = 55 males), soccer (n = 100 males), volleyball (n = 32 [females n = 30]), track and field (n = 27 [females n = 11]), baseball (n = 22 [females n = 1]), and artistic gymnastics (n = 16 females), and the nonsport group composed of 172 adolescents (55 females).

To participate in the study, adolescents were required to provide informed consent forms signed by a parent or guardian. The Ethical Board of the Sao Paulo State University (UNESP) approved the investigation (process no. 02891112.6.0000.5402, 1.677.938/2016) and all procedures performed in this study were conducted in accordance with the 1964 Declaration of Helsinki for human studies by the World Medical Association.

Anthropometry. Stature was measured using a stadiometer (accurate to 0.1 cm; Sanny, American Medical of the Brazil Ltda, Brazil). The body mass was measured using an electronic scale (with a precision of 0.1 kg; Filizzola PL 150, Filizzola Ltda, Brazil). All measures were assessed using standardized techniques by a single trained researcher. The technical errors of measurement were 0.04% and 0.11% for body mass and height, respectively.

Somatic maturation. Stature measurements and chronological age were used to calculate the maturity offset years from age PHV using equation proposed by Moore et al. (20). This is a somatic biological maturity indicator and reflects the maximum growth velocity during adolescence, and the coefficient of determination has been reported ($r^2 = 0.90$, SE = 0.5) (20). Lastly, aiming to decrease the bias of estimation of PHV (21) mainly in samples with large age range (outside the optimal band of estimation [1 yr after/before the peak]), the adolescents were divided into three categories: 1) Pre-PHV (maturity offset <-1), 2) At-PHV (maturity offset ≥ -1 and ≤ 1), and 3) Post-PHV (maturity offset >1). These categories were used as a somatic maturation variable of the sample and considered as an adjustment variable in the analysis.

Volume and frequency of training. The athletes and coaches provided information about the time of training per day (minutes trained daily) and frequency of training per week (number of days trained in a week). These variables were used to calculate the weekly training volume, as follows: time of training per day × frequency of training per week. Training volume is a widely used variable in studies involving sports training characteristics and able to affect the accumulation of BMD in adolescents (22).

Bone densitometry and soft tissue assessment. A whole-body DXA scan (Lunar DPX-NT; General Electric Healthcare, Little Chalfont, Buckinghamshire, UK) was used to assess whole-body aBMD ($g \cdot cm^{-2}$), lean soft tissue (kg), and fat mass (kg) at the university laboratory in a temperature-controlled room by using a GE Medical System Lunar software (version 4.7). A trained researcher performed all scan and tested the scanner quality before the first exam of each day. The coefficient of variation for this device was 0.66% (in whole-body aBMD analysis, $n = 30$ participants not involved in this study), setting the lines (regions of interest) in the extremities (upper limbs, lower limbs, and spine) as requested for the General Electric Healthcare company and stated in previous studies (8) realized by a trained researcher. The scans were performed using a standardized protocol with the participants remaining in the supine position and wearing only light clothing, without shoes. Regional analysis for aBMD of upper limbs, lower limbs, spine, and whole body (less head) occurred off-line after the scans took place.

The BMAD ($g \cdot cm^{-3}$) is an approach to estimate the volumetric BMD and remove the size differences. It can be calculated by dividing BMC by the three-dimensional bone volume derived from its two-dimensional projected bone area (BA) and body height as proposed by Katzman et al. (13): $BMAD_{TB}$ = BMC / (total body BA^2 / body height).

Statistical analysis. All anthropometric characteristics, bone, and soft tissue parameters were expressed as mean values, SD, and 95% confidence intervals. The data normality was tested using the Shapiro–Wilk test. The comparisons of dependent variables among groups were performed by using the generalized estimating equation model and the Bonferroni *post hoc* test. All covariates were selected after checking for multicollinearity and by including possible mediators of bone density based on previous evidence (22–24). Specifically, when comparing bone density variables, the models were adjusted for sex, PHV status, lean soft tissue, fat mass, and weekly training volume. To quantify the differences, the results were presented by using percentage of difference. The data were analyzed using the SPSS software (version 24.0), and the level of statistical significance was set at a P value less than 0.05.

RESULTS

Table 1 shows the descriptive characteristics of each group, and Table 2 shows the bone variables by sports modalities without adjustments. The adjusted comparisons of dependent variables are presented in Figures 1–3. The results of these comparisons are presented hierarchically (from highest to lowest) in figures to facilitate a practical categorization and visualization.

At whole-body aBMD, the highest value was observed in soccer (1.082 $g \cdot cm^{-2}$) and the lowest in swimming (0.959 $g \cdot cm^{-2}$). The swimmers had significantly lower whole-body aBMD compared with all groups (−4.9% to −11.3%). Kung fu presented significant lower whole-body aBMD compared with soccer (−6.7%) and judo (−4.3%). Baseball, basketball, karate, and nonsport group had significant lower values at whole-body aBMD compared with soccer (−3.9% to −6.5%) (Fig. 1A). Spine aBMD in the judo group was the highest (1.052 $g \cdot cm^{-2}$), whereas the swimming group had the lowest spine aBMD (0.971 $g \cdot cm^{-2}$). In comparisons among groups, the swimming group had significantly lower spine aBMD than judo (−7.7%), volleyball (−7.3%), and soccer (−5.8%) (Fig. 1B).

At lower limb aBMD, soccer (1.302 $g \cdot cm^{-2}$) and swimming (1.129 $g \cdot cm^{-2}$) were the sports with highest and lowest aBMD, respectively. Swimmers had significantly lower limb aBMD compared with all groups (−5.4% to −13.3%). Baseball, kung fu, basketball, nonsport group, karate, judo, and volleyball had significant lower limb aBMD compared with soccer (−4.2% to −8.4%) (Fig. 1C). At the upper limb aBMD, the highest value was observed in the gymnastics group (0.868 $g \cdot cm^{-2}$), whereas the lowest upper limb aBMD value was found in the basketball group (0.750 $g \cdot cm^{-2}$). In the comparisons among the groups, basketball had significantly lower upper limb aBMD than gymnastics (−13.6%), judo (−12.1%), baseball (−6.9%), and track and field (−6.5%). Swimming, kung fu, and karate had significantly lower upper limb aBMD than gymnastics (−9.5% to −10.3%) and judo (−8.0% to −8.8%). Soccer, track and field, volleyball, nonsport, and baseball presented significantly lower upper limb aBMD compared with gymnastics (−7.2% to −8.8%) (Fig. 1D).

The whole-body BMAD ($g \cdot cm^{-3}$) results can be seen in Figure 2. The highest BMAD value was observed in the gymnastics group (0.094 $g \cdot cm^{-3}$), and the lowest BMAD value was found in the swimming group (0.085 $g \cdot cm^{-3}$). Swimmers had significantly lower whole-body BMAD compared with gymnastics (−10.0%), track and field (−9.0%), soccer (−8.9%), karate (−5.8%), volleyball (−5.5%), judo (−5.4%), nonsport (−5.4%), and basketball (−4.5%) groups. Baseball also had significantly lower whole-body BMAD than gymnastics (−7.4%), track and field (−6.3%), and soccer (−6.3%). Kung fu had significantly lower whole-body BMAD than gymnastics

(−6.5%) and soccer (−5.4%). Basketball also had significantly lower whole-body BMAD than gymnastics (−5.8%).

The soft tissue results showed that baseball had the highest value of fat mass (19.8 kg), whereas the gymnastics group had the lowest fat mass (8.0 kg). The gymnastics group had significantly lower fat mass compared with baseball (−59.4%), kung fu (−49.0%), volleyball (−47.1%), judo (−44.8%), and swimming (−41.4%) groups. Soccer also presented significantly lower fat mass compared with baseball (−59.3%), kung fu (−48.9%), volleyball (−46.9%), judo (−44.5%), swimming (−41.3%), basketball (−38.7%), and karate (−32.0%). Lastly, track field had significantly lower fat mass than baseball (−59.0%), kung fu (−48.5%), volleyball (−46.6%), judo (−44.1%), swimming (−48.8%), and basketball (−38.3%) (Fig. 3A). Lean soft tissue was the highest at the soccer group (43.8 kg), whereas the baseball group had the lowest lean mass (37.1 kg). The comparisons among groups showed that the baseball, volleyball, and karate groups had significantly lower lean soft tissue than the soccer (−11.2% to −15.3%), track and field (−11.2% to −15.3%), and basketball groups (−8.7% to −12.9%), whereas the nonsport, kung fu, judo, and swimming groups had significantly lower lean soft tissue than the soccer group (−7.1% to −11.2%) (Fig. 3B).

DISCUSSION

This study analyzed the aBMD, BMAD, lean soft tissue, and fat mass of adolescents of 10 different sports and categorized the sports according to the bone and soft tissue profiles. The present study included sports that have not previously investigated for these outcomes and by adjusting for potential covariates. The main findings showed that the soccer and gymnastics groups had the highest aBMD and BMAD values at most skeletal sites. By contrast, the swimming group had the lowest aBMD values at most skeletal sites. The main findings of the soft tissue profiles showed that soccer had the highest lean soft tissue whereas gymnastics had the lowest fat mass.

Whole-body aBMD and BMAD. Regarding aBMD values of whole body, the greatest differences observed in the present study were between soccer and judo. Participation in these sports includes high mechanical stimulus, which may justify these results. According the position statement from the American College of Sports Medicine (2004) (10), soccer is a ball sport and requires considerable osteogenic movements, such as running, acceleration and deceleration, jumping, changes of directions, and lower leg impacts when touching and shooting the ball (25). The results of the present study show that these weight-bearing movements appear to be beneficial not only for lower limb aBMD where the initial loading is applied but also for whole-body aBMD. These findings might be explained by the combined components included as part of the training routine of these soccer players (26). In addition, judo is a martial art that includes high frequency of different muscle contractions (eccentric, concentric, and isometric), as well as body rotations, physical contact with the opponent, and frequent falls on the ground (27), and these characteristics

TABLE 1. Descriptive characteristics of the sample stratified by sports ($N = 625$).

Descriptive Characteristics	Basketball, $n = 55$	Soccer, $n = 100$	Swimming, $n = 67$	Volleyball, $n = 32$	Karate, $n = 41$	Judo, $n = 54$	Kung fu, $n = 39$	Baseball, $n = 22$	Gymnastics, $n = 16$	Track and Field, $n = 27$	Nonsport, $n = 172$
	Mean (SD)										
Numbers of males/females	55/0	100/0	45/22	2/30	20/21	36/18	29/10	21/1	0/16	16/11	117/55
Chronological age (yr)	13.8 (1.3)	15.0 (1.8)^{a}	13.2 (1.8)^{b}	15.0 (1.1)^{a,c}	13.1 (1.8)^{b,d}	13.1 (1.8)^{b,d}	13.4 (1.7)^{b,d}	12.1 (1.6)^{a,b,d}	13.6 (1.7)	15.6 (1,8)^{a,c,e,f,g,h,i}	14.5 (2.3)^{c,e,f,g,h}
Body mass (kg)	65.8 (17.4)	63.8 (13.2)	55.6 (13.2)^{a,b}	59.1 (10.8)	50.4 (14.0)^{a,b}	54.4 (13.7)^{a,b}	57.8 (12.9)	51.1 (15.4)^{a,b}	45.6 (7.7)^{a,b,c,d,f,g}	62.6 (17.1)^{i}	55.8 (14.4)^{a,b,i}
Height (cm)	176.3 (10.3)	173.3 (10.6)	163.3 (10.5)^{a,b}	165.6 (6.6)^{a,b}	157.5 (11.0)^{a,b,d}	157.7 (12.0)^{a,b,d}	162.5 (10.4)^{a,b}	153.0 (12.1)^{a,b,c,d}	156.2 (8.2)^{a,b,d}	171.9 (10.3)^{c,e,f,g,h,i}	163.3 (11.5)^{a,b,h,j}
Age from PHV (yr)	0.8 (1.2)	1.4 (1.5)	0.4 (1.5)^{b}	2.7 (1.1)^{a,b,c}	0.3 (1.7)^{b,d}	0.0 (1.7)^{b,d}	0.4 (1.7)^{b,d}	−1.2 (1.3)^{a,b,c,d,e,f,g}	1.3 (1.5)^{d,h}	2.4 (1.6)^{a,c,e,f,g,h}	1.1 (1.9)^{d,f,h,j}
Lean soft tissue (kg)	49.5 (9.1)	52.5 (10.4)	40.7 (9.6)^{a,b}	36.1 (4.9)^{a,b}	35.2 (7.9)^{a,b}	36.3 (10.4)^{a,b}	38.8 (9.0)^{a,b}	34.1 (7.7)^{a,b}	32.5 (5.3)^{a,b,c,g}	49.5 (13.0)^{d,e,f,g,h,i}	38.4 (9.6)^{a,b,i,j}
Fat mass (kg)	12.6 (12.0)	7.9 (3.5)	11.8 (7.7)^{b}	20.1 (9.1)^{a,b,c}	12.0 (8.2)^{d}	14.0 (8.1)^{b}	15.6 (10.4)^{b}	13.9 (10.1)	9.3 (3.9)^{d,g}	9.5 (7.5)^{d}	13.8 (9.5)^{b,d,i}
Training parameters											
Days per week	4.4 (1.5)	4.7 (1.0)	5.8 (0.7)^{a,b}	2.9 (1.2)^{a,b,c}	4.1 (0.9)^{b,c,d}	3.1 (0.5)^{a,b,c,e}	2.5 (0.9)^{a,b,c,e,f}	3.7 (1.1)^{b,c,g}	3.0 (0.9)^{a,b,c,e}	5.6 (0.7)^{a,b,d,e,f,g,h,i}	–
Time per day (min)	182.9 (45.0)	163.3 (31.5)	164.0 (33.7)	121.9 (28.4)^{a,b,c}	139.0 (56.4)^{a}	104.2 (40.9)^{a,b,c,e}	106.4 (41.5)^{a,b,c}	191.4 (58.8)^{d,e,f,g}	206.3 (48.8)^{b,c,d,e,f,g}	161.1 (40.9)^{d,f,g}	–
Training volume (min·wk^{-1})	836.6 (364.1)	775.5 (225.6)	947.0 (245.3)^{b}	373.1 (207.8)^{a,b,c}	559.0 (230.1)^{a,b,c,d}	339.7 (239.0)^{a,b,c,e}	262.1 (156.1)^{a,b,c,e}	716.8 (275.4)^{c,d,f,g}	626.3 (259.7)^{c,d,f,g}	914.4 (277.1)^{d,e,f,g,i}	–

Comparisons among groups using the generalized estimating equation model. Training volume is the multiplication of the amount of training days per week by time trained per day. The letters denote significant difference between groups following the order of the sports modalities in the table (left to right) (e.g., a = significant difference compared with the first sport modality in the table [basketball], b = difference compared with second sport modality in the table [soccer]; $P < 0.05$).
APHV, age at peak height velocity.

TABLE 2. Descriptive bone characteristics of the sample (without adjust by confounders) ($N = 625$).

	Basketball, $n = 56$	Soccer, $n = 100$	Swimming, $n = 67$	Volleyball, $n = 32$	Karate, $n = 41$	Judo, $n = 54$	Kung fu, $n = 39$	Baseball, $n = 22$	Gymnastics, $n = 16$	Track and Field, $n = 27$	Nonsport, $n = 172$
	Mean (SD)										
Numbers of males/females	55/0	100/0	45/22	2/30	20/21	36/18	29/10	21/1	0/16	16/11	117/55
aBMD (g·cm^{-2})											
DXA, upper limbs	0.821 (0.111)	0.880 (0.148)^{a}	0.775 (0.105)^{b}	0.802 (0.087)^{b}	0.731 (0.090)^{a,b,d}	0.800 (0.166)^{b,e}	0.760 (0.081)^{b}	0.725 (0.090)^{a,b}	0.802 (0.089)	0.884 (0.141)^{c,e,g,h}	0.773 (0.117)^{b,j}
DXA, lower limbs	1.340 (0.165)	1.446 (0.177)^{a}	1.134 (0.132)^{a,b}	1.238 (0.106)^{a,b,c}	1.170 (0.152)^{a,b}	1.172 (0.165)^{a,b}	1.163 (0.119)^{a,b}	1.103 (0.149)^{a,b,d}	1.182 (0.124)^{a,b}	1.386 (0.200)^{c,d,e,f,g,h,i}	1.185 (0.162)^{a,b,j}
DXA, spine	1.065 (0.157)	1.108 (0.166)	0.977 (0.139)^{b}	1.151 (0.134)^{c}	0.982 (0.160)^{b,d}	0.996 (0.158)^{b,d}	0.971 (0.154)^{b,d}	0.888 (0.132)^{a,b,d}	1.040 (0.160)	1.123 (0.169)^{c,e,g,h}	1.002 (0.172)^{b,d,h,j}
DXA, whole body LH	1.095 (0.23)	1.180 (0.141)^{a}	0.965 (0.108)^{a,b}	1.052 (0.089)^{b,c}	0.974 (0.116)^{a,b}	0.995 (0.141)^{a,b}	0.980 (0.097)^{a,b}	0.927 (0.116)^{a,b,d}	0.997 (0.102)^{b}	1.139 (0.155)^{c,e,f,g,h,i}	0.994 (0.126)^{a,b,j}
BMAD (g·cm^{-3})	0.090 (0.006)	0.095 (0.006)^{a}	0.088 (0.005)^{a,b}	0.088 (0.005)^{b}	0.090 (0.006)^{b,c}	0.089 (0.006)^{b,c}	0.087 (0.005)^{b}	0.088 (0.005)^{b}	0.094 (0.006)^{c,d}	0.095 (0.006)^{c,d,f,g,h}	0.089 (0.007)^{b,c,i,j}

Comparisons among groups using the generalized estimating equation model. The letters denote significant difference between groups following the order of the sports modalities in the table (left to right) (e.g., a = significant difference compared with the first sport modality in the table [basketball], b = difference compared with second sport modality in the table [soccer]; $P < 0.05$).

Whole body LH, whole body less head.

support the beneficial impact of this sport modality on the bone health of whole-body aBMD. By contrast, swimming was the sport that presented the lowest whole-body BMD, indicating that the absence of ground reaction forces during swimming training might not be beneficial for whole-body aBMD (28). The latter is recently supported by a systematic review that included 64 studies across different ages and found that swimming participation does not induce beneficial effects on different skeletal sites compared with controls (28).

The BMAD estimation allows the volumetric expression of aBMD by decreasing the risk of overestimating participants with high stature and the risk of underestimating those with short stature (13). Interestingly, the findings of the present study indicate that the gymnastics presented the highest BMAD values among the groups, which was followed by soccer and track and field. Considering that gymnasts had the second shortest stature among the groups, the results of the present study removed the size bias and reinforces the importance of height adjustment when comparing bone variables in children derived from DXA outcomes as previously supported (29). By contrast, swimmers consistently were found to have significantly lower BMAD values compared with most groups, which strengthens the hypothesis that adolescents engaged in nonimpact sport tend to have lower bone density, independently of the body size. Although BMAD analysis is not a new method in the pediatric bone field, studies involving this technique and comparing sport modalities in adolescents are scarce in the literature. It is of our knowledge that only one study in the literature, by Dyson et al. (14), observed that female gymnasts had higher BMAD at the whole body, femur neck, and lumbar spine compared with the control group, which corroborates our findings. However, there is no evidence on other sports, which highlights the novelty of the evidence provided in the present study.

Lumbar spine aBMD. At the spine aBMD, all groups presented similar values except the swimming group, which had significantly lower lumbar spine aBMD compared with the judo, volleyball, and soccer groups. The lumbar spine skeletal site receives tension in the bone matrix during most of the human stand position actions, and this tension is increased during participation in sports that involve rotation of the core body segment. However, the core movements of the body do not differ considerably among sports, which may justify the similarity between the groups. By contrast, during participation in judo, volleyball, and soccer, there is a high weight-bearing load (jumps, running, fast short movements, changes of directions, and falls on the ground) applied to the core body part and therefore lumbar spine, which might improve this skeletal site (8,30,31).

By contrast, swimming practice involves rotation of the core part of the body, but due to hypogravity in the water, all the forces applied in the lumbar spine are horizontal and mainly applied in upper limbs (6,32) and, therefore, do not induce adaptations. Studies in the literature corroborate our findings (28), such as the recent manuscript developed by Bellver et al. (2019) with female young adult athletes, competitors of

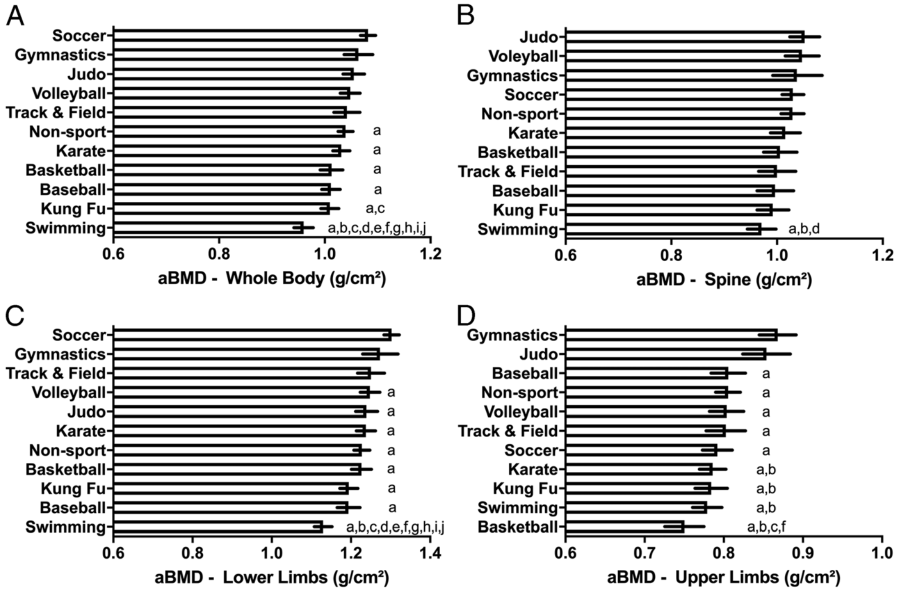

FIGURE 1—Comparisons of BMD (g·cm^{-2}) among 10 sports and nonsport group categorized hierarchically (from highest to lowest) using the generalized estimating equation (GEE) model adjusted by sex, PHV status, lean soft tissue, fat mass, and weekly training volume. The letters denote significant lower values between groups following hierarchical order (e.g., a = significant lower values compared with the first sport modality, b = difference compared with second sport modality; $P < 0.05$).

World Championships and Olympic Games. In this study, swimmers showed lower BMD in lumbar spine than soccer and volleyball players, although it was similar to the control group (31), denoting that the effects of sports participation on bone health during adolescence remained similar in early adulthood.

Lower limb aBMD. In the analyses of the lower limb aBMD, soccer players had the highest aBMD values, which were significantly higher compared with most groups studied (except with track and field and gymnastics). Soccer is a sport modality in which the lower limbs are predominantly used as part of the movements needed to achieve a high-level performance. These specific performance outcomes, such as running, jumping, changes of direction, acceleration and braking, and many small impacts of touching and shooting the ball (25), have high osteogenic potential to induce bone adaptations. Previous cross-sectional and longitudinal studies found that soccer practice induces positive adaptations to improve bone formation and, consequently, aBMD (3,8,32). These previous findings are in line with the results of the present study. Similarly, some previous studies also have found that swimmers have similar or lower bone outcomes in lower limbs even compared with the control group (3,8). During swimming practice, the lower limbs are used as stabilizer and float (33), which limits the muscular contractions and, consequently, the stress in the bone matrix.

Upper limb aBMD. At the upper limbs, gymnastics had significantly higher aBMD values compared with all groups, except judo, which presented the second highest aBMD. The female artistic gymnastics is a sport with high amount of movements involving tension, compression, and torsion in the upper limbs. These movements performed during the practice involve jumps, muscular contractions, and impulse forces. The arms are predominantly used during the vault and uneven bars apparatus movements, which generate greater impact at the distal and proximal portions of the radius (34), increasing trabecular and cortical BMD mainly in the forearm (34). Besides that, a study by Helge and Kanstrup (35) comparing rhythmic against artistic gymnasts observed significantly higher values of aBMD at the distal radius in artistic gymnastics athletes, attributing these results to the direct impact on the upper limbs during the practice, which might be the case for the findings observed in gymnasts of the present study.

The higher aBMD values at the upper limbs in judo participants compared with karate, kung fu, and swimming have been debated in the literature in a recent systematic review (30), and the results showed judo as a beneficial sport for site-specific BMD accrual in children and adolescents, including

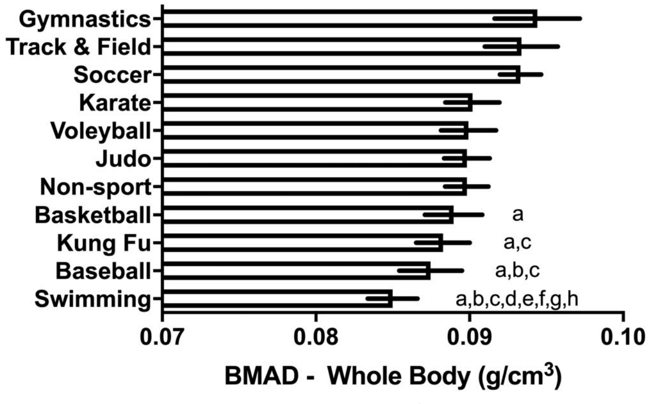

FIGURE 2—Comparisons of BMAD (g·cm^{-3}) among 10 sports and nonsport group categorized hierarchically (from highest to lowest) using the generalized estimating equation (GEE) model adjusted by sex, PHV status, lean soft tissue, fat mass, and weekly training volume. The letters denote significant lower values between groups following hierarchical order (e.g., a = significant lower values compared with the first sport modality, b = difference compared with second sport modality; $P < 0.05$).

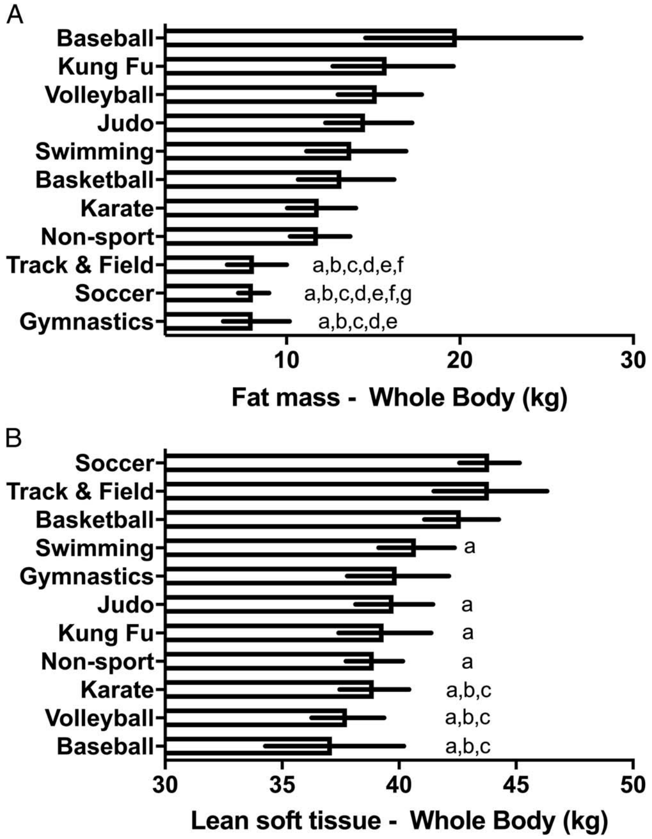

FIGURE 3—Comparisons of soft tissues (kg) among 10 sports and nonsport group categorized hierarchically (from highest to lowest) using the generalized estimating equation (GEE) model. The results adjusted by sex, PHV status, weekly training volume, and lean soft tissue (A), and the results were adjusted by sex, PHV status, weekly training volume, and fat mass (B). The letters denote significant lower values between groups following hierarchical order (e.g., a = significant lower values compared with the first sport modality, b = difference compared with second sport modality; *P* < 0.05).

the upper limbs (30). Ito et al. (27), for example, found significantly higher aBMD for upper limbs in judokas compared with the control group and attributed these results to the movements performed during the practice of the modality and fall techniques.

The differences observed in aBMD in this study between basketball and baseball might be explained by the movement patterns of baseball, which involve direct and indirect impact with upper limbs, especially during pitches and rebound (36). Lastly, the upper limbs were the unique segment in which the swimmers did not present the lowest values, perhaps because this body region concentrates all the propulsion force during the practice (6,33), causing variations of muscular contractions and improving BMD (6).

Soft tissues. There is evidence in the literature that body composition and muscular fitness affect bone health, but the direction is not clear for fat mass (37). Besides that, Forero-Bogotá et al. (38) showed that a poor bone health is significantly related to low lean mass. Thus, understanding the impact of different sports on body composition is crucial for bone health during growth and to improve performance in specific sports.

The comparison of soft tissues showed that soccer, gymnastics, and track and field presented the lowest fat mass from the groups studied. Soccer is a sport with intermittent training patterns, and it includes aerobic and anaerobic components during practice. Considering that long distance running is the predominant part of the game (39), this could explain the low fat mass values for these soccer players. For instance, in a study by Seabra et al. (40), a 6-month soccer intervention on obese male adolescents proved effective for reducing body fat. Similarly, track and field is a sport that involves up to 21 different disciplines, and most of these disciplines require a high metabolic demand through two main energy pathways (aerobic and anaerobic) (41), justifying the low fat mass observed in this group.

In gymnastics, the specific physical characteristics in athletes are needed to allow the performance of technical moves and to succeed in the sport (42). Because of the high variability of the movements performed in gymnastics, athletes with a genetic predisposition of short stature, lower body mass, and low fat mass have increased chances to perform the exercises well and, therefore, are continuing to participate in the sport (40).

The lean soft tissue was higher in soccer compared with the most other groups in the present study. In general, sports with the highest values of aBMD at most skeletal sites had also the highest lean mass and lowest body fat mass in the present study, mainly soccer. Lean mass is the strongest predictor of bone density at different skeletal sites (whole body, lumbar spine, lower limbs, and upper limbs) in athletes (43) and, therefore, is crucial to understand the differences between the different sports practiced during adolescence. Although there are no studies comparing the lean soft tissue of a large number of sports practiced during adolescence, the literature has also shown that soccer players have higher lean soft tissue compared with other sports (such as swimming, karate, and judo) (8) and control group (31). This result can be explained by the fact that soccer involves a large amount of muscle contractions (predominantly in the lower limbs) mainly in the control of the ball and maintain balance (39), in addition to training performed out of game with the aim of improving neuromuscular adaptations and muscle hypertrophy (39).

In addition, each sport has distinct training characteristics, including training volume. Recent literature has shown that increased training volume results in changes of body composition and increase of BMD in adolescents soccer players (22). For this reason, the present study adjusted for weekly training load, allowing the comparisons between the sports to be more homogeneous and to understand the direct relation of sport and bone density.

Strengths and limitations. The literature was scarce in studies involving adolescents practicing a high number of different loading sports, and this is the first study to compare 10 different sports, some of which for the first time, and a control group. The strengths of this study include the large sample size and the inclusion of many sports, which allowed us to categorize the sports according to bone density and soft tissue profiles. The present study controlled for the important covariates of sex, PHV, lean soft tissue, fat mass, and weekly training volume (22–24) as these variables have a strong relationship with bone mass and development, indicating the strong internal validity of the results presented.

However, it is important to highlight that the cross-sectional results cannot make any causational inferences about sport participation. The findings can only show the cross-sectional status and the differences of bone and soft tissues between the sports compared. To analyze the effects of growth and maturation alongside the possible training effect, longitudinal studies are needed to indicate the long-term effect of each sport on bone and soft tissue profiles in comparison with a control group without the causality limitations of cross-sectional studies. However, there is a limited number of longitudinal studies conducted, with smaller number of sports groups compared and number of participants included (3,44,45). Randomized controlled trial studies are lacking because most children and adolescents are already engaged in different sports and activities, which makes the allocation to specific training hours of a single sport difficult. Besides that, the method of estimating age of PHV might have an estimation error because of the range of the chronological age of the groups included, which are outside the optimal band of estimation (1 yr after/before the peak). For this reason, to minimize the estimation error, the results were adjusted by the categorical variables of PHV (Pre-PHV, At-PHV, and Post-PHV) (21); however, future studies are encouraged to consider recruiting participants from narrower age ranges preferably close to the PHV. Moreover, the sample size did not allow for sex-specific comparisons, and for this reason, the analyses have been adjusted by sex. Finally, the genetic predisposition of different bone density and soft tissues could not be controlled.

Lastly, the study did not control habitual physical activity that might affect bone density and soft tissues, but previous evidence indicates that the sport-specific training components are stronger predictors of bone density over and above the contribution of physical activity (43), beyond the lack of control of resistance training practice that can affect the bone mineral accrual.

CONCLUSION

In summary, the soccer and the gymnastics groups had the highest BMAD and aBMD at most skeletal sites. By contrast, swimming had the lowest aBMD at most skeletal sites. The soft tissue findings indicated that soccer had the highest lean soft tissue, whereas volleyball, baseball, and karate had the lowest lean soft tissue. Finally, the baseball and the volleyball groups had the highest fat mass, whereas the soccer and the gymnastics groups had the lowest fat mass. This study provides new collective findings about the bone and soft tissue profiles of 10 different sports practiced during adolescence and categorize the sports according to highest and lowest values.

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R. R. A. collected the data (including DXA scans) and drafted the manuscript. R. A. F. designed the study, coordinated the data collection, and critically reviewed the manuscript and approved the final version. P. H. N. and S. M. V. contributed to the acquisition of data and critically reviewed the manuscript and approved the final version. A. O. W. contributed to the acquisition of data, statistical expertise, and critically reviewed the manuscript and approved the final version. D. V. designed the study, had the conceptual idea of the study, planned the data analysis and interpretation, and critically reviewed all parts of the manuscript.

The authors declare that they have no competing interests. The authors declare that the results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. Results of this study do not constitute endorsement by the American College of Sports Medicine.

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