

# Mechanical loading with or without weight-bearing activity: influence on bone strength index in elite female adolescent athletes engaged in water polo, gymnastics, and track-and-field

David A. Greene · Geraldine A. Naughton ·  
Elizabeth Bradshaw · Mark Moresi · Gaele Ducher

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**Abstract** Bone health is considered not to benefit from water-based sports because of their weight-supported nature, but available evidence primarily relies on DXA technology. Our purpose was to investigate musculoskeletal health in the upper and lower body in well-trained adolescent female athletes using pQCT and compare these athletes with less-active, age- and sex-matched peers. Bone mineral content, volumetric cortical and trabecular BMD, total and cortical area, and bone strength index were assessed at the distal and proximal tibia and radius in four groups of adolescent females (mean age, 14.9 years) including water polo players ( $n = 30$ ), gymnasts ( $n = 25$ ), track-and-field athletes ( $n = 34$ ), and nonactive controls ( $n = 28$ ). Water polo players did not show any benefit in bone strength index or muscle size in the lower leg when compared with controls. In contrast, gymnasts showed 60.1 % and 53.4 % greater bone strength index at the distal and proximal tibia, respectively, than nonactive females ( $p < 0.05$ ). Similarly, track-and-field athletes displayed 33.9 % and 14.7 % greater bone strength index at the distal and proximal tibia, respectively, compared with controls ( $p < 0.05$ ). In the upper body, water polo players had 31.9 % greater bone strength index at the distal radius, but not the radial shaft, and 15.2 % larger forearm muscle cross-sectional area than controls ( $p < 0.05$ ). The greatest musculoskeletal benefits in the upper body were found in gymnasts. In conclusion, despite training at an elite level, female water polo players

did not show any benefits in musculoskeletal health in the lower leg and only limited benefits in the upper body when compared with nonactive girls.

**Keywords** Adolescent · Musculoskeletal health · Strength strain index

## Introduction

Non-weight-bearing activities such as swimming and cycling are among the most popular and accessible activities throughout the world and are synonymous with numerous health gains [1–3]. Bone health, however, is considered to benefit less from these activities, because their weight-supported nature is insufficient for mechanical loading on the skeleton. Direct evidence to support this is actually lacking, because most studies investigating the effects of exercise on bone health focus on high-impact loading activities such as gymnastics or tennis.

Water-based sports represent an interesting opportunity for the general population to be active. Water resistance requires the production of high muscular forces, which are considered as potent osteogenic stimuli [4, 5]. Lower areal BMD is frequently reported in swimmers and water polo players when compared with nonactive sex- and age-matched individuals [6–9]. These findings are somewhat contradictory considering these athletes usually present with greater lean mass than nonactive peers [7, 10–14]. Further contradiction in the literature stems from several reports indicating some skeletal benefits are achievable in the upper limbs [7, 15–17], possibly through a redistribution of mineral mass from the legs toward the arms [7].

Existing evidence is essentially based on two-dimensional investigations using dual-energy X-ray absorptiometry

D. A. Greene (✉) · G. A. Naughton · E. Bradshaw · G. Ducher  
Centre of Physical Activity Across the Lifespan (CoPAAL),  
School of Exercise Science, Australian Catholic University,  
Locked Bag 2002, Strathfield, NSW 2763, Australia  
e-mail: david.greene@acu.edu.au

M. Moresi  
New South Wales Institute of Sport, Sydney, Australia

(DXA), which limits the capacity to elucidate the mechanisms underlying skeletal adaptations in water sports. Low areal BMD could be caused by bone enlargement at the expense of bone density. A relatively recent technology called peripheral quantitative computed tomography (pQCT) provides measures of volumetric bone mineral density and bone geometry in the arms and legs, and therefore represents a suitable option to address the question of skeletal adaptations and potential redistribution of mineral mass in a variety of sports.

Our objective was to compare musculoskeletal health between the upper and lower body in elite-level adolescent female water polo players, track-and-field athletes, elite gymnasts, and nonactive peers. Our hypothesis was that mechanical loading without any weight-bearing activity (water polo) would have minimal effects on bone strength index in the upper body but no effect on the lower body. Additional weight-bearing activity (in the upper and lower body in gymnastics, in the lower body only in track-and-field) would provide larger musculoskeletal benefits in active adolescent girls than their less-active peers.

## Materials and methods

### Participants

Participants in this study were female adolescents aged 11–16 years (mean age, 14.9 years) who were competing at a state or national level in track-and-field ( $n = 34$ ), gymnastics ( $n = 25$ ), and water polo ( $n = 30$ ). Gymnasts and track-and-field athletes were chosen to contrast the type of mechanical loading experienced by the water polo players: although the three activities require high muscular work, gymnastics induces weight-bearing in both the upper and lower body, track-and-field (sprint and jump) induces weight-bearing in the lower body only, and water polo has no weight-bearing component. An age- and sex-matched, less-active, control group was recruited from a local high school ( $n = 28$ ). The control group was necessary for understanding nonathletic responses to less intensive musculoskeletal loading in everyday life of less-active adolescents. Participation in the control group included adolescents who routinely completed less than 4 h of physical training per week. The following inclusion criteria applied to all participants:

- In good health with no recent history of hospitalization (past 2 years) or of systemic illness lasting more than 2 weeks.
- No known history of metabolic bone or muscle disease or fracture. No medication, hormones, or calcium preparations taken in the 6 months preceding the study.

Ethical approval was granted by the University's Human Research Ethics Committee.

### Research design

#### *Growth*

Participants were measured according to anthropometrics recommendations (International Society for the Advancement of Kinanthropometry) for standing height and body mass, as well as radial (olecranon process–styloid process) and tibial (tibiale mediale–malleolus medialis limb lengths [18]).

#### *Maturation*

Participants completed Tanner staging via self-assessed pubertal rating for pubic hair and breast or genital development [19, 20] and self-reported menstrual cycle, where appropriate. Menstrual history was determined by a questionnaire that included age at menarche and number of menses in the previous 12 months. Where applicable, menstrual status was coded into two categories: oligomenorrhea (menstrual periods occurring at intervals of greater than 35 days) and eumenorrhea (>9 cycles per year) [21].

#### *Hours of training and physical activity questionnaire*

Among athletes, a modified version of an existing questionnaire to assess training loads for the previous 12 months was administered. The questionnaire has moderate reliability for the age range [22]. For control participants, physical activity levels were assessed using a prospective Bouchard Three-day Physical Activity Record (2 weekdays and 1 weekend day). Results were averaged over a 7-day week to correspond with weekly training loads of athletes and expressed as mean hours of physical activity per week.

#### *Musculoskeletal parameters*

The nondominant tibia and radius were measured by pQCT (XCT 2000; Stratec Medizintechnik, Pforzheim, Germany) using software version 5.50d. Tibial length (cm) was determined externally using the midpoint of the distal medial malleolus and the proximal medial tibial plateau as landmarks. Radius length (cm) was measured from the olecranon process to the ulna styloid process. Scans were performed at 4 % (distal site) and 66 % (proximal site) of bone length (measured as a relative distance from the distal end of the bone). Volumetric trabecular bone mineral density (trabecular vBMD) was measured at the 4 % distal

sites after the removal of cortical bone. A contour mode with a threshold of 180 mg/cm<sup>3</sup> was used to separate soft tissue and bone to analyze trabecular bone. A constant default threshold of 711 mg/cm<sup>3</sup> was used to identify and remove cortical bone. Estimates of bone strength index (strength strain index, SSI mm<sup>3</sup>) were provided by the manufacturer's software. The precision of repeat measurements in our department is 0.8–2.9 % at the tibia and radius after repositioning in eight adults. Repeat measurements were not undertaken with adolescents because of the need to minimize cumulative radiation exposure.

### Calcium and energy intake

Dietary calcium (mg), protein, and total energy intake (kJ) was determined using a 3-day (2 weekdays and 1 weekend day) food diary. Instructions regarding completion of a 3-day food diary were provided to all participants by the same investigator (D.G.). Completed diaries were analyzed using Foodworks Food Analysis program (Xyris Software 1999, Version 2.04.104) by the same investigator (D.G.). Calcium (mg) and energy intake (kJ) were calculated as absolute daily intake and expressed as mean values.

### Statistical analysis

Data were tested for normal distribution. Normally distributed data are presented in means  $\pm$  standard deviations and treated with parametric analyses. Means and standard deviations are reported for descriptive statistics. Analysis of covariance (ANCOVA) was used to compare cortical and trabecular density, cortical and trabecular area, and strength strain index between athletes and control participants, after controlling for weight and height. Statistical

analyses were performed using SPSS version 16.0 for Windows (SPSS, Chicago, IL, USA), and significance was accepted at an alpha level of  $p < 0.05$ .

### Results

Descriptive characteristics of participants are shown in Table 1. Controls and gymnasts were younger in chronological age than track-and-field athletes and water polo players ( $p < 0.001$ ). Track-and-field athletes, water polo players, and controls were taller and heavier than gymnasts ( $p < 0.001$ ). Track-and-field athletes and water polo players were taller than their less-active peers ( $p < 0.001$ ). Water polo players were heavier than all other groups ( $p < 0.001$ ). Gymnasts engaged in more hours of training per week than all other groups ( $14.0 \pm 5.2$  h week<sup>-1</sup>,  $p < 0.001$ ) followed by track-and-field athletes ( $10.1 \pm 2.5$  h week<sup>-1</sup>,  $p < 0.001$ ), water polo players ( $9.7 \pm 2.2$  h week<sup>-1</sup>,  $p < 0.001$ ), and controls ( $1.4 \pm 0.9$  h week<sup>-1</sup>,  $p < 0.001$ ). All athletic groups also trained more hours per week than the less-active group. Gymnasts were younger in maturational age (breast development) than track-and-field athletes and water polo players and younger in maturational age (pubic hair development) than all other groups ( $p < 0.001$ ). No between-groups differences were found in estimates for macronutrient intake per day or average kilojoule intake per day. Age at menarche (excluding gymnasts, who were all premenarcheal) did not differ between groups. No participants reported fractures in the 12-month period preceding the study.

Unadjusted values (mean  $\pm$  SD) for distal and proximal tibia and radius are shown in Table 2. Table 3 presents height- and weight-adjusted mean percentage differences

**Table 1** Descriptive characteristics of adolescent female athletes and nonactive peers

	Gymnasts ( $n = 28$ ) Mean (SD)	Track-and-field ( $n = 34$ ) Mean (SD)	Water polo ( $n = 30$ ) Mean (SD)	Controls ( $n = 28$ ) Mean (SD)
Age (years)	13.7 (1.8) <sup>wp, tf</sup>	15.9 (1.2) <sup>c, g</sup>	16.2 (0.7) <sup>c, g</sup>	14.3 (1.1) <sup>wp, tf</sup>
Height (cm)	146.3 (7.9) <sup>wp, tf, c</sup>	168.7 (6.8) <sup>c, g</sup>	171.9 (6.1) <sup>c, g</sup>	163.9 (5.6) <sup>wp, g, tf</sup>
Weight (kg)	39.1 (7.3) <sup>wp, tf, c</sup>	58.8 (7.5) <sup>wp, g</sup>	67.3 (8.1) <sup>c, g, tf</sup>	58.3 (9.3) <sup>wp, g</sup>
Average kilojoules per day (kJ)	8,140.4 (2605.1)	9,235.8 (2007.1)	8,495.1 (2093.4)	8,516.8 (2480.7)
Average carbohydrates per day (mg)	246.0 (87.8)	265.8 (54.9)	203.5 (40.4)	241.3 (82.4)
Average protein per day (mg)	85.0 (20.8)	99.5 (32.9)	140.2 (77.6)	83.5 (29.7)
Average fats per day (mg)	65.6 (23.1)	78.8 (21.9)	67.6 (22.2)	77.2 (23.5)
Average calcium per day (mg)	957.5 (205.2)	1,113.6 (366.4)	810.9 (234.3)	1,311.2 (299.6)
Hours training per week (h/week <sup>-1</sup> )	14.0 (5.2) <sup>c</sup>	10.1 (2.5) <sup>c</sup>	9.7 (2.2) <sup>c</sup>	1.4 (0.9) <sup>wp, g, tf</sup>
Tanner stage (breast)	2.0 (0.3) <sup>wp, tf</sup>	3.3 (1.1) <sup>g</sup>	3.5 (0.9) <sup>g</sup>	3.2 (0.8)
Tanner stage (pubic hair)	2.3 (1.0) <sup>wp, tf, c</sup>	3.9 (0.9) <sup>g</sup>	4.1 (0.6) <sup>g</sup>	3.7 (0.9) <sup>g</sup>
Age at menarche (years)	N/A	12.4 (1.3)	13.1 (0.8)	12.7 (1.4)

Superscript letters indicate statistical difference between groups: g gymnasts, tf track-and-field, wp water polo, c controls ( $p < 0.001$ )

**Table 2** Unadjusted values for peripheral quantitative computed tomography (pQCT)-derived parameters obtained at the distal and proximal tibia and radius for all participants

	Gymnasts ( <i>n</i> = 28) Mean (SD)	Track-and-field ( <i>n</i> = 34) Mean (SD)	Water polo ( <i>n</i> = 30) Mean (SD)	Controls ( <i>n</i> = 28) Mean (SD)
<b>Distal tibia</b>				
BMC (g/cm)	3.6 (0.5)	3.6 (0.5)	3.5 (0.5)	3.7 (0.5)
Total cross-sectional area (mm <sup>2</sup> )	1,043.9 (101.8)	1,136.8 (122.7)	1,062.5 (116.6)	1,114.6 (118.6)
Trabecular density (g/cm <sup>2</sup> )	363.3 (63.1)	293.2 (54.6)	229.9 (41.7)	241.4 (36.4)
Strength strain index (mm <sup>3</sup> )	2,179.3 (312.4)	2,235.6 (557.7)	1,819.6 (425.6)	1,665.6 (498.4)
<b>Proximal tibia</b>				
BMC (g/cm)	3.0 (0.4)	4.1 (0.5)	3.8 (0.4)	3.4 (0.5)
Total cross-sectional area (mm <sup>2</sup> )	471.6 (70.1)	586.8 (78.9)	622.2 (103.5)	541.3 (82.6)
Cortical density (g/cm <sup>2</sup> )	1,064.2 (29.3)	1,105.6 (28.1)	1,110.3 (23.9)	1,095.2 (29.9)
Cortical area (mm <sup>2</sup> )	289.7 (35.8)	371.2 (48.3)	345.4 (31.2)	3,20.2 (48.7)
Strength strain index (mm <sup>3</sup> )	1,654.2 (355.3)	2,407.8 (442.1)	2,430.8 (473.3)	2,024.8 (406.7)
Muscle cross-sectional area (mm <sup>2</sup> )	5,535.8 (478.6)	6,606.7 (406.8)	5,955.8 (466.6)	5,971.9 (717.5)
<b>Distal radius</b>				
BMC (g/cm)	1.6 (0.2)	1.2 (0.2)	1.2 (0.1)	1.0 (0.1)
Total cross-sectional area (mm <sup>2</sup> )	406.4 (41.5)	392.3 (65.1)	435.3 (79.6)	363.9 (57.6)
Trabecular density (g/cm <sup>2</sup> )	374.7 (37.1)	300.1 (28.1)	204.8 (38.6)	265.7 (67.2)
Strength strain index (mm <sup>3</sup> )	574.5 (173.2)	371.4 (80.1)	417.4 (86.9)	274.7 (78.5)
<b>Proximal radius</b>				
BMC (g/cm)	1.1 (0.2)	1.1 (0.1)	1.0 (0.1)	1.0 (0.1)
Total cross-sectional area (mm <sup>2</sup> )	137.1 (24.8)	139.9 (21.9)	130.7 (18.5)	129.3 (20.2)
Cortical density (g/cm <sup>2</sup> )	1,100.5 (58.7)	1,078.4 (22.6)	1,118.8 (46.4)	1,078.5 (38.1)
Cortical area (mm <sup>2</sup> )	84.2 (19.9)	84.5 (14.5)	72.3 (6.4)	75.1 (12.7)
Strength strain index (mm <sup>3</sup> )	296.7 (65.5)	296.6 (83.1)	280.1 (55.7)	277.3 (42.2)
Muscle cross-sectional area (mm <sup>2</sup> )	2,537.4 (341.6)	2,578.3 (358.7)	2,674.4 (283.5)	2,172.4 (429.5)

(95 % CI) in bone variables between athletic groups and controls.

**Tibia**

As shown in Table 3, after covarying for height and weight, water polo players showed no benefit in bone mineral content (BMC), trabecular vBMD, cortical bone area, bone strength index, or muscle cross-sectional area at the lower leg compared with nonactive peers. Total bone cross-sectional area at the distal tibia was 9.4 % (*p* < 0.05) smaller in water polo players than nonactive peers. Conversely, water polo players showed marginally higher cortical density (1.5 %, *p* < 0.05) at the proximal tibia than nonactive participants. In contrast, gymnasts showed 53.4 % greater bone strength index at the proximal tibia, as a consequence of 17 % greater BMC, 16.9 % greater total bone cross-sectional area, and 14.7 % greater cortical bone area than nonactive participants (*p* < 0.05). They also had 60.1 % greater bone strength index at the distal tibia as a result of 37.1 % greater trabecular vBMD than nonactive participants (*p* < 0.05). Similarly, track-and-field athletes

displayed 33.9 % at the proximal tibia (as a result of 14.9 % greater BMC and 12.7 % greater cortical bone area) and 14.7 % greater bone strength index at the distal tibia. Track-and-field athletes were the only group of athletes showing larger muscle cross-sectional area (+10.3 %) at the lower leg than nonactive peers (*p* < 0.05).

**Radius**

In the upper body, water polo players showed greater BMC (+10.7 %), total bone cross-sectional area (+16.9 %), and bone strength index at the distal radius (+31.9 %) than nonactive peers (*p* < 0.05). At the proximal radius, water polo players displayed greater muscle cross-sectional area (+15.2 %) and cortical density (+3.2 %), but not bone strength index, than nonactive peers (*p* < 0.05).

Compared with their less-active peers, gymnasts showed greater bone strength index at the distal (+157.3 %) and proximal radius (+83.2 %) because of greater BMC, larger total bone cross-sectional area, and higher trabecular and cortical vBMD (*p* < 0.05). Additional advantages to the musculoskeletal health of gymnasts included a larger

**Table 3** Height- and weight-adjusted mean percentage differences (95 % CI) in bone variables between athletic groups and controls

	Gymnasts ( <i>n</i> = 28)	Track-and-field ( <i>n</i> = 34)	Water polo ( <i>n</i> = 30)
<b>Distal tibia</b>			
BMC (g/cm)	2.7 (−8.3 to 13.8)	−1.8 (−8.8 to 6.4)	−7.9 (−16.2 to 0.38)
Total cross-sectional area (mm <sup>2</sup> )	4.1 (−3.4 to 11.6) <sup>a</sup>	−0.6 (−5.8 to 4.5) <sup>a</sup>	−9.4 (−15.1 to −3.8)
Trabecular density (g/cm <sup>2</sup> )	37.1 (21.7 to 52.3) <sup>a</sup>	26.4 (−15.9 to 36.9) <sup>a</sup>	1.3 (−10.1 to 12.8)
Strength strain index (mm <sup>3</sup> )	60.1 (39.7 to 80.3) <sup>a,b</sup>	33.9 (20.1 to 47.9) <sup>a</sup>	−3.8 (−19.1 to 11.3)
<b>Proximal tibia</b>			
BMC (g/cm)	17.0 (0.9 to 24.3) <sup>a</sup>	14.9 (9.9 to 19.9) <sup>a</sup>	−1.5 (−6.3 to 3.9)
Total cross-sectional area (mm <sup>2</sup> )	16.9 (0.8 to 25.7) <sup>a</sup>	3.3 (−2.8 to 9.4)	0.8 (−5.7 to 7.5)
Cortical density (g/cm <sup>2</sup> )	−3.1 (−5.1 to −1.2) <sup>a,b</sup>	1.2 (−0.1 to 2.6)	1.5 (0.1 to 2.9)
Cortical area (mm <sup>2</sup> )	14.7 (0.7 to 22.6) <sup>a</sup>	12.7 (7.3 to 18.1) <sup>a</sup>	−3.3 (−9.2 to 2.6)
Strength strain index (mm <sup>3</sup> )	53.4 (36.1 to 70.8) <sup>a,b</sup>	14.7 (3.9 to 25.5) <sup>a</sup>	−2.5 (−14.4 to 9.4)
Muscle cross-sectional area (mm <sup>2</sup> )	7.5 (−2.1 to 17.1) <sup>a</sup>	10.3 (3.7 to 16.9) <sup>a</sup>	−7.2 (−14.3 to 0.1)
<b>Distal radius</b>			
BMC (g/cm)	74.1 (61.4 to 86.9) <sup>a,b</sup>	10.7 (2.1 to 19.6) <sup>a</sup>	10.7 (1.2 to 20.3)
Total cross-sectional area (mm <sup>2</sup> )	17.4 (3.9 to 30.9)	6.9 (2.3 to 16.2) <sup>a</sup>	16.9 (6.8 to 27.1)
Trabecular density (g/cm <sup>2</sup> )	49.2 (36.8 to 61.5) <sup>a,b</sup>	15.2 (6.5 to 23.7) <sup>a</sup>	−26.8 (−36.1 to −17.5)
Strength strain index (mm <sup>3</sup> )	157.3 (129.1 to 185.5) <sup>a,b</sup>	29.6 (10.2 to 49.1)	31.9 (10.7 to 53.1)
<b>Proximal radius</b>			
BMC (g/cm)	33.4 (21.5 to 45.2) <sup>a,b</sup>	5.4 (−2.7 to 13.6) <sup>a</sup>	−6.3 (−15.1 to 2.6)
Total cross-sectional area (mm <sup>2</sup> )	18.6 (5.7 to 30.6) <sup>a</sup>	6.4 (−2.2 to 14.9) <sup>a</sup>	−3.5 (−12.8 to 5.9)
Cortical density (g/cm <sup>2</sup> )	3.2 (0.2 to 6.2) <sup>b</sup>	0.1 (−2.1 to 2.1) <sup>a</sup>	3.2 (0.9 to 5.4)
Cortical area (mm <sup>2</sup> )	43.1 (29.4 to 56.8) <sup>a,b</sup>	11.7 (2.3 to 21.2) <sup>a</sup>	−11.6 (−21.8 to −1.3)
Strength strain index (mm <sup>3</sup> )	83.2 (61.6 to 104.8) <sup>a,b</sup>	15.4 (0.5 to 30.3) <sup>a</sup>	−7.8 (−24.1 to 0.8)
Muscle cross-sectional area (mm <sup>2</sup> )	34.8 (21.8 to 47.7) <sup>a,b</sup>	19.8 (11.1 to 28.8)	15.2 (5.6 to 24.9)

<sup>a</sup> Difference between designated athletic group and water polo ( $p < 0.05$ )

<sup>b</sup> Difference between designated athletic group and track-and-field ( $p < 0.05$ )

muscle cross-sectional area at the proximal forearm (34.8 %) than the less-active girls ( $p < 0.05$ ).

Although the magnitude of the benefits was lower than in gymnasts, track-and-field athletes also showed greater bone strength index at the distal (29.6 %) and proximal (15.4 %) radius, and larger muscle cross-sectional area at the proximal forearm (19.8 %), than the nonactive girls ( $p < 0.05$ ).

Figure 1 highlights the differences in BMC and bone strength index (strength strain index, SSI) between athletic groups and nonactive participants (as shown by the zero line) at the forearm and lower leg.

After adjusting for years of training, gymnasts had greater bone strength index than the water polo players (radius and tibia) and track-and-field athletes (radius only). Water polo players and track-and-field athletes did not show any differences in bone strength index at the radius and tibia.

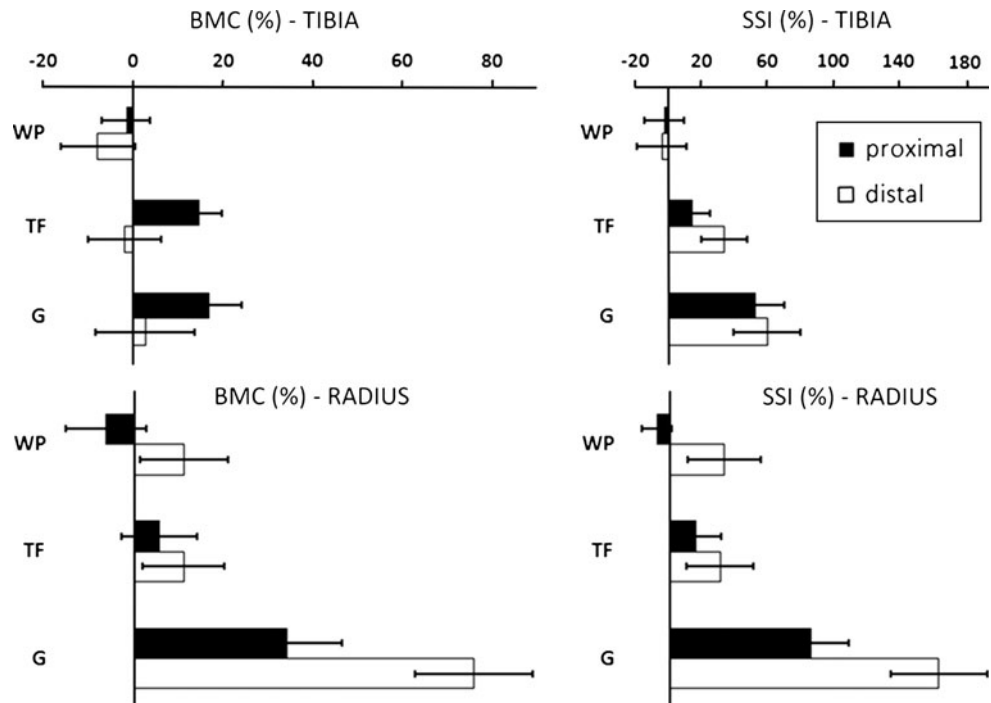
## Discussion

Despite training at an elite level, female adolescent athletes engaged in water polo, a non-weight-bearing sport, did not

show any benefit in bone strength index or muscle size in the lower leg when compared with their nonactive peers. In contrast, girls engaged in gymnastics and track-and-field had stronger tibias and larger muscle cross-sectional area (track-and-field only) in the lower leg than nonactive peers (after adjustment for height and weight), confirming the importance of weight-bearing activity for lower body musculoskeletal health. In the upper body, water polo players had greater bone strength index at the distal radius, but not the radial shaft, and larger forearm muscle cross-sectional area than nonactive girls. The greatest musculoskeletal benefits in the upper body skeleton were found in athletes engaged in gymnastics, which combines the production of high muscle forces and weight-bearing loading.

Observed differences between groups of athletes may be related to years of exposure to training. After adjustment for training history, water polo players and track-and-field athletes no longer differed for bone strength index in the upper and lower body. However, the exposure to training recorded in the water polo players may have been underestimated. Almost half the water polo players were swimmers before starting water polo, but previous

**Fig. 1** Height- and weight-adjusted mean percentage differences (95 % CI) in bone mineral content (*BMC*) and bone strength index (strength strain index, *SSI*) at the distal and proximal tibia and radius between athletic groups and controls



participation in swimming was not accounted for in their training history.

Previous investigations using DXA showed swimmers and water polo players had areal BMD similar to, or lower than, that of sedentary counterparts at the spine [6, 8, 11, 23–27] and hip [6, 11, 23–28]. Higher areal BMD at the radius is supported in some [29] but not all studies [11, 30]. Our findings using pQCT confirm that mechanical loading without weight-bearing activity fails to improve musculo-skeletal health in the lower limbs but provides some benefits in the upper limbs. Skeletal benefits were observed at the distal radius, but not the radial shaft, in our study. Similarly, Nikander et al. [16] reported swimmers had greater bone mineral content at the distal radius, but not radial shaft, although this did not translate into an increase in bone strength index. The humeral shaft, which was not measured in the present study, also showed greater bone mineral mass and strength in swimmers [16, 17]. Water polo and swimming may induce bending and torsional forces onto the humeral shaft and distal radius, thereby favoring bone mineral accrual. The absence of skeletal gains at the proximal radial shaft relative to control participants is difficult to explain. However, it is possible that the origin and insertion of dominant muscles for the throwing action involved in water polo may have contributed to these findings. Specifically, the origin and insertion of wrist flexors and extensors at the humerus and hand could have generated bone strain at the distal radius, especially subchondral bone, but not at the proximal radius.

Compared with less-active peers, the greater bone strength index found at the distal radius was the result of

larger bone cross-sectional area (despite lower trabecular vBMD) in water polo players. Greater bone strength index found at the distal radius in gymnasts and, to a lesser extent, track-and-field athletes was attributed to both greater trabecular vBMD and bone cross-sectional area than in the less-active girls, thereby maximizing the benefits in bone strength index at the distal forearm. Interestingly, girls engaged in track-and-field, which has no weight-bearing component in the upper body, showed greater bone strength index at both the distal radius and radial shaft and larger forearm muscle cross-sectional area than their less-active peers.

The absence of skeletal benefits in the lower leg in water polo players, when compared with less-active girls, is consistent with some [16] but not all reports [31] investigating tibial bone strength index in swimmers using pQCT. In the present study, no benefits were found in muscle cross-sectional area of the lower leg. Although this finding supports the idea that muscle and bone tissues form a “functional unit,” it seems counterintuitive not to see larger muscles in adolescent girls who have been involved in elite water polo for several years. Several reports have found greater lean mass at the whole body in swimmers and water polo players when compared with nonactive peers [7, 10–14], but this was not necessarily associated with skeletal benefits [11, 13, 14], at least not at all skeletal sites [7]. The absence of gravitational forces in the legs of water polo players may negate skeletal benefits from muscle forces [9]. Furthermore, bone shift toward the skeletal sites exposed to higher mechanical strains is a well-accepted mechanism of skeletal adaptations to loading

[32–34]. In the case of sports with no weight-bearing component, where the whole body bone mineral mass is lower than in weight-bearing sports, this shift might induce lower than expected bone mineral density at unloaded sites [7].

The major limitation of the present study is its cross-sectional nature. A potential selection bias cannot be ruled out; i.e., the athletes may have had different musculo-skeletal characteristics than their less-active peers even before starting their training. To some extent, these characteristics may even have predisposed them to succeed in their sport. Longitudinal studies that carefully monitor pubertal development in active and nonactive cohorts are needed to clarify this point and account for potential differences in growth rate and maturation between sports. Also, controlling for training history proved to be difficult because almost half the water polo players were previously swimmers, but this training history was not quantified and therefore was not taken into account. Although pQCT provides additional information on the determinants of bone strength index such as volumetric bone mineral density and bone geometry, it is only applicable to the peripheral skeleton. Further work using axial computed tomography [10] or magnetic resonance imaging [13, 26] is needed to investigate the effects on water sports on bone strength index at the hip and spine, which are clinically relevant sites of fracture.

Despite training at an elite level, female adolescent athletes engaged in water polo did not show any benefits in musculoskeletal health in the lower leg when compared with nonactive girls; this was not the case in gymnasts and track-and-field athletes, who showed greater lower limb benefits than their nonactive peers. In the upper body, water polo players had greater bone strength index at the distal radius and larger forearm muscle cross-sectional area than nonactive girls. Overall, the musculoskeletal benefits in water polo players were clearly less than in girls engaged in elite gymnastics, which combines muscle-driven mechanical loading with weight-bearing activity. Whether additional weight-bearing activity can help athletes engaged in water sports to improve their bone health warrants further investigation.

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