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Loading modalities and bone structures at nonweight-bearing upper extremity and weight-bearing lower extremity: A pQCT study of adult female athletes

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Abstract

This cross-sectional study of adult female athletes assessed whether the apparent loading-related differences in bone structure are primarily associated with the loading type or the muscle performance-related joint moments. Several structural variables at shaft sites of the tibia, radius and humerus, and distal sites of the tibia and radius were measured with peripheral quantitative computed tomography (pQCT) among 113 female national level athletes (representing hurdling, volleyball, soccer, racket-sports and swimming) and their 30 nonathletic referents. For the weight-bearing lower extremities, the loading modalities of the above sports were classified into high-impact (hurdling, volleyball), odd-impact (soccer, racket-sports) and repetitive, nonimpact (swimming) loadings; and for the nonweight-bearing upper extremities into high magnitude (functional weightlifting in hurdling and soccer), impact (volleyball, racket-sports) and repetitive, nonimpact (swimming) loadings.

As expected, athletes' bone mass was substantially higher at loaded bone sites compared with the nonathletic referents, but more pertinently to the locomotive perspective, the loading-induced additional bone mass seemed to be used to build mechanically strong and appropriate bone structures. Compared with controls, the weight-bearing bone structures of female athletes (swimmers excluded) were characterized by larger diaphysis, thicker cortices and somewhat denser trabecular bone. The athletes' bones at the nonweight-bearing upper extremity were generally larger in cross-sectional area. The estimated indices of joint moment (muscle force × estimated lever arm) were explained from 29% to 50%, and the loading modalities from 8% to 25%, of the variance in most bone variables ($P < 0.05$) of the tibia (shaft and distal site). In contrast to the weight-bearing tibia, only the estimated joint moment was positively associated ($P < 0.05$) with the structural characteristics of the radius and humerus, accounting for 6% to 26% of the variance in bone variables of the shafts of these bones. Such association was not observed at the distal radius.

In conclusion, at the weight-bearing lower extremity, the strong bone structure of the female athletes was attributable to muscle performance-related estimated joint moments and impact loading modality. At the shaft sites of the nonweight-bearing upper extremity, the strong bone structure was mainly attributable to the estimated joint moments. Thus, different loading history and other features of loading seemed to govern the skeletal adaptation at the upper and lower extremity.

Keywords: Bone strength; Exercise; Osteoporosis; Mechanical loading; Sports

Introduction

High peak bone mass is associated with reduced risk of osteoporotic fractures later in life [1–3]. Different sports activities, in turn, are known to result in high peak bone mass particularly at the loaded bone sites [4], and some loading types, such as high-impact, odd-impact and high-magnitude loadings, have been shown to be clearly more effective than others [5–8]. However, relatively little is known about the relationships between different loading types and structural characteristics of bone, which principally determine the whole bone strength [9]. At the lower extremities, the strongest bone structures appear in

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the athletes representing high-impact and odd-impact loading sports [10–13], while the athletes in nonweight-bearing sports, such as swimmers, despite their considerable muscle work in training, do not seem to have improved bone structure at the femoral neck [13,14]. At the upper extremities, strongest bone structures have been observed among athletes whose sports involve high-magnitude loading, such as weightlifting, or impact loading, such as tennis [15–17].

Crucial to bone adaptation is the mechanism by which the load is transmitted to and absorbed within the given musculoskeletal structure. Body weight and loading induced direct ground reaction forces and impacts acting through the closed kinetic chain apparently play a key role for lower extremities [18]. This is obvious for bones with a direct ground contact, such as the calcaneus and the contiguous straight-shafted tibia. The direct influence of concomitant muscle contraction forces during jumping and leaping cannot be ignored in these bones either. However, for the more proximal lower extremity sites, such as the femoral neck, the influence of muscle performance becomes probably more accentuated since continuous muscle work is required for maintaining the natural erect body position in normal human locomotion and other movements [19]. Even during normal daily exercises, the related peak hip joint moments have been shown to be positively associated with proximal femur bone mass [20,21]. It is, however, evident that more vigorous loading, such as maximal jumping, can override the influence of light-intensity physical activities such as walking and jogging [11].

In contrast to the lower extremities, the upper extremities lack the regular weight-bearing component, a fact that may underline the role of muscle performance and modulate the skeletal response to incident loading. Accordingly, while structure of the weight-bearing tibia has clearly deteriorated in weightless conditions in space, the nonweight-bearing radius has not shown any general trend for bone loss [22].

The effect of exercise in strengthening the bones is commonly evaluated with respect to bone mineral density (BMD)—mostly the DXA-derived BMD. However, the interpretation of BMD is deemed inherently ambiguous and one is thus not able to accurately determine structural particulars, e.g., the cortical bone [23]. The contribution of cortical bone to the bone strength is evident [36]. Since the cortical bone also seems more responsive to loading (probably through corticalization of trabecular bone adjacent to the endosteal cortical surface) [24] than bone density, the predominance of BMD as the main outcome in exercise studies can be challenged. The main focus should be laid on assessing such bone structural particulars which are apparently most relevant in terms of mechanical rigidity [9].

The purpose of this cross-sectional study was thus to broaden and deepen the present, mostly DXA-based information [10–17] on the apparent influence of different sports and associated loadings on bone structure. Specifically, we assessed the relationship between the bone structure and the loading modality, and estimated the contribution of muscle performance and related joint moments to the structure of weight-bearing and nonweight-bearing bones. The main research questions were whether the higher bone mass in athletes is used for building mechanically reasonable bone structure and whether the lack of constant weight-bearing at the upper extremity is reflected to the structure of its bones.

Material and methods

Subjects

A total of 113 premenopausal competitive national-level female athletes and 30 nonathletic referents participated in the study. The athletes were 21 volleyball players, 24 hurdlers, 23 racket players (13 tennis, 8 badminton and 2 squash players), 18 soccer players and 27 swimmers, and they were recruited from national sport associations and local clubs. The referents were volunteers who were recruited from a local medical school. The study protocol was approved by the Ethics Committee of The Pirkanmaa Hospital District, and each participant gave her written informed consent prior to the measurements.

The training history inquiry included sport-specific-training hours during the previous year, sport-specific training years and total weekly training hours including all sports activities during a week. This information was documented via a recalled questionnaire, which covered at least a 5-year training history. Information on health history, medication, use of hormonal contraceptives, cigarettes, coffee and alcohol consumption, sport and other injuries and previous fractures, was collected with a questionnaire. Menstrual status was also inquired, and if a woman had ever had menses (after onset of menarche) less than once in 6 months, she was classified as amenorrheic. Dietary calcium intake was estimated with a 7-day calcium intake diary [25] and analyzed by Micro-Nutrica software (Social Insurance Institution, Helsinki, Finland). The use of calcium supplements was also asked.

Muscle performance

Maximal isometric leg extension force of the lower extremities was measured at 90° knee flexion angle with an isometric dynamometer (Tamtron, Tampere, Finland), and elbow flexion force with a strain gauge dynamometer (Digitest, Muurame, Finland). In vivo precision of repeated measurements (coefficient of variation, %) of these muscle force measurements is about 5% [26]. Dynamic maximal take-off force and power were measured with a force-plate (Kistler Ergojump 1.04, Kistler Instrumente AG, Winterthur, Switzerland) during a vertical counter-movement jump. Precision of the vertical jump measurement is 2.6% [27].

Bone characteristics

Single axial 2.5 mm thick tomographic slices at the right distal tibia and shaft sites (5% and 50% of the estimated length of the tibia proximal to the distal endplate), at the dominant[1] (the playing or writing arm) distal radius and shaft (4% and 30% of the estimated length of the radius proximal to the distal endplate) and humeral midshaft (50% of the estimated length of the humerus) were scanned with peripheral quantitative computed tomography (pQCT, XCT 3000, Stratec Medizintechnik GmbH, Pforzheim, Germany) according to our standardized measurement and analysis procedures [28]. For the shaft regions, bone mineral content (BMC, mg), total cross-sectional area (ToA, mm^2), mean cortical cross-sectional wall thickness (CWT, mm), cortical density (CoD, mg/cm^3) and density-weighted polar section modulus (BSI, an index of bone strength against torsion and bending, mm^3) were determined. In addition to above-mentioned variables (CoD excluded), trabecular density (TrD, mg/cm^3) was determined for the distal sites. In our laboratory, the in vivo precision of these pQCT measurements ranges from 0.9% (TrD) to 4.2% (BSI) for the distal tibia, from 0.7% (CoD) to 2.5% (BSI) for the tibial shaft, from 2.2% (TrD) to 7.7% (BSI) for the distal radius, from 0.8% (CoD) to 4.3% (BSI) for the radial shaft, and 0.5% (CoD) to 5.6% (BSI) for the humeral midshaft [28].

Classification of loading modality

According to categories described in our previous study [13], we classified the sport-specific loading modalities qualitatively into specific categories

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[1] All subjects but one racket-player were right-handed.

Table 1
Group characteristics, mean (SD)

	N	Age (year)	Height (cm)	Weight (kg)	Sport-specific training hours/week (in the last inquiry year)	Sport-specific training (years)	Proportion of weight training of total training hours (%)	Isometric leg extension force (kg)	Isometric forearm flexion force (kg)	Take-off force of counter movement jump (N)	Power of counter movement jump (W/kg)
Volleyball	21	21.2 (3.0)	179 (5)	74.4 (8.3)	9.9 (2.5)	8.6 (3.3)	23 (10)	185 (36)	15.7 (4.7)	1633 (239)	42.1 (6.2)
Hurdling	24	20.2 (2.1)	170 (6)	62.1 (4.0)	9.1 (2.4)	10.4 (3.0)	25 (9)	196 (39)	15.6 (3.1)	1494 (164)	48.6 (5.1)
Racket games	23	23.6 (4.5)	167 (7)	64.0 (10.0)	4.6 (1.9)	9.6 (3.5)	21 (16)	175 (39)	15.4 (3.1)	1391 (199)	38.8 (5.5)
Soccer	18	21.4 (3.0)	168 (6)	63.4 (6.2)	8.6 (5.5)	10.7 (3.8)	20 (20)	175 (30)	16.3 (3.6)	1397 (132)	40.7 (4.2)
Swimming	27	20.6 (2.8)	169 (6)	62.1 (7.0)	13.5 (4.5)	10.6 (4.3)	17 (9)	153 (39)	12.9 (3.5)	1292 (195)	38.0 (4.8)
Referents	30	24.3 (3.1)	165 (5)	60.7 (7.9)	2.9 (2.0)			138 (22)	13.3 (2.0)	1280 (155)	34.6 (4.9)

separately for the lower and upper extremities. These definitions of the loading modalities does not take only the typical sports performance into account, but also the typical training forms, which together establish the loading modality of the given sports.

The lower extremities

Both volleyball and hurdling include maximal jumping and leaping to vertical and onward directions during a typical sports performance and training. These sports were considered to represent high-impact loading modality. Soccer and racket games (squash, tennis and badminton) are intense in nature and include rapidly accelerating and decelerating movements, often to directions the lower extremities are not normally accustomed to. In addition, kicking and receiving the ball in soccer can result in impacts to the foot and shin. These two sports were considered to represent odd-impact loading modality. Swimming is an endurance sports with a great number of similar movements but lacks practically the ground-impacts, and it was considered to represent repetitive, nonimpact loading modality.

The upper extremities

Both volleyball and racket games include a great number of high-velocity ball impacts onto hands and forearm, or onto the racket, from different directions. In racket games, the racket also increases the lever arm magnifying the incident joint moments within the upper extremities. These sports were considered to represent impact loading modality. Swimming performance includes a great number of high joint moments, which are due to the substantial drag of water against the movements of the upper extremities. These movements are nearly exclusively generated

Table 2
The absolute mean (SD) values of the bone characteristics of the athlete and reference groups

	Volleyball	Hurdling	Racket games	Soccer	Swimming	Referents
Lower extremity						
Distal tibia						
BMC, mg	900 (94)	838 (83)	790 (115)	820 (83)	671 (101)	663 (93)
Total cross-sectional area, mm^2	1000 (105)	895 (119)	858 (146)	877 (114)	842 (95)	801 (107)
Cortical wall thickness, mm	2.4 (0.8)	2.5 (0.5)	2.3 (0.5)	2.4 (0.5)	1.7 (0.3)	1.8 (0.4)
Trabecular density, mg/cm^3	260 (24)	268 (19)	261 (20)	266 (21)	231 (25)	238 (25)
Polar section modulus, mm^3	1804 (320)	1624 (273)	1500 (258)	1649 (250)	1146 (293)	1155 (249)
Tibial shaft						
BMC, mg	1033 (100)	993 (91)	925 (135)	973 (93)	817 (113)	805 (111)
Total cross-sectional area, mm^2	547 (36)	511 (49)	480 (69)	494 (46)	442 (44)	423 (50)
Cortical wall thickness, mm	5.7 (0.4)	5.6 (0.4)	5.4 (0.5)	5.6 (0.5)	4.9 (0.6)	4.9 (0.5)
Cortical density, mg/cm^3	1120 (30)	1131 (13)	1138 (17)	1134 (27)	1137 (23)	1146 (18)
Polar section modulus, mm^3	2324 (250)	2143 (302)	1960 (428)	2049 (264)	1716 (288)	1657 (304)
Upper extremity						
Distal radius						
BMC, mg	310 (30)	283 (34)	278 (35)	280 (40)	269 (41)	238 (34)
Total cross-sectional area, mm^2	347 (42)	322 (43)	301 (59)	312 (42)	316 (44)	272 (34)
Cortical wall thickness, mm	1.8 (0.3)	1.7 (0.2)	1.8 (0.2)	1.7 (0.3)	1.7 (0.3)	1.6 (0.2)
Trabecular density, mg/cm^3	229 (30)	208 (25)	210 (19)	218 (29)	207 (24)	201 (28)
Polar section modulus, mm^3	369 (59)	350 (79)	338 (63)	336 (68)	305 (78)	276 (63)
Radial shaft						
BMC, mg	252 (21)	238 (26)	240 (33)	237 (32)	226 (27)	219 (22)
Total cross-sectional area, mm^2	120 (14)	108 (14)	106 (17)	108 (17)	103 (17)	94 (11)
Cortical wall thickness, mm	2.9 (0.3)	2.9 (0.2)	2.9 (0.2)	2.9 (0.2)	2.8 (0.2)	2.9 (0.2)
Cortical density, mg/cm^3	1181 (21)	1188 (14)	1198 (19)	1187 (22)	1185 (23)	1205 (17)
Polar section modulus, mm^3	265 (36)	237 (44)	228 (52)	234 (55)	214 (42)	193 (32)
Humeral shaft						
BMC, mg	640 (43)	562 (52)	589 (61)	556 (60)	565 (78)	509 (58)
Total cross-sectional area, mm^2	342 (37)	306 (30)	304 (47)	298 (27)	301 (39)	264 (30)
Cortical wall thickness, mm	4.4 (0.4)	4.0 (0.4)	4.2 (0.3)	4.0 (0.4)	4.1 (0.5)	3.9 (0.3)
Cortical density, mg/cm^3	1138 (26)	1149 (19)	1149 (18)	1150 (25)	1143 (20)	1156 (28)
Polar section modulus, mm^3	1228 (137)	1026 (141)	1058 (193)	1011 (128)	1013 (195)	844 (144)

by repeated concentric muscle activity. Although swimmers also use functional weightlifting in their training, it is mainly performed with pulleys and small weights without high eccentric muscle work [29]. Accordingly, swimming was considered to represent repetitive, nonimpact loading modality. Soccer and hurdling are sports in which the upper extremities are not particularly loaded during typical sports performances, but the functional weightlifting forms an essential part of training program in both of these sports. Weightlifting exercises require high muscle strength and power production by upper extremities during training. Accordingly, these sports were considered to represent high-magnitude loading modality.

Estimation of the joint moment

Due to tendon attachments close to the joints, the lever arms provided by the long bones of lower and upper extremities are mechanically poor requiring high force production from the involved muscles during movements [30]. The incident muscle forces can be clearly higher than that can be inferred from ground reaction forces (multiples of body weight) or other external loads. Therefore, the bone loading apparently is more related to incident joint moments than the body weight alone [20,31]. In this study, we estimated the muscle performance-related joint moments using the body height and muscle force measurement in the following way. For the lower extremities, the index of joint moment was calculated as a product of the body height (a surrogate for the length of the lever arm) and absolute maximal take-off force (a surrogate for incident muscle performance) of a counter movement jump [31,32]. Absolute take-off force takes the body weight in account [33], and together with body height, this variable gives an estimate of an individual's capacity to load the bone in a maximal, explosive dynamic performance [34]. For the upper extremities, the index of joint moment was calculated as a product of the isometric elbow flexion force and body height [35]. It is stressed here that the abovementioned estimations of muscle performance-related joint moments are coarse and simple in relation to complex loading situations in real life, but were considered adequate surrogates of actual maximal joint moments.

Statistical analysis

Means and standard deviations (SD) are given as descriptive statistics. One-way analysis of variance (ANOVA) was used for evaluating differences between the groups in anthropometry, muscle performance, training history and calcium intake. Between-group differences in bone characteristics were analyzed by analysis of covariance (ANCOVA) using age, weight and height as covariates. Sidak correction was used in the post hoc tests of the ANOVA and ANCOVA. When zero was not within the 95% confidence intervals (95% CI), the between-group difference was statistically significant at a level of $P < 0.05$.

In order to provide consistency for the predictors of bone structural characteristics within the biomechanical approach, three-phase regression analysis was performed, comprising backward regression analysis, forward stepwise regression analysis and forced entry regression model. For the lower extremity data, the independent variables served for the backward regression analysis were: age (in years), body weight (in kg) and height (in m), absolute estimated joint moment (in Nm), the loading modality (classified as high-impact, odd-impact, and repetitive, nonimpact loading), relative muscle power in counter movement jump (in W/kg) and isometric leg extension force (in N/kg), amount of training

Table 3

The age, body weight and height adjusted mean percentage differences (95% CI) in bone variables between athlete groups and the reference group

	Volleyball	Hurdling	Racket games	Soccer	Swimming
Lower extremity					
Distal tibia					
BMC	18.9 (5.4 to 34.0)[a]	25.7 (14.1 to 38.4)[a]	15.4 (5.1 to 26.8)[a]	22.1 (10.5 to 34.8)[a]	0.1 (−8.7 to 9.8)
Total cross-sectional area	7.6 (−4.9 to 21.7)	8.8 (−1.5 to 20.3)	2.6 (−6.9 to 13.0)	7.1 (−3.3 to 18.6)	3.1 (−6.3 to 13.4)
Cortical wall thickness	30.4 (3.2 to 64.8)[a]	44.8 (19.9 to 75.0)[a]	26.6 (5.4 to 52.0)[a]	36.8 (12.7 to 66.1)[a]	−1.9 (−18.1 to 17.5)
Trabecular density	6.8 (−3.8 to 18.5)	12.7 (3.6 to 22.5)[a]	9.9 (1.4 to 19.2)[a]	11.5 (2.3 to 21.5)[a]	−3.0 (−10.5 to 5.1)
Section modulus	36.7 (12.2 to 66.6)[a]	43.9 (22.7 to 68.8)[a]	27.1 (9.0 to 48.3)[a]	43.5 (21.8 to 69.0)[a]	−0.2 (−14.3 to 16.2)
Tibial shaft					
BMC	14.4 (2.7 to 27.4)[a]	25.8 (15.3 to 37.2)[a, b]	11.8 (2.7 to 21.6)[b]	21.3 (10.9 to 32.6)[a]	2.8 (−5.3 to 11.7)
Total cross-sectional area	15.4 (4.5 to 27.3)[a]	21.5 (12.2 to 31.5)[a, b]	9.9 (1.8 to 18.7)[b]	16.3 (7.2 to 26.2)[a]	5.0 (−2.6 to 13.3)
Cortical wall thickness	9.7 (−0.4 to 21.0)	17.2 (8.4 to 26.8)[a]	8.1 (0.2 to 16.7)	15.6 (6.7 to 25.3)[a]	0.4 (−6.9 to 8.2)
Cortical density	−2.3 (−4.4 to −0.2)	−0.9 (−2.6 to 0.8)	−0.6 (−2.2 to 1.1)	−0.7 (−2.5 to 1.0)	−0.5 (−2.1 to 1.2)
Section modulus	18.1 (1.9 to 36.8)	31.6 (16.9 to 48.2)[a, b]	13.4 (1.1 to 27.1)[b]	23.8 (9.7 to 39.9)[a]	5.0 (−6.2 to 17.6)
Upper extremity					
Distal radius					
BMC	19.6 (4.0 to 37.6)	19.1 (6.4 to 33.3)	15.2 (3.3 to 28.5)	16.8 (4.1 to 31.2)	12.9 (1.4 to 25.8)
Total cross-sectional area	10.8 (−4.3 to 28.2)	13.9 (1.3 to 28.2)	5.6 (−5.7 to 18.4)	11.7 (−1.1 to 26.0)	12.7 (0.7 to 26.1)
Cortical wall thickness	12.9 (−5.3 to 34.7)	11.6 (−3.2 to 28.7)	15.1 (0.3 to 32.1)	8.8 (−6.0 to 26.0)	5.0 (−8.3 to 20.3)
Trabecular density	12.3 (−2.1 to 28.9)	2.1 (−8.6 to 14.1)	5.0 (−5.7 to 17.0)	7.0 (−4.5 to 19.9)	1.8 (−8.4 to 13.2)
Section modulus	21.7 (−4.5 to 55.2)	30.6 (7.3 to 58.8)	22.4 (1.3 to 47.9)	24.0 (1.4 to 51.6)	12.7 (−6.5 to 35.9)
Radius shaft					
BMC	4.9 (−6.4 to 17.5)	9.5 (−0.1 to 20.0)	6.4 (−2.6 to 16.3)	8.0 (−1.7 to 18.6)	3.7 (−5.0 to 13.2)
Total cross-sectional area	14.6 (−0.7 to 32.3)	13.4 (1.0 to 27.4)	8.2 (−3.3 to 21.0)	12.8 (0.1 to 27.0)	8.4 (−2.9 to 21.1)
Cortical wall thickness	−4.1 (−13.0 to 5.8)	1.2 (−6.5 to 9.6)	1.6 (−5.9 to 9.7)	0.3 (−7.5 to 8.8)	−1.7 (−8.9 to 6.0)
Cortical density	−1.4 (−3.0 to 0.2)	−0.4 (−1.7 to 0.9)	−0.3 (−1.6 to 1.0)	−0.7 (−2.1 to 0.6)	−0.8 (−2.0 to 0.5)
Section modulus	21.2 (−0.4 to 47.3)	25.2 (6.9 to 46.6)	13.0 (−3.0 to 31.6)	20.9 (2.8 to 42.1)	12.7 (−3.1 to 31.0)
Humeral shaft					
BMC	12.4 (0.8 to 25.3)	9.7 (0.5 to 19.8)	13.5 (4.3 to 23.6)	7.9 (−1.4 to 18.1)	9.7 (0.9 to 19.3)
Total cross-sectional area	16.9 (3.7 to 31.8)	14.7 (4.1 to 26.3)	12.3 (2.2 to 23.3)	11.6 (1.0 to 23.2)	12.5 (2.5 to 23.5)
Cortical wall thickness	4.9 (−5.4 to 16.5)	1.4 (−6.8 to 10.3)	8.5 (0.1 to 17.7)	1.3 (−7.1 to 10.4)	4.0 (−4.1 to 12.8)
Cortical density	−1.5 (−3.6 to 0.7)	−0.2 (−2.0 to 1.6)	−0.5 (−2.2 to 1.2)	−0.1 (−1.9 to 1.8)	−0.7 (−2.3 to 1.0)
Section modulus	26.7 (7.6 to 49.1)	21.0 (6.0 to 38.0)	21.2 (6.7 to 37.7)	18.9 (3.8 to 36.1)	18.6 (4.6 to 34.5)

Note that when the confidence interval (95% CI) does not include the zero line (the value of nonathletic referents), the result is statistically significant ($P<0.05$).

[a] Difference between the designated athlete group and swimmers ($P<0.05$).

[b] Difference between hurdling and racket-games ($P<0.05$).

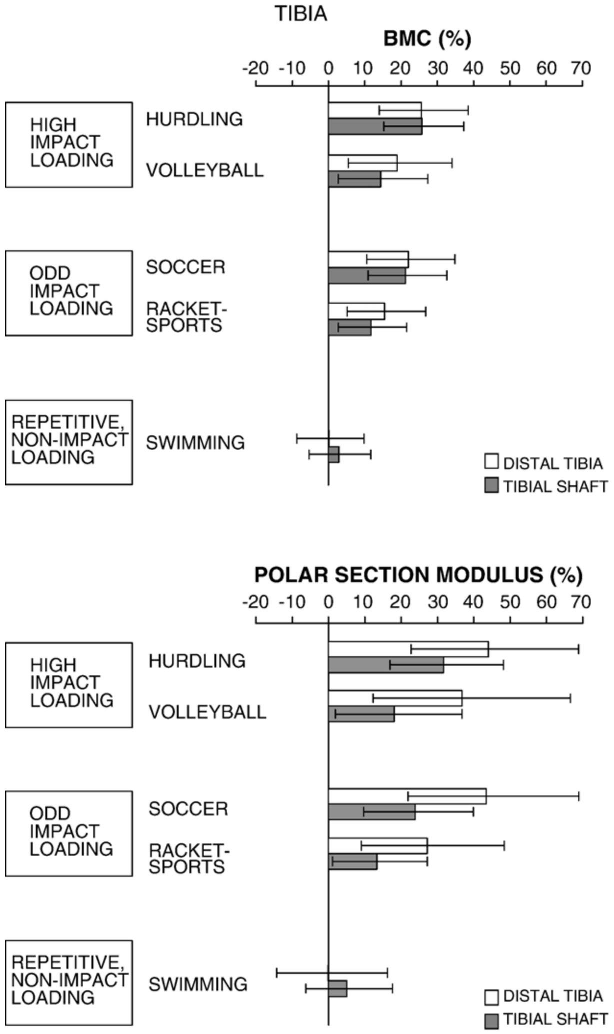

Fig. 1. Lower extremity: the age, body weight and height-adjusted mean percentage differences in BMC (upper panel) and polar section modulus (lower panel) between the five sport groups and the nonathletic referents (95% CI). The classification of the loading modality (see Material and methods) is also indicated (boxes on left). Note that when the confidence interval (95% CI) does not include the zero line (the value of nonathletic referents), the difference is statistically significant ($P < 0.05$).

during last year (in hours/week), number of training years, calcium intake (mg) and proportion of weight training from the total training (%). For the upper extremity model, the independent variables served for the backward regression analysis were: age (in years), estimated joint moment (in Nm), body height (in m), the loading modality (classified as impact; repetitive, nonimpact; and high-magnitude loading modalities), amount of training during last year (in hours/week), number of training years, calcium intake (in mg), proportion of weight training from the total training (in %) and relative isometric elbow flexion force (in N/kg). Then, forward stepwise regression analysis starting with the strongest predictor was performed to ensure the consistency of observed predictive variables using the same list of potential predictive variables.

Finally, the forced entry model, being consistent with the results of backward and forward regression analyses, was used to determine the contribution of different variables to the bone structural characteristics. Accordingly, age, body height, indices of joint moment, loading modality, relative muscle power in counter movement jump (for the lower extremities only), relative isometric leg extension muscle force (for the lower extremities only), number of training years, calcium intake and proportion of weightlifting (three latter variables for the upper extremities only) were entered into the forced model. A P value <0.05 was considered statistically significant.

Results

Group characteristics are shown in Table 1. The volleyball players were taller and heavier, and the referents and racket play ers were somewhat older than the other groups. As regards the athletes, the mean of the weekly training hours varied from 4.6 to 13.5 h. The referents reported 2.9 training hours a week on average. Physical activity of the reference group included various types of exercise from walking to more intense sports, such as aerobics and floorball. Compared with the referents, weekly sports-specific training hours during the last inquiry year were significantly higher in all athlete groups except that of the racket players'. Mean daily calcium intake was in line with the recommendations in all study groups, ranging from referents' 911 mg to swimmers' 1377 mg. There were no amenorrheic subjects in

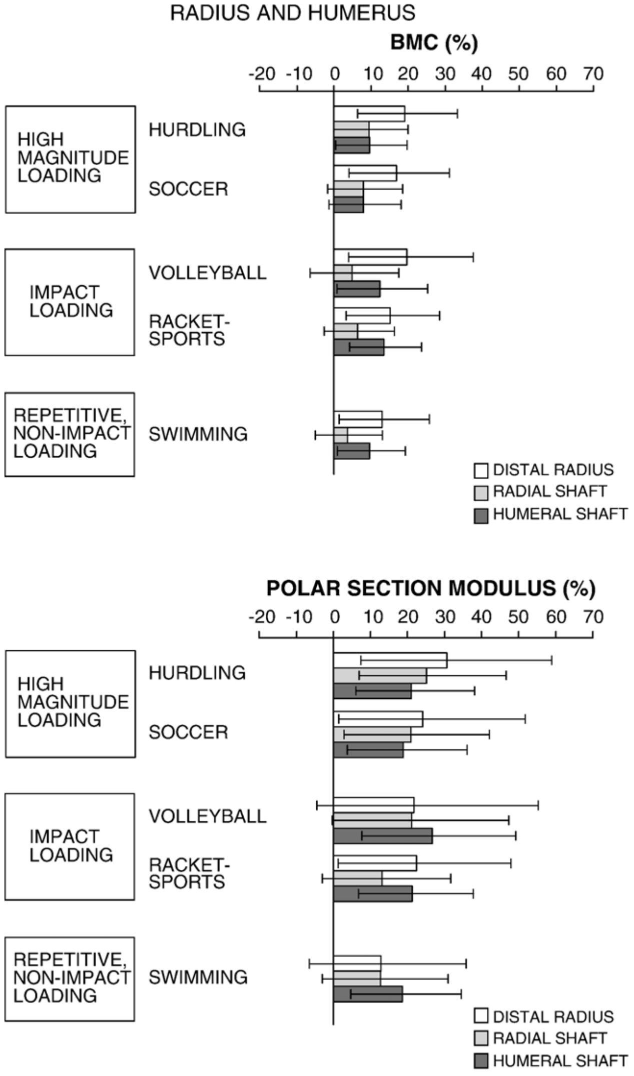

Fig. 2. Upper extremity: The age, body weight and height-adjusted mean percentage differences in BMC (upper panel) and polar section modulus (lower panel) between the five sport groups and the nonathletic referents (95% CI). The classification of the loading modality (see Material and methods) is also indicated (boxes on left). Note that when the confidence interval (95% CI) does not include the zero line (the value of nonathletic referents), the difference is statistically significant ($P < 0.05$).

Table 4
Contribution (R^2) of different predictive variables to bone characteristics at the tibia according to the forced entry regression model

	Distal tibia					Tibial shaft				
	BMC	ToA	CWT	TrD	BSI	BMC	ToA	CWT	CoD	BSI
Age						**0.5**			**4.2**	0.2
Estimated joint moment	**44.6**	**33.3**	7.6	8.7	**39.6**	**45.8**	**50.0**	**28.9**		**49.8**
Height	**0.9**	**9.6**				**0.6**	**1.4**			**1.7**
Loading modality	**15.6**	**1.3**	**25.0**	**19.0**	**17.6**	**12.8**	**9.8**	**14.5**		**8.1**
Muscle power (W/kg) [a]	1.0	**2.3**								
Muscle force (N/kg) [b]			**3.5**							
Total R^2	**62.4**	**46.6**	**45.8**	**55.5**	**57.4**	**59.8**	**61.2**	**44.5**	**6.6**	**59.8**

Statistically significant predictors are given in bold face ($P < 0.05$). Borderline predictors ($0.05 < P < 0.1$) are shown with normal type of text.

[a] Relative muscle power in counter movement jump (W/kg).

[b] Relative isometric muscle force of leg extension (N/kg).

any of the groups. The use of hormonal contraceptives varied from 35% among the hurdlers to 61% among the racket players, and was 50% among the referents.

Bone characteristics at lower and upper extremities

Unadjusted, absolute bone values are given in Table 2. Table 3 shows the age, body weight and height-adjusted mean %-differences in the bone variables between the athlete groups and the reference group.

At the distal tibia (Table 3), the athletes had statistically significantly higher BMC (adjusted mean difference from 15 to 26%) and polar section modulus (from 27 to 44%), and thicker cortical walls (from 27 to 45%) than the referents with the exception of the swimmers, who showed no difference compared with the referents. At the tibial shaft, each athlete group, except the swimmers, had significantly higher BMC (adjusted mean difference from 12 to 26%), total cross-sectional area (from 10 to 22%), cortical wall thickness (from 8 to 17%) and polar section modulus (from 13 to 32%) compared with that of the referents. As regards the cortical bone density at the tibial shaft, the volleyball players had somewhat lower density (adjusted mean difference from −0.5% to −2.3%) than that in other athlete groups or in the reference group. Trabecular density of the distal tibia was significantly higher in the hurdlers (adjusted mean difference 13%), racket players (10%) and soccer players (12%) compared with the referents. Fig. 1 illustrates the age, body weight and height-adjusted differences in bone mineral content and polar section modulus (index of bone strength) in tibia among the five athlete groups in relation to nonathletic referents.

Athletes' BMC at the distal radius and humeral shaft was significantly higher than that of the referents', the adjusted differences ranging from 13% to 20% at the distal radius and from 10% to 14% at the humeral shaft (Table 3). Total cross-sectional area of the humeral midshaft was 12% to 17% greater in the athlete groups compared with the referents. Furthermore, the hurdlers and soccer players had some 13% larger total cross-sectional areas at the distal radius and radial shaft. Among the racket players, the cortical wall was 15% (distal radius) and 9% (humerus) thicker than that in the referents, while there were no differences among the other groups (Table 3). The athlete groups showed from 13% to 31% greater polar section moduli compared with the referents at all upper extremity sites, even though the mean difference did not quite reach the statistical significance at all forearm sites among the volleyball players, swimmers, and the racket players. Fig. 2 illustrates the age, body weight and height-adjusted differences in bone mineral content and polar section modulus (index of bone strength) in radius and humerus among the five athlete groups in relation to nonathletic referents. Noteworthy, the swimmers' polar section modulus at the humeral shaft was quite comparable to that of the impact-sports athletes.

Table 5
Contribution (R^2) of different predictive variables to bone characteristics at the radius and humerus according to the forced entry regression model

	Distal radius					Radial shaft					Humeral shaft				
	BMC	ToA	CWT	TrD	BSI	BMC	ToA	CWT	CoD	BSI	BMC	ToA	CWT	CoD	BSI
Age			**4.6**						**28.9**					**7.0**	
Estimated joint moment	13.1				8.4	**25.6**	**19.8**	**6.0**		**20.0**	**19.6**	**14.5**	**10.8**		**16.4**
Height		15.4													
Loading modality	0.7			3.5	2.3				4.8		**3.8**		**7.6**		1.5
Training years	5.8	2.0			**4.1**	2.4	1.8			5.2	1.3	**2.0**			**2.6**
Muscle force (N/kg) [a]						**3.4**	2.4			4.1	**3.5**	5.4			**4.2**
Calcium intake							2.7								
% of weightlifting										2.7					
Total R^2	**34.4**	**26.0**	**4.6**	**9.3**	**26.5**	**44.0**	**35.7**	**7.5**	**35.9**	**49.4**	**41.9**	**36.0**	**23.8**	**10.1**	**40.9**

Statistically significant predictors are given in bold face ($P < 0.05$). Borderline predictors ($0.05 < P < 0.1$) are shown with normal type of text.

[a] Relative isometric muscle force (N/kg) of forearm flexion.

Predictors of bone structural characteristics

For the lower extremities, major predictors of BMC, total area, cortical wall thickness, cortical and trabecular density and polar section modulus are shown in Table 4. Estimated joint moment accounted from 29% (CWT of the tibial shaft) to 50% (BSI of the tibial shaft) ($P < 0.05$), and the sport-related loading without classifying into specific modalities from 8% (BSI of the tibial shaft) to 25% (CWT of the distal tibia) ($P < 0.05$), for the variance of the tibial bone variables. In addition to joint moment and loading modality, body height, relative muscle power (W/kg) and relative muscle force (N/kg) were slightly but statistically significantly associated with some of these variables. Of note, after classifying the loading modality into specific types, the high-impact and odd-impact loading modalities (i.e., all sports but swimming) turned out to be important predictors of BMC, total area, cortical thickness, trabecular density and polar section modulus at the lower extremities (data not shown). The total variance explained by the forced regression models ranged from 45% to over 60% (Table 4).

For the upper extremities, major predictors of BMC, total area, cortical wall thickness, cortical and trabecular density and polar section modulus are shown in Table 5. Similarly to the lower extremities, estimated joint moment accounted for most of the variance, ranging from 6% to 26% (CWT and BMC of the radial shaft, respectively) ($P < 0.05$). In addition, the relative isometric muscle force of the elbow flexion (N/kg) was explained from 3% to 5% ($P < 0.05$), training years from 2% to 4% ($P < 0.05$) and loading modality from 4% to 8% ($P < 0.05$) of the total variance in some of the bone variables. The regression models explained the variance better at the humeral and radial shaft than at the distal radius. Of note, after classifying the loading modality into specific types, the impact loading modality (volleyball, racket-sports) and the high magnitude loading modality (hurdling, soccer) were associated with thicker cortical walls or greater BMC of the humeral shaft (the area of muscle insertions) (data not shown). The regression models explained from less than 10% up to 50% of the total variance in different bone variables (Table 5).

Discussion

This pQCT study of female athletes showed that women, whose sports exert impact loading, had apparently stronger bones at both the weight-bearing and nonweight-bearing skeleton compared with the nonathletic referents. These findings corroborate the relevance of impact loading as an efficient mean to improve bone rigidity [10–17]. In sport-specific and natural loading conditions, the ground impacts can differ a lot in terms of number, magnitude of force, rate of force production and repetition frequency, and they substantiate the predominant loading environment with which the musculoskeletal system of the lower extremities should be able to cope. Therefore, the constant weight-bearing component and regular locomotion-related reaction forces and impacts against the ground may partly conceal the anticipate modulation of muscle performance on bone structure. As regards the upper extremity, this was not the case.

Quite interestingly, swimming, involving vigorous muscle activity without impacts, was almost equally beneficial for strengthening the nonweight-bearing humeral midshaft as were the impact loading sports, such as racket-sports and volleyball. Large muscles (biceps brachii, triceps brachii, and the lower part of deltoid muscle) are attached to humeral diaphysis, and in accordance with this, the estimated joint moment, reflecting the incident muscle performance during movements, was the strongest determinant of bone strength at nonweight-bearing humeral and radial shafts. It is recalled that the estimated joint moment was also the major predictor of strong bone structure at the weight-bearing tibia, but the contribution of specific loading modality was more pronounced compared with what was observed for the upper extremity.

Regulation of bone mass and structure is principally governed by local mechanical demands placed on the skeleton [36]. Since the bone mineral mass represents basically the bulk of material of which the bone structure is made, higher BMC values in loaded bones of athletes can be well anticipated, and this is a well-known fact among many athlete groups [4–8]. Massive skeleton is probably a strong one, but in evolutionary and locomotive terms, a mechanically adequate structure should not cause excess metabolic cost for locomotion as being an unduly heavy organ. Consequently, a mechanically competent bone structure should evolve in relation to magnitude and modality of customary loading. In the present athlete groups, bone mass was substantially higher at the loaded bone sites compared with the corresponding bone sites of the nonathletic referents, and even more importantly, the loading-induced additional bone mass was used to build mechanically strong and appropriate bone structure—fully in line with the locomotive perspective.

Biomechanically enhanced bone structure is not a straightforward consequence of increased BMC, but is attributable to specific structural particulars (cross-sectional size and geometry, cortical thickness, cortical and trabecular density and bone tissue organization and composition), which, in turn, are subjects to apparent modulation of prevalent loading modality. In this respect, our study exposed some interesting findings. First, at the weight-bearing distal tibia, the athletes had thicker cortices (the swimmers excluded), while total cross-sectional area of the bone was similar. Thus, athletes showed endocortical contraction without periosteal enlargement. Second, the tendency for increased trabecular density in sports involving impact is worth noting, as bone structure with higher apparent density (mass of bone tissue divided by the bone volume determined from its outside dimensions) absorbs more load energy per unit volume [30]. Third, as regards the nonweight-bearing distal radius, there was a tendency for somewhat greater total cross-sectional area among athletes. Fourth, for the loaded diaphyseal sites in general, the total cross-sectional area of athletes' tibiae and humeri was larger thus providing to the bone structure the required rigidity against torsion and bending during the sport-specific vigorous movements, while thicker cortices appeared to be associated with impact loading. These observations are quite accordant with what is known about the optimum shape of tubular bones in terms of minimal weight and rigidity; relatively thick walls are indeed appropriate for coping with impact loading [30].

In cross-sectional studies of adult athletes, the possibility of self-selection bias is always a concern that cannot be ignored. As the observed mean group differences were so large, corresponding to even up to two standard deviations above the mean reference level, it is very unlikely that these differences could entirely, or even to a large extent, be explained by heredity or other unknown issues. It is, however, acknowledged that individuals with initially better muscle performance and physical abilities are probably more inclined towards athletic activities already in childhood and have thus better opportunity to build strong bones. Substantial differences in training intensity and frequency between different athlete groups can also affect the results; e.g., in this study, the amount of weekly training among racket players was lower compared with other sports. Whether this issue was associated with a reduced effect on the racket players' tibiae (odd-impact loading) compared with high-impact sports cannot be answered. Also, the frequent application of weight training as a complementary training among athletes is a factor that can confound the assessment of loading modality and needs thus to be considered. In our study, the proportion of weight training among the swimmers was quite comparable to other athlete groups. However, the swimmers do typically a lot of pulley training with small weights and high number of repetitions, while, e.g., soccer players and hurdlers do mainly jerk lifts with relatively heavy weights and low number of repetitions. During a jerk performance, particularly the forearm is subjected to substantial bending moments. Fully in line with our earlier study of weightlifters with some 40% stronger radius [16], the soccer players' and hurdlers' distal radii and radial shafts were 20 to 30% stronger than those of the referents and swimmers. Finally, it is recalled that the estimation of muscle performance-related joint moments and qualitative categorization into different loading modalities in the present study are simple, and thus subject to some uncertainty. Clearly, further studies with more refined approaches (e.g., the assessment of joint kinematics in actual movements using force plates and motion analysis systems) are warranted to get more definite answers. The present study is intended to provide the impetus to assess more comprehensively the causal relationship between the bone structure and the underlying loading environment.

Although athlete studies basically pertain to quite extreme conditions, those beyond the scope and capacity of ordinary people, the present findings have certain clinical implications. High impacts, although undoubtedly effective in strengthening of healthy bones of young adults, also have the potential to compromise the health of the loaded cartilage tissue, e.g., at the ankle and knee. Consequently, the high impacts involving maximal jumping and dropping can be unfeasible for elderly people, not to mention the osteoporotic or frail persons. Instead, dynamic exercise regimen, which includes low-to-moderate magnitude impacts from odd directions with accompanying workouts to improve muscle force (i.e., leading to increased joint moments) in dynamic movements, may turn out to be the most appropriate and effective means to improve not only the bone rigidity but also the muscle strength, balance and coordination among aging nonathletic people, and eventually, reduce their risk of falling and fractures in later life [37]. Naturally convincing data from appro12priately designed exercise intervention trials based on the odd-impact concept are called for.

In summary, female athletes' bone mass was, as expected, substantially higher at the loaded bone sites compared with that of the nonathletic referents, but more pertinently to the locomotive perspective, the loading-induced additional bone mass seems to be used to build mechanically strong and appropriate bone structures. Compared with controls, the weight-bearing bone structures of athletes, swimmers excluded, were characterized by larger diaphysis, thicker cortices and somewhat denser trabecular bone, and the strong bone structure was attributable to muscle performance-related high joint moments as well as to impact loading modality. The athletes' bones at the shaft sites of the nonweight-bearing upper extremity were generally larger in total cross-sectional area and the strong bone structure was mainly associated with the muscle performance-related high joint moments. Thus, different loading history and other features of loading seemed to govern the skeletal adaptation at the upper and lower extremity.

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