Cross-sectional geometry of weight-bearing tibia in female athletes subjected to different exercise loadings

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ORIGINAL ARTICLE

Cross-sectional geometry of weight-bearing tibia in female athletes subjected to different exercise loadings

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Abstract
Summary The association of long-term sport-specific exercise loading with cross-sectional geometry of the weight-bearing tibia was evaluated among 204 female athletes representing five different exercise loadings and 50 referents. All exercises involving ground impacts (e.g., endurance running, ball games, jumping) were associated with thicker cortex at the distal and diaphyseal sites of the tibia and also with large diaphyseal cross-section, whereas the high-magnitude (power-lifting) and non-impact (swimming) exercises were not.

Introduction Bones adapt to the specific loading to which they are habitually subjected. In this cross-sectional study, the association of long-term sport-specific exercise loading with the geometry of the weight-bearing tibia was evaluated among premenopausal female athletes representing 11 different sports.

Methods A total of 204 athletes were divided into five exercise loading groups, and the respective peripheral quantitative computed tomographic data were compared to data obtained from 50 physically active, non-athletic referents. Analysis of covariance was used to estimate the between-group differences.

Results At the distal tibia, the high-impact, odd-impact, and repetitive low-impact exercise loading groups had ~30% to 50% ($p<0.05$) greater cortical area (CoA) than the referents. At the tibial shaft, these three impact groups had ~15% to 20% ($p<0.05$) greater total area (ToA) and ~15% to 30% ($p<0.05$) greater CoA. By contrast, both the high-magnitude and repetitive non-impact groups had similar ToA and CoA values to the reference group at both tibial sites.

Conclusions High-impact, odd-impact, and repetitive low-impact exercise loadings were associated with thicker cortex at the distal tibia. At the tibial shaft, impact loading was not only associated with thicker cortex, but also a larger cross-sectional area. High-magnitude exercise loading did not show such associations at either site but was comparable to repetitive non-impact loading and reference data. Collectively, the relevance of high strain rate together with moderate-to-high strain magnitude as major determinants of osteogenic loading of the weight-bearing tibia is implicated.

Keywords Bone rigidity · Bone structure · Exercise · High impact · Mechanical loading · Odd impact · Osteoporosis · pQCT

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Introduction

Bones adapt to the increased loads to which they are habitually subjected. According to Frost's classic mechanostat theory, the magnitude of load-induced strains within the bone tissue is the primary driving force in bone adaptation [1, 2], whereas Lanyon considered other strain-related factors more important [3]. Obviously, strain magnitude accounts for bone adaptation, but the rate at which the strains occur is more influential [4–7]. Also, the distribution of strains and consequent strain gradients within the loaded bone are essential to bone adaptation. Collectively, dynamic loading from unusual directions is apparently more osteogenic than common predictable loading, even if the latter is performed vigorously.

The mechanical competence of bone, as an organ, is basically provided by a combination of bone microarchitecture, bone cross-sectional size and geometry, and bone material [8, 9]. For example, periosteal expansion and accompanying changes in long bone cross-sectional geometry are modulated by mechanical loading environment [10–12], and even a slightly increased bone diameter can substantially increase the resistance of bone diaphysis to bending loads [13]. The gain in cortical thickness, in turn, is mainly attributable to periosteal expansion during axial growth, which is a process also modulated by mechanical loading [13–15]. From the clinical perspective, both of these adaptive processes of bone are important because not only the bone diameter but also the cortical thickness account for bone fragility in later life [16–19].

In this study, we were particularly interested in whether and to what extent a long-term engagement in sports comprising mainly of (1) high-magnitude vertical impacts, (2) moderate-magnitude impacts from varying, unusual directions, (3) high-magnitude muscle forces, (4) a great number of consecutive low-to-moderate-magnitude impacts, and (5) a great number of consecutive non-weight-bearing muscle contractions were associated with the cross-sectional geometry of weight-bearing tibia. From a broader perspective, this study can be viewed as an attempt to translate the aforementioned principles of bone adaptation into the context of prevention of bone fragility by means of exercise.

Material and methods

Subjects

The present study material consisted of peripheral quantitative computed tomographic (pQCT) images of the distal tibia and tibial shaft of 204 competitive female athletes and their 50 non-athletic referents. The data were obtained from our database of pQCT scans [20, 21]. The athletes were recruited through national sports associations and local athletics clubs. The referents were recruited from the local medical and nursing schools and they did not practice any competitive sports except recreational exercises two to three times a week. None of the participants had diseases or took medication known to affect bone tissue. The study protocol was approved by the Ethics Committee of Pirkanmaa Hospital District, and each participant gave her written informed consent prior to the measurements.

Classification of athletes by exercise loading type

We recently refined an earlier classification scheme [22] and divided different sports into five near-distinct types of exercise loading, i.e., high-impact, odd-impact, high-magnitude, repetitive low-impact, and repetitive non-impact [20, 21, 23]. Briefly, high-impact loading refers to maximal vertical jumps and the accompanying ground impacts; odd-impact loading refers to rapid turns and stops while spurting/running and the accompanying ground impacts; high-magnitude loading refers to maximally applied muscle forces in slow well-coordinated movements without ground impacts; repetitive low-impact loading refers to ground impacts that occur during long-lasting running performances at a relatively constant speed; and repetitive non-impact loading refers to applied muscle forces occurring during long-lasting performances without ground impacts. Note that the classification considers not only the typical sports performance, but also the typical forms of training, which together establish the predominant type of exercise loading in the given sports. Apparently, this classification is not fully exclusive but is considered to provide a reasonable qualitative basis to characterize different exercise loadings and their association with bone traits.

In the present study, high-impact exercise loading included volleyball (N=21), hurdling (N=24), triple jump (N=9), and high jump (N=10). Odd-impact exercise loading comprised soccer (N=27) and racket games (squash, tennis, and badminton; N=33). Powerlifting (N=17) represented high-magnitude exercise loading, while endurance running (N=18) represented repetitive, low-impact exercise loading. Swimming (N=45) represented repetitive, non-impact exercise loading.

Training and health history

The questionnaires on athletes' training history included sport-specific training hours during the previous year and sport-specific years of competing. This information covered at least a 5-year period of training history. Information on health history, medication including use of hormonal contraceptives, coffee and alcohol consumption, smoking, injuries, and previous fractures was also collected. Menstrual status was also elicited, and if a woman 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 [24] and analyzed by Micro-Nutrica software (Social Insurance Institution, Helsinki, Finland). The use of calcium supplements was also elicited.

Muscle performance

Maximal isometric leg extension force was measured at 90° knee flexion angle with a leg press dynamometer (Tamtron, Tampere, Finland). In vivo precision of isometric force measurements (coefficient of variation, in percent) is about 5% in our laboratory [25]. Dynamic maximal take-off force and power were measured with a force plate (Kistler Ergojump 1.04, Kistler Instrumente AG, Winterthur, Switzerland) in a vertical countermovement jump test. The precision of the vertical jump measurement is about 3% [26].

Bone traits

The pQCT (XCT 3000, Stratec Medizintechnik GmbH, Pforzheim, Germany) was performed at the dominant distal tibia (at the 5% site of the estimated tibial length proximal to the distal endplate) and tibial shaft (at the 50% site) according to our standard measurement procedures [27]. The dominant side denoted the lower limb primarily used for taking off from the ground or kicking the ball, as appropriate for the given sports.

Bone traits were evaluated according to our standard analysis procedures [27]. In short, the total cross-sectional area (ToA, in square millimeters) of both tibial sites was determined using an iterative contour detection algorithm (contour mode 2, peel mode 2). Cortical area (CoA, in square millimeters) of the distal site was also provided by the above algorithm, while the shaft CoA was determined using a simple threshold of 0.690 cm^{-1}. As the bone traits of interest, bone mineral content (BMC, in milligrams) as a surrogate for the amount of material the given bone site is made of, ToA, CoA, and density-weighted polar section modulus (BSI, in cubic millimeters) as an index of bone strength against torsion and bending were determined for both sites. Also, a schematic diagram from right-legged subjects of the study group in 20° sectors of the average endocortical and periosteal radii was accomplished to represent the average cross-section in each exercise loading group. Please note also that no statistical testing was conducted on these radii for the diagram since the data were analyzed only for the right-legged subjects (representing 78% of the total sample).

According to repeated scans of 25 subjects, the in vivo precision of the above-mentioned pQCT measurements was 1.0% for BMC, 2.0% for ToA, 2.8% for CoA, and 2.3% for BSI at the distal tibia and 0.6% for BMC, 1.2% for ToA, 0.9% for CoA, and 1.9% for BSI at the tibial shaft in our laboratory.

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 traits in relation to the reference group were estimated 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. To control for possible skewed distribution in outcome variables, log-transformed variables of all outcomes were used in ANCOVA. Percentage differences (in percent) and their 95% confidence intervals (95%CI) were achieved by the antilog of mean differences between the groups. When zero (indicating the mean of the reference group) was not within the 95%CI, the between-group difference was considered statistically significant at a level of $p<0.05$.

Results

Descriptive data on anthropometric characteristics, training history, and muscle performance in the study groups and group differences (ANOVA) from the reference group are shown in Table 1. Table 2 shows the absolute values of the bone traits in the exercise loading groups and adjusted group differences (ANCOVA), while Figs. 1 and 2 illustrate the percentage group differences in bone traits in relation to the reference data.

BMC

At the distal tibia, the high-impact, odd-impact, and repetitive low-impact exercise loading groups had 15% to 26% greater mean BMC than the referents ($p<0.05$). In the high-magnitude group and repetitive non-impact group, the mean distal tibia BMC was similar to that of the referents.

At the tibial shaft, the mean BMC of the high-impact and odd-impact groups was 28% to 44% greater than referents ($p<0.05$), whereas the mean BMC of the high-magnitude group was 28% lower than the controls ($p<0.05$). The mean shaft BMC of the repetitive low-impact and non-impact groups was similar to the reference data ($p<0.05$).

Table 1 Group characteristics, mean (SD)

Exercise loading	N=254	Age (years)	Height (cm)	Weight (kg)	Body mass index	Sport-specific training hours/week	Competing career (years)	Isometric leg extension force (kg)	Power of counter movement jump (W/kg)
High impact	64	21.3 (3.2)*	174 (7)*	65.5 (8.7)*	21.5 (2.2)	11.8 (2.8)*	9.8 (3.3)	191 (38)*	47.8 (7.0)*
Odd impact	60	23.5 (5.1)	167 (7)	62.6 (8.6)	22.5 (2.1)	7.8 (3.1)*	9.9 (4.0)	180 (36)*	41.0 (5.5)*
High magnitude	17	27.5 (6.3)*	158 (3)*	63.3 (13.2)	25.2 (4.2)*	9.1 (2.7)*	8.0 (4.7)	226 (39)*	47.8 (7.1)*
Repetitive, low impact	18	28.9 (5.6)*	168 (5)	53.7 (3.4)*	19.0 (1.1)*	10.9 (3.4)*	12.4 (6.7)	170 (46)	38.9 (5.1)
Repetitive, non-impact	45	20.2 (2.6)*	170 (6)*	63.3 (6.6)	21.7 (2.1)	17.2 (5.6)*	10.0 (3.8)	163 (40)	40.1 (5.2)*
Reference group	50	24.1 (3.4)	165 (5)	60.4 (7.6)	22.1 (2.4)	2.9 (1.5)[a]	–	141 (23)	35.5 (4.6)

*$p<0.05$, statistically significant difference from the reference data (ANOVA with Sidak correction)

[a] The referents did not engage in any specific sport but they took recreational exercise ~3 h/week on average

Cross-sectional geometry

At the distal tibia, only the high-impact exercise loading group had significantly greater (8%, $p<0.05$) mean ToA than the referents, while the differences in the two other impact exercise groups did not reach statistical significance. The mean ToA in the high-magnitude and repetitive non-impact exercise groups was quite similar to that of the referents. As regards distal tibia CoA, all three impact exercise loading groups had 33% to 53% greater mean values than the referents ($p<0.05$), while the mean value of the high-magnitude and repetitive non-impact exercise groups was comparable to the reference data.

At the tibial shaft, all three impact exercise loading groups had 13% to 21% greater mean ToA and 18% to 28% greater mean CoA than those of the referents ($p<0.05$). The high-magnitude exercise loading group had comparable mean shaft ToA and CoA to those of the referents. Also, the mean ToA and CoA of repetitive non-impact exercise loading group were similar to the reference data.

Differences in the cross-sectional geometry of the tibial shaft in the exercise loading groups are illustrated in Fig. 3.

Table 2 Mean (SD) absolute values and the age-, weight-, and body height-adjusted statistical comparison of the bone traits of the athlete groups representing different exercise loading types and the reference group

	High impact	Odd impact	High magnitude	Repetitive, low impact	Repetitive, non-impact	Reference group
Distal tibia						
BMC (mg)	870 (89)[a,b,d]	801 (96)[a,b,d]	667 (104)[c,e,f]	732 (82)[a,b,d]	690 (100)[c,e,f]	664 (90)[c,e,f]
Total cross-sectional area (mm^2)	935 (124)[a,b]	847 (121)	772 (126)	846 (71)	844 (90)[f]	797 (101)[f]
CoA (mm^2)	254 (56)[a,b,d,e]	235 (47)[a,b,d,f]	184 (43)[c,e,f]	219 (45)[a,b,d]	173 (30)[c,e,f]	171 (32)[c,e,f]
Polar section modulus (mm^3)	1,699 (286)[a,b,c,d]	1,594 (266)[a,b,d]	1,244 (317)[e,f]	1,290 (232)[a,f]	1,205 (270)[e,f]	1,146 (234)[c,e,f]
Tibial shaft						
BMC (mg)	939 (162)[a,b,c,d]	862 (176)[a,b,c,d]	527 (124)[a,b,c,e,f]	626 (126)[d,e,f]	698 (178)[d,e,f]	676 (187)[d,e,f]
Total cross-sectional area (mm^2)	530 (48)[a,b,d,e]	482 (55)[a,b,d,f]	423 (56)[c,e,f]	495 (48)[a,b,d]	450 (49)[c,e,f]	421 (49)[c,e,f]
CoA (mm^2)	369 (36)[a,b,d,e]	335 (38)[a,b,d,f]	284 (38)[c,e,f]	344 (44)[a,b,d]	294 (36)[c,e,f]	280 (38)[c,e,f]
Polar section modulus (mm^3)	2,277 (309)[a,b,d,e]	1,989 (340)[a,b,d,f]	1,663 (338)[c,e,f]	2,063 (315)[b,d]	1,777 (316)[a,c,e,f]	1,646 (296)[c,e,f]

The following statistical differences refer to results from the age-, weight-, and height-adjusted ANCOVA with Sidak correction

[a] Statistically significantly different from the reference group

[b] Statistically significantly different from the repetitive, non-impact group

[c] Statistically significantly different from the repetitive, low-impact group

[d] Statistically significantly different from the high-magnitude group

[e] Statistically significantly different from the odd-impact group

[f] Statistically significantly different from the high-impact group

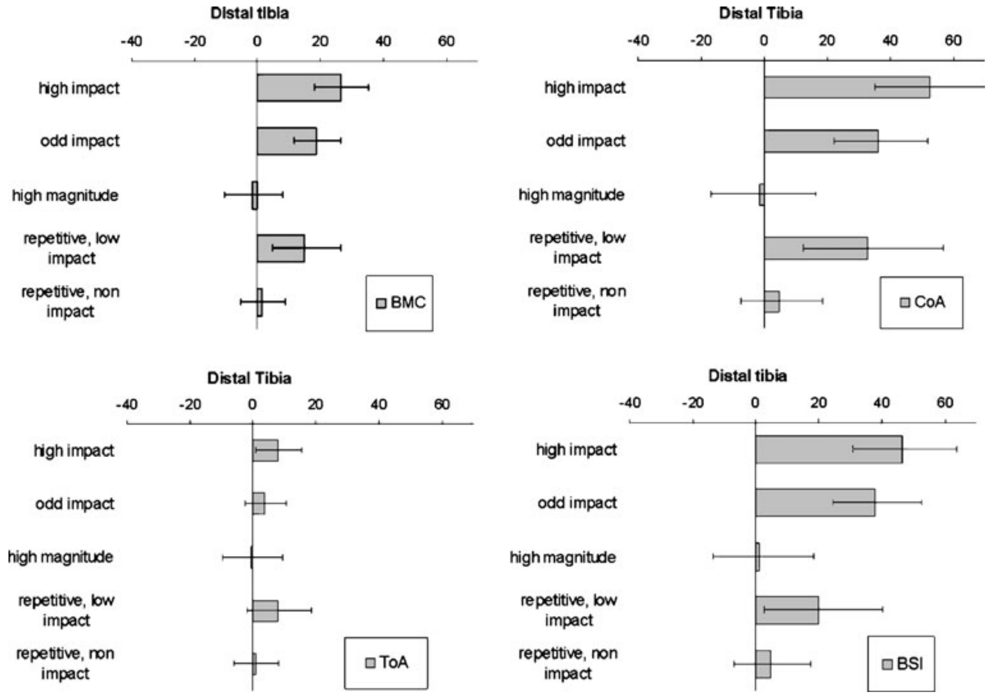

Fig. 1 The age-, weight-, and height-adjusted mean percentage differences (95%CI) between the female athletes and the non-athletic referents (the *0% line* indicates the mean of the reference group) in BMC (*left upper panel*), ToA (*left lower panel*), CoA (*right upper panel*), and BSI (*right lower panel*) of the distal tibia. The *bars* indicate the mean difference and the *whiskers* indicate the 95%CI. The exercise loading type is indicated on the *left*. Please see the classification of sports in the "Material and methods" section

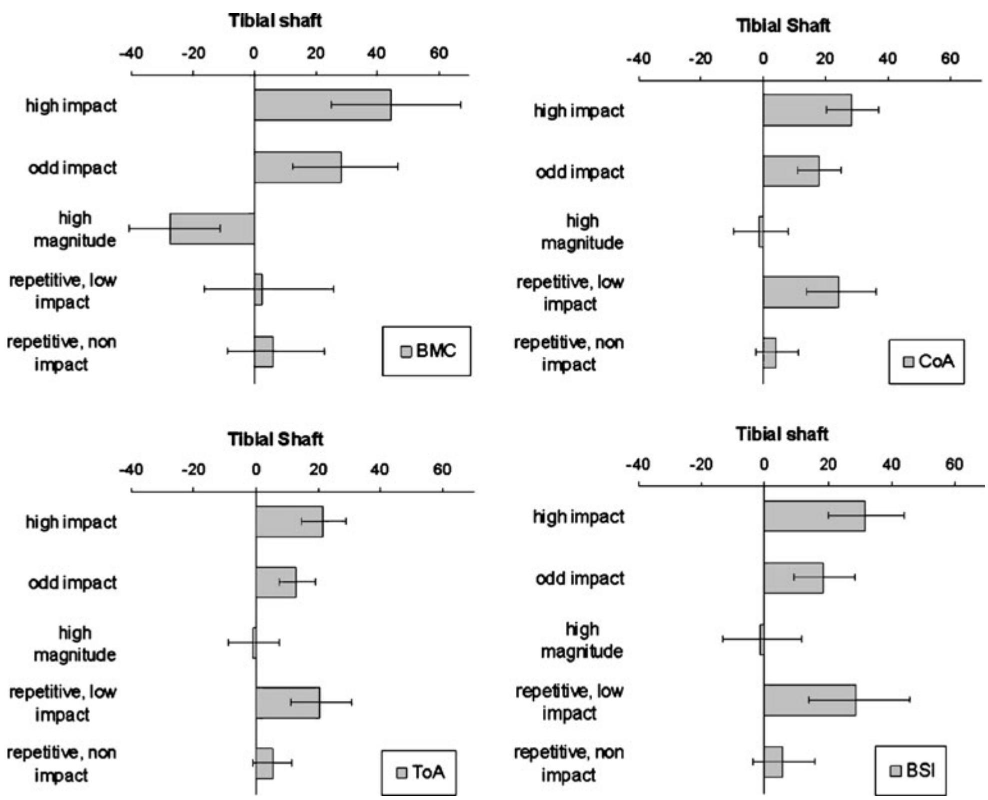

Fig. 2 Age-, weight-, and height-adjusted mean percentage differences (95%CI) between the female athletes and the non-athletic referents (the *0% line* indicates the mean of the reference group) in BMC (*left upper panel*), ToA (*left lower panel*), CoA (*right upper panel*), and BSI (*right lower panel*) of the tibial shaft. The *bars* indicate the mean difference and the *whiskers* indicate the 95%CI. The exercise loading type is indicated on the *left*. Please see the classification of sports in the "Material and methods" section

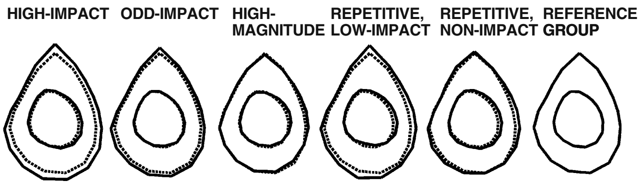

Fig. 3 Cross-sectional geometry of the tibial shaft among the right-legged subjects (representing 78% of the total sample) in the exercise loading groups. The illustrations were drawn by obtaining the average endosteal and periosteal radii from the area center of mass in 20° sectors and by plotting the average radii around the center of mass. The cross-section of the reference group is also overlaid with a *broken line* on the cross-sections of the exercise loading groups

Bone strength

At the distal tibia, the mean BSI in the high-impact, odd-impact, and repetitive low-impact exercise loading groups was 20% to 46% greater than that of the reference group ($p<0.05$), whereas the high-magnitude group and repetitive non-impact group had similar values to those of the referents.

At the tibial shaft, the mean BSI of the high-impact, odd-impact, and repetitive low-impact groups was 19% to 32% greater than that of the referents ($p<0.05$). In the high-magnitude group and repetitive non-impact group, the mean shaft BSI was similar to the reference data.

Discussion

The present large pQCT study on the association of different exercise loading types with tibial geometry corroborated earlier observations that high-impact and odd-impact exercise loadings are associated with larger CoA in relation to the total cross-sectional area both at the distal and diaphyseal sites of the weight-bearing tibia [20]. A novel finding in the present study was that repetitive low-impact exercise loading, represented by endurance running, was associated with a tibial geometry that provides resistance against bending and torsional loads that are as strong as those observed for the high-impact and odd-impact sports. In addition, the observation that the high-magnitude exercise loading, represented by powerlifting, was not associated with stronger tibia than referents was quite surprising.

Maximal muscle contractions apparently subject bones to the greatest loads [28]. Thus, it is a common and justified notion that high-magnitude loading caused by maximal weightlifting is osteogenic, let alone the evidence that weightlifting has substantial influence on bone mass at the weight-bearing axial skeleton in female athletes [29, 30]. However, with regard to our earlier pQCT findings on the tibial shaft in a mixed group of weightlifters and powerlifters [31], the present findings appear contradictory. Whereas Olympic weightlifting is based on explosive, well-coordinated consecutive movements, powerlifting typifies a pure high-magnitude exercise loading comprising maximal muscle forces exerted at a relatively low rate on a well-coordinated basis. While weightlifting and powerlifting together were associated with 10% larger CoA and BSI than those of the referents [31], pure powerlifting in this study was associated with similar CoA and BSI values. We conclude that the mechanical competence provided by the similar cross-section of the tibia is sufficient for the loading imposed on tibia during a typical powerlifting performance (e.g., a squat or deadlift). While requiring maximal muscle force, the speed of movement in a typical powerlifting performance is steady and slow, apparently keeping muscle contraction-induced strain rates low. As regards impact loading, the rate of load-induced strains is high [32–34], and this could also be the case in Olympic weightlifting, at least to some extent. However, we recognize that some aspects of training between powerlifting and weightlifting may overlap, reducing the distinction between these activities.

It was recently proposed by Bramble and Lieberman that the human musculoskeleton has been evolved for endurance running [35]. In this respect, a noteworthy finding in the present study was that the endurance runners representing the repetitive, low-impact loading had ~20% greater cortical bone area and total cross-sectional area at the tibial midshaft but similar BMC compared with the reference data. These observations in runners can be interpreted as a reflection of the major principle of bone adaptation; the amount of bone tissue (~mass) is utilized to construct such a bone structure that is most appropriate for the prevailing mechanical environment and functional purpose [36]. Thus, bone should be simultaneously structurally rigid but relatively light. This kind of bone structure with wider diaphysis may well cope with a great (~>10,000) number of successive bending loads and ground impacts caused by a typical endurance running performance. Higher strain magnitude increased periosteal bone formation, while lower strain magnitude did not, as shown in an experimental study [37]. As regards the potential osteogenicity of running, it can produce strain magnitudes and strain rates comparable to those caused by jumping from different heights [33–35].

While endurance runners appeared to have more rigid tibia than the referents, this was not the case for the more proximal femoral neck in our previous magnetic resonance imaging study of the hip region. In that study, the total cross-sectional area and relative CoA of the femoral neck were similar in endurance runners and referents [21]. This difference in tibia and proximal femur geometry may be attributable to the loading environment of the given bone. Obviously, direct ground reaction forces (~impacts) mainly underlie the strain environment within the tibia, while incident muscle forces predominate the strain environment within the proximal femur.

Regarding the further role of muscle contractions, it is also noted that the repetitive, non-impact exercise loading represented by swimming was not different from the referents in any way concerning the tibial geometry. Apparently, the similarly high number of successive loads caused by leg movements against water drag and accompanying muscle contractions do not provide a sufficient strain stimulus for bone adaptation, either in terms of magnitude or rate, to the extent that it would override the influence of normal habitual locomotion. Conversely, a relatively light skeleton may offer some mechanical advantage for a swimmer. Furthermore, the influence of muscle contractions on the structure of the non-weight-bearing humerus of swimmers and throwers has previously been demonstrated [20, 38].

This study has limitations that need to be taken into account. A cross-sectional design is neither free from selection bias nor able to show direct causal effects but rather to generate hypotheses. Individuals with genetically strong musculature and skeleton may be more likely to start an athletic career in their youth. Differences in the starting age, duration, intensity, and frequency of competitive athletic training may also have confounded the present findings to some extent. However, all the athletes studied were among the best in their sport in Finland, typically representing the national top level but some of them actually being world-class athletes, and they all had a long and intense training history in their respective sports. Thus, their tibiae had sufficient time to receive the maximal loading stimuli due to their sports. Moreover, it is recalled that the reference group comprised healthy students who engaged in various recreational sports and exercises about three times a week on average. This being the case, it is possible that actual loading-associated influences on tibial geometry would have been even greater if compared to a sedentary reference group.

In conclusion, high-impact, odd-impact, and repetitive low-impact exercise loadings were associated with thicker cortex at the distal tibia. At the tibial shaft, impact loading was not only associated with thicker cortex, but also a larger cross-sectional area. High-magnitude exercise loading did not show such associations at either site but was comparable to repetitive non-impact loading and reference data. Collectively, this supports the relevance of high strain rate together with moderate-to-high strain magnitude as major determinants of osteogenic loading of the weight-bearing tibia.

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Conflicts of interest None.

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