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Effects of bone-specific physical activity, gender and maturity on tibial cross-sectional bone material distribution: a cross-sectional pQCT comparison of children and young adults aged 5–29 years

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ABSTRACT

Growth is the opportune time to modify bone accrual. While bone adaptation is known to be dependent on local loading and consequent deformations (strain) of bone, little is known about the effects of sex, and bone-specific physical activity on location-specific cross-sectional bone geometry during growth. To provide more insight we examined bone traits at different locations around tibial cross sections, and along the tibia between individuals who vary in terms of physical activity exposure, sex, and pubertal status. Data from 304 individuals aged 5–29 years (172 males, 132 females) were examined. Peripheral quantitative computed tomography (pQCT) was applied at 4%, 14%, 38%, and 66% of tibial length. Maturity was established by estimating age at peak height velocity (APHV). Loading history was quantified with the bone-specific physical activity questionnaire (BPAQ). Comparisons, adjusted for height, weight and age were made between sex, maturity, and BPAQ tertile groups. Few to no differences were observed between sexes or BPAQ tertiles prior to APHV, whereas marked sexual dimorphism and differences between BPAQ tertiles were observed after APHV. Cross-sectional location-specific differences between BPAQ tertiles were not evident prior to APHV, whereas clear location-specificity was observed after APHV. In conclusion, the skeletal benefits of physical activity are location-specific in the tibia. The present results indicate that the peri- or post-pubertal period is likely a more favourable window of opportunity for enhancing cross-sectional bone geometry than pre-puberty. Increased loading during the peri-pubertal period may enhance the bone of both sexes.

Introduction

Animal experiments have established that bones adapt mass and geometry to the prevalent loading environment [1–5]. Lower than normal loading leads to bone loss and higher than normal loading leads to bone gains [1,3]. Data from humans mirror observations from animal studies; with disuse (bed rest, immobilization, paralysis) leading to relatively rapid and marked bone loss [6], and increased loading (e.g. exercise intervention) leading to bone gains [7–9]. Moreover, animal experiments, in which the bone has been loaded in bending, have suggested that the adaptation is locally driven by the location-specific strains (deformation caused by the loading) [1,3]. Similarly, location-specific bone accrual has been reported at the tibial shaft in response to exercise interventions in pre- to peri-pubescent boys [10] and in post-menopausal women [11]. Further, bed rest leads to location-specific bone loss at the tibial shaft [12]. In the aforementioned studies bone was primarily added or lost from the anterior and posterior surfaces of the tibia, which corresponds to the dominant pattern of sagittal plane bending at the tibial shaft during typical weight bearing loading [13–17].

It appears that the skeleton is more sensitive to loading during growth than after it [18,19], and consequently it has been suggested that growth is the opportune time for exercise interventions [19–25]. Examination of growth is encumbered by differences in the timing of puberty between individuals and between sexes. However, when age is expressed with respect to puberty (identified by peak height velocity [PHV] [26] or menarche), a rather more consistent picture of skeletal growth during the peri-pubertal period emerges [27–31]. PHV is followed by peak total body bone mineral content accrual velocity (PBMCV) with only a 0.7 year lag, and in girls PBMCV all but coincides with menarche [27]. Therefore age at PHV (APHV) is a convenient marker of maturity. Around a quarter of the adult skeletal mass is accrued in the two-year period around PBMCV [27].

Abbreviations: APHV, age at peak height velocity; ANOVA, analysis of variance; BMC, bone mineral content; BPAQ, bone-specific physical activity questionnaire; EndoR, endocortical radii; MANCOVA, multivariate analysis of covariance; PHV, peak height velocity; PBMCV, peak total body bone mineral content accrual velocity; PeriR, pericortical radii; pQCT, peripheral quantitative computed tomography; PA, physical activity; SD, standard deviation; vBMD, volumetric bone mineral density

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Sexual dimorphism of the skeleton emerges during puberty when boys gain more bone than girls [32–35]. In addition to the amount of bone gained during puberty, relative endosteal and periosteal surface deposition differs between boys and girls; girls accumulating more endosteal bone than boys [32,35,36]. While animal studies suggest the bones of females are less sensitive to loading than those of males due to the effects of oestrogen [36], location-specificity of tibial shaft adaptation appears to be similar between the sexes [18,37]. However, little is known about the effects of sex on the association between physical activity and diaphyseal location-specific cross-sectional bone geometry during growth.

Therefore, the purpose of the present study was to examine whether bone material distribution is dependent on bone-relevant physical activity (PA) exposure when sex and maturational status are controlled. It was hypothesised that a difference would be observed in bone material distribution between bone-relevant PA groups. Further, it was hypothesised that there would be no difference in location-specific differences between bone-relevant PA groups prior to, and after PHV. And finally, due to the sexual dimorphism in skeletal ontogeny over puberty [32,35,36], we hypothesised that there would be a sex–maturity effect in the association between bone-relevant PA and bone material.

Materials and methods

The present study is a re-examination of the intersection of estimated bone strength from peripheral quantitative computed tomography (pQCT) and exposure to osteogenic physical activity estimated from the bone-specific physical activity questionnaire (BPAQ) [38] data from participants of previous studies conducted at Griffith University, Gold Coast, Australia aged 5 to 29 years-of-age. Some of the data has been published previously in support of exercise or validation studies [39–43]. The inclusion criteria common for the pooled studies included sound general health and being fully ambulatory. Exclusion criteria included medications known to affect bone, medical conditions that restrict physical activity participation, and recovering from a lower limb fracture or other immobilized injury. Strategies used to recruit the participants included contacting local schools, advertising in the local community with flyers, and messages to e-mail posting lists. The projects in which the data were originally acquired were approved by the Griffith University Human Research Ethics Committee (PES/12/05/HREC, PES/09/09/HREC, PES/25/11/HREC). Written informed consent was acquired from all participants and/or their legal guardians prior to the assessments.

Anthropometry

Participants were weighed to the nearest 0.1 kg with electronic scales (Soehnle Co., Switzerland). Height and sitting height were determined to the nearest millimetre with a portable stadiometer (HART Sport & Leisure, Australia). Leg length was calculated by subtracting the sitting height from the total height, which yields sub-ischial leg length.

Maturity assessment

Maturity was determined from age at peak height velocity (APHV) as the marker of puberty [26]. APHV was derived from age, height, sitting height and leg length using the sex-specific regression equations from Mirwald et al. [26];

$$M = \begin{cases} -9.236 + 2.708 * L_l * H_s - 0.1663 * A * L_l + 0.7216 * A * H_s \\ \quad + 0.022952 * {}^{W}/_{H}; \text{ boys} \\ -9.376 + 1.882 * L_l * H_s + 0.22 * A * L_l \\ \quad + 0.5841 * A * H_s - 0.002658 * A * W + 0.07693 * {}^{W}/_{H}; \text{ girls} \end{cases}$$

where M = maturity offset in years, L_l = leg length in metres, H_s = sitting height in metres, H = height in metres, A = age in years, and W = weight in kg. Note that the coefficients are different from those of Mirwald et al. to account for expressing the lengths in metres instead of centimetres. Also, the W/H ratio coefficients have not been adjusted, as the coefficients reported in Mirwald et al. [26] were too low by a factor of 100, which is accounted for by expressing height in metres. An estimate of APHV was obtained by subtracting maturity offset (M) from age. In the Canadian population the regression equation was developed with the maturity offset estimate error at 0.24 (SD 0.65) years for boys, and 0.001 (0.68) years for girls, while the coefficients of determination were between 0.91 and 0.92 for boys and girls, respectively [26].

Bone-specific physical activity questionnaire (BPAQ)

Participants were asked to complete a bone-specific physical activity questionnaire (BPAQ) as previously described [38]. Briefly, the BPAQ is a questionnaire designed to capture bone-relevant weight-bearing exercise history. The data is then analysed using a purpose-built on-line calculator (http://www.fithdysign.com/BPAQ/) developed from algorithms based on force platform testing of a wide range of typical physical activities to derive a relative load rating index [38]. We have previously reported that the BPAQ score is positively associated with dual-energy x-ray absorptiometry-derived areal bone mineral density with the coefficients of determination varying from 0.36 to 0.68 depending on bone site [38]. Although the calculator produces past (whole of life), current (previous 12 months) and total BPAQ score (tBPAQ), only tBPAQ was used in the present study. We have reported that BPAQ measures exhibit excellent inter-tester (ICC 0.93–0.97) and intra-tester reliability (ICC 0.86–0.93) for male and female participants from 5 to 83 years of age [41].

Bone assessments

Peripheral quantitative computed tomography (pQCT) was used to evaluate the cross-section of the tibia at 4%, 14%, 38% and 66% of tibial length from the distal endplate (in-plane pixel size 0.5 × 0.5 mm, slice thickness 2.3 mm, XCT 3000, Stratec Medizintechnik GmbH, Pforzheim, Germany). The pQCT scans were taken from the non-dominant limb (non-kicking leg for lower limb).

pQCT analysis

All pQCT analyses were conducted using the BoneJ [44] ImageJ-plugin (rsbweb.nih.gov/ij). A threshold value of 280 mg/cm^3 was used to analyse the tibial shaft. Polar cortical volumetric bone mineral density (vBMD) distribution, cortical bone mineral mass (BMC) distribution, and endo- (EndoR, mm) and pericortical radii (PeriR, mm) were calculated for shaft slices as previously described [45]. In brief, the centre of the medullary cavity was defined and a radius was incremented by 0.1 mm from the centre until the endocortical border was detected. Thereafter, the vBMD of each pixel was noted by appending the latest value to a vector (empty at first) with further increments of the radius until reaching the pericortical border. Thereafter the direction of the radius was incremented by one degree and the radius incrementing process repeated. The acquired 360 vBMD vectors were aligned by defining the angle between the initial direction of radius incrementation in the image and the line going from the centre of the tibia to the centre of fibula and selecting the first vBMD vector in such a way that it corresponded to 5° counter clockwise from the tibia to the fibula line. Starting from that vector, the values of ten consecutive vectors were averaged to represent the vBMD of a 10° sector, resulting in 36 10° polar sectors in total (Fig. 1). A similar approach was used for BMC and for endo- and pericortical radii.