



Bone mineral density and hip structure changes over one-year in collegiate distance runners and non-athlete controls

Nicole A. Infantino^b, William P. McCormack^a, Hawley C. Almstedt^{a,*}

^a Human Performance Laboratory, Department of Health and Human Sciences, 1 LMU Drive, MS 8888, Los Angeles, CA 90045, USA

^b Department of Biology, 1 LMU Drive, MS 8888, Los Angeles, CA 90045, USA

ARTICLE INFO

Keywords:

Hip structure analysis
Peak bone mass
Femur bone geometry
Stress fracture

ABSTRACT

Modification of bone is continuous throughout life and influenced by many factors, including physical activity. This study investigated changes in areal bone mineral density (aBMD) and hip structure among male and female collegiate distance runners and non-athlete controls over 12 months. Using dual-energy x-ray absorptiometry (DXA) and hip structure analysis (HSA) software, aBMD at the posterior-anterior (PA) and lateral spine, femoral neck, total hip (TH), whole body (WB), and bone geometry at the narrow neck (NN) of the femur was measured three times over 12 months. HSA included cross-sectional area (CSA), cross-sectional moment of inertia (CSMI), and Z-section modulus (Z). Male runners had significantly higher aBMD at TH and WB and greater CSA, CSMI, and Z than male controls at the end of 12 months. Female controls had higher aBMD at the PA spine than female runners at the end of 12 months. Male runners had significant increases in aBMD at the PA ($p = 0.003$) and lateral spine ($p = 0.002$), and TH ($p = 0.002$), female runners had significant decreases in aBMD at TH ($p = 0.015$) and WB ($p = 0.002$), male controls had significant increases in aBMD at the PA spine ($p < 0.001$) and WB ($p < 0.001$), and female controls had significant decreases in aBMD at lateral spine and TH ($p = 0.008$) over the year. When applying covariates of bone-free lean mass and vitamin D, male distance runners demonstrated significant improvement in CSA (3.602 ± 0.139 vs. 3.675 ± 0.122 cm², $p = 0.05$), CSMI (3.324 ± 0.200 to 3.467 ± 0.212 cm⁴, $p < 0.05$), and Z (1.81 ± 0.08 to 1.87 ± 0.08 cm³, $p = 0.05$) during the study. No other changes in hip structure occurred over the year. Distance running may be beneficial to aBMD and hip structure in college-age males but not females. Further research is needed on potential influences of weight-bearing activity, energy availability, and hormonal status on aBMD and hip structure in males and females.

1. Introduction

Osteoporosis is a chronic disease caused by low areal bone mineral density (aBMD) often resulting from the creation of new bone occurring to a lesser degree than the normal breakdown of aged bone. This can cause the skeleton to become weak and increase fracture risk (*NIH Consensus Development Panel on Osteoporosis Prevention, Diagnosis, and Therapy*, 2001; van Staa et al., 2001). One in 3 women (Melton et al., 1992) and 1 in 5 men (van Staa et al., 2001) over the age of 50 will suffer an osteoporotic fracture in their lifetime. Over 2 million fragility fractures are predicted to occur in the United States annually, resulting in \$17 billion in medical expenses. Hip fractures account for only 14% of

fractures but make up 72% of the total costs. Additionally, the cost and number of fractures is expected to reach \$25 billion and over 3 million by the year 2025 (Burge et al., 2007).

Physical activity and exercise are shown to influence aBMD and femur geometry contributing to optimal bone health and reducing risk for fracture (van Staa et al., 2001; Snow-Harter et al., 1992). Weight-bearing activities improve bone health, including aBMD, bone mineral content (BMC), and bone geometry (Kohrt et al., 2004; Fonseca et al., 2014). When impact activity is performed during childhood, especially in the peripubertal years, it may optimize bone mass, reducing the risk of osteoporosis later in life (Gunter et al., 2012). Over 25% of total bone mineral in adults is accrued during the two-year period before and after

Abbreviations: ANCOVA, analysis of covariance; BFLM, bone-free lean mass; aBMD, areal bone mineral density; BMI, body mass index; CSA, cross-sectional area; CSMI, cross-sectional moment of inertia; DXA, dual-energy x-ray absorptiometry; EA, energy availability; FFQ, Food Frequency Questionnaire; HSA, Hip Structure Analysis; METs, metabolic equivalents; NN, narrow neck; RDA, recommended dietary allowance; Z, Z-section modulus.

* Corresponding author.

E-mail address: Hawley.Almstedt@lmu.edu (H.C. Almstedt).

<https://doi.org/10.1016/j.bonr.2021.101056>

Received 13 November 2020; Received in revised form 1 March 2021; Accepted 19 March 2021

Available online 23 March 2021

2352-1872/© 2021 The Authors.

Published by Elsevier Inc.

This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

puberty (Bailey et al., 1999). Hind et al. (2012) reported distance runners to have higher aBMD in the narrow neck than non-runners when adjusted for age, height, and weight (Hind et al., 2012a). However, some research has shown no benefit to bone variables in distance runners (Barrack et al., 2017; Fredericson et al., 2007; Tenforde et al., 2015; Tenforde et al., 2018). Additionally, it appears there may be site specific areas of low aBMD in distance runners. In particular, the lumbar spine is an area of concern among runners (Fredericson et al., 2007; Barrack et al., 2008; Hind et al., 2006; Tam et al., 2018). Longitudinal studies examining changes in aBMD in young-adult distance runners over 8 to 12 months have displayed varying results. Over 12 months, one study reported significant increases in femur aBMD in middle and long distance runners (Bennell et al., 1997). Other work has shown non-significant decreases in lumbar spine and femoral neck bone mass with non-significant increases in whole body aBMD in female distance runners over an eight month period (Taaffe et al., 1997) and trends toward significant decreases in total body aBMD and dominant distal radius aBMD (Pollock et al., 2010).

Beyond physical activity, there are many other influences on bone health, including nutrient intake, energy availability, age of menarche, and menstrual status (Kohrt et al., 2004; Nattiv et al., 2007). Among athletes, the female athlete triad, and Relative Energy Deficiency in Sport (RED-S) are also conditions of concern. The triad is comprised of three interrelated disorders, low energy availability, menstrual dysfunction, and poor bone health, which occur on a spectrum of severity (Nattiv et al., 2007). RED-S is a term used to describe a syndrome that expands upon the female athlete triad and brings attention to all the physiological effects of energy deficiency on health in male and female athletes, skeletal or otherwise (Mountjoy et al., 2018; Mountjoy et al., 2014).

Bone size, osteocyte density, mineral density, and whole bone geometry are also factors that contribute to bone health and risk of fracture (Fonseca et al., 2014). Hip Structure Analysis (HSA) enables researchers to study indicators of bone health beyond aBMD. HSA software combines the average aBMD of the region of interest with dimensional information inherent to the image within the plane to estimate bone structure (Beck and Broy, 2015). This additional component of analysis quantifies mineral placement within the bone and can be used as a surrogate of bone strength.

However, HSA has not been used extensively to study bone under long-term mechanical loading influences (Faulkner et al., 2003; Kaptoge et al., 2003). Previous research suggests that high-impact and odd-impact loading is optimal for increasing bone strength in premenopausal women (Nikander et al., 2005). Yet, geometrical changes during prolonged moderate-impact loading, such as running, are less studied. HSA has been used recently in research to demonstrate advantageous femur structure in male athletes compared to non-athletic males (Hind et al., 2012a). Furthermore, the effects of running on bone health has been studied in males 18–35 years of age, but little research has been conducted on females in this age group (Hind et al., 2012a; Barrack et al., 2008; Ackerman et al., 2013). Research exploring hip structure in females has predominantly focused on pre-pubertal and postmenopausal populations since considerable skeletal change occurs during these periods of life (Nikander et al., 2005; Alwis et al., 2008; Devlin et al., 2010; McNamara and Gunter, 2012). Yet, bone modification is continuous throughout life as skeletal tissue responds to biochemical and physical stimuli (Hind et al., 2012a). There appears to be a lack of research examining HSA and aBMD in young adult males and females. Therefore, it is important to compare femur structure between young-adult males and females to understand bone health and fracture prevention more fully. Additionally, because runners have been shown to have low aBMD (Barrack et al., 2017; Barrack et al., 2008; Dengel et al., 2019), it is important that we investigate further into the hip structure of athletes to gain a more holistic understanding of this population's bone health and to reduce fracture risk.

This study investigates differences in aBMD and hip structure

between collegiate distance runners and non-athletic controls matched for age, size, and sex. Additionally, we studied changes in these measures of bone health over a one-year period. We hypothesized that aBMD and hip structure measures would be greater at baseline among the runners than in non-athletic controls. Secondly, we theorized that measures of bone health in runners would increase over the yearlong study. Lastly, we hypothesized that male and female runners would have similar aBMD and hip structure and display parallel improvements.

2. Methods

Athletes, between the ages of 18–23, were recruited from a NCAA Division I cross-country team and included 21 males and 18 females. Each week, the participants were running more than 100 km, completing two cross-training workouts (water running or stationary bike) and performing two resistance training sessions. The cross-country races were 8000 or 10,000 m in the fall season for the male runners and 5000 or 6000 m for the female runners. In the spring track season, the runners trained for and competed in 1500 m, 5000 m and 10,000 m disciplines. During the 12-month study, all participants competed in cross-country in the fall and the distance events of track in the spring.

To form a non-runner comparison group, 22 males and 24 females were selected from a larger study investigating life style choices and bone health of college students (LaBrie et al., 2018). Inclusion criteria for the non-athletic group was physical activity and exercising energy expenditure under 500 kcals per day. Additionally, non-runner participants were matched with the distance runners for height, body mass index (BMI), and age. Participant demographic data including previous bone injuries, energy availability, menstrual status, and ethnicity are presented in Table 1. Measurements were taken at baseline, at approximately 4–6 months, and then 12 months for both groups. For the runners, the baseline assessments were made before the fall collegiate cross-country season, the second measurements after cross-country season and before track season, and the final data collection took place before a second cross-country season. The non-athletic participants underwent baseline assessments in February/March, six-month assessments in September/October, then again in February/March at 12 months. All participants gave informed consent, and the research protocol was approved in accordance with the Helsinki Declaration by the Loyola Marymount University Human Subject's Institutional Review Board.

2.1. Bone health

Areal BMD of the posterior-anterior (PA) spine, lateral spine, femoral neck (FN), total hip (TH), and whole body (WB) were made using dual-energy x-ray absorptiometry (DXA; Hologic Delphi A, Waltham, MA, USA). All scans were performed after daily calibration using a spine phantom. The DXA scan of the entire body was used to determine bone-free lean mass (BFLM). DXA-derived z-scores compare aBMD to healthy age, sex, and ethnicity-matched norms and are reported for descriptive purposes in this paper (Kelly et al., 2009). Due to a lack of normative data for people of a particular ethnicity and certain age, z-scores were not available for all participants at each site. Previous research (Nattiv et al., 2007) identifies a z-score < -1.0 as low aBMD and may increase the risk fractures in athletes in high impact and repetitive sports.

Using the total proximal femur DXA scans, the HSA software (Hologic Apex version 4.5) was used to evaluate bone structure at the narrow neck (NN) region, the slightest segment of the proximal femur. Three geometric measurements were calculated from the HSA algorithm and utilized in this study: cross-sectional area (CSA, cm²), cross-sectional moment of inertia (CSMI, cm⁴), and Z-section modulus (Z, cm³). As explained by others (Ainsworth et al., 2011), HSA is a method that moves beyond the two-dimensional DXA image by using certain structural parameters of the DXA assessment. Derived with the HSA method, CSA is calculated as bone area minus non-bony tissue. CSMI is calculated by the integral of the bone mass weighted by the square of the

Table 1
Baseline characteristics of distance runners and non-athletic controls (mean \pm SD or n, %).

	Male runners n = 21	Male control n = 22	Female runners n = 18	Female control n = 24
Age (years)	19.0 \pm 1.0	19.5 \pm 0.8	19.2 \pm 1.2	19.2 \pm 0.6
Height (cm)	177.7 \pm 5.5 ^b	179.4 \pm 5.6	163.3 \pm 6.0	162.3 \pm 5.9
Weight (kg)	66.1 \pm 5.0 ^b	65.8 \pm 4.2	53.5 \pm 5.1	55.4 \pm 5.1
BMI (kg/m ²)	21.0 \pm 1.3	20.5 \pm 1.2	20.1 \pm 1.5	21.0 \pm 1.2
Bone-free lean mass (kg)	54.0 \pm 3.9 ^{a,b}	50.6 \pm 5.1	39.2 \pm 3.7	37.5 \pm 3.0
Calcium intake (mg/day)	1524.3 \pm 399.0	1186.8 \pm 464.6	1216.6 \pm 543.2	884.3 \pm 357.7
% meeting RDA for calcium	85.7	54.5	50.0	25.0
Vitamin D intake (IU/day)	347.8 \pm 181.0	433.1 \pm 450.7	319.1 \pm 264.7	264.6 \pm 223.6
% meeting RDA for vitamin D	4.8	13.6	11.1	4.2
Current physical activity (MET-hours/week)	124.9 \pm 37.7 ^a	34.2 \pm 26.0	108.9 \pm 20.6 ^c	23.5 \pm 15.4
Past bone-loading physical activity	57.3 \pm 33.5 ^d	38.0 \pm 19.6	56.5 \pm 35.5	40.0 \pm 33.3
Participants with previous bone injuries (n)	8	1	6	2
Energy availability (kcal·kgBFLM ⁻¹)	35.3 \pm 3.1	42.3 \pm 3.1	39.1 \pm 3.5	39.7 \pm 2.9
Very low (<30 kcal·kgBFLM ⁻¹) n (%)	8 (38.1)	3 (14.3)	4 (25.0)	7 (29.2)
Low (30–44 kcal·kgBFLM ⁻¹) n (%)	8 (38.1)	10 (47.6)	8 (50.0)	7 (29.2)
Healthy (\geq 45 kcal·kgBFLM ⁻¹) n (%)	5 (23.8)	8 (38.1)	4 (25.0)	10 (41.7)
Menstrual status n (%)				
Regular	NA	NA	7 (38.7)	9 (37.5)
Irregular			5 (27.8)	1 (4.2)
Hormonal contraception			6 (33.3)	14 (58.3)
Years since menarche	NA	NA	4.86 \pm 2.67 ^d	6.87 \pm 1.84
Ethnicity n (%)				
Black/African American	0	3 (13.6)	0	0
White	15 (71.4)	11 (50.0)	9 (50.0)	9 (37.5)
Hispanic	5 (23.8)	3 (13.6)	8 (44.4)	3 (12.5)
Asian	1 (4.8)	5 (22.8)	1 (5.6)	11 (45.8)
Other	0	0	0	1 (4.2)

Means \pm SD or number (percent) as indicated, BMI = body mass index, RDA = recommended dietary allowance, MET = metabolic equivalents, kcal = kilocalories, BFLM = bone-free lean mass, MR = male runners; FR = female runners; MC = male controls; FC = female controls, ^aMR vs MC, ($p < 0.05$), ^bMR vs FR, ($p < 0.001$), ^cFR vs FC, ($p < 0.001$), ^dFR vs FC, ($p < 0.05$).

distance from the center of mass to indicate the bending stress in a cross section (Ramamurthi et al., 2012). Z is the maximal bending strength of the cross-section estimated by calculating ($Z = \text{CSMI}/y$), where y is the maximum distance from the center of mass to the medial or lateral cortical margin (Beck and Broy, 2015). Repeated scans performed in this laboratory show a coefficient of variation of <1.5% for aBMD of the hip and spine and <2.4% for HSA of the NN. History of sport and exercise-related bone injuries, including fractures, stress fractures, and stress reactions were recorded in a health history questionnaire at baseline. Information on bone injuries during the yearlong study was collected at subsequent lab visits.

2.2. Physical activity

Physical activity was determined using the Aerobics Center Longitudinal Questionnaire which assesses regular exercise, performed at least once per week, over the previous three months. This validated questionnaire takes into account the number of days per week, duration, frequency, intensity, and type of exercise performed (Pereira et al., 1997). Hours of exercise were combined with metabolic equivalents (METs) from the compendium of physical activity to calculate MET-hours per week of activity (Ainsworth et al., 2011). A measure of previous bone-loading physical activity and exercise was assessed using the Bone-specific Physical Activity Questionnaire (BPAQ) (Weeks and Beck, 2008). This valid and reliable method of assessment incorporates bone-loading characteristics of reported activities with years and the age at which the exercise was performed to calculate a unitless variable in which higher scores indicate a greater history of weight-bearing activity (<http://www.fithdysign.com/BPAQ/>). The non-runners in this study reported no history of competing in impact-loading sports on the BPAQ.

2.3. Dietary intake

Calcium and vitamin D intake were assessed using the full-length Block 2014 Food Frequency Questionnaire (FFQ) which assesses nutrient intake over the previous year (Block and Subar, 1992). Dietary and supplemental sources of calcium and vitamin D were summed in this analysis. Participants completed the survey independently through on-line delivery, while estimation of portion sizes was assisted with visual aids.

2.4. Energy availability

Similar to previous research (McCormack et al., 2019; Beermann et al., 2020) energy availability (EA) was calculated by deducting exercising energy expenditure (EEE) from energy intake, then dividing by bone-free lean mass (BFLM). Daily energy intake was determined by the Block 2014 FFQ and BFLM was obtained via DXA. Exercising energy expenditure was ascertained from activities with >4.0 METs on the physical activity questionnaire. The EEE was further adjusted to eliminate the quantity of energy from resting metabolic rate, estimated by the Cunningham equation (Cunningham, 1991), during the hours of exercise. Based on previous research showing detriment to bone mineral metabolism and reproductive function, very low EA was defined as <30 kcal·kgBFLM⁻¹, low EA as 30–44 kcal·kgBFLM⁻¹, and healthy EA as \geq 45 kcal·kgBFLM⁻¹ (Loucks et al., 2011). Energy availability could not be calculated for three participants because an acute injury at the time of data collection prevented estimation of an accurate exercising energy expenditure.

2.5. Menstrual status

Female participants completed a menstrual history questionnaire which also inquired about contraceptive use. Participants reported their age at onset of menstruation which was used to calculate years since menarche. Women using hormonal contraceptives or an intrauterine device at baseline or during the study were categorized as contraceptive users. Women not using hormonal contraception, were asked to identify their menstrual cycle as regular (10–12 cycles per year) or irregular, experiencing amenorrhea (less than 3 cycles per year or no period for the last 3 months) or oligomenorrhea (4–9 cycles per year).

2.6. Statistical analysis

Data analysis was carried out using IBM SPSS Statistics for Windows version 24 (IBM Corp., Armonk, N.Y., USA). Group differences in demographic variables were evaluated using an analysis of variance for continuous variables and a Pearson's chi square test for categorical

variables. As is common in the research literature comparing aBMD between different groups (Hind et al., 2012a; Barrack et al., 2008; McCormack et al., 2019), relationships between anthropometric variables and aBMD were explored using Pearson correlations to identify potential covariates based on the theoretical and genuine associations to bone density. BFLM was significantly correlated with baseline aBMD measures at all five bone sites ($r = 0.28\text{--}0.54$, $p < 0.01$) and was therefore used as a covariate in the aBMD analysis. To test the hypotheses regarding baseline differences and changes in aBMD over time, a repeated-measure analysis of covariance (ANCOVA; group x sex x time), controlling for BFLM, was utilized to determine significant differences in aBMD between groups (runners, non-athletes) and between sexes (male, female) for each scan site. The Bonferroni correction was used to

account for multiple comparisons.

A stepwise regression was applied to determine covariates for HSA. The analysis explored baseline measurements of age, height, weight, BMI, BFLM, calcium intake, vitamin D intake, and physical activity as possible covariates for CSA, CSMI, and Z at the NN site. BFLM was a significant predictor ($p < 0.001$) of CSA. BFLM and total vitamin D intake were significant predictors ($p = 0.049$) of CSMI, and Z ($p = 0.031$). Because the underlying physiology shows different covariates for aBMD and HSA variables, HSA variables were tested with a second ANCOVA. Therefore, an additional repeated-measure ANCOVA (group x sex x time) with Bonferroni correction was performed to assess CSA, CSMI, and Z differences between groups, between sexes, and over time at the NN site, while adjusting for the previously mentioned covariates.

Table 2

Areal bone mineral density (adjusted for bone-free lean mass) and z-scores in male and female distance runners and non-athletic controls.

aBMD site	Visit 1	% z-score < -1.0 visit 1	Visit 2	% z-score < -1.0 visit 2	Visit 3	% Change in aBMD from visit 1 to 3	% z-score < -1.0 visit 3
PA spine							
MR	0.956 ± 0.029	14%	0.979 ± 0.029 ^a	14%	0.984 ± 0.028 [#]	+2.9%	14%
MC	0.939 ± 0.023	52%	0.962 ± 0.023 ^a	43%	0.966 ± 0.022 [#]	+2.9%	43%
FR	0.970 ± 0.026	39%	0.951 ± 0.026 ^a	39%	0.955 ± 0.025	-1.5%	39%
FC	1.024 ± 0.027	22%	1.016 ± 0.026 ^c	25%	1.016 ± 0.026 ^c	-0.8%	17%
Lateral spine							
MR	0.783 ± 0.025	NA	0.793 ± 0.026	NA	0.817 ± 0.024 ^{b,+,#}	+4.3%	NA
MC	0.758 ± 0.019	NA	0.766 ± 0.020	NA	0.774 ± 0.019	+2.1%	NA
FR	0.736 ± 0.022	NA	0.726 ± 0.023	NA	0.723 ± 0.022	-1.8%	NA
FC	0.785 ± 0.023 ^c	NA	0.776 ± 0.024 ^c	NA	0.764 ± 0.023 [#]	-2.7%	NA
Femoral neck							
MR	0.944 ± 0.039 ^a	0%	0.938 ± 0.037 ^a	0%	0.942 ± 0.036	-0.2%	0%
MC	0.865 ± 0.031	35%	0.865 ± 0.030	26%	0.873 ± 0.029	+0.9%	23%
FR	0.930 ± 0.035	18%	0.924 ± 0.033	25%	0.919 ± 0.032	-1.2%	38%
FC	0.914 ± 0.036	9%	0.911 ± 0.034	4%	0.904 ± 0.033	-1.1%	4%
Total hip							
MR	1.065 ± 0.037 ^a	0%	1.076 ± 0.037 ^a	0%	1.089 ± 0.035 ^{a,+,#}	+2.3%	0%
MC	0.965 ± 0.029	24%	0.966 ± 0.029	26%	0.975 ± 0.028	+1.0%	18%
FR	1.057 ± 0.033	18%	1.051 ± 0.033	17%	1.037 ± 0.032 ^{+,#}	-1.9%	38%
FC	1.033 ± 0.034	0%	1.020 ± 0.034 ^a	4%	1.012 ± 0.032 [#]	-2.0%	0%
Whole body							
MR	1.134 ± 0.026 ^a	0%	1.117 ± 0.026 ^{a,*}	14%	1.130 ± 0.026 ^{b,+}	-0.4%	0%
MC	1.046 ± 0.021	43%	1.052 ± 0.021	43%	1.066 ± 0.021 ^{+,#}	+1.9%	43%
FR	1.102 ± 0.024	28%	1.091 ± 0.023	39%	1.083 ± 0.023 [#]	-1.7%	28%
FC	1.082 ± 0.024	42%	1.075 ± 0.024	42%	1.074 ± 0.024	-0.7%	42%

Means ± SE, aBMD = areal bone mineral density, PA = posterior-anterior, MR = male runners; FR = female runners; MC = male controls; FC = female controls, NA = not available.

^a MR vs MC ($p < 0.05$).

^b MR vs FR ($p = 0.018$).

^c FR vs FC ($p < 0.049$).

* Visit 1 vs visit 2 ($p < 0.047$).

+ Visit 2 vs visit 3 ($p < 0.014$).

visit 1 vs visit 3 ($p < 0.002$).

Significance was set to an alpha level of 0.05 for all tests.

3. Results

3.1. Baseline comparisons

Males were taller and heavier than females but of similar age, BMI, and vitamin D intake (Table 1). Male runners had 6.7% greater BFLM than male controls and 37.8% greater BFLM than female runners. Questionnaire results confirmed the athletes to have greater current physical activity levels. Although the runners showed 41–51% greater history of bone-loading physical activity when they enrolled in the study, the BPAQ values were not significantly different between groups. The female controls displayed about 2 more years since menarche than the female runners ($p < 0.05$). At baseline, male runners had significantly higher aBMD compared with male controls by 8.3% at the FN, 10.4% at the TH, and 8.4% at the WB (Table 2). In contrast, there were no significant differences in aBMD between female runners and female controls at baseline, except at the lateral spine where controls showed significantly greater aBMD than runners by 6.7%. Hip structure was similar across groups at baseline for all three variables of the NN (Table 3).

3.2. Longitudinal changes

Across the year, male runners maintained approximately 10% greater aBMD at the TH and about 8% greater aBMD at the WB than the male controls (Table 2). As displayed in Fig. 1, over the 12-month study, male runners showed significant improvements in nearly all the measures of bone health at the hip, except the FN. These increases led male

Table 3
Adjusted hip structure variables in male and female distance runners with non-athletic controls.

Bone site	Visit 1	Visit 2	Visit 3	% Change from visit 1 to 3
NN CSA[@] (cm²)				
MR	3.618 ± 0.139	3.602 ± 0.134	3.675 ± 0.122 ^{a,b,+}	+1.6%
MC	3.385 ± 0.110	3.372 ± 0.106	3.362 ± 0.097	-0.7%
FR	3.341 ± 0.124	3.303 ± 0.120	3.284 ± 0.110	-1.7%
FC	3.399 ± 0.127	3.382 ± 0.122	3.349 ± 0.112	-1.5%
NN CSMI[†] (cm⁴)				
MR	3.271 ± 0.251	3.324 ± 0.200 ^b	3.467 ± 0.024 ^{d,+}	+6.0%
MC	3.090 ± 0.199	3.117 ± 0.159	3.023 ± 0.168	-2.2%
FR	2.613 ± 0.224	2.521 ± 0.179	2.473 ± 0.189	-5.6%
FC	2.892 ± 0.230	2.735 ± 0.183	2.753 ± 0.194	-4.8%
NN Z[‡] (cm³)				
MR	1.80 ± 0.10	1.81 ± 0.08 ^b	1.87 ± 0.08 ^{a,b,+}	+3.9%
MC	1.69 ± 0.08	1.72 ± 0.07	1.69 ± 0.07	0.0%
FR	1.54 ± 0.08	1.49 ± 0.08	1.47 ± 0.07	-4.5%
FC	1.65 ± 0.09	1.59 ± 0.08	1.61 ± 0.08	-2.4%

Means ± SE, NN = narrow neck, CSA = cross-sectional area, CSMI = cross-sectional moment of inertia, Z = z-section modulus bending strength, MR = male runners; MC = male controls; FR = female runners; FC = female controls.

[@] Adjusted for bone-free lean mass.

[†] Adjusted for bone-free lean mass and vitamin D intake.

^a MR vs MC, ($p < 0.05$).

^b MR vs FR, ($p = 0.05$)

^d MR vs all other groups ($p \leq 0.05$).

⁺ Visit 2 vs visit 3 ($p \leq 0.05$).

runners to exhibit significantly greater CSA, CSMI, and Z than male controls at visit 3 (Table 3). Changes over time for male runners also led to significantly greater CSMI ($p < 0.05$) than all other groups at visit 3. As seen in Fig. 2, male runners also showed significant increases in aBMD at the PA spine (2.9%) and lateral spine (4.3%), while male controls significantly increased at the PA spine (2.9%) and WB (1.9%).

At the end of the year, female controls had approximately 6% greater aBMD at the PA spine compared with the female runners (Table 2). Female runners and controls showed significant declines in aBMD of the TH by 1.9% and 2.0%, respectively (Fig. 1). None of the groups displayed a statistically significant change in aBMD of the FN during the year of study. Female runners and controls did not experience any significant longitudinal changes in hip structure. Female controls declined significantly in aBMD at the lateral spine by 2.7% while female runners lost 1.8% of aBMD of the WB (Fig. 2).

During the year of study, three male runners (14.2%) sustained one bone stress injury, three female runners (22.2%) sustained one bone stress injury, and one female runner sustained two bone stress injuries for a total of eight bone injuries among seven athletes. All the bone injuries recorded during the study were at primarily cortical bone sites; six at tibia and two at fourth metatarsal. Of the three male runners who sustained a stress injury, none had reported a previous stress injury and the one female runner who had two previous stress injuries had another stress injury during the study period. Amid the 4 female runners who sustained a stress injury during the study, two were taking oral contraceptives, one was eumenorrheic and one was oligomenorrheic. None of the control participants reported bone stress injuries during the year of study.

3.3. Sex differences between runners

When controlling for BFLM, the only significant difference in aBMD between the male runners and female runners was at visit three for the lateral spine, with the male runners showing 13.0% higher aBMD than the female runners. During the study, male runners increased aBMD by 2.2–4.3% at the PA spine, lateral spine, and TH while female runners declined 1.8–1.9% at the TH and WB. Male runners demonstrated 2.0–4.3% improvement in hip structure during one year of distance running while female runners exhibited no significant changes. The geometrical changes in hip structure for male runners led to significantly greater CSA, CSMI, and Z than female runners at visit 3.

4. Discussion

The results of this investigation reveal that at baseline only male runners had significantly greater aBMD at the FN, TH, and WB than male controls but no advantages in hip structure. Contrary to our hypothesis, the female controls in this study displayed greater aBMD at the spine than female runners but were similar at other sites and in hip structure. Additionally, we report that males between the ages of 18–23 continued to accrue bone at various sites and improve hip geometry which may be influenced by weight-bearing activity. Specifically, non-athletic males in this study, demonstrated significant improvements in aBMD of the PA spine and WB while the male runners showed bone accrual at the PA spine, lateral spine, and TH as well as significant improvements in hip structure. For the most part, females in this study declined in bone health over the year which reached significant levels at some sites, like the TH for female runners and controls, lateral spine for controls, and whole body for runners. Male athletes seemed to experience skeletal benefits due to training as we hypothesized, however female athletes did not.

4.1. Baseline comparisons

Our findings are similar to other cross-sectional studies reporting higher aBMD in male runners in comparison to non-athletic controls

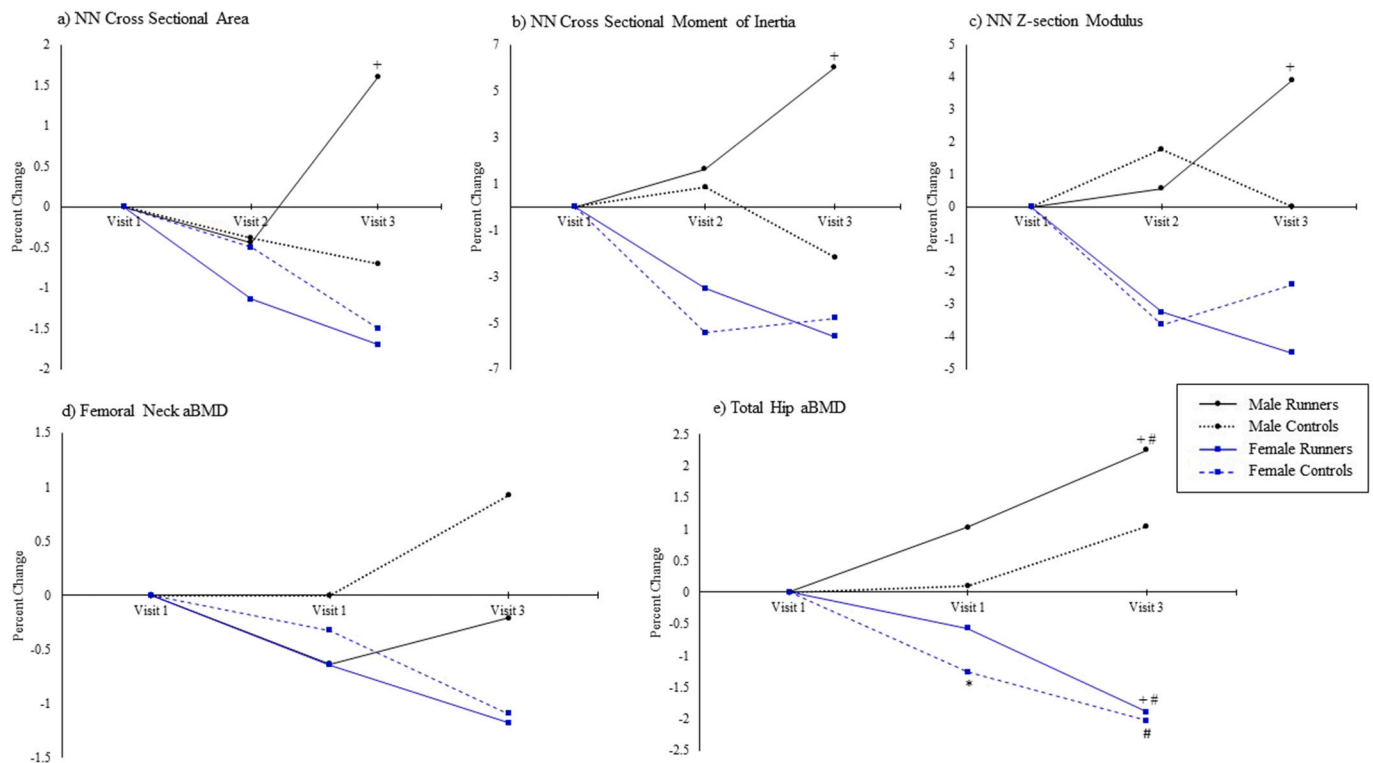


Fig. 1. Percent change in bone health at the hip from baseline (visit 1) to about 4–6 months (visit 2) and 12 months (visit 3) in male and female runners and non-athletic controls. NN = narrow neck, aBMD = areal bone mineral density, *visit 1 vs visit 2 ($p < 0.047$), +visit 2 vs visit 3 ($p < 0.014$), #visit 1 vs visit 3 ($p < 0.002$).

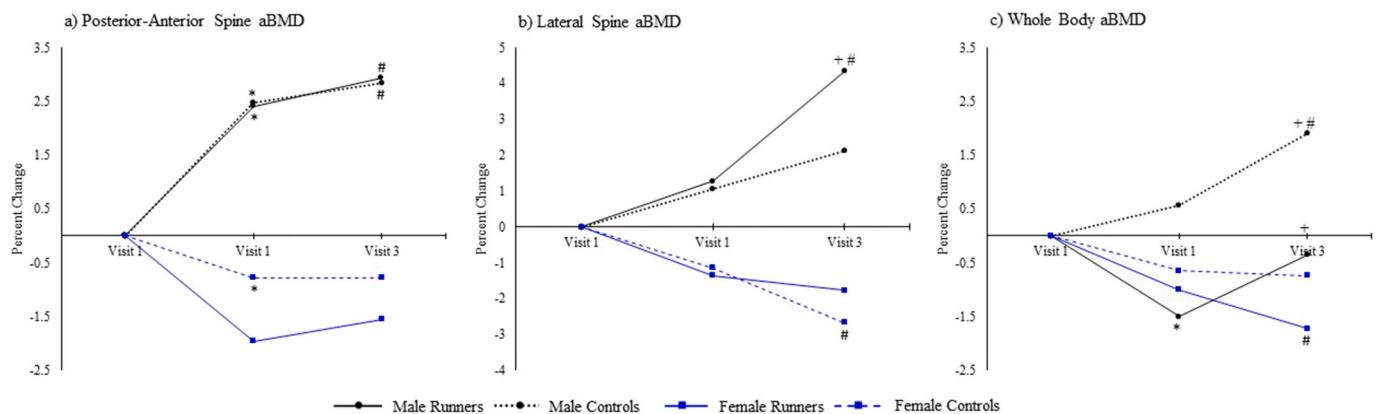


Fig. 2. Percent change in areal bone mineral density (aBMD) from baseline (visit 1) to about 4–6 months (visit 2) and 12 months (visit 3) in male and female runners and non-athletic controls. *visit 1 vs visit 2 ($p < 0.047$), +visit 2 vs visit 3 ($p < 0.014$), #visit 1 vs visit 3 ($p < 0.002$).

(Tam et al., 2018; McCormack et al., 2019; Kemmler et al., 2006). As with previous research (Fredericson et al., 2007), we also report advantages in aBMD at bone sites loaded during running like the FN, TH, and WB but not at relatively unloaded sites, such as the PA or lateral spine (Hind et al., 2006). The significantly greater aBMD in the male runners at the TH and WB over the male controls are likely the result of impact forces achieved through running (Kohrt et al., 2004; Bennell et al., 1997).

Few studies have investigated the hip structure of college-age populations. The focus of previous research is predominantly adolescent, pubescent, and post-menopausal women (Barrack et al., 2008; Devlin et al., 2010; McNamara and Gunter, 2012). The homogenous age and BMI of participants in this study allows for better understanding of bone health pertaining to young adults. Although they did not specifically study distance runners, Nikander et al. reported advantages in hip

structure of the narrow neck for female weight-bearing athletes in comparison to controls (Nikander et al., 2005), suggesting perhaps women of this age need greater impact loads than running to develop superior hip structure. In two studies investigating hip structure, Hind et al. (Hind et al., 2012a; Hind et al., 2012b) reported greater CSA, CSMI, and Z in male athletes over controls of slightly greater age than our participants. Their findings for men resemble the data presented in this paper, as our male runners were found to have significantly greater hip geometry compared to the non-athletic controls which could be attributed to the weight-bearing nature of running (Table 3).

CSA has been shown to be greater in eumenorrheic than amenorrheic athletes (Ackerman et al., 2013) while CSA and CSMI are shown to be lower in females with irregular menstruation (Mallinson et al., 2016). In a longitudinal investigation of young females from ages 12 to 22, Devlin et al. 2010 concluded that hormones like estrogen have a

profound effect on bone structure in young adults and may influence the osteogenic effects of weight-bearing exercise (Devlin et al., 2010). In our study, a subset analysis via independent *t*-test showed that all the females with normal menstruation ($n = 16$) had greater aBMD and hip structure measures than the females with amenorrhea or oligomenorrhea ($n = 6$), though these differences were not statistically significant. In Nattiv et al.'s study of bone stress in collegiate track and field athletes, skeletal injuries sustained by athletes with amenorrhea and oligomenorrhea were more severe in MRI grading and took longer to heal than athletes with eumenorrheic menstruation (Nattiv et al., 2013). Interpretation of the influence of menstrual regularity on development of hip structure is complicated by the common use of hormonal contraceptives. Future research assessing estrogen levels throughout the menstrual cycle and among contraceptive users should be carried out to help better understand the extent of this potential influence on femur geometry.

Table 1 displays z-scores at each bone site for all the participants in which normative values are available. Similar to the results of Pollock et al. (2010) who reported 34% of the women in their study had low aBMD at the PA spine (as measured by z-scores), the present study showed 38.9% of the female runners with low aBMD at the PA spine (z-scores < -1.0). Surprisingly, a greater percent of female athletes had a z-score < -1.0 at the TH and FN when compared with the female non-athletes, although the Chi Square analysis did not show statistical differences in this proportion. It might be expected that the impact of running would lead to greater aBMD than normal at the hip for the female runners.

4.2. Longitudinal changes and sex differences

While some research reports that mechanical loading due to running may not be enough to elicit bone accrual or elicit structural changes (Barrack et al., 2017; Fredericson et al., 2007; Tenforde et al., 2015; Tenforde et al., 2018), we report skeletal gains among male athletes and not females. The positive increases in aBMD for all males in this study could indicate that males of this age may be accumulating bone mass while only male athletes in weight-bearing sports experience improvements in hip structure and aBMD of the hip. Additionally, at visit three, there were significantly fewer male runners with z-scores < -1.0 at the WB than all other groups. This is similar to the results reported by Bennell et al. (1997) on male collegiate distance runners of comparable age showing increases in aBMD at the lumbar spine (0.9%) and femur (0.7%) (Bennell et al., 1997). Over the year, both female runners and controls decreased in aBMD at all five sites investigated, some of which reached a level of statistically significant loss. Our results in female collegiate distance runners are similar to previous studies showing a decrease in aBMD over 6–8 months (Taaffe et al., 1997; Bemben et al., 2004). Taaffe and colleagues reported decreases in aBMD at the lumbar spine of 0.3% and 1.3% decrease at the FN. In addition, the pilot work of Pollock et al. also showed a concerning decline in aBMD of the spine and forearm in elite female distance runners (Pollock et al., 2010). This contrasts with the work of Bennell et al. (1997) who reported increases in aBMD of female collegiate distance runners at the lumbar spine (+1.7%) and femur (+1.4%) (Bennell et al., 1997). Similarly, Gremion and colleagues reported a maintenance of aBMD in the peripheral skeleton over a one-year timeframe in competitive female distance runners (Gremion et al., 2001).

A leveling of bone accrual may be expected for females at the mean age of 19 years who likely achieved peak bone mass (Bailey et al., 1999), but a significant decline is concerning. The differences in the change of aBMD between male and female athletes could be accounted for by age and timing of peak bone accrual. The female runners likely already achieved peak bone mass while the male runners may still be accumulating bone as research shows that peak bone mass likely occurs approximately 2 years later for males, compared to females (Baxter-Jones et al., 2011). The male and female runners reported similar exercise intensity and duration (Table 1), suggesting that factors other

than exercise training are responsible for the improvements solely among males.

We report a significant decrease in aBMD of the TH and WB in female runners, however these changes did not produce significant differences between female runners or controls at the end of the study. Several factors could help explain the decline in aBMD in the female runners including low EA, poor nutrient intake, and menstrual dysfunction which may all impact bone density. There were no significant differences in calcium intake, vitamin D consumption, or EA between the groups in this study. In fact, there were fewer female runners with EA < 30 kcal·kgBFLM⁻¹ compared to the male runners, although these proportional differences were not significant. Over the past three decades, EA has emerged as a possible factor influencing bone health in distance runners (Mountjoy et al., 2018; McCormack et al., 2019; Burke et al., 2018). In this population as a whole, EA, as a continuous variable, was not correlated to aBMD or hip geometry, however, when examining only the 16 female runners for which data was available, significant relationships between EA and aBMD were observed at the FN ($r = 0.518$ – 0.566 , $p < 0.05$) and WB ($r = 0.535$ – 0.594 , $p < 0.05$) for all three visits. A relationship between EA and bone health was not observed for males or female controls.

Hind et al. (Hind et al., 2012a) found that running was of skeletal benefit for adult male athletes in comparison to swimmers and controls. Hormone levels may explain the lack of improvement in hip structure for female athletes in our study, despite the exercise (Devlin et al., 2010; De Souza et al., 2008; Misra, 2012). Androgens are known to stimulate periosteal bone expansion, while estrogen is known to prevent periosteal bone formation, yet preserve trabecular and endocortical bone (Turner, 2003). In this way, typical estrogen levels among women could play a considerable role in bone geometry. CSMI and CSA have been shown to be greater in adult female athletes than non-athletes (Hind et al., 2012b), however there was no significant difference in hip structure between female runners and controls in this study. Nor was there significant change in CSMI of either female group within the year reported here. CSMI is a measurement of periosteal apposition and since Z is influenced by CSMI, changes in CSMI may be inhibited by low estrogen levels in the female runners. As suggested earlier in this paper, perhaps activities with higher impact than running, or with atypical loading directions, are necessary to induce skeletal benefits for women of this age (Nikander et al., 2005).

Comparisons to other research investigating longitudinal changes in hip structure is difficult because there is a lack of longitudinal studies and of those previously published, the age and hormonal status of our populations differs drastically. One study that may be comparable to the present investigation reported approximately 1% increase in CSA and 3% increase in Z of the NN for female non-athletes between the ages of 17–22 (Petit et al., 2004). These researchers identified lean mass and participation in sports as significant predictors of adult hip structure (Petit et al., 2004). The data presented in this paper shows that significant change in hip geometry can occur in college-age males who exercise, urging further research of this population to better understand the potential for enhancing bone structure during young-adult years and potentially reducing risk for fracture in later years. We may be the first to report an improvement in hip geometry at the NN during one year of training of male runners while simultaneously measuring no significant change in aBMD of the FN. This finding supports the importance of evaluating hip geometry in addition to aBMD measures for a more holistic assessment of bone health and strength (Fonseca et al., 2014).

In examining the bone stress injuries that occurred during the yearlong study, half occurred during the fall cross-country season and half in the spring track season. All these injuries occurred at bone sites which are primarily composed of cortical bone (six at the tibia, and two at the fourth metatarsal). Previous research indicates that bone stress injuries at predominantly cortical sites, such as the tibia and metatarsal, are not related to low bone mass but rather may be due to overuse or highly repetitive impact loading (Tenforde et al., 2018; Tenforde et al.,

2017; Marx et al., 2001). In this group of female distance runners, it is challenging to judge whether menstrual function was a contributor to bone injuries, with only four injuries over the year and two of those by women on oral contraceptives. Similar calcium, vitamin D, and EA in the male and female distance runners, and the diversity in menstrual/hormonal status, suggests that the injuries at cortical bone sites may be due to training rather than diet or menstrual function.

4.3. Strengths and weaknesses

A strength of this paper is the simultaneous and comprehensive evaluation of bone health by examination of aBMD at multiple bone sites as well as hip structure. Further, the longitudinal consideration of changes in bone health is rarely reported in the literature for emerging adults, especially among males and females. As such, this comprehensive evaluation presents an issue with multiple statistical comparisons. To account for this weakness, the Bonferroni correction was used to address concerns over multiple comparisons. While it is a strength to evaluate longitudinal changes over time, the 6- and 12-month evaluations performed in this study may be too short to make conclusions about lifetime health implications. The bone remodeling cycle requires about 3 months (Kohrt et al., 2004), accordingly it calls to question the meaning of 6- and 12-months results derived via DXA with a CV for aBMD of <1.5% and HSA of <2.4%. Future studies investigating hip structure and aBMD in athletes should be of longer duration.

The data presented here is robust in its reduction of outlying variables by comparing the distance runners to non-athletes with a similar BMI and age, but significantly different exercise patterns. This tightly controlled methodology diminishes the influence of body mass on the hip geometry and maximizes the ability to observe the influence of moderate-impact exercise. Additionally, this study is strengthened by the presentation of longitudinal change by measuring aBMD and hip geometry at three times over the course of one year.

Since vitamin D intake was significantly correlated with CSMI and Z, further investigation into the influence of vitamin D on hip structure should be carried out. Research shows that blood levels of vitamin D are influenced by age, sex, cultural behavior, genetics, latitude, season, outdoor activities, and dietary intake of the nutrient (Mithal et al., 2009). Considering that more than 85% of participants were not meeting the RDA for vitamin D intake (800 IU/day), measuring serum levels of vitamin D in all participants would strengthen understanding of the possible influence of this nutrient and hormone on bone structure. Additionally, assessment of estrogen and androgen hormones would be helpful in exploring potential mechanisms of the findings reported here. We have used valid and reliable methods to measure dietary intake (Block and Subar, 1992) and quantify EA (Beermann et al., 2020), however experts agree that these variables are difficult to measure accurately (Burke et al., 2018).

5. Conclusion

It appears that collegiate male distance runners continue to accrue bone early in their third decade of life and that running may be beneficial to skeletal health in this population. However, the lumbar spine may be an area of concern for female distance runners. The population of collegiate female distance runners in this investigation, as a group, declined in aBMD at all five bone sites. Further research is needed on potential influences of weight-bearing activity, energy availability, and hormonal status on longitudinal changes in aBMD and hip structure in males and females. Hip structure did not change significantly for female distance runners and male or female controls over 12 months. In concurrence with the aBMD findings, collegiate male distance runners significantly increased in CSA, CSMI, and Z over the course of one year. Interestingly, male runners displayed no change in aBMD at the FN while demonstrating a significant increase in hip structure of the NN. This finding emphasizes the importance of measuring both bone mass

and bone geometry to better understand skeletal health and risk of fracture. Distance running may be more advantageous for the bone accrual and hip structure in college-age males than females.

Funding

This research was funded by the National Institute of Alcohol Abuse and Alcoholism at the National Institutes of Health with Grant number R21AA022942. Support was also provided by the Frank R. Seaver College of Science and Engineering, the Bellarmine College of Liberal Arts, and the Rains Research Assistance program at Loyola Marymount University.

CRedit authorship contribution statement

Nicole Infantino: Formal analysis, Writing – original draft, Writing – review & editing. **William P. McCormack:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration. **Hawley C. Almstedt:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

All of the authors of this manuscript report no conflict of interest.

Acknowledgements

We are very grateful to the research participants, Scott Guerrero, Caitlin Jennings, Joseph W. LaBrie, Todd Shoepe, Liam Shorrock, and Jason Zarb-Cousin for their role in the success of this research project. We also acknowledge contributions from student research assistants involved with the data analysis and data management including Lily Bramble, Makenzie Cook, and Rowena Feng. We acknowledge Sarah Boyle, Andrew Earle, Nicole Froidevaux, and Danielle Good for their valuable contributions to this project. We also appreciate the many people who worked as part of the data collection team including Olivia Abdo, Sienna Baldwin, Kate Collins, Kelsey Crispeno, Christa Demos, Zoe Daily, Isabella Kuroyama, Stephanie Lee, Haley Loeffler, Allison Leggett, Kyna Lin, Diana Martinez, Sydnie Maltz, Grant Mello, Savannah Mersola, Nhandi Scott, Fiona Shorrock, Alejandra Silva, Daniel Smith, and Lauren Sutherland.

References

- Ackerman, K.E., Pierce, L., Guereca, G., Slaterry, M., Lee, H., Goldstein, M., Misra, M., 2013. Hip structural analysis in adolescent and young adult oligoamenorrheic and eumenorrheic athletes and nonathletes. *J. Clin. Endocrinol. Metab.* 98 (4), 1742–1749.
- Ainsworth, B.E., Haskell, W.L., Herrmann, S.D., Meckes, N., Bassett Jr., D.R., Tudor-Locke, C., Greer, J.L., Vezina, J., Whitt-Glover, M.C., Leon, A.S., 2011. 2011 compendium of physical activities: a second update of codes and MET values. *Med. Sci. Sports Exerc.* 43 (8), 1575–1581.
- Alwis, G., Linden, C., Stenevi-Lundgren, S., Ahlberg, H.G., Besjakov, J., Gardsell, P., Karlsson, M.K., 2008. A one-year exercise intervention program in pre-pubertal girls does not influence hip structure. *BMC Musculoskelet. Disord.* 9, 9.
- Bailey, D.A., McKay, H.A., Mirwald, R.L., Crocker, P.R., Faulkner, R.A., 1999. A six-year longitudinal study of the relationship of physical activity to bone mineral accrual in growing children: the university of Saskatchewan bone mineral accrual study. *J. Bone Miner. Res.* 14 (10), 1672–1679.
- Barrack, M.T., Rauh, M.J., Barkai, H.-S., Nichols, J.F., 2008. Dietary restraint and low bone mass in female adolescent endurance runners. *Am. J. Clin. Nutr.* 87 (1), 36–43.
- Barrack, M.T., Fredericson, M., Tenforde, A.S., Nattiv, A., 2017. Evidence of a cumulative effect for risk factors predicting low bone mass among male adolescent athletes. *Br. J. Sports Med.* 51 (3), 200–205.
- Baxter-Jones, A.D., Faulkner, R.A., Forwood, M.R., Mirwald, R.L., Bailey, D.A., 2011. Bone mineral accrual from 8 to 30 years of age: an estimation of peak bone mass. *J. Bone Miner. Res.* 26 (8), 1729–1739.
- Beck, T.J., Broy, S.B., 2015. Measurement of hip geometry—technical background. *J. Clin. Densitom.* 18 (3), 331–337.

- Beermann, B.L., Lee, D.G., Almstedt, H.C., McCormack, W.P., 2020. Nutritional intake and energy availability of collegiate distance runners. *J. Am. Coll. Nutr.* 1–9.
- Bemben, D.A., Buchanan, T.D., Bemben, M.G., Knehan, A.W., 2004. Influence of type of mechanical loading, menstrual status, and training season on bone density in young women athletes. *J. Strength Cond Res* 18 (2), 220–226.
- Bennell, K.L., Malcolm, S.A., Khan, K.M., Thomas, S.A., Reid, S.J., Brukner, P.D., Ebeling, P.R., Wark, J.D., 1997. Bone mass and bone turnover in power athletes, endurance athletes, and controls: a 12-month longitudinal study. *Bone* 20 (5), 477–484.
- Block, G., Subar, A.F., 1992. Estimates of nutrient intake from a food frequency questionnaire: the 1987 National Health Interview Survey. *J. Am. Diet. Assoc.* 92 (8), 969–977.
- Burge, R., Dawson-Hughes, B., Solomon, D.H., Wong, J.B., King, A., Tosteson, A., 2007. Incidence and economic burden of osteoporosis-related fractures in the United States, 2005–2025. *J. Bone Miner. Res.* 22 (3), 465–475.
- Burke, L.M., Close, G.L., Lundy, B., Mooses, M., Morton, J.P., Tenforde, A.S., 2018. Relative energy deficiency in sport in male athletes: a commentary on its presentation among selected groups of male athletes. *Int. J. Sport Nutr. Exerc. Metab.* 28 (4), 364–374.
- Cunningham, J.J., 1991. Body composition as a determinant of energy expenditure: a synthetic review and a proposed general prediction equation. *Am. J. Clin. Nutr.* 54 (6), 963–969.
- De Souza, M.J., West, S.L., Jamal, S.A., Hawker, G.A., Gundberg, C.M., Williams, N.L., 2008. The presence of both an energy deficiency and estrogen deficiency exacerbate alterations of bone metabolism in exercising women. *Bone* 43 (1), 140–148.
- Dengel, D.R., Keller, K.A., Stanforth, P.R., Oliver, J.M., Carbhun, A., Bosch, T.A., 2019. Body composition and bone mineral density of division I collegiate track and field athletes, a consortium of college athlete research (C-CAR) study. *J. Clin. Densitom.* 23 (2), 303–313.
- Devlin, M.J., Stetter, C.M., Lin, H.M., Beck, T.J., Legro, R.S., Petit, M.A., Lieberman, D.E., Lloyd, T., 2010. Peripubertal estrogen levels and physical activity affect femur geometry in young adult women. *Osteoporos. Int.* 21 (4), 609–617.
- Faulkner, R.A., Forwood, M.R., Beck, T.J., Mafukidze, J.C., Russell, K., Wallace, W., 2003. Strength indices of the proximal femur and shaft in prepubertal female gymnasts. *Med. Sci. Sports Exerc.* 35 (3), 513–518.
- Fonseca, H., Moreira-Goncalves, D., Coriolano, H.J., Duarte, J.A., 2014. Bone quality: the determinants of bone strength and fragility. *Sports Med.* 44 (1), 37–53.
- Fredericson, M., Chew, K., Ngo, J., Cleek, T., Kiratli, J., Cobb, K., 2007. Regional bone mineral density in male athletes: a comparison of soccer players, runners and controls. *Br. J. Sports Med.* 41 (10), 664–668 (discussion 668).
- Gremion, G., Rizzoli, R., Slosman, D., Theintz, G., Bonjour, J.P., 2001. Oligo-amenorrheic long-distance runners may lose more bone in spine than in femur. *Med. Sci. Sports Exerc.* 33 (1), 15–21.
- Gunter, K.B., Almstedt, H.C., Janz, K.F., 2012. Physical activity in childhood may be the key to optimizing lifespan skeletal health. *Exerc. Sport Sci. Rev.* 40 (1), 13–21.
- Hind, K., Truscott, J.G., Evans, J.A., 2006. Low lumbar spine bone mineral density in both male and female endurance runners. *Bone* 39 (4), 880–885.
- Hind, K., Gannon, L., Whatley, E., Cooke, C., Truscott, J., 2012a. Bone cross-sectional geometry in male runners, gymnasts, swimmers and non-athletic controls: a hip-structural analysis study. *Eur. J. Appl. Physiol.* 112 (2), 535–541.
- Hind, K., Gannon, L., Whatley, E., Cooke, C., 2012b. Sexual dimorphism of femoral neck cross-sectional bone geometry in athletes and non-athletes: a hip structural analysis study. *J. Bone Miner. Metab.* 30 (4), 454–460.
- Kaptoge, S., Dalzell, N., Loveridge, N., Beck, T.J., Khaw, K.T., Reeve, J., 2003. Effects of gender, anthropometric variables, and aging on the evolution of hip strength in men and women aged over 65. *Bone* 32 (5), 561–570.
- Kelly, T.L., Wilson, K.E., Heymsfield, S.B., 2009. Dual energy X-ray absorptiometry body composition reference values from NHANES. *PLoS One* 4 (9), e7038.
- Kemmler, W., Engelke, K., Baumann, H., Beeskow, C., von Stengel, S., Weineck, J., Kalender, W.A., 2006. Bone status in elite male runners. *Eur. J. Appl. Physiol.* 96 (1), 78–85.
- Kohrt, W.M., Bloomfield, S.A., Little, K.D., Nelson, M.E., Yingling, V.R.M., 2004. American College of Sports, American College of Sports Medicine Position Stand: physical activity and bone health. *Med. Sci. Sports Exerc.* 36 (11), 1985–1996.
- LaBrie, J.W., Boyle, S., Earle, A., Almstedt, H.C., 2018. Heavy episodic drinking is associated with poorer bone health in adolescent and young adult women. *J. Stud. Alcohol Drugs.* 79 (3), 391–398.
- Loucks, A.B., Kiens, B., Wright, H.H., 2011. Energy availability in athletes. *J. Sports Sci.* 29 (Suppl. 1), S7–15.
- Mallinson, R.J., Williams, N.I., Gibbs, J.C., Koehler, K., Allaway, H.C.M., Southmayd, E., De Souza, M.J., 2016. Current and past menstrual status is an important determinant of femoral neck geometry in exercising women. *Bone* 88, 101–112.
- Marx, R.G., Saint-Phard, D., Callahan, L.R., Chu, J., Hannafin, J.A., 2001. Stress fracture sites related to underlying bone health in athletic females. *Clin. J. Sport Med.* 11 (2), 73–76.
- McCormack, W.P., Shoepe, T.C., LaBrie, J., Almstedt, H.C., 2019. Bone mineral density, energy availability, and dietary restraint in collegiate cross-country runners and non-running controls. *Eur. J. Appl. Physiol.* 119 (8), 1747–1756.
- McNamara, A., Gunter, K., 2012. The influence of participation in better bones and balance on skeletal health: evaluation of a community-based exercise program to reduce fall and fracture risk. *Osteoporos. Int.* 23 (6), 1813–1822.
- Melton III, J.L., Chrischilles, E.A., Cooper, C., Lane, A.W., Riggs, B.L., 1992. Perspective. How many women have osteoporosis? *J. Bone Miner. Res.* 7 (9), 1005–1010.
- Misra, M., 2012. Effects of hypogonadism on bone metabolism in female adolescents and young adults. *Nat Rev Endocrinol* 8 (7), 395–404.
- Mithal, A., Wahl, D.A., Bonjour, J.P., Burckhardt, P., Dawson-Hughes, B., Eisman, J.A., El-Hajj Fuleihan, G., Josse, R.G., Lips, P., Morales-Torres, J., Group, I.O.F.C.o.S.A.N. W., 2009. Global vitamin D status and determinants of hypovitaminosis D. *Osteoporos. Int.* 20 (11), 1807–1820.
- Mountjoy, M., Sundgot-Borgen, J., Burke, L., Carter, S., Constantini, N., Lebrun, C., Meyer, N., Sherman, R., Steffen, K., Budgett, R., Ljungqvist, A., 2014. The IOC consensus statement: beyond the female athlete triad—relative energy deficiency in sport (RED-S). *Br. J. Sports Med.* 48 (7), 491–497.
- Mountjoy, M., Sundgot-Borgen, J., Burke, L., Ackerman, K.E., Blauwet, C., Constantini, N., Lebrun, C., Lundy, B., Melin, A., Meyer, N., Sherman, R., Tenforde, A.S., Torstveit, M.K., Budgett, R., 2018. International Olympic Committee (IOC) consensus statement on relative energy deficiency in sport (RED-S): 2018 update. *Int. J. Sport Nutr. Exerc. Metab.* 28 (4), 316–331.
- Nattiv, A., Loucks, A.B., Manore, M.M., Sanborn, C.F., Sundgot-Borgen, J., Warren, M.P. M., 2007. American College of Sports, American College of Sports Medicine position stand. The female athlete triad. *Med. Sci. Sports Exerc.* 39 (10), 1867–1882.
- Nattiv, A., Kennedy, G., Barrack, M.T., Abdelkerim, A., Goolsby, M.A., Arends, J.C., Seeger, L.L., 2013. Correlation of MRI grading of bone stress injuries with clinical risk factors and return to play: a 5-year prospective study in collegiate track and field athletes. *Am. J. Sports Med.* 41 (8), 1930–1941.
- NIH Consensus Development Panel on Osteoporosis Prevention, Diagnosis, and Therapy, 2001. Osteoporosis prevention, diagnosis, and therapy. *JAMA* 285 (6), 785–795.
- Nikander, R., Sievanen, H., Heinonen, A., Kannus, P., 2005. Femoral neck structure in adult female athletes subjected to different loading modalities. *J. Bone Miner. Res.* 20 (3), 520–528.
- Pereira, M.A., FitzGerald, S.J., Gregg, E.W., Joswiak, M.L., Ryan, W.J., Suminski, R.R., Utter, A.C., Zmuda, J.M., 1997. A collection of physical activity questionnaires for health-related research. *Med. Sci. Sports Exerc.* 29 (6 Suppl), S1–S205.
- Petit, M.A., Beck, T.J., Lin, H.M., Bentley, C., Legro, R.S., Lloyd, T., 2004. Femoral bone structural geometry adapts to mechanical loading and is influenced by sex steroids: the Penn State young women's health study. *Bone* 35 (3), 750–759.
- Pollock, N., Grogan, C., Perry, M., Pedlar, C., Cooke, K., Morrissey, D., Dimitriou, L., 2010. Bone-mineral density and other features of the female athlete triad in elite endurance runners: a longitudinal and cross-sectional observational study. *Int. J. Sport Nutr. Exerc. Metab.* 20 (5), 418–426.
- Ramamurthi, K., Ahmad, O., Engelke, K., Taylor, R.H., Zhu, K., Gustafsson, S., Prince, R. L., Wilson, K.E., 2012. An in vivo comparison of hip structure analysis (HSA) with measurements obtained by QCT. *Osteoporos. Int.* 23 (2), 543–551.
- Snow-Harter, C., Bouxsein, M.L., Lewis, B.T., Carter, D.R., Marcus, R., 1992. Effects of resistance and endurance exercise on bone mineral status of young women: a randomized exercise intervention trial. *J. Bone Miner. Res.* 7 (7), 761–769.
- Taaffe, D.R., Robinson, T.L., Snow, C.M., Marcus, R., 1997. High-impact exercise promotes bone gain in well-trained female athletes. *J. Bone Miner. Res.* 12 (2), 255–260.
- Tam, N., Santos-Concejero, J., Tucker, R., Lamberts, R.P., Micklesfield, L.K., 2018. Bone health in elite Kenyan runners. *J. Sports Sci.* 36 (4), 456–461.
- Tenforde, A.S., Fredericson, M., Sayres, L.C., Cutti, P., Sainani, K.L., 2015. Identifying sex-specific risk factors for low bone mineral density in adolescent runners. *Am. J. Sports Med.* 43 (6), 1494–1504.
- Tenforde, A.S., Carlson, J.L., Chang, A., Sainani, K.L., Shultz, R., Kim, J.H., Cutti, P., Golden, N.H., Fredericson, M., 2017. Association of the female athlete triad risk assessment stratification to the development of bone stress injuries in collegiate athletes. *Am. J. Sports Med.* 45 (2), 302–310.
- Tenforde, A.S., Parziale, A.L., Popp, K.L., Ackerman, K.E., 2018. Low bone mineral density in male athletes is associated with bone stress injuries at anatomic sites with greater trabecular composition. *Am. J. Sports Med.* 46 (1), 30–36.
- Turner, C.H., 2003. Periosteal apposition and fracture risk. *J. Musculoskelet. Neuronal Interact.* 3 (4), 410 (discussion 417).
- van Staa, T.P., Dennison, E.M., Leufkens, H.G., Cooper, C., 2001. Epidemiology of fractures in England and Wales. *Bone* 29 (6), 517–522.
- Weeks, B.K., Beck, B.R., 2008. The BPAQ: a bone-specific physical activity assessment instrument. *Osteoporos. Int.* 19 (11), 1567–1577.