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Estradiol Levels Predict Bone Mineral Density in Male Collegiate Athletes: A Pilot Study

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SUMMARY

Objective—Strenuous training commonly results in amenorrhea, which contributes to bone loss in some female collegiate athletes. However, the impact of athletic training on endocrine function and bone mineral density (BMD) in male collegiate athletes is less well understood. The objective of the study was to investigate the specific endocrine determinants of BMD in male collegiate runners and wrestlers, including the potential impact of gonadal steroid levels.

Design—Cross-sectional study

Patients—26 division I collegiate male athletes (wrestlers, runners, and golfers)

Measurements—Main outcome measures included 1) BMD endpoints measured by dual energy x-ray absorptiometry (DXA); 2) endocrine endpoints: total and free estradiol, total and free testosterone; 3) body composition endpoints: fat-free and fat mass, measured by DXA; and 4) exercise endpoints: maximal oxygen uptake (VO₂ max), number of miles run weekly, and grip strength.

Results—Free and total estradiol levels were important positive determinants of BMD. In contrast, total and free testosterone levels were not significant predictors of BMD at any skeletal site (except for free testosterone at the radius). In addition, fat-free mass, % ideal body weight, total body weight, body mass index (BMI), and hours per week of resistance training were positive predictors of BMD. VO₂ max was a negative predictor of BMD. Mean BMD was higher at all skeletal sites in the wrestlers compared to the runners and a comparison group (golfers).

Conclusions—Our data suggest that estradiol levels, BMI, and resistance training are more important determinants of BMD in male collegiate athletes than testosterone.

Keywords

Estrogen; Testosterone; Bone Density; Wrestlers; Runners

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Introduction

Despite the establishment of a “female athlete triad”, a term first coined in the early 1990s to describe the interrelationship of disordered eating, amenorrhea, and low bone density,(1) a male equivalent, with low testosterone and bone loss, has not been identified. Whether such a syndrome exists in men is unclear. A high prevalence of amenorrhea, bone loss and fractures has been demonstrated in a number of studies of female runners.(2) Although a 2006 report demonstrated low BMD in male endurance runners,(3) frankly low testosterone levels have not been observed in long distance male runners, despite low weight.(4, 5) In addition, although studies have not identified an increased rate of significant, clinical eating disordered behavior in male wrestlers, many wrestlers are known to engage in a number of questionable weight loss techniques involving rapid weight cycling in order to attain target weight for matches in-season.(6, 7) Whether these athletes have reduced BMD is unknown. Wrestlers and runners require different physiques for competitive advantage in their respective sports. Whether endocrine, body composition or training type or intensity and/or duration are significant determinants of bone density in male athletes has not been established.

Studies have demonstrated that estrogens may be at least as important as, if not more important, than androgens for maintenance of skeletal health in men.(8–10) This was demonstrated in a study in which men were randomized to testosterone, estradiol, both gonadal steroids or double placebo after chemical castration with a GnRH agonist and the blocking of estrogen to androgen conversion with an aromatase inhibitor.(11) Estrogens were shown to be necessary for maintenance of normal bone formation and suppression of bone resorption. In addition, extremely low bone mineral density (BMD) has been reported in a man with an estrogen receptor mutation, which blocked the effects of estrogen on the skeleton,(12)and in a population-based, cross-sectional study of 314 men, bioavailable estradiol was the most consistent predictor of volumetric BMD.(13) Insulin-like growth factor 1 (IGF-1) is a nutritionally dependent hormone that is an important determinant of BMD in young people, including women with anorexia nervosa, in whom over-exercise is common and in whom IGF-1 levels are markedly reduced compared to those of healthy women (14–16).

Both weight-bearing endurance training and resistance power training also have been shown to increase BMD in young men.(17, 18) The effect of resistance exercise is relatively site-specific to the working muscles and bones to which they attach. Although weight-bearing aerobic activity has positive BMD effects and some studies have shown a higher BMD in runners (19), resistance exercise has been shown to have a more potent effect on BMD.(18) Thus, we hypothesized that a group of collegiate runners would have a lower mean BMD than that of a group of collegiate wrestlers, and that mechanisms underlying the variation in bone density between the groups would involve estradiol levels (rather than testosterone levels), IGF-1 levels, differences in body composition, and volume of endurance training versus resistance training. We also chose to compare these groups to a less fit group of collegiate athletes, golfers. All three sports involve individual performance and regular group practices, but differ in their sport-specific demands (e.g. endurance versus power versus precision skills). In addition, the comparison group (golfers) did not engage in regular cardiovascular or resistance training.

Methods

Subjects

Nineteen Division I athletes (13 long distance runners, 6 wrestlers, and 7 golfers) were recruited from a local university for this study. Wrestlers were studied during their off-

season in order to minimize short-term weight-cycling effects. All athletes were non-smokers and were included in the study only if they were generally healthy, a member of a Division I athletic team at a local university, and were free from chronic disease. The protocol was approved by the Partners Healthcare Inc. Human Research Committee, the Massachusetts Institute of Technology Institutional Review Board and the Boston University Institutional Review Board. All subjects provided written informed consent before study participation.

Protocol

Study participants attended one outpatient visit, during which a medical history was taken, and a physical examination was performed. Nutritional evaluation by a research bionutritionist was performed, including weight in a gown, height and frame size, and evaluation of calcium and vitamin D intake using a validated food frequency questionnaire (20). Percent ideal body weight (IBW) was calculated using the 1983 Metropolitan Life Tables,(21) which provides weights at each height based on frame size (see Supplementary Table). BMI was calculated. BMD was measured by dual x-ray absorptiometry (DXA) (Hologic, Inc, Waltham, MA) at the posteroanterior (PA) spine, total hip and radius, with a variation of less than 1% for bone,(22) 1.4% for body fat mass and 1.5 % for fat-free mass. (23) Grip strength was measured using a Jamar hydraulic hand dynamometer (Sammons Preston Rolyan, Bolingbrook, IL). A graded treadmill test of aerobic capacity [maximal oxygen uptake (VO_2 max)] was measured by co-investigator G.S. using the modified Åstrand protocol (24) and the ParvoMedics TrueMax 2400 Metabolic Measurement System (Salt Lake City, UT). Determination of maximal effort on the treadmill included two of the three following criteria being met: leveling off of heart rate with increasing exercise intensity, a respiratory exchange ratio equal to or greater than 1.0, and/or a plateau of O_2 uptake.

Serum testosterone was measured by radioimmunoassay (RIA) [Diagnostic Products Corp (DPC), Los Angeles, CA] with a sensitivity of 0.35 nmol/L, and an intra-assay coefficient of variation (CV) of 4.1 – 10.5%. Sex hormone binding globulin (SHBG) was measured by IRMA (DPC), with a sensitivity of 0.5 nmol/L, and an intra-assay CV of 2.8 – 5.3%. Insulin-like growth factor 1 (IGF-1) was measured using an IRMA [Diagnostic Systems Laboratories (DSL), Webster, TX], with a sensitivity of 0.52 nmol/L and intra-assay CV of 3.9 – 7%. Total estradiol was measured using an RIA (DSL), with a sensitivity of 9.2 pmol/L, and an intra-assay CV of 6.5 – 8.9%. Free testosterone and free estradiol were calculated from total testosterone, total estradiol, and SHBG using the laws of mass action. The calculated value for free testosterone has been validated to have a high degree of agreement with the free testosterone concentrations determined by equilibrium dialysis.(25) 25-hydroxy vitamin D was measured using liquid chromatograph/tandem mass spectrometry with a CV of 7.5%.

Statistical Analysis

Statistical analysis was performed using JMP Statistical Discoveries (version 4.0.2, SAS Institute, Inc., Cary, NC). All data were natural log transformed prior to performing statistical comparisons to approximate a normal distribution. Clinical characteristics were compared by Fisher's least significant difference test. Further adjustment for multiple comparisons with the Fisher's least significant difference test was not necessary due to the use of a preliminary test of significance with 3 groups.(26) Univariate regression models were constructed to investigate determinants of BMD, and Pearson coefficients reported. Results after Bonferroni corrections (p values multiplied by 70) are also reported. Multivariate stepwise regression models were constructed to investigate determinants of BMD and determinants of estradiol levels. Fisher's exact testing was performed to compare

the number of study subjects with osteopenia in each group. Statistical significance was defined as $p \leq 0.05$. Data are reported as the mean $\pm$ SEM.

Results

Clinical Characteristics

The clinical characteristics of the study participants can be found in Table 1. Mean age and height were similar among the groups. The wrestlers had a higher mean BMI, lean body mass, and grip strength than the runners and golfers. The wrestlers' mean weight and hours per week of resistance training were higher than the runners'. The runners had a higher mean VO_2 max and reported a higher mean number of hours of cardiovascular exercise per week than the wrestlers and comparison group (golfers) (Table 1). Mean 25-hydroxy vitamin D levels did not differ between the groups (66 ± 5 nmol/L [runners] vs. 74 ± 8 nmol/L [wrestlers] vs. 55 ± 4 nmol/L [golfers]).

BMD

BMD was higher in the wrestlers than the runners and comparison group at all skeletal sites measured. Mean BMD was more than one standard deviation above the mean for age for wrestlers at the PA spine, total hip and femoral neck and below the mean for age (Z-score < 0) for runners and controls at the PA spine and radius (Table 2). Seven of 13 runners and two of the seven golfers had PA spine BMD Z-scores ≤ -1.0 , whereas all wrestlers had above average (> 0) Z-scores ($p=0.083$).

Hormone Levels

Mean hormone levels of each group are shown in Table 3. Mean total and free estradiol levels were significantly lower in the runners than wrestlers. Mean total and free testosterone, IGF-1, and SHBG levels did not differ among the groups. Only one of the runners and none of the wrestlers or golfers had a testosterone level below 8.50 nmol/L, the lower limit of normal for this assay.

Linear regression models demonstrated that free testosterone ($R=0.45$, $p=0.021$) and total fat mass ($R=0.40$, $p=0.042$) were both positive predictors of free estradiol levels. Free testosterone levels and body fat mass were entered into a stepwise regression model, which demonstrated that free testosterone determined 20% of the variability of free estradiol levels, with an additional 8% predicted by body fat mass.

Determinants of Bone Density

Linear regression models (Table 4) demonstrated positive associations between both total and free estradiol and: 1) PA spine BMD, 2) lateral spine BMD; and 3) radius BMD. The only skeletal site for which free testosterone was a significant predictor of BMD was the radius, while total testosterone and IGF-1 were not significant predictors at any sites. Percent IBW, BMI, weight, and fat-free mass were positive predictors of BMD at all sites. Resistance training was a better predictor of BMD than grip strength, with significance at the spine and radius. VO_2 max was a negative predictor of BMD at the PA and lumbar spine. Neither IGF-1, 25-hydroxy vitamin D nor number of hours of week of cardiovascular exercise were predictors of BMD at any site.

Stepwise multivariate regression models were constructed for all skeletal sites. Free estradiol, fat-free mass and VO_2 max were the chosen variables entered into the model, because linear regression modeling determined them to be the strongest predictors of BMD in the following categories, respectively: endocrine, body composition and cardiovascular training. Fat-free mass accounted for 37%, VO_2 max 28%, and free estradiol 5% of the

variability of PA spine BMD. Fat-free mass accounted for 44%, VO_2 max 22%, and free estradiol 6% of the variability of lateral spine BMD. The correlation of free estradiol to lateral spine BMD is shown in figure 1. Fat-free mass accounted for 44% and free estradiol 19% of the variability of radius BMD. Fat-free mass accounted for 24% of the variability of total hip BMD and 26% of the variability of femoral neck BMD.

Discussion

Our data suggest that total and free estradiol, % IBW, and fat-free mass are important positive determinants of BMD, while VO_2 max is an important negative determinant of BMD at the spine in male collegiate athletes. In contrast and contrary to our hypothesis, we could not detect an important role for IGF-1. We demonstrated lower total and free estradiol levels in male long-distance runners compared to wrestlers. These relationships may contribute to the below average spine BMD in long-distance runners and higher-than-average BMD at all skeletal sites measured in the wrestlers studied. Higher estradiol levels in the wrestlers may reflect their higher mean fat mass, as estradiol is synthesized primarily in adipose cells by aromatases in men. This hypothesis is supported by our data demonstrating that fat mass is a predictor of free estradiol levels. Our data are the first to demonstrate that estrogen levels may be a significant determinant of BMD in collegiate athletes. Our findings that free and total estradiol are stronger predictors of BMD than testosterone in male athletes may have important implications and certainly merit further study. This cross-sectional study provides the basis for larger longitudinal studies to investigate whether intensive running training results in diminished bone density over time and whether this effect is mediated, at least in part, by a reduction in estradiol levels.

Although the female athlete triad is established as a prevalent syndrome of bone loss and fractures, mechanistically related to restrictive eating behavior that results in amenorrhea, (1) no such syndrome has been established in their male counterparts. Because female long-distance runners are specifically affected with this syndrome, (2) we chose to study male long-distance runners. We demonstrate lower than average-for-age spine BMD, but not hip BMD in male collegiate long-distance runners. A study of 65 female and 44 male endurance runners, ages 19–50, demonstrated a similar proportion and degree of bone loss in men as in women. (3) In addition, in men, multiple regression models determined that weekly running distance and training years were both negative predictors and, together, best predicted lumbar BMD; number of years of training was the best (negative) predictor of hip BMD. (3) These previously published data are consistent with our data demonstrating VO_2 max as an important negative predictor of BMD in male athletes. We did not find a correlation with hours of cardiovascular exercise per week, and this may be because levels of exertion and fitness could not be interpreted simply from hours of training. The preservation of hip BMD in our runners is likely related to the positive weight-bearing effects of running in moderation on the hip, as has been shown in prior work, where training volume and energy availability have not been analyzed. (27)

The failure of other studies to identify an endocrine predictor of low bone density in male runners may be due to the prior focus of investigators on androgens rather than estrogens. Androgen levels have been shown to be normal or low-normal in studies of male athletes. (4, 28) Of note, one study demonstrated an inverse relationship between androgen levels, all within the normal range, and training volumes of more than 64 km weekly. (5) In the same study, a positive association was reported between training volumes less than 80 km weekly and BMD at the proximal femur, but no association was observed between either testosterone or free testosterone and BMD. (5) This is consistent with our data in which neither total nor free testosterone levels were important determinants of bone density at any site, except for free testosterone's positive relationship with bone density at the radius. Mean

testosterone and free testosterone levels were similar in the runners and wrestlers, despite the difference in mean bone density between the groups, and very few of the athletes were hypogonadal.

The lack of a high prevalence of hypogonadism in male athletes, in contrast to their female counterparts, raises the issue of whether there are sex-specific effects, with less sensitivity of the hypothalamic-pituitary-gonadal (HPG) axis to physical stress in men. However, some studies investigating the differential effects of fasting on the HPG axis have suggested that the male HPG axis may be more sensitive to starvation than that of females.(29–31) Sex-specific effects of exercise on the HPG axis have not been as well characterized. Such studies are often confounded by differences in body fat and/or prevalence of eating disordered behavior in females compared to males, as in a study in which delayed menarche was reported in young elite female gymnasts but normal pubertal development in their male counterparts.(32) Although percent body fat was reduced in both genders, it was more severely reduced in girls than boys, possibly contributing to the more profound effects on the HPG axis in the girls. Body fat may also impact endocrine mechanisms of bone maintenance in males through its central role in the conversion of androgens to estrogens by aromatases. This hypothesis is supported by our data demonstrating both free testosterone and body fat mass to be significant positive predictors of free estradiol levels.

Estrogens have been shown to play a critical role in maintenance of normal BMD in men, (8–10) including a report by Falahati-Nini et al., who administered leuprolide and letrozole to 59 elderly men to reduce testosterone levels and prevent conversion of androgens to estrogens.(11) Study participants were subsequently randomly assigned to receive: 1) estradiol plus placebo patches, 2) testosterone plus placebo patches, 3) testosterone plus estradiol patches or 4) double placebo patches. Serum osteocalcin, a marker of bone formation, decreased in the absence of both testosterone and estradiol, suggesting that both sex steroids were needed to maintain normal osteocalcin levels. However, estradiol, but not testosterone, was necessary to prevent an increase in bone resorption markers. Cross-sectional studies have also demonstrated the importance of estradiol as a determinant of BMD.(13) Moreover, a case report of a 28-year-old man with estrogen resistance caused by a mutation in the estrogen receptor gene demonstrated that without estradiol action, BMD is extremely low and epiphyses closure is delayed extensively.(12)

Limitations of our study include our small sample size. We had sufficient power to detect more significant effects, such as those of estradiol, but we may not have had sufficient power to detect weaker effects of other hormones and determinants on bone that nonetheless may exist, and we cannot rule these out. Another limitation of our study was that we did not include an exhaustive list of potential hormonal and other determinants. Instead, we tested a fairly focused hypothesis that was reasonable to investigate in the available sample size. Thus, we cannot rule out that there may be other important determinants of BMD in male athletes that we did not study, such as PTH or leptin. In fact, bone metabolism is a complex process and important mechanisms, in addition to estrogen's actions, must also be imputed. We did test a fair number of hypotheses in this exploratory study, and it is conceivable that the results are spurious due to multiple comparisons. We do not intend that this is a definitive study. Rather, we believe that it should generate further investigation in this interesting and novel area, focusing on the role of estrogens in skeletal health in male athletes. Another potential limitation of the study was the lack of a totally sedentary control group. However, we purposefully chose the golfing team as a comparison group because its members share a common "college team" environment and exposures with the other two groups in many regards, but are not involved in organized athletic training – either resistance exercise or endurance training. As indicated in Table 1, the golfers engaged in a mean of 1.5 hours of exercise weekly, which is approximately 13 minutes a day. Nevertheless, an

entirely sedentary control group may have added additional interesting information. Finally, as this is a cross-sectional study, causation cannot be established. Prospective studies with frequent sampling, more hormonal markers, a larger cohort of athletes in a variety of sports, detailed training histories, a non-athletic control group and additional bone imaging technology such as quantitative computed tomography, are needed to confirm our findings.

Although weight, in the form of BMI and % IBW, was an important predictor of bone density in athletes, the correlation coefficient for fat-free mass at the PA spine was higher. These findings are consistent with published data in healthy male adolescents and adults, in whom lean body mass and resistance exercise,(33–38) have been established to be important predictors of bone mass.

Our data suggest that endogenous estrogens are more important determinants of BMD than androgens, which were normal in collegiate long-distance runners. VO_2 max and weekly running mileage were important negative predictors of BMD at the spine, likely reflecting a negative effect of high running volume over time. Whether this translates into an elevated risk for fractures is unknown. Percent IBW and fat-free mass were also important predictors of BMD in the athletes studied, reflected in higher BMD at all sites in the wrestlers compared to the runners, and confirming the importance of weight and muscle mass as a determinant of BMD. The exact interactive effects of lean mass, strength training, estradiol, and other mediators of BMD still need to be elucidated. With a better understanding of the interrelationship of fitness, body composition, and the hormonal milieu in male athletes, improved training regimens can be established to optimize both performance and skeletal health.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Free estradiol was strongly associated with lateral spine BMD in all of the athletes combined ($\ln$ lateral spine BMD = $0.27 \times \ln$ free estradiol - 0.34; $R=0.57$, $p=0.002$).

Table 1

Clinical Characteristics

	Runners	Wrestlers	Golfers
Age (yrs)	20.2 ± 0.6	20.7 ± 0.3	19.3 ± 0.6
Height (cm)	179.5 ± 1.7	175.4 ± 1.7	175.7 ± 2.8
Weight (kg)	67.7 ± 1.5	80.1 ± 1.7 [†]	71.9 ± 5.0
BMI (kg/m²)	21.0 ± 0.5 [*]	26.1 ± 0.2 ^{*†}	23.2 ± 1.4
Lean body mass (kg)	58.9 ± 1.2	69.9 ± 1.4 ^{*†}	57.0 ± 3.1
Fat mass (%)	10.6 ± 0.3 [*]	11.4 ± 0.5 [*]	18.4 ± 1.8
Total exercise (hrs/week)	10.9 ± 0.1 [*]	4.6 ± 1.5 [†]	1.5 ± 0.7
Resistance training (hrs/week)	0.4 ± 0.2 [*]	3.6 ± 1.1 [†]	1.2 ± 0.8
Cardiovascular exercise (hrs/week)	10.6 ± 1.1 [*]	0.6 ± 0.2 [†]	0.5 ± 0.3
Grip strength (1/kg)	50.4 ± 1.4	61.2 ± 2.9 ^{*†}	53.2 ± 3.1
VO₂ max (mL/kg)	71.8 ± 1.6 [*]	54.3 ± 2.1 [†]	52.9 ± 1.7

Data indicate mean ± SEM

* p < 0.05, compared to golfers;

[†] p < 0.05, compared to runners

Age, height, body mass index (BMI), lean body mass, percent fat mass, total exercise, resistance training, cardiovascular exercise, grip strength, and maximal oxygen uptake (VO₂ max) are compared between collegiate runners, wrestlers and golfers

Table 2

Bone Density

	Runners	Wrestlers	Golfers
PA spine BMD (g/cm ²)	0.99 ± 0.02	1.26 ± 0.05 ^{*†}	1.02 ± 0.02
PA spine Z-score	-0.8 ± 0.2	1.4 ± 0.4 ^{*†}	-0.6 ± 0.2
Lateral spine BMD(g/cm ²)	0.81 ± 0.02	1.04 ± 0.04 ^{*†}	0.85 ± 0.03
Total hip BMD (g/cm ²)	1.09 ± 0.03	1.29 ± 0.05 ^{*†}	1.08 ± 0.04
Total hip Z-score	0.2 ± 0.3	1.5 ± 0.2 ^{*†}	0.2 ± 0.3
Femoral neck BMD (g/cm ²)	0.98 ± 0.03	1.22 ± 0.05 ^{*†}	0.95 ± 0.03
Femoral neck Z-score	0.1 ± 0.3	1.8 ± 0.2 ^{*†}	0.2 ± 0.3
Radius BMD (g/cm ²)	0.60 ± 0.02	0.73 ± 0.02 ^{*†}	0.61 ± 0.02
Radius Z-score	-0.9 ± 0.2	1.0 ± 0.4 ^{*†}	-0.7 ± 0.1

Data indicate mean ± SEM

* p< 0.05, compared to golfers;

† p < 0.05, compared to runners

Posterior anterior spine bone mass density (BMD), posterior anterior spine Z-scores, lateral spine bone mineral density (BMD), total hip bone mineral density (BMD), total hip Z-scores, femoral neck bone mineral density (BMD), femoral neck Z-scores, radius bone mass density (BMD), and radius Z-scores are compared between collegiate runners, wrestlers and golfers

Table 3

Endocrine Data

	Runners	Wrestlers	Golfers
Total estradiol (pmol/L)	87.0 ± 6.2 (55.4 – 122.2)	110.9 ± 8.8 [†] (84.8 – 139.1)	105.4 ± 5.5 (86.3 – 118.2)
Free estradiol (pmol/L)	1.8 ± 0.1* (0.9 – 2.7)	2.4 ± 0.1 [†] (1.9 – 2.9)	2.3 ± 0.1 (1.7 – 2.6)
Total testosterone (nmol/L)	16.4 ± 1.7 (7.7 – 27.4)	18.0 ± 2.9 (8.6 – 29.3)	21.3 ± 2.8 (11.7 – 31.3)
Free testosterone (pmol/L)	45.8 ± 5.2 (23.3 – 85.4)	56.9 ± 9.0 (20.5 – 80.2)	64.6 ± 8.3 (37.1 – 101.0)
SHBG (nmol/L)	19.2 ± 3.1 (4.7 – 40.5)	14.4 ± 4.2 (4.9 – 30.8)	16.3 ± 3.7 (8.0 – 35.3)
IGF-1 (nmol/L)	60.8 ± 5.6 (36.3 – 101.4)	54.1 ± 0.5 (43.8 – 77.6)	64.1 ± 9.8 (27.8 – 101.7)

Data indicate mean ± SEM or median (IQR).

* p < 0.05, compared to golfers;

[†] p < 0.05, compared to runners

Total estradiol, free estradiol, total testosterone, free testosterone, sex hormone-binding globulin (SHBG), and insulin-like growth factor-1 (IGF-1) are compared between collegiate runners, wrestlers and golfers

Table 4

Regional Bone Determinants

	PA spine BMD		Lateral spine BMD		Radius BMD		Total hip BMD		Femoral Neck BMD	
	R	p	R	p	R	p	R	p	R	p
Total Testosterone (nmol/L)	-0.02	0.929	0.08	0.699	0.37	0.061	-0.09	0.662	-0.08	0.684
Free Testosterone (pmol/L)	0.07	0.739	0.21	0.304	0.47	0.014	-0.04	0.864	-0.05	0.806
Estradiol (pmol/L)	0.41	0.038	0.48	0.012	0.58	0.002	0.19	0.357	0.17	0.402
Free Estradiol (pmol/L)	0.49	0.012	0.57	0.002	0.61	<0.0001*	0.26	0.205	0.21	0.300
Ideal body weight (%)	0.49	0.011	0.72	<0.0001*	0.62	<0.0001*	0.52	0.007	0.43	0.027
BMI (kg/m ²)	0.50	0.010	0.70	<0.0001*	0.63	<0.0001*	0.46	0.019	0.40	0.044
Weight (kg)	0.50	0.010	0.63	<0.0001*	0.52	0.007	0.44	0.023	0.44	0.026
Lean body mass (kg)	0.62	<0.0001*	0.68	<0.0001*	0.61	<0.0001*	0.54	0.004	0.54	0.004
Resistance training (hrs/week)	0.62	0.019	0.59	0.026	0.74	0.002	0.40	0.158	0.44	0.111
Grip strength (1/kg)	0.40	0.059	0.44	0.034	0.43	0.039	0.28	0.197	0.31	0.157
VO ₂ max (mL/kg/min)	-0.61	0.002	us;0.55	0.005	-0.33	0.110	-0.35	0.095	-0.35	0.091

P values ≤ 0.05 are bolded.

*, Significant after Bonferroni adjustment

Total testosterone, free testosterone, estradiol, free estradiol, percent ideal body weight, body mass index (BMI), weight, lean body mass, grip strength, and maximal oxygen uptake (VO₂ max) associations with site-specific bone mineral density (BMD) are shown