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COMPETITIVE ATHLETIC PARTICIPATION, THIGH MUSCLE STRENGTH, AND BONE DENSITY IN ELITE SENIOR ATHLETES AND CONTROLS

Jean L. McCrory^{1,2}, Amanda J. Salacinski^{2,4}, Sarah E. Hunt Sellhorst^{2,5}, and Susan L. Greenspan³

¹Division of Exercise Physiology, Department of Human Performance and Applied Exercise Science, School of Medicine, West Virginia University, Morgantown, WV

²Department of Health and Physical Activity, School of Education

³Department of Medicine, School of Medicine, University of Pittsburgh, Pittsburgh, PA

⁴Department of Kinesiology and Physical Education, School of Education, Northern Illinois University, DeKalb, IL

⁵Department of Exercise Science, University of South Carolina Lancaster, Lancaster, SC

Abstract

The relationship between participation in highly competitive exercise, thigh muscle strength, and regional and total body bone mineral density (BMD) in elite senior athletes and healthy elderly controls was investigated. One hundred and four elite senior athletes (72.6±6.4yrs, 168.7±8.6cm, 72.6±13.5kg, 57M:47F) and 79 healthy controls (75.4±5.6yrs, 170.8±25.5cm, 79.5± 11.7kg, 46M:33F) participated in this cross-sectional study. Vitamin D and calcium intake were assessed via a recall survey. Isometric knee extension and flexion peak torque was measured via a custom strength measurement device. Total body and regional BMD of the hip, radius, and spine were assessed with DXA. For each BMD site assessed, multivariate linear regression analysis was performed in four steps ($\alpha=0.10$) to examine the contribution of (1) age, sex, bodyweight, and calcium and vitamin D intake (2) group (elite senior athlete, control), (3) knee extension peak torque and (4) knee flexion peak torque on BMD. Sex, age, bodyweight, and calcium and vitamin D intake explained a significant amount of variance in BMD in each site. Group was not significant. Knee extension peak torque explained an additional 3.8% of the variance in hip BMD ($p=0.06$). Knee flexion peak torque was not correlated to BMD at any of the sites assessed. In conclusion, participation in highly competitive athletics was not related to total body or regional BMD. Age, sex, bodyweight, and vitamin D and calcium intake were significantly related to BMD at all of the sites assessed. Quadriceps strength contributed slightly to hip BMD. Our results imply that participation in highly competitive senior athletics does not have a protective effect on BMD, perhaps because of a lower bodyweight or other confounding factors.

Corresponding author: Jean L. McCrory, PhD, Division of Exercise Physiology, Department of Human Performance and Applied Exercise Science, West Virginia University, 8315 Health Sciences Center – South, PO Box 9227, Morgantown, WV 26506-9227, Telephone: (304) 293-0442, Fax: (304) 293-7105, ; Email: jlmccrory@hsc.wvu.edu

Laboratory: The University of Pittsburgh Clinical and Translational Research Center

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aged; exercise; isometric exercise; BMD; knee joint torque

INTRODUCTION

Currently, more than 40.2 million individuals over the age of 65 reside in the United States (36). These individuals are at increased risk of sustaining an osteoporotic fracture because of the bone loss that accompanies the aging process (16, 30). Participation in physical activity is advocated for older individuals because of its protective effects on bone mineral density (BMD) (5, 14). Numerous intervention studies have reported positive effects of exercise on BMD (1, 5, 10, 12, 13, 14, 19, 21, 23, 25, 26, 30, 31, 34, 35). Most of these studies have either been on younger individuals or have been short-term exercise interventions in the elderly. At present, the effects of long-term elite highly competitive exercise on BMD in older individuals are unknown.

Bone remodeling increases in response to mechanical stress (28, 30). The mechanical stress associated with exercise is delivered via two methods: the longitudinal loading of the skeleton, such as during weight bearing exercise, and the tensile pull of the muscles on the bone (28). However, the beneficial effects of exercise on BMD may be mitigated by the fact that the greater body mass of heavier individuals has a protective effect against bone loss because of the concomitant increases in longitudinal loading of the skeleton from the larger body mass as well as the greater muscle forces required to move a larger person (2, 3, 14, 29). Previous data confirm that elite highly-competitive elderly athletes have less body mass than do healthy age-matched controls (18).

Muscle strength has been studied as a predictor of BMD (10, 12, 17, 21, 22, 27, 34, 35). Much of the research in this area has been performed on adolescents or young adults (1, 10, 12, 21, 26, 27). Conroy and colleagues reported that muscle strength may explain 30–65% of the variance in BMD in elite young weightlifters (10). Others have reported that the relationship between muscle strength and BMD is stronger among sedentary than active individuals (1, 12, 21, 27). Investigators who have studied elderly individuals also report a positive association between muscle strength and BMD (2, 3, 13, 14, 24, 27, 31, 33, 34, 35, 37), elucidating the importance of exercise for an aging population.

The National Senior Games Association is an American non-profit organization dedicated to motivating older adults to lead healthy lifestyles. The National Senior Games, also known as the “Senior Olympics”, is the largest multi-sport event in the world for senior athletes. All events are divided into five year age categories so that the participants compete against other athletes approximately the same age. Approximately 250,000 individuals participate in the community-level games. The competitors who make it to the National (i.e. American) Senior Games represent the upper 5% of older competitive athletes in the US. The National Senior Olympians comprise a unique study cohort because of their history of success at highly competitive level over a number of years. Study of these senior athletes has the potential to provide more information on the benefits of long-term competitive exercise than what can be learned from short-term exercise interventions. Examining these unique athletes can provide

insight into the effects of long-term highly-intense exercise on the mitigation of the musculoskeletal decline associated with aging.

Various aspects of BMD and muscle strength have been examined previously in this cohort of senior athletes who participated in the current study. Stone and colleagues reported that these senior athletes had lower bodyweight, BMI, and percent body fat as well as greater lean mass compared to a group of healthy controls (32). Additionally, in women, age and weight significantly contributed to BMD, but athlete status (i.e. athlete or control) did not (32). Velez et al. reported significantly greater total body BMD in runners compared to controls, while senior swimmers did not differ from controls (38). Additionally, we reported that these senior athletes have greater knee extension and flexion strength than healthy aged-matched controls (18). Given that total body BMD was greater in these senior runners, and that the senior athletes displayed greater strength of the knee musculature, one may assume that the greater muscle strength is associated with greater BMD. However, the correlation between BMD and strength in these unique highly-competitive athletes has not been established.

The goals of our project were to examine the association between (a) participation in highly competitive exercise and site-specific BMD as well as (b) the relationship between knee extensor and flexor strength and BMD, while controlling for age, bodyweight, sex, and vitamin D and calcium intake, in a cohort of individuals aged 65 or older. We hypothesized that (a) participation in highly competitive athletics would be positively related to total body and regional BMD and (b) maximum knee flexion and extension strength would be predictive of total hip BMD when age, group (i.e. elite athlete or control), bodyweight, sex, and dietary considerations are used as covariates.

METHODS

Experimental Approach to the Problem

The rationale for this study is as follows: given that this group of senior Olympians have demonstrated greater total body BMD than controls and given that the athletes displayed greater strength of the knee musculature, our two primary research objectives were to examine whether (a) participation in highly competitive elite exercise provides a protective effect against bone demineralization associated with aging at four sites in the body and (b) if their greater thigh muscle strength (i.e. knee extensors and flexors) is predictive of BMD in this study cohort. We included known covariates to BMD in our statistical model, namely age, sex, bodyweight, and dietary vitamin D and calcium. We recruited 104 senior athletes from the National Senior Games and 79 healthy community dwelling seniors to participate. Our independent predictor variables include: age, weight, sex, dietary calcium and vitamin D; group (i.e. senior Olympian or control); knee extensor peak torque; and knee flexor peak torque. Our dependent variables included: total body BMD, and BMD at the forearm, lumbar spine, and hip. A stepwise multivariate linear regression analysis was performed to determine the ability of our independent variables to predict BMD. Step 1 examined the ability to age, sex, bodyweight, and dietary calcium and vitamin D to predict BMD at the four sites. Step 2 examined the ability of participation in highly competitive elite exercise to further predict site-specific BMD. Step 3 involved the ability of knee extensor strength to

further predict site-specific BMD. In Step 4, knee extensor strength was removed from the multivariate regression analysis and knee flexor strength was included. This study will provide information for athletes, coaches, and clinicians on whether long-term intense exercise is protective against typical BMD losses that accompany aging, as well as whether knee muscle strength is indicative of site-specific BMD in the elderly.

Subjects

A group of elite senior athletes ($n = 104$) and a control group of healthy community dwelling seniors ($n = 79$) participated in this study. All subjects were aged 65 or older. The subjects in the athletically competitive group were participants of the 2005 National Senior Games (aka the “Senior Olympics”). They competed in one of the following sports: running events longer than 400 m ($n = 44$; 28 males, 16 females), cycling events longer than 5K ($n = 17$; 11 males and 6 females), and any swimming event ($n = 43$; 25 males and 18 females). These events were chosen because data from this study were collected simultaneously with another study, an aim of which was to investigate the magnitude of lower extremity loading (i.e. high, medium, and low impact sports) on bone density (37). All subjects signed an informed consent document approved by the university Institutional Review Board.

Considering the age range of our participants, disease or injury could have been strong confounding factors. Therefore, we recruited as healthy a subject population as possible in both the athlete and control groups. The control group consisted of healthy individuals whose activity levels ranged from very sedentary to active in sports other than running, cycling and swimming (e.g. softball and tennis). However, none of the controls were competitively active in these or any other sports. Subject demographics are provided in Table 1. Controls were significantly older and heavier ($p < 0.05$) than the athletes.

Subjects were excluded from the study if they had a history of any of the following: chronic obstructive pulmonary disease, myocardial infarction, or coronary artery disease; cerebral vascular accident or a history of transient ischemic attacks; rheumatoid arthritis, gout, or osteoarthritis severe enough to limit activity; lower extremity joint replacement, use of a cane or walker; history of osteoporosis or bisphosphonate therapy; current use of antidepressant drugs or any drugs that may interfere with neurological, musculoskeletal, or cognitive function; history of insulin dependent diabetes mellitus, or neurological or rheumatological disorders that might interfere with sensory input; fracture, ligament reconstruction, or sprain within the past 12 months; and any other disease, injury, or disorder that may affect strength.

Procedures

Athletes were recruited from the registration area of the 2005 Summer National Senior Games, which were held in Pittsburgh, PA, USA. Community dwelling healthy control subjects were recruited through the University of Pittsburgh’s Claude D. Pepper Older Americans Independence Center, a federally funded research center focused on keeping elders independently living and functioning. We did not control for the activity level of this group; therefore, their self-reported activity levels ranged from sedentary to active (i.e. exercising more than three days per week for more than one hour per day). However, none

were active in running, cycling, or swimming, and none competed in the Senior Olympics, even at the local level. This group represented healthy but not competitively active individuals.

All subjects completed the same experimental protocol. All procedures were approved by the University of Pittsburgh Institutional Review Board prior to data collection. Each subject participated in one data collection session which lasted for approximately three hours. Data collection occurred at the Clinical and Translational Research Center (CTRC) in the University of Pittsburgh Medical Center Montefiore Hospital.

Because of the strong inverse association between quadriceps strength and morbidity/mortality (33), we assessed the strength of the thigh musculature. All measurements were taken on the subject's left side. Isometric knee extension and flexion torque of the left leg was measured with a tension/compression load cell (Lebow Products Inc., model 3132, Troy, MI, USA). Data were collected at 100 Hz. The load cell was attached to an adjustable bar, which was attached to a metal bar secured to a custom designed aluminum chair. This design allowed for adjustments to be made for height/leg length differences of the subjects. Pilot testing in our laboratory has determined that the output of the chair has an ICC of 0.907 with that of a Biodex dynamometer. This strength assessment device has been used in previously published research (18).

Subjects were placed in a comfortable seated position on the 'strength chair' and secured using canvas straps to minimize extraneous body movements. The hip was positioned in 90° of flexion and the knee was positioned in 45° of flexion. The load cell was attached to the adjustable bar so that the load cell could be positioned just proximal to the malleoli. The distance from the knee to the adjustable bar was recorded in order to calculate torque. Subjects were asked to position their arms either crossed at the chest level or resting on their lap in order to avoid bracing or pulling on the chair.

After gravity effect torque was calculated, subjects performed three repetitions of maximal isometric knee extension or flexion lasting five seconds each. The order in which flexion or extension was tested was counterbalanced to avoid the influence of any learning effect on the data. Thirty seconds of rest was provided between contractions. Similarly, subjects performed three repetitions, each lasting five seconds, of maximal isometric knee flexion or extension. Thirty seconds of rest was again provided between contractions.

Subjects were instructed to continue breathing during the tests and to not hold their breath in order to prevent against doing the Valsalva maneuver during the tests. The subjects were also instructed that they could stop the test at any time. During the test, subjects were instructed to begin and were encouraged to "push" for the extension trials and to "pull" for the flexion trials. The test administrator loudly repeated the word "push" or "pull" each second for a total of five seconds.

Data were analyzed using Matlab 7.1 (Mathworks, Inc., Natick, MA, USA). Raw data were filtered with a fourth order low-pass Butterworth filter with a cutoff frequency of 25 Hz. This was chosen as the cutoff frequency based on the residual analysis described by Winter (40). Torque was calculated as the product of the force in the load cell times the distance

from the knee to the adjustable bar. Peak torque was recorded as the maximum torque value for each trial of knee extension and flexion. The three trials were averaged to yield representative values for each subject. Isometric peak torque has an intraclass correlation coefficient of greater than 0.89 (4).

Bone density measurements were made using a Hologic QDR-4500A (Hologic, Inc., Bedford, MA, USA) dual-energy x-ray absorptiometer (DXA). A licensed DXA technician performed the scans. BMD was obtained for each of the following body regions: total hip, lumbar spine, distal radius, and total body. For the total hip and the forearm, measurements were obtained on the left side only because on the majority of the US population, it is their non-dominant side. In our study, 89 of the athletes declared themselves right leg dominant, three left leg dominant, and remainder stated that they had no preference. Seventy of the controls stated that they were right leg dominant.

Participants completed food frequency questionnaires to evaluate calcium and vitamin D intake in their diet and vitamin supplements (11). These questionnaires were administered orally to each subject by an investigator. Subjects were also asked to complete a physical activity questionnaire to determine lifetime and current physical activity (15). The questionnaire was handed to the subjects and they were instructed to complete it before leaving the testing center. From this questionnaire, we confirmed that the senior athletes had been competitively active for at least 20 years. The activity levels of the healthy controls ranged from sedentary to active, but not competitively active.

Statistical Analysis

After the data were collected, independent t-tests were performed to compare senior athletes with controls on the demographic variables of age, height, and weight ($\alpha = 0.05$). Prior to analysis of the experimental strength and BMD data, an exploratory statistical analysis was conducted to determine whether the statistical assumptions were fulfilled for the planned analysis. Descriptive statistics were obtained on each of the variables.

For each of the four BMD sites assessed, multivariate linear regression analysis was performed in four steps ($\alpha = 0.10$). Because age (yrs), bodyweight (N), sex (M, F), dietary calcium (mg), and dietary Vitamin D (IU) are all known to be related to BMD, these factors were first entered into the model simultaneously as a block to determine their relationship with BMD at the hip, spine, forearm, and total body. Secondly, the variable of group (i.e. elite senior athlete or healthy control) was added and the change in R^2 at each of the BMD sites was noted.

In the third step in the regression analysis, knee extension peak torque (in Nm) was added to the model. The amount of variance explained by this variable (R^2) was noted. Then knee extension peak torque was removed from the model. Finally, knee flexion peak torque (in Nm) was added to the original model to determine the amount of variance explained by that variable. The two strength variables were not entered into the model together because of the high correlation between them ($R = 0.66$). The alpha level was set to 0.10 in order to achieve a statistical power of 80%. Peak torque was analyzed in units of Nm and not normalized to

bodyweight. Bodyweight is known to be positively correlated to BMD (2, 3). Because of this, bodyweight itself was a predictor in the regression model.

Strength data on seven subjects were not included in the analysis because of equipment malfunction. Three subjects (athlete group, 2 male, 1 female) were outliers because of the extreme level of their strength. These subjects were removed from the multivariate regression analysis because very high Mahalanobis distance scores indicated that the subjects were multivariate outliers and would have undue influence on the statistical results of the study.

RESULTS

In the first stage of the regression model, age, sex, bodyweight, dietary calcium and dietary vitamin D were entered as a block. At each of the sites assessed, these factors were highly correlated to BMD ($p < 0.001$, Table 2). The block explained roughly 24%, 53%, 25%, and 34% of the variance in BMD at the hip, radius, spine, and total body, respectively. Group (i.e. elite senior athlete or healthy control) was entered into the statistical model in the second stage of the regression analysis. Group did not add significantly to the model at any of the four sites assessed (Table 2).

Knee extension peak torque (Nm) was added to the model in step three of the multivariate regression analysis. Its inclusion significantly added to the model for hip BMD by increasing the R^2 by 3.8% ($p = 0.06$). However, knee extension peak torque did not contribute significantly to the model at the forearm, spine or total body (Table 2). In step four, knee extension peak torque was removed and knee flexion peak torque (Nm) was added to the model. Knee flexion peak torque was not found to be a significant contributor to BMD at the hip, forearm, spine, or total body (Table 2). Visual representations of the association of BMD at each of the four sites to knee extension and flexion peak torque are provided in Figures 1–4.

DISCUSSION

The influence of elite competitive exercise in seniors and thigh muscle strength on BMD at the hip, forearm, spine, and total body was examined in this study. We determined that, as a block, age, sex, bodyweight, and dietary vitamin D and calcium explained a significant amount of the variance in BMD in each of the four body regions assessed. Participation in elite highly competitive exercise did not affect BMD at any of the regional sites or in the total body. Additionally, knee extension strength explained 3.8% of the variance in hip BMD, but knee flexion strength did not have an influence at any of the sites.

When entered as a block into the statistical model, the factors of age, bodyweight, sex and dietary calcium and vitamin D were significantly correlated to BMD. This finding was expected, as numerous other researchers have reported similar findings (3, 20, 29, 34, 35). Strong evidence supports the contribution of these factors to BMD. These factors were considered in the first step of the model so that we could examine any additional contribution of exercise level and thigh muscle strength.

Both cross-sectional and intervention studies have reported a positive correlation between physical activity and BMD (6, 7, 8, 13, 19, 30, 31, 37). Also, we have previously reported that the senior Olympians who were runners had greater total body BMD compared to controls (38), and that the senior athletes demonstrated greater knee extension and flexion strength than these controls (18). As such, we expected to find that 'group', or whether the person was an elite senior athlete or a control, would be related to BMD. Our results do not support this. We believe that there are several reasons for this finding. Our control group was not necessarily sedentary. The activity level of the control group was in the typical range of a healthy person over the age of 65 years, ranging from sedentary to active in sports other than running, cycling, and swimming. However, the control group was not competitively active, nor did they participate in the level of training needed for competitive activities. Additionally, bodyweight is highly correlated to BMD (2, 3, 14, 29). The senior athletes in this study weighed significantly less by approximately 7kg when compared to the control group. The lower bodyweight may mitigate any positive effects of exercise in this population. Additionally, we did not assess endocrine factors in this study. Given that the senior Olympians have been life-long athletes, hormonal effects on BMD may have confounded the study results.

Knee extension strength was related to total hip BMD but not BMD at the other sites assessed. This relationship is most likely due to the close anatomical association between the quadriceps and the hip. For example, the highest activation of the quadriceps during walking and running is immediately following heel contact, when the quadriceps are eccentrically controlling knee flexion during the landing (9). Similarly, the compressive forces at the hip during locomotion are at a peak following heel contact when the leg is supporting the bodyweight and absorbing the inertial forces associated with impacting the ground (39). Knee flexion strength was not related to hip BMD, however. The results of other studies support this finding (12).

Others researchers have reported a positive association between quadriceps strength and BMD. Eickhoff, Molczyk, Gallagher, and De Jong (12) reported that knee extensor strength, but not flexor strength, was predictive of femoral neck BMD in sedentary young women. Our results are similar, although we measured older men and women, some of whom were competitively active. Taaffe, Pruitt, et al. (35) stated that the portion of BMD variance explained by strength (11–21%) is low. In our sample population, we found the amount of variance explained by knee extension peak torque to be 3.8%. Taaffe, Luz Villa et al. (34) also noted that the relationship of dynamic strength to BMD in older individuals is generally not site specific.

The association between knee extension strength and hip BMD in this study was not as strong as that reported by others. This weaker association may be due to the design of our statistical model. In our study, the data of the athletes and the controls were included in the prediction model together. Others have analyzed athlete and control data separately and found a relationship in the non-athletes only (24). Therefore, for the purpose of this discussion, separate analyses were run on the data of the athletes and controls. However, no new information was gained. The results were the same, except that when the data were

separated into two groups, the sample size of each of much smaller than in the combined data set, and quadriceps strength was no longer predictive of BMD in either group.

In some of the research published by others, strength alone was correlated to BMD, and no other variables that are known to affect BMD were considered in the statistical model. In the current study, we chose to determine the relationship of strength to BMD after variables already known to strongly influence BMD were considered in the model. Ribom et al. (27) performed one univariate regression analysis to correlate knee extension strength with total body BMD in women, as well as a second regression analysis to correlate knee flexion strength with total body BMD. They reported significant correlations with R^2 being 0.27 ($p < 0.001$) for each (27). If we had simply correlated knee extension strength to BMD and no confounding variables were considered, the R-value would be 0.341 ($p < 0.001$). Similarly, Ribom et al. reported that correlation of flexion peak torque and hip BMD is 0.199 ($p = 0.010$) (27). However, we do not consider this model to be accurate because strength is not independent of age, bodyweight, and sex. We feel that it is important to consider these confounding variables in the statistical model.

Madsen and co-authors (17), like us, chose to account for age and bodyweight first, and then include quadriceps strength in their prediction of forearm and tibial BMD. They reported that quadriceps strength was associated with tibial BMD but not forearm BMD (17). These associations are not surprising considering the close anatomical connection between the quadriceps and the tibia and the distant anatomical connection between the quadriceps and the forearm. We also did not find a relationship between quadriceps strength and forearm BMD.

There are several limitations to this study. The study is cross-sectional in design and therefore the influence of the addition of a physical activity regimen on BMD within a single person cannot be assessed. The sample size of 183 individuals was relatively small for a study of this nature. Because we did not personally administer the physical activity questionnaire to our participants, but rather they were given the questionnaire and told to complete it before they left the testing center, the results may not be as complete and accurate as they would have been if the questionnaire was personally administered to each subject. Therefore, these data were not analyzed in detail. Rather, the questionnaires were used to confirm that the senior athletes exercised for at least the past 20 years, and that the controls did not participate in highly competitive exercise. The lifetime physical activity of the study participants is unknown. The control group was healthy and did not have many of the health complications commonly seen in individuals over age 65.

Following completion of the study, we realized that our activity surveys were incomplete, particularly in regard to resistance training. Therefore, we cannot truly quantify the amount of resistance training done by the subjects. We accept that this is a major limitation of the study as resistance training can have a large influence on BMD (10, 12, 14, 27). However, of the 104 senior Olympians, 50 definitively stated that they either did resistance training ($n = 32$) or that they did not ($n = 18$), while the other 54 subjects did not answer that question. For the purpose of this discussion, we performed a post-hoc ANOVA on BMD at each of the four sites in those senior athletes who reported resistance training and those who reported

that they did not resistance train. Sex (M, F) and resistance training (yes, no) were the independent variables in this analysis and BMD was the dependent variable ($\alpha=0.05$). The results of this analysis are shown in Table 3. BMD at the hip, radius, spine, and total body BMD was not different between those senior athletes who performed resistance training and those who did not; although sex was a significant factor in each analysis ($p < 0.05$). The sex by resistance training interaction was also not statistically significant. While we agree that resistance training can have a very large impact on BMD, we did not see a difference in BMD between those athletes who resistance trained and those who did not. We accept that the lack of complete resistance training information is a limitation of the study and it may confound the results, but we believe that our results are valid given resistance training was not significant in this study sub-sample.

Because we were trying to get as many senior Olympians as possible to participate in our study, we scheduled their testing sessions at their convenience. We did not control for nutrition or hydration status at the time of testing. To our knowledge, most of the athletes requested to be tested on a non-competition day. We do not believe that we tested any athletes immediately following competition. Nutrition and hydration may therefore be confounding factors, although we do not believe that they are.

The master athlete maybe considered an ideal model of aging because of their long-term participation in high intensity exercise. Most individuals would not be amenable to performing the amount, intensity, and long-term duration of exercise training reported by senior athletes of this level. Therefore, a training intervention of this magnitude would not be feasible. This study examined the influence of highly competitive exercise, and the training it entails, on BMD in healthy elders. This intense training for the National Senior Games may be considered a best-case scenario for a training intervention. Our ultimate goal in this line of research is to determine the extent to which intense exercise training in the elderly improves physical function and ultimately, reduces or delays frailty and morbidity.

PRACTICAL APPLICATIONS

While exercise is likely to protect against the bone demineralization that accompanies the aging process, this study revealed that participation in long-term highly competitive exercise does not necessarily protect the senior athlete from age-associated bone loss. Numerous factors are known to contribute to BMD: age, sex, bodyweight, dietary considerations, exercise participation particularly as it relates to skeletal loading, strength, etc. Bodyweight, sex, age, and dietary calcium and vitamin D were better able to predict bone mineral density than participation in elite competitive exercise. This may be because the senior Olympians weighed less than the control group, and bodyweight is strongly correlated to BMD. Furthermore, quadriceps strength is only marginally predictive of hip BMD and not predictive of wrist, spine, or whole body BMD. Senior Olympians must be aware that although exercise does improve BMD, bone health is multifactorial. Being a senior Olympian was not automatically protective of BMD and athletes should therefore have bone mineral density tests at the same intervals as their non-competitively active counterparts.

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Figure 1.

Total hip BMD plotted against knee flexion peak torque (top graph) and knee extension peak torque (lower graph). Data for the senior athletes are shown based on the subjects' competitive sports: runners (*), cyclists (+), and swimmers (x). Controls are shown as open circles(○).

Figure 2. Total radius BMD plotted against knee flexion peak torque (top graph) and knee extension peak torque (lower graph). Data for the senior athletes are shown based on the subjects' competitive sports: runners (*), cyclists (+), and swimmers (x). Controls are shown as open circles (○).

Figure 3. Total spine BMD plotted against knee flexion peak torque (top graph) and knee extension peak torque (lower graph). Data for the senior athletes are shown based on the subjects' competitive sports: runners (*), cyclists (+), and swimmers (x). Controls are shown as open circles (○).

Figure 4. Total body BMD plotted against knee flexion peak torque (top graph) and knee extension peak torque (lower graph). Data for the senior athletes are shown based on the subjects' competitive sports: runners (*), cyclists (+), and swimmers (x). Controls are shown as open circles (○).

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Table 1

Subject Demographics (Mean ± SD)

Group	N	Age (yrs) *	Height (cm)	Mass (kg) *	Males: Females
Senior Athlete	104	72.6 ± 6.4	168.7 ± 8.6	72.6 ± 13.5	57:47
Control	79	75.4 ± 5.6	170.8 ± 25.5	79.5 ± 11.7	46:33

* Control participants were significantly older and heavier than the athletes (p < 0.05).

Table 2

Results of the multivariate regression analysis. Correlations are shown (R), as are the R^2 for Step 1 and the change in R^2 (ΔR^2) for Steps 2–4 and the p-value for the regression at each step. ($\alpha = 0.10$).

	Hip BMD	Radius BMD	Spine BMD	Total Body BMD
Step 1	R = 0.513	R = 0.727	R = 0.498	R = 0.580
<i>Age</i>	$R^2 = 0.241$	$R^2 = 0.529$	$R^2 = 0.248$	$R^2 = 0.336$
<i>Sex</i>	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
<i>Wgt(N)</i>				
<i>Dietary Ca</i>				
<i>Dietary Vit D</i>				
Step 2	R = 0.513	R = 0.727	R = 0.504	R = 0.580
<i>Group (Athlete or Control)</i>	$R^2 = 0.000$	$R^2 = 0.000$	$R^2 = 0.006$	$R^2 = 0.001$
	p = 0.922	p = 0.929	p = 0.235	p = 0.752
Step 3	R = 0.528	R = 0.729	R = 0.518	R = 0.577
<i>Ext Peak Torque (Nm)</i>	$R^2 = 0.038$	$R^2 = 0.002$	$R^2 = 0.014$	$R^2 = -0.004$
	$p = 0.06$	p = 0.986	p = 0.158	p = 0.418
Step 4	R = 0.516	R = 0.729	R = 0.512	R = 0.581
<i>Flex Peak Torque (Nm)</i>	$R^2 = 0.025$	$R^2 = 0.000$	$R^2 = 0.006$	$R^2 = 0.001$
	p = 0.982	p = 0.439	p = 0.961	p = 0.584

Post-hoc analysis comparing the effects of resistance training and gender on BMD of the hip, radius, spine, and total body for those senior athletes for which we have resistance training information.

Table 3

	Resistance Training (n = 32)		Non-resistance Training (n = 18)		p
	Male	Female	Male	Female	
Hip BMD (g·cm ⁻²)	1.017 ± 0.142	0.830 ± 0.135	0.945 ± 0.145	0.827 ± 0.134	<i>p_s</i> = 0.001 <i>p_{rt}</i> = 0.394 <i>p_{s*rt}</i> = 0.437
Radius BMD (g·cm ⁻²)	0.661 ± 0.043	0.505 ± 0.055	0.637 ± 0.054	0.515 ± 0.048	<i>p_s</i> = 0.001 <i>p_{rt}</i> = 0.665 <i>p_{s*rt}</i> = 0.272
Spine BMD (g·cm ⁻²)	1.118 ± 0.136	0.903 ± 0.186	1.036 ± 0.154	0.908 ± 0.138	<i>p_s</i> = 0.001 <i>p_{rt}</i> = 0.433 <i>p_{s*rt}</i> = 0.369
Total Body BMD (g·cm ⁻²)	1.186 ± 0.094	0.999 ± 0.121	1.13 ± 0.107	1.030 ± 0.038	<i>p_s</i> = 0.001 <i>p_{rt}</i> = 0.804 <i>p_{s*rt}</i> = 0.24

p_s = p -value for 'sex' factor (M,F), *p_{rt}* = p -value for 'resistance training' factor (yes, no), and *p_{s*rt}* = p-value for the 'sex' x 'resistance training' interaction.