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The Effect of Weight-Bearing Exercise on Bone Mineral Density: A Study of Female Ex-Elite Athletes and the General Population

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ABSTRACT

The aim of this retrospective cohort study was to estimate the changes in bone mineral density (BMD) as a consequence of exercise in female ex-athletes and age-matched controls. Eighty-three ex-elite female athletes (67 middle and long distance runners, 16 tennis players, currently aged 40–65) were recruited from the original records of their sporting associations. Controls were 585 age-matched females. The main outcome measures were BMD of lumbar spine (LS), femoral neck (FN), and forearm, estimated by dual-energy X-ray absorptiometry (DXA) scan. Levels of physical activity were assessed using a modified Allied Dunbar Fitness Survey scale and classified as (a) ex-athletes, (b) active controls ($\geq$1 h of vigorous physical activity currently and in the past), (c) low activity controls with inconsistent or intermediate levels of activity, and (d) inactive controls (<15 minutes of exercise per week). After adjustment for differences in age, weight, height, and smoking, athletes had greater BMDs than controls: 8.7% at the LS (95% confidence interval [CI] 5.4–12.0; $p < 0.001$) and 12.1% at FN (CI 9.0–15.3; $p < 0.001$). The benefits of exercise appeared to persist after cessation of sporting activity. Active controls ($n = 22$) had greater BMDs than the inactive group ($n = 347$): 7.9% LS (CI 2.0–13.8; $p = 0.009$) and 8.3% FN (CI 2.7–13.8; $p = 0.004$). The low activity controls ($n = 216$) had an intermediate BMD. Tennis players had greater BMDs compared with runners: 12.0% LS (CI 5.7–18.2; $p = 0.0004$) and 6.5% FN (CI −0.2–13.2; $p = 0.066$). The BMD of tennis players' dominant forearms were greater than their nondominant forearms. In conclusion, regular vigorous weight-bearing exercise of 1 h or more per week is associated with an increase in BMD within a normal population. This study confirms long-term weight-bearing exercise as an important factor in the regulation of bone mass and fracture prevention. (J Bone Miner Res 1996;11:1333–1338)

INTRODUCTION

There is substantial evidence to support the view that weight-bearing physical activity promotes increased bone mineral density (BMD) and is a factor that reduces the risk of developing osteoporosis.(1,2) However, the studies from which this conclusion is drawn have their limitations. Cross-sectional studies of athletes have generally shown significant differences between athletes' BMD and controls',(3) but the groups tend to be small and unrepresentative of the majority of the exercising population. By selecting for study those athletes who are currently active, there is a bias toward the most successful and best adapted athletes. Small population-based studies have shown a positive association with exercise,(4) and prospective studies of exercise programs tend to confirm a benefit of exercise over sedentary behavior,(5–7) but are, by their nature, short in duration and have a potential for selection bias.

The long-term effects of exercise are more difficult to quantify, but one study has shown higher BMDs in the

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elderly who reported a lifetime of physical activity.(8) Other studies suggest that this benefit may be temporary; BMD accrued by exercise was lost when this was stopped.(9,10)

The benefit of exercise on BMD may be dependent on the type of exercise undertaken. For example, cyclists have similar total leg bone mineral contents (BMC) to sedentary controls,(11) and swimmers have been shown to have significantly lower BMDs in the lumbar spine compared with nonathletes and amenorrheic runners.(12) These findings suggest that weight-bearing is an important determinant of BMD independent of muscular activity alone. Weight-bearing exercise is therefore advocated to improve BMD, but the level of activity required to produce a benefit is unknown. Likewise, the point at which exercise can be detrimental to health is uncertain. Studies in female elite athletes competing in weight-bearing endurance events show that an expected benefit of exercise may be lost by the induction of estrogen deficiency, which manifests itself as amenorrhoea, in those training at the highest level. Whereas lower levels of exercise appear to stimulate an increase in BMD, higher levels of training may lead to a decrease in bone mass.(13,14) The detrimental effect of demineralization at a time when peak bone mass is normally being accrued may be crucial.(15)

The implications of physical activity do not apply just to high-level performance athletes; different effects of the type of exercise, the duration of activity, and the lasting benefit of exercise are of public health importance. Most of the general population is sedentary, and compliance requires a recommended level of exercise to be both realistic and worthwhile.

Aware of the methodologic problems of previous studies, we performed a retrospective cohort study relating reported exercise levels with BMD in a group of ex-elite female athletes and a large age-matched female general population control group. We addressed the following questions: Do athletes have higher BMDs at all sites than the general population? Is an increasing level of exercise associated with an increase in BMD within the general population? Does the benefit persist after discontinuing regular exercise? and Are there any differences in BMD related to the site of the body most exercised?

MATERIALS AND METHODS

Athletes

One hundred and fifty-seven names were obtained of elite female middle and long distance runners and tennis players from the original records of the International Athletics Club and the Lawn Tennis Association of Great Britain. These athletes had competed at national or international level between 1950 and 1979 and are currently aged between 40–65 years. These included two Olympic gold medalists and two Wimbledon singles champions. Names and addresses of 117 (74%) athletes were traced, and the athletes were invited to attend a clinical and radiological examination which included X-rays, blood sampling, and dual-energy X-ray absorptiometry (DXA) scans of the lumbar spine (LS) and femoral neck (FN). In the tennis players, both forearms were studied for bone density. Detailed information was collected on running and playing history, age, weight, menopausal status, hormone replacement therapy (HRT) use, smoking status, and joint injuries.

Controls

The controls consisted of 1003 women aged 44–67 from a general population survey carried out in Chingford, Northeast London. This population was drawn from an age-sex register of a large group general practice with a response rate of 78% and has been described in detail elsewhere.(16) It is similar to the U.K. averages in terms of height, weight, smoking habits, and socioeconomic status. Information on physical activity and other demographic variables was obtained from two separate questionnaires. Complete physical activity information was obtained in 585 subjects, and these constituted the main control group. Neither athletes nor controls were aware of the hypothesis being tested, although all had agreed to participate in a survey of "bones and joints" which involved X-rays and bone densitometry.

Assessment of physical activity

Assessment of physical activity was performed using the same method as the Allied Dunbar National Fitness Survey in the U.K.(17) but was modified to exclude non–weight bearing exercise. From this, units of activity engaged in per week could be calculated; 1 unit was defined as 15 minutes of vigorous weight bearing exercise or 30 minutes of moderate exercise. Vigorous categories of activity included running and squash, whenever it occurred, and tennis, hockey, badminton, and aerobics when associated with breathlessness or sweating. Moderate activity included the former categories if not breathless or sweating, and additionally, table tennis, golf, social dancing, and stretching exercises. Walking and such activities as bowling and light gardening were not considered sports for the purpose of this analysis, and non–weight bearing sports such as swimming and cycling were excluded. Women reporting less than 1 unit of activity per week were categorized as having a zero score.

Activity scores for the controls were compiled from data obtained from two questionnaires. The first was nurse administered at the time of the initial assessment of the athlete or control and referred to as the subject's current level of activity. The second, distributed by mail 5–6 years later, was self-administered and inquired both into present physical activity, including walking, and that recalled by the subject to be their peak level of activity between the ages of 20 and 30. The second questionnaire was used to obtain more detailed information about current levels of activity. In this way, three periods of time were studied: current activity at the baseline assessment, current activity at years 5–6, and reported past levels of exercise.

The control population was categorized into overall lifetime sports groups: active (>4 units per week of sport) and inactive (<1 unit) in all periods studied. Those with low levels of sport (1–4 units) during all periods or with inconsistent levels were classified as low activity. We examined

TABLE 1. DEMOGRAPHIC CHARACTERISTICS OF THE ATHLETE AND CONTROL GROUPS

Variable	*Athletes* *(n = 83)* *(mean [SD])*	*Controls** *(n = 585)* *(mean [SD])*	*Controls†* *(n = 1003)* *(mean [SD])*
Age	52.4 (6.1)	54.6 (6.0)	54.2 (6.0)
Weight (kg)	61.2 (9.0)	66.5 (11.8)	66.9 (11.8)
Height (cm)	166.2 (6.1)	161.8 (6.0)	160.6 (13.9)
HRT (%)	20 (24.1)	147 (25.1)	238 (23.7)
Years postmenopause	6.5 (5.2)	8.1 (5.7)	8.2 (5.9)
Age at menopause	50.3 (3.7)	49.1 (4.1)	48.9 (4.1)
Smoking (%)	10 (12.0)	244 (41.7)	463 (46.7)
Crude BMD LS	1.060 (0.16)	0.960 (0.16)	0.970 (0.16)
Crude BMD FN	0.860 (0.12)	0.760 (0.12)	0.760 (0.12)

* Controls with complete exercise information.
† Total group.

the consistency of the reported current level of exercise between the two questionnaires. All active controls remained in the same category between questionnaires. In the inactive category, 13.8% (48/347) had increased their activity level by one grade, but none increased by two grades to the most active level. In the intermediate group, levels of activity remained consistent; only 1.9% (4/216) fell in level and 1% (2/216) increased to the highest level of activity. These changes in group stability appear to be within the limits expected for alteration in activity over time or errors in reporting.

Radiologic methods

Estimations of BMD were performed using DXA with the Hologic QDR 1000/W (Hologic, Inc., Waltham, MA, U.S.A.). The BMD was measured from L1 to L4, at the FN, and in the forearm. In the control group and runners, measurements were performed on the nondominant forearm. In tennis players, both sides were assessed. Forearm measurements were made at three sites along the mid- to distal region of the forearm. These were the "ultradistal radius," which consisted of a 1.5 cm band adjacent to the end plate of the radius, a "one-third radius" region, consisting of a 2 cm band one-third of the distance between the ulnar styloid and the olecranon, and a larger "middistal" region, comprising the rest of the distal forearm between these two sites. Reproducibility, assessed in 10 healthy volunteers, ranged from 0.8 to 1.8% between the skeletal sites.

Statistical analysis

Comparisons of means were made between the athlete group, the whole control population, and within the population comparing active, low, and inactive groups. Analysis of covariance was used to adjust for differences in age, weight, height, and smoking between groups using the Statistical Package for the Social Sciences (SPSS).

RESULTS

Sixty-seven runners and 16 tennis players agreed to take part in the study (70.9% of those traced) and 13 declined. DXA scans and complete information on exercise levels were available on 83 athletes and 585 Chingford controls. Fifteen out of 16 tennis players (94%) and 40 out of 67 (60%) runners were still active in their sport. Twenty-seven, all runners, had stopped all forms of training. The mean duration of competition at national level for tennis players was 237.0 months (SE 35.2) and 183.3 (SE 15.9) for runners. There was no statistically significant difference between these two durations. Some athletes still compete, nationally and internationally, as veterans.

Table 1 details the two control groups (the 585 exercise questionnaire responders and the total 1003 Chingford control group from which they are taken) as well as the athletes. Similarity in the demographic data and BMD of the controls suggests that the 585 are representative of the larger population. As expected, the athletes were lighter, taller, and smoked less than the controls. There was an equal use of HRT, and mean ages at menopause and years postmenopausal were similar. Crude BMD was greater in the athletes than controls at the FN (0.860 SD 0.12 vs. 0.760, 0.12) and LS (1.060, 0.16 vs. 0.960, 0.16). Of the 585 controls, 22 (3.8%) were classified as active, 216 (36.7%) were in the low activity group, and 347 (59.3%) were inactive.

Table 2 shows the difference in BMD at the FN and LS between the athletes and control groups when adjusted for age, height, weight, and smoking status. Athletes had significantly greater BMD at the FN, 12.1% (CI 9.0–15.3; $p <$ 0.001), and the LS, 8.7% (CI 5.4–12.0; $p < 0.001$), compared with controls. Active controls had greater BMDs than the inactive group: 7.9% at the LS (CI 2.0–13.8; $p = 0.009$) and 8.3% at the FN (CI 2.7–13.8; $p = 0.004$). The low activity controls had a 3.1% (CI 0.8–5.5; $p = 0.012$) greater BMD at the FN than the inactive group, though no significant difference in BMD at the LS. Adjusting the means, within the control group, for the level of reported walking

TABLE 2. DIFFERENCES IN BMD BY ACTIVITY LEVELS

BMD (g/cm²) (SE)	*Inactive controls (LS, n = 345) (FN, n = 335)*	*Low activity controls (LS, n = 213) (FN, n = 203)*	*Active controls (LS, n = 22) (FN, n = 21)*	*All controls (LS, n = 580) (FN, n = 559)*	*Athletes (n = 83)*	p-*value analysis of covariance for data marked**
LS	0.957* (0.008)	0.968* (0.010)	1.038* (0.030)	0.965 (0.006)	1.056* (0.017)	<0.001
FN	0.744* (0.006)	0.768* (0.007)	0.810* (0.023)	0.755 (0.005)	0.859* (0.013)	<0.001

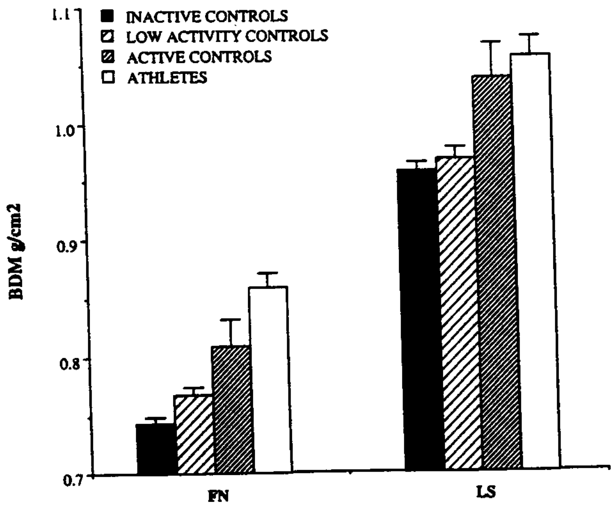

FIG. 1. Differences in BMD by activity levels. Mean BMD by activity level with standard errors, following analysis of covariance. Adjusted for age, height, weight, and smoking status. FN = femoral neck; LS = lumbar spine.

did not affect these results. Likewise, further adjustment for alcohol intake, hysterectomy, use of the oral contraceptive pill or HRT, and age at menopause did not account for the differences in BMD. Athletes had a 13.9% greater BMD at the FN (CI 10.7–17.1; $p < 0.001$) and 10.1% greater BMD at the LS compared with the inactive control group (CI 6.6–13.5; $p < 0.001$). These results are represented graphically in Fig. 1.

Athletes overall had higher BMDs than the most active exercisers in the population, with a significant difference at the FN of 7.1% (CI 0.7–13.5; $p = 0.038$) and nonsignificant difference at the LS of 5.1% (CI −1.4–11.7; $p = 0.148$). Tennis players had significantly higher BMDs at the LS than runners, 12.0% (CI 5.7–18.2; $p = 0.0004$), but there was a nonsignificant difference at the FN of 6.5% (CI −0.2–13.2; $p = 0.066$). This was not explained by differences in any of the measured characteristics.

There were 27 athletes, all runners, who reported giving up all forms of sporting activity. There was little difference between their BMDs and runners who continued with their training. The LS means for both groups were identical (1.029 g/cm²). There was a small but nonsignificant reduction at the FN in the inactive runners (0.815 g/cm²; SD 0.128) compared with the active (0.856 g/cm²; SD 0.114).

In tennis players, when adjusting for age, weight, and height, the total BMD of the dominant arm was significantly greater than that of the nondominant arm (5.9% greater; CI 11.0–0.7%; $p = 0.036$). Within the three radiographic areas studied, their dominant arms were higher in BMD at the one-third radius region (6.0%, CI 10.6–1.5%; $p = 0.015$) and the middistal region (5.7%; CI 10.3–1.1%; $p = 0.024$) and to a nonsignificant extent at the ultradistal radius region.

DISCUSSION

This study shows that athletes with a lifetime history of strenuous weight-bearing physical activity had markedly higher BMDs at the FN and LS than controls. Within the general population, increasing levels of exercise were associated with increasing BMD, a finding also recently described in males.(18) Tennis players had higher BMDs than runners in the LS. There were regional differences in BMD at the forearm: the dominant arms of tennis players were denser than their nondominant arms, which were, in turn, lower than controls. The benefit of exercise on BMD appears to persist after cessation of training, a finding contrary to previous studies.(9,10)

Because of the observational nature of the study, it was open to possible bias or confounding factors. Selection bias for the athletes was minimized by obtaining their names from the original records of their sporting associations, avoiding selection of only those currently active, and obtaining a reasonable response rate of 73% of those traced. Selection bias may have been a problem with the control group chosen for detailed study, but the demographic characteristics and the BMDs in this group were very similar to the overall control population. It is therefore likely that the smaller group was representative of the larger.

There is no "gold standard" for assessing exercise levels within a population. Our definitions of exercise and activity level were taken from the Allied Dunbar National Fitness Survey, modified to include only weight-bearing exercise. The criteria for level of activity are specific, but assigning a subject to the appropriate level relies on accurate reporting and recall of activity. Recalled levels of exercise may be inaccurate but were generally reproducible and consistent in our study. By asking the subject about their peak level of exercise in their third decade, it was felt that we would obtain an assessment of their highest level of activity at their most active time of life. We adjusted for potential confounders that are associated with exercise and BMD, such as age, weight, height, and smoking.

The average U.K. population, like those in most developed countries, is sedentary. In the Allied Dunbar National Fitness Survey of adults in England, very few took exercise at a frequency or regularity that was likely to confer benefit.(17) Seventy percent or more of participants in each age group were below an acceptable activity threshold that would confer significant health or functional benefits. Exercise levels within our 585 female controls were equally low; 59.3% reported virtually no sporting activity. By using a large cohort of middle-aged females with varying levels of current and past sporting activity, we hoped to detect changes in BMD associated with relatively small differences in exercise level. Despite the low levels of activity, there were significant differences in BMD, indicating that a small increase in the level of lifetime exercise may significantly increase BMD, at least in certain parts of the skeleton. Whereas a previous study, in a similar group of women, has indicated that exercise levels of 4 h of vigorous activity per week can increase BMD,(19) our results suggest that the threshold for benefit is much lower, as long as it is sustained.

The benefits of exercise are likely to be related to the type of activity.(20) The apparent differences in BMD in runners and tennis players are intriguing and cannot be accounted for by potential confounding variables measured between the groups. There was no increased rate of amenorrhoea in the runners during their training years, in contrast to female athletes of today with similar ability. Female athletes of the era we recruited from were prevented from competing at distances greater than 5000 m and actively discouraged from running long distances in training because it was considered unsafe. Consequently, the development of amenorrhoea in their competing years was uncommon. A review of cross-sectional studies of athletes suggest similar findings, that higher BMDs are found in strength and power trained athletes compared with running and endurance athletes.(21) Our results suggest that regular prolonged running, even at a level that does not provoke estrogen deficiency, may not be any more beneficial to BMD than 1 h of regular vigorous exercise per week. In the athlete groups we studied, differences may be accounted for by tennis players spending more time actively weight-bearing than runners, or, more likely, that running is a less effective stimulus of BMD than tennis. Tennis is a sport that involves intermittent sudden torsional strains on the limbs and spine which may be a greater stimulus for bone mineral development than a sport that produces a repetitive high frequency axial stress such as running. This may explain why the difference in BMD between the two sports is greater in the LS where the torsional effect is presumably greater. A similar torsional effect on the LS is seen in rowing and may account for the enhanced spinal BMD in female rowers compared with runners and dancers.(14) In animal studies, the frequency at which a strain is applied to a bone and the rate at which that strain changes has been shown to be important in bone mass production.(22–24)

Walking has been studied as an independent factor for the stimulation of BMD, with conflicting results. A significant increase in BMD has been reported with postmenopausal women walking 1 mi/day,(25) but distances up to three times greater were not associated with an increase in the premenopausal group studied.(26) In our study, adjusting for reported walking distance made no difference to the results.

There were differences in BMD between dominant and nondominant arms in the tennis players, the only subjects in which both arms were scanned. It has been reported elsewhere that the dominant arm has a higher bone density in racquet players, explicable in terms of the level of weight-bearing stress placed upon it.(27) Krahl(28) reports an increase in bone density associated with an increase in bone length and diameter. In our study, the difference was most marked at the "one-third radius" region of the forearm. This may be a function of the maximum moment acting on the forearm at the point of impact of the ball on the racquet, but there is no accepted biomechanical model for this racquet action on which to confirm this. A recent study has concluded that females commencing a racquet sport career premenarche have significantly greater humeral and forearm BMC than controls and those players who start their career later, the optimum time to develop maximum BMC being 5 or more years before the menarche.(29) In our study, similar analysis has found no difference in BMD related to the time of onset of a tennis career, although we did not design the study to address this question.

It is accepted that a reduced BMD is associated with a higher incidence of fracture. The relative risks of fracture of the hip associated with a decrease in BMD of 1 SD below the population mean has been calculated as between 2.1 and 2.7.(30,31) Assuming a relative risk of fracture of 2.5 for 1 SD below the mean and a population difference in BMD at the FN, attributable to exercise, of 8.3% (SE 2.8%), then the lower BMD equates to 1.7-fold increased risk of fracture to the inactive members of the control population. It is possible, therefore, that exercise at the level reported by the active group may substantially reduce the lifetime risk of fracture.

In summary, in this middle-aged female population sample, an increase in BMD was associated with the level of long-term weight-bearing sporting exercise performed by the individual. Ex-elite athletes have higher levels of BMD than controls, which presumably reflects a lifetime of high levels of weight-bearing activity. Tennis players have greater benefit conferred on them by their sport than do runners who had BMDs similar to the most active of the population. In the general population, long-term exercise of only 1 h/week appears to confer benefit on BMD. This study confirms weight bearing exercise as an important modifiable risk factor in the population for the regulation of bone mass and fracture prevention.

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