Original Article

Relative Influence of Physical Activity, Muscle Mass and Strength on Bone Density

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Abstract. In a population-based sample of 348 men (age 22–90 years) and 351 women (age 21–93 years), we evaluated the relationship of bone density assessed at a variety of skeletal sites by dual-energy X-ray absorptiometry (DXA) with various muscle mass estimates obtained also from the DXA scan and with physical activity by interview and strength assessed both subjectively and objectively. All these parameters declined with age as judged from these cross-sectional data. All estimates of total skeletal muscle mass were strongly correlated with bone density at different skeletal sites. Muscle mass, in turn, was correlated with physical activity and hand strength. In multivariate models including these variables, muscle mass was the strongest determinant of bone density, accounting for 6–53\% (mean 27\%) of the variance at the different skeletal sites. Physical activity (and/or a physical activity × age interaction) was an independent predictor of bone mass in 48\% of the site-specific models and accounted for 0.03–39\% (mean 10\%) of the variance, while hand strength (and/or a hand strength × age interaction) accounted for up to 4\% (mean 1\%) of the variance as an independent predictor of bone density in a third of the models. Although these variables together accounted for a large proportion of the variance in bone density, other potential predictors were not assessed in these analyses. The dramatic decline in physical activity over life seemed unable to completely explain the age-related loss of bone mass, and additional research is needed to determine whether the relationship of muscle mass with bone density is a direct one or due instead to other factors such as circulating hormone levels.

Keywords: Aging; Bone density; Epidemiology; Muscle (or lean) mass; Physical activity; Strength

Introduction

Because bone mass clearly is influenced by muscle-induced strains on bone [1], it has been suggested that the decline in bone mineral density (BMD) with aging could be due almost entirely to disuse associated with the age-related reduction in physical activity [2]. Certainly, the skeleton is acutely responsive to the dramatic reductions in loading associated with chronic bedrest [3] or spaceflight [4], but it has been more difficult to demonstrate a strong relationship between bone density and physical activity within the sedentary range experienced by most older Americans [5]. This is due partly to the fact that physical activity is difficult to measure accurately [6]. Because physical activity and muscle mass are correlated [7], direct assessment of lean body mass (\textasciitilde muscle mass) might provide a useful surrogate measure. An association between lean body mass and bone mass has been reported previously [8–17] and, like the age-related decline in BMD, there is a reduction in muscle mass (‘sarcopenia’) with aging [18,19]. However, this association could be an indirect one because both lean mass [19] and BMD [20,21] are

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related to body size, which is also less among older individuals. Moreover, there is an age-related reduction in strength which is disproportionate to the decline in lean mass and attributable to neuromuscular remodeling and impaired synthesis of muscle-specific proteins with aging [22]. To better understand these relationships, we studied an age-stratified sample of community men and women to assess the association of muscle mass with bone mass. We then evaluated the independent contributions of physical activity and strength after adjusting for muscle mass.

**Subjects and Methods**

**Study Subjects**

Following approval by the Mayo Clinic’s Institutional Review Board, subjects were recruited from an age-stratified random sample of Rochester, Minnesota men and women that was selected using the medical records linkage system of the Rochester Epidemiology Project [23]. Over half the Rochester population is identified annually in this system and almost all are seen in any 3-year period. Thus, the enumerated population approximates the underlying population of the community, including both free-living and institutionalized individuals. Altogether, 1138 men aged 20 years and over were approached, but 239 men were ineligible (109 were demented and could not give informed consent; 13 were radiation workers; 91 died before contact; 25 were so debilitated, e.g., with terminal cancer, that they were not approached; and 1 man was unable to participate due to pending legal action). Of the 899 eligible men, 348 participated (39%) and body composition data were available for 345. Similarly, 938 women were approached for study but 126 were ineligible (89 were demented; 11 were pregnant; 9 were radiation workers; 8 were participating in a clinical trial of osteoporosis prophylaxis; and 9 died before they could be contacted). Of the 812 eligible women, 351 participated (43%) and body composition was available for 349. The men ranged in age from 22 to 90 years (mean ± SD, 55.4 ± 19.6 years). There were 138 premenopausal women (35.0 ± 8.6 years; range 21–54 years) and 213 postmenopausal women (67.8 ± 13.2 years; range 34–93 years). All but 13 men and 2 women were white, reflecting the ethnic composition of the population (96% white in 1990).

**Physical Activity and Strength**

After providing written informed consent, subjects were interviewed in accordance with a standard protocol to collect clinical, demographic and lifestyle data. To assess habitual physical activity levels over the preceding 12 months, subjects were provided with two questionnaires: one assessed the frequency (average times per week/year) and duration (hours per day) and one assessed the intensity (vigorous, moderate, light) of various daily activities, as well as stair climbing/walking and the number of sweat-producing activities per week. The first questionnaire, a modified version of the Paffenbarger physical activity questionnaire [24], listed 32 recreational and sports activities and allowed subjects to write in other leisure-time activities not included in this list. All physical activities were subsequently categorized as ‘constant intensity,’ ‘skill-related’ or ‘competitive’ (variable intensity and skill). Caloric expenditure estimates (total, light, moderate and vigorous activity) were derived from the second questionnaire based on body weight, duration of activity and published MET values [25]. As an independent measure of activity [26], we also assessed energy expenditure as total dietary kilocalories per day estimated from a 7-day diet diary [27]. This estimate was also adjusted for body weight. Finally, the interview included an assessment of difficulties in ambulation and the activities of daily living that was adapted for the Study of Osteoporotic Fractures [28]. At the time of the interview, each subject also underwent anthropometric assessment, which included measurements of height to the nearest 0.1 cm and weight in light clothes without shoes to the nearest 0.1 kg. The strength of various muscle groups (right and left iliopsoas, quadriceps, anterior tibialis and gastrocnemius groups) was assessed qualitatively (scored 1 for normal to 3 for severely impaired) for each muscle group (total score 8–24). Handgrip strength was assessed quantitatively with a dynamometer (JAMAR model 0030J4, J. A. Preston, Jackson, MI).

**Bone Density and Body Composition**

Bone mineral content (BMC, g) and BMD (g/cm²) were determined for the lumbar spine (L2–L4) in anteroposterior (AP) as well as lateral projection, proximal femur (total, femoral neck and trochanteric regions) and wrist (total, 1/3 radius and distal radius) using dual-energy X-ray absorptiometry (DXA) with the Hologic QDR 2000 Plus instrument (Hologic, Waltham, MA) with software version 5.67. The coefficients of variation for the total AP spine, hip and forearm BMD measurements were 0.6%, 1.8% and 0.8%, respectively. To adjust for the confounding of these measurements by body size, we also estimated volumetric bone mineral apparent density (BMAD, g/cm³) from these data as previously described [29], using the following formulae: Spine $\text{BMAD} = \text{BMC} / \text{A}^{3/2}$; radius and femoral neck $\text{BMAD} = \text{BMC} / \text{A}$; where BMC is the bone mineral content and A is the projected bone area. Where these calculations could not be made, we corrected for bone size by dividing BMD by the subject’s height measured on the day the densitometry scan was obtained. Total lean body mass (LBM, kg), total fat mass (FM, kg) and total body bone mineral (TBBM, g) were determined from a whole body scan using the same instrument. The coefficients of variation for total LBM, FM and TBBM were 0.6%, 2.0% and 0.8%, respectively. In addition, we estimated