AMERICAN COLLEGE of SPORTS MEDICINE®

POSITION STAND

Physical Activity and Bone Health

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SUMMARY

Weight-bearing physical activity has beneficial effects on bone health across the age spectrum. Physical activities that generate relatively high-intensity loading forces, such as plyometrics, gymnastics, and high-intensity resistance training, augment bone mineral accrual in children and adolescents. Further, there is some evidence that exercise-induced gains in bone mass in children are maintained into adulthood, suggesting that physical activity habits during childhood may have long-lasting benefits on bone health. It is not yet possible to describe in detail an exercise program for children and adolescents that will optimize peak bone mass, because quantitative dose-response studies are lacking. However, evidence from multiple small randomized, controlled trials suggests that the following exercise prescription will augment bone mineral accrual in children and adolescents:

Mode:	impact activities, such as gymnastics, plyometrics, and jumping, and moderate intensity resistance training; participation in sports that involve running and jumping (soccer, basketball) is likely to be of benefit, but scientific evidence is lacking
Intensity:	high, in terms of bone-loading forces; for safety reasons, resistance training should be $<60\%$ of 1-repetition maximum (1RM)
Frequency:	at least 3 d·wk^{-1}
Duration:	10–20 min (2 times per day or more may be more effective)

During adulthood, the primary goal of physical activity should be to maintain bone mass. Whether adults can increase bone mineral density (BMD) through exercise training remains equivocal. When increases have been reported, it has been in response to relatively high intensity weight-bearing endurance or resistance exercise; gains in BMD do not appear to be preserved when the exercise is discontinued. Observational studies suggest that the age-related decline in BMD is attenuated, and the relative risk for fracture is reduced, in people who are physically active, even when the activity is not particularly vigorous. However, there have been no large randomized, controlled trials to confirm these observations, nor have there been adequate dose-response studies to determine the volume of physical activity required for such benefits. It is important to note that, although physical activity may counteract to some extent the *aging-related* decline in bone mass, there is currently no strong evidence that even vigorous physical activity attenuates the *menopause-related* loss of bone mineral in women. Thus, pharmacologic therapy for the prevention of osteoporosis may be indicated even for those postmenopausal women who are habitually physically active. Given the current state of knowledge from multiple small randomized, controlled trials and large observational studies, the following exercise prescription is recommended to help preserve bone health during adulthood:

Mode:	weight-bearing endurance activities (tennis; stair climbing; jogging, at least intermittently during walking), activities that involve jumping (volleyball, basketball), and resistance exercise (weight lifting)
Intensity:	moderate to high, in terms of bone-loading forces
Frequency:	weight-bearing endurance activities 3–5 times per week; resistance exercise 2–3 times per week
Duration:	30–60 min·d^{-1} of a combination of weight-bearing endurance activities, activities that involve jumping, and resistance exercise that targets all major muscle groups

It is not currently possible to easily quantify exercise intensity in terms of bone-loading forces, particularly for weight-bearing endurance activities. However, in general, the magnitude of bone-loading forces increases in parallel with increasing exercise intensity quantified by conventional methods (e.g., percent of maximal heart rate or percent of 1RM).

The general recommendation that adults maintain a relatively high level of weight-bearing physical activity for bone health does not have an upper age limit, but as age increases so, too, does the need for ensuring that physical activities can be performed safely. In light of the rapid and profound effects of immobilization and bed rest on bone loss, and the poor prognosis for recovery of mineral after remobilization, even the frailest elderly should remain as physically active as their health permits to preserve skeletal integrity. Exercise programs for elderly women and men should include not only weight-bearing endurance and resistance activities aimed at preserving bone mass, but also activities designed to improve balance and prevent falls. Maintaining a vigorous level of physical activity across the lifespan should be viewed as an essential component of the prescription for achieving and maintaining good bone health.

INTRODUCTION

In Caucasian, postmenopausal women, osteoporosis is defined as a bone mineral density (BMD) value more than 2.5 standard deviations below the young adult mean value (52), with or without accompanying fractures. Whether the same criteria should apply to premenopausal women, women of other races, or men remains to be confirmed. In the U.S. and other developed countries the incidence of osteoporosis is increasing at rates faster than would be predicted by the increase in the proportion of aged individuals. Multiple

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vertebral fractures and, in particular, hip fractures have a devastating effect on functional abilities and quality of life. The mortality rate for elderly individuals in the first year following hip fracture is as high as 15–20% (105). Even with no change in current incidence rates, it has been estimated that the number of hip fractures will double to 2.6 million by the year 2025, with a greater percentage increase in men than in women (38).

Because low BMD greatly elevates the risk of fractures with minimal trauma, as with a fall to the floor, strategies that maximize bone mass and/or reduce the risk of falling have the potential of reducing morbidity and mortality from osteoporotic fractures. Although bone mass can be increased through pharmacologic therapy, physical activity is the only intervention that can potentially both 1) increase bone mass and strength and 2) reduce the risk of falling in older populations. There exist other bone health issues associated with exercise, including the risk of stress fractures with high-volume training and the bone loss associated with amenorrhea. However, the focus of this position stand will be on the effectiveness of physical activity to reduce risk for osteoporotic fracture, without specific reference to nutritional or genetic influences.

Well-known principles of exercise training apply to the effects of physical activity on bone. For example, overloading forces must be applied to bone to stimulate an adaptive response, and continued adaptation requires a progressively increasing overload. It is important to emphasize that the stimulus to bone is literally physical deformation of bone cells, rather than the metabolic or cardiovascular stresses typically associated with exercise (e.g., % $\dot{V}O_{2max}$). Physical deformation can be measured by strain gauges on the bone surface, but is more commonly estimated by such surrogate measures as ground-reaction forces engendered during weight-bearing activities. Muscle contraction forces in the absence of ground-reaction forces (e.g., swimming) may also stimulate bone formation, but this is more difficult to estimate. A factor that is unique to skeletal adaptations to training is the slow turnover of bone tissue. Because it takes 3–4 months for one remodeling cycle to complete the sequence of bone resorption, formation, and mineralization (85), a minimum of 6–8 months is required to achieve a new steady-state bone mass that is measurable.

The most common outcome measure used to assess the effects of physical activity on bone mass in humans is BMD, which describes the amount of mineral measured per unit area or volume of bone tissue (51). Dual-energy x-ray absorptiometry (DXA) is the standard method of measuring areal BMD in clinical and research settings. The lumbar spine and proximal femur are the most common sites of measurement by DXA because they are prone to disabling osteoporotic fractures. Other methods of assessing risk for osteoporosis include computed tomography (CT) measurement of spine volumetric BMD, and ultrasonography of the calcaneus, which provides an index of bone stiffness. Ultrasonography is widely available, easy to perform, and does not involve exposure to ionizing radiation, but should be used only as a screening test.

Currently, BMD is the best surrogate measure of bone strength in humans and BMD has been estimated to account for 60% or more of the variance in bone strength (20,125). However, studies of animals suggest that changes in BMD in response to mechanical stress underestimate the effects on bone strength. For example, 5–8% increases in BMD were associated with increases in bone strength of 64–87% (48,116). The size of bone has a significant contribution to bone strength because the resistance of bone to bending or torsional loading is exponentially related to its diameter; furthermore, bone size may continue to increase during adulthood (93). Because bone architecture (i.e., geometry) is an important determinant of strength (104), evaluation of the effects of mechanical stress on bone should consider not only changes in bone mass, but changes in structural strength and material and geometric properties when possible (120).

The two generally accepted strategies to make the skeleton more resistant to fracture are to 1) maximize the gain in BMD in the first three decades of life and 2) minimize the decline in BMD after the age of 40 due to endocrine changes, aging, a decline in physical activity, and other factors. Because bone strength and resistance to fracture depend not only on the quantity of bone (estimated by BMD) but also bone geometry, methods are being developed that enable the assessment of cross-sectional geometry with existing DXA technology or with peripheral quantitative computed tomography (pQCT) or high-resolution magnetic resonance imaging (MRI). The microarchitecture of cancellous, or trabecular, bone (i.e., the lattice-work of bone inside vertebral bodies or ends of long bones) is important to the mechanical strength of the femoral neck, vertebral bodies, and other cancellous bone-rich regions. However, microarchitecture of cancellous bone can be assessed at present in humans only by bone biopsy, sophisticated MRI analyses, or the most advanced micro-CT devices not yet generally available. Additional valuable information can be gained from mechanical testing of bone samples from human cadavers and from animals subjected to various training protocols, and from histological and gene expression analyses from trained animals. Recent advances in protocols that enhance the osteogenic response to mechanical loading in animals have not yet been evaluated in humans, but are expected to stimulate new research in this area (116).

The purpose of this position stand is to provide recommendations for the types of physical activities that are likely to promote bone health. The current state-of-knowledge regarding physical activity as it relates to 1) increasing peak bone mass, 2) minimizing age-related bone loss, and 3) preventing injurious falls and fractures will be discussed.

ANIMAL STUDIES

Various animal models have been utilized to study mechanical loading of the skeleton, but this section will focus mainly on the commonly used rat model. Multiple factors characterize the physical activities that are likely to influence properties of bone, including the type, intensity, duration, and frequency of the bone-loading activity. Studies of animals enable controlled manipulations of these factors to determine their relative contributions to the osteogenic response (i.e., bone formation).

Type of loading

Mechanical forces have osteogenic effects only if the stress to bone is unique, variable, and dynamic in nature. Static loading of bone (i.e., single, sustained force application) does not trigger the adaptive response that occurs with dynamic loading (11). Studies of rats have evaluated the osteogenic responses to several types of unique (i.e., not usual cage activity) exercise interventions, including running (treadmill and voluntary), swimming, jumping, standing, climbing, and resistance training. Results have been equivocal, demonstrating that mechanical stress can enhance (26,40,47,48,121,127,131) or compromise (8,26,92,132) bone mass, formation, and/or mechanical properties. In general, running and swimming of moderate intensity have been found to have positive effects on bone mass and material properties in the cortical and trabecular regions of the tibia and femur in growing and mature rats (8,26,47,121,127,131). However, decreases in bone mass, trabecular thinning, and structural properties have been observed in response to exercise that is very intense and/or excessive, particularly in growing animals (26,47,92,132). Activities that simulate resistance training in humans, including jumping up to a platform, voluntary tower climbing, and simulated "squat" exercises, have been found to have positive effects on both cortical and trabecular bone regions of the tibia and femur (91,92,126).

Another experimental paradigm that has been used to evaluate the osteogenic effects of mechanical stress in animals is controlled *in vivo* external loading, including compression of the ulna and four-point bending of the tibia. This approach has an advantage over physical activity interventions in that it enables precise control and quantification of the mechanical loading forces. Studies of external loading strongly support favorable adaptations of bone to mechanical stress (116). For example, the four-point bending model was used in rats to demonstrate that the osteogenic response to loading is markedly enhanced when a given number of daily loading cycles are partitioned into multiple sessions separated by rest periods (116). It has not yet been determined whether such findings are relevant to humans.

Intensity of loading

The primary mechanical variables associated with load intensity include strain magnitude and strain rate. Strain is a measurement of the deformation of bone that results from an external load and is expressed as a ratio of the amount of deformation to the original length. It has long been recognized that strain magnitude is positively related to the osteogenic response, but accumulating evidence suggests that strain rate is also an important factor (11). Increasing strain rate, while holding loading frequency and peak strain magnitude constant, was found to be a positive determinant of changes in bone mass (11). High strain rates also increased endocortical bone formation rate in an *in vivo* impact-loading protocol (27,50). Such observations emphasize the need for further studies of the osteogenic effects of exercises that generate high strain magnitude and rate, such as jumping activities.

Duration and frequency of loading

The seminal work of Rubin and Lanyon (102) using external loading demonstrated that only a few loading cycles (e.g., 36 per day) of relatively high magnitude were necessary to optimize the bone formation response; increasing the number of loading cycles by 10-fold had no additional effect. Similarly, in a more physiologic model of loading in which rats jumped down from a height of 40 cm, as few as 5 jumps per day increased bone mass and strength of the tibia; increasing the number of jumps beyond 10 per day did not yield further benefit (118). It should be noted that, in these studies, the levels of strain likely exceeded those generated during typical human physical activities. The interactions between frequency (repetitions per day and sessions per week) and intensity of loading cycles with respect to the resulting osteogenic response in humans is not known.

There is intriguing evidence from recent studies that applying a given number of loading cycles in multiple daily sessions is more osteogenic than applying the same number of cycles in a single daily session (116). Rat ulnas that were loaded 360 times per day in a single session (1×360) for 16 wk absorbed 94% more energy before failing than the contralateral unloaded ulnas. However, ulnas that received the same 360 daily loading cycles over 4 sessions (4×90) absorbed 165% more energy before failing than unloaded bones (116). These results suggest that bone cells lose sensitivity to mechanical stimulation after a certain number of loading cycles, and that recovery periods are needed to restore sensitivity to loading. It has been estimated that complete restoration of sensitivity to loading requires a recovery time of 8 h in rats, but recovery times as short as 0.5–1.0 h have been found to be more osteogenic than no recovery period (116). It will be important to determine in humans whether multiple, short daily exercise bouts are more osteogenic than a single, longer daily exercise session.

Other considerations

The ability of the skeleton to respond to mechanical loading can be either constrained or enabled by nutritional or endocrine factors. One example of this is calcium insufficiency, which diminishes the effectiveness of mechanical loading to increase bone mass (66). Another example is estrogen status. The independent effects of estrogen on bone metabolism are well described, but recent studies have determined that the adaptive response of bone cells to mechanical stress involves the estrogen receptor; blocking the estrogen receptor impairs the bone formation response to mechanical stress (133). This observation has led to the hypothesis that a down-regulation of estrogen receptors as a consequence of postmenopausal estrogen deficiency decreases the sensitivity of bone to mechanical loading.

The mechanisms of mechanotransduction in bone (i.e., how mechanical forces are translated into metabolic signals) remain to be elucidated, and the discovery of key elements in the mechanistic pathways will likely reveal factors, potentially modifiable, that influence the osteogenic response to loading. As an example, it has been observed that prostaglandins and nitric oxide are produced by bone cells in response to mechanical loading, and that blocking their production impairs the bone formation response (16,115). The translation of such information generated from studies of animals and cultured bone cells will be critical in finding strategies to maximize the osteogenic effects of physical activity in humans.

HUMAN STUDIES

In humans, physical activity appears to play an important role in *maximizing bone mass* during childhood and the early adult years, *maintaining bone mass* through the fifth decade, *attenuating bone loss* with aging, and *reducing falls and fractures* in the elderly. The benefits of physical activity on bone health have typically been judged by measuring associations of physical activity level with bone mass and, in fewer studies, incidence of fractures, or by evaluating changes in bone mass that occur in response to a change in physical activity level or to a specific exercise training program. In evaluating the osteogenic effects of exercise training programs, the following principles should be noted:

Specificity. Only skeletal sites exposed to a change in daily loading forces undergo adaptation.

Overload. An adaptive response occurs only when the loading stimulus exceeds usual loading conditions; continued adaptation requires a progressively increasing overload.

Reversibility. The benefits of exercise on bone may not persist if the exercise is markedly reduced. However, the rate at which bone is lost when an exercise program is discontinued, and whether this is different in young vs older individuals, is not well understood.

The associations of physical activity and specific types of exercise with bone mass have been assessed in a variety of research paradigms. As reviewed previously (51,123), the majority of studies have been cross-sectional, comparing nonathletes with athletes who participate in a variety of sports, or comparing people who report being sedentary with those who report varying levels of physical activity. Because of the numerous confounding factors inherent to cross-sectional studies, these will be discussed only briefly. The response of bone to changes in physical activity and exercise training has also been assessed, including prospective studies (e.g., athletes followed through peak and off-season training cycles) and controlled intervention studies in which physical activity is increased (e.g., exercise training) or decreased (e.g., bed rest). Perhaps the most compelling evidence that mechanical loading is essential to bone integrity comes from studies of bed rest, space flight, and spinal cord injury, which demonstrate that bone loss is rapid and profound when mechanical forces acting on the skeleton are markedly diminished (31).

Further research is needed to better understand the interactions of physical activity with genetics, diet, hormones, overuse, and other factors, with respect to the influence on bone health. However, due to a paucity of evidence to date, these issues will not be addressed.

Role of physical activity in maximizing bone mass in children and adolescents

A primary factor associated with risk for osteoporosis is the peak bone mass developed during childhood and the early adult years. Cross-sectional data suggest that trabecular bone loss begins as early as the third decade, whereas cortical bone increases or remains constant until the fifth decade (74,100). One longitudinal study found that both cortical and trabecular bone mass continued to increase slightly in healthy young women well into the third decade (99).

It has been observed that bone mass is higher in children who are physically active than in those who are less active (108), and higher in children who participate in activities that generate high impact forces (e.g., gymnastics and ballet) than in those who engage in activities that impart lower impact forces (e.g., walking) or are not weight bearing (e.g., swimming) (12,19,58). Recent studies have focused on jumping and other high-impact activities based on the theory that high-intensity forces, imposed rapidly, produce greater gains in bone mass than low- to moderate-intensity forces (29,70,72,78,83,96). Ground-reaction forces during jumping can reach 6–8 times body weight and some gymnastics maneuvers generate forces that are 10–15 times body weight; in contrast, ground-reaction forces during walking or running are 1–2 times body weight (79). Most of the intervention studies of children were implemented as part of school programs and lasted between 7 and 20 months (29,70,72,78,83,96). These studies uniformly found that children who participated in the experimental high-impact jumping and calisthenics programs increased bone mass to a greater extent than children who participated in usual activities. One study that added weight lifting to other high-impact loading exercises found robust increases in bone mass of the hip, spine, and total body (83). Based on this evidence, it is recommended that physical activity for children should include activities that generate relatively high ground-reaction forces, such as jumping, skipping, and running and, possibly, strengthening exercises.

Peak bone mineral accrual rate has been reported to occur at puberty (2), with 26% of adult total body bone mineral accrued within a 2-yr period of this time (3). Thus, the peri-pubertal period may represent a relatively short window of time in which to maximize peak bone mass. Cross-sectional studies indicate that male and female adolescent athletes have higher, site-specific BMD when compared with nonathletic adolescents (123). The effect is most pronounced in athletes who participate in sports that generate high-intensity ground- or joint-reaction forces (e.g., gymnastics, weight lifting) and less pronounced in athletes who participate in sports that generate lower-intensity loading forces.

There have been few exercise intervention studies of adolescents, all involving girls only, with contradictory results. No significant changes in BMD were found in response to 6 months of resistance training (7), 9 months of resistance training and plyometrics with weighted vests (129), or 9 months of step aerobics and plyometrics (44). In contrast, significant increases in BMD occurred in response to 3 yr of artistic gymnastics (65), or 15 months of resistance training (89). The most obvious difference between the studies that elicited an effect of exercise and those that failed to do so was the duration of the intervention. However, these studies involved a very small number of participants and must be interpreted cautiously. There have been no well-controlled studies that isolated the effects of exercise training duration on the bone response, independent of changes in exercise volume or intensity.

Three studies have attempted to determine at what point in the peri-pubertal period the skeleton is most responsive to the benefits of physical activity or exercise training. One study determined the effect of 9 months of step aerobics and plyometrics on bone mineral content (BMC) in premenarcheal and postmenarcheal girls; control subjects were matched on menarche status. BMC increased in response to exercise in premenarcheal girls only (44). Another study assessed the effect of 7 months of plyometrics on BMC and BMD in prepubertal (Tanner stage I) and early pubertal (Tanner stages II and III) girls. Significant bone gains were observed in the early pubertal, but not the prepubertal, girls when compared with controls (71). A cross-sectional study evaluated humeral BMD of both the dominant and nondominant arms of female junior tennis players matched with controls for Tanner stage of maturity (39). Bilateral differences in BMD were similar in athletes and controls at Tanner stage I (9.4 yr), but became progressively larger in athletes at Tanner stages II (10.8 yr), III (12.6 yr), and IV (13.5 yr) with a plateau at stage V (15.5 yr). Based on these observations, bone appears to be most responsive to mechanical stress during Tanner stages II through IV, corresponding to the 2-yr window that has been identified (3) for peak bone mineral accrual around the time of puberty.

There remains a need for further research to elucidate the best type and duration of exercise to augment bone accrual and the time during the growth period when loading is most effective. The evidence to date supports the same prescription noted previously for children (i.e., relatively high impact and strengthening activities, such as plyometrics, gymnastics, soccer, volleyball, and resistance training). These activities appear to be most effective in promoting bone mineral accrual when started before or in the early pubertal period. Further, because measures of bone geometry may emerge as important determinants of bone strength that are independent of BMD (96), and because it seems plausible that geometric factors could be particularly responsive to mechanical stress during periods of growth, it will be important to determine the influence of exercise on bone geometry in children and adolescents.

Role of physical activity in young adults

Because peak bone mass is thought to be attained by the end of the third decade, the early adult years may be the final opportunity for its augmentation. Numerous cross-sectional studies of male and female athletes representing a variety of sports suggest that athletes have higher, site-specific BMD values when compared with nonathletes (123). BMD values tend to be highest in athletes who participate in sports that involve high-intensity loading forces, such as gymnastics, weight lifting, and body building, and lowest in athletes who participate in non–weight bearing sports such as swimming. As noted previously, inherent limitations of cross-sectional studies include confounding variables such as genetics, self-selection, diet, hormones, and other factors.

A handful of prospective, controlled studies of athletes have monitored changes in bone mass through periods of training or detraining. Bilateral differences in arm BMC of national level male tennis players (13–25%) were significantly greater than in controls (1–5%) and persisted after 4 yr of retirement (63). Studies of runners, rowers, power athletes, and gymnasts, ranging in duration from 7 months to 2 yr all showed significant increases (1–5%) in either BMC or BMD of skeletal regions loaded by the specific type of exercise performed during periods of training (123). In competitive gymnasts followed for 2 yr (111), BMD increased during the competitive seasons (2–4%) and decreased during the off-seasons (1%).

A number of intervention studies ranging in duration from 6 to 36 months have evaluated the effects of exercises that generate relatively high ground-reaction and/or joint-reaction forces (e.g., resistance training, plyometrics) on bone mass of previously sedentary women. The majority of these studies found significant increases in femoral neck and/or lumbar spine BMD (1–5%) (4,5,28,43,68,77, 112,128). In two of three studies of resistance training that failed to elicit a significant effect on BMD, exercise intensity was only low to moderate (i.e., 60% or less of 1-repetition maximum, 1RM) (34,107). Exercise intensity was high in the third study (i.e., 80% 1RM; 5 sets; 10 repetitions; 4 $d \cdot wk^{-1}$) (122), but only the unilateral leg press exercise was performed and this exercise may have lacked site-specificity for adaptation of the spine and femoral neck because it was performed in a seated position (109). Two studies found an unexpected decrease in BMD in response to relatively high-impact exercise. In one (101), there was no change in femoral neck BMD but a 4% decrease in lumbar spine BMD after 9 months of resistance training; exercise intensity was moderate (i.e., 70% 1RM). In the other (124), there was a significant increase in total body BMC (1–2%), a nonsignificant increase in spine BMD (1%), and a significant decrease in femoral neck BMD (1.5%) in response to 2 yr of resistance training and rope skipping; however, exercise compliance was poor (i.e., 45%). Thus, although there is evidence that exercise training can increase BMD in young adult women, a number of factors such as intensity of loading forces, site-specificity of the exercise, and adherence to the program may be important determinants of the relative effectiveness.

Exercise training that generates high-intensity loading forces (i.e., high strain magnitude) may also induce changes in body composition (i.e., fat and fat-free mass) and muscular strength. This has stimulated interest in the potential additive and interactive effects of changes in body composition and strength with the direct effects of mechanical loading on BMD. Significant correlations of body mass, fat mass, fat-free mass, and strength with total and regional BMD have been found in several studies, with these factors accounting for up to 50% of the variance in BMD (109,113). Weight lifters typically have high levels of fat-free mass and strength compared with other athletes and BMD also tends to be highest in these athletes. For exercises, such as weight lifting, that introduce loading forces to the skeleton primarily through joint-reaction forces (i.e., muscle contractions) rather than ground-reaction forces, it seems likely that increases in bone mass will occur only if the exercise is of sufficient intensity to cause an increase in muscle mass.

Although physical activities that involve high-intensity skeletal loading are recommended to optimize and maintain bone mass in young adults, the benefits may not be realized in the presence of hormonal or dietary deficiencies or an overuse syndrome. The Female Athlete Triad, consisting of disordered eating, amenorrhea, and osteoporosis, is an example of the ineffectiveness of exercise to fully counteract the deleterious effects of other factors on bone health; this is reviewed in an ACSM Position Stand on this topic (94). Calcium and other nutritional deficiencies that can limit the osteogenic effects of exercise have been reviewed previously (67), as have overuse syndromes such as stress fractures resulting from extreme, repetitive loading forces (10).

Role of physical activity in middle-aged and older adults

Bone mass decreases by about 0.5% per year or more after the age of 40, regardless of sex or ethnicity. In this context, it is important to recognize that benefits of exercise in middle-aged and older people may be reflected by an attenuation in the rate of bone loss, rather than an increase in bone mass. The rate of loss varies by skeletal region and is likely influenced by such factors as genetics, nutrition, hormonal status, and habitual physical activity, making it difficult to determine the extent to which the decline in bone mass is an inevitable consequence of the aging process. In women, estrogen withdrawal at the menopause results in rapid bone loss that is distinct from the slower age-related bone loss. Comparisons of pre- and postmenopausal athletes suggest that even very vigorous levels of physical activity do not prevent the menopause-induced loss of bone mineral (32,41,59,81,103). There have been no intervention studies of perimenopausal women to determine whether exercise can attenuate the loss of bone during the menopausal transition. However, the Nurses' Health Study (24) examined the interaction between use of hormone therapy and physical activity with respect to relative risk for hip fracture. Hip fracture risk was reduced by 60–70% in women on hormone therapy, regardless of physical activity level, when compared with sedentary women not on hormone therapy. Among women not on hormone therapy, those in the highest quintile of physical activity ($>$24 MET·h·wk^{-1}) also had a 67% reduction in hip fracture risk, suggesting that a high level of physical activity may prevent fractures even if it does not attenuate bone loss. Fat-free mass remains a stronger determinant of bone mass with aging than either total mass or fat mass, although fat mass may also be an independent determinant (1,6). Thus, physical activities that help preserve muscle mass (e.g., resistance exercise) may also be effective in preserving bone mass.

The effect of exercise intervention on bone mass of postmenopausal women has received considerable attention over the past three decades; exercise programs have included brisk walking, jogging, stair climbing/descending, rowing, weight lifting, and/or jumping exercises. The general conclusion from meta-analyses of published studies is that a variety of types of exercise can be effective in preserving bone mass of older women (54,55).

Walking exercise programs of up to 1 yr have yielded only modest effects (88), if any (13,88), on the preservation of bone mass. This is not surprising as walking does not generate high-intensity loading forces, nor does it represent a unique stimulus to bone in most individuals. These findings do not rule out the possibility that habitual walking for many years helps to preserve bone. Studies that included activities with higher intensity loading forces, such as stair climbing and jogging, generally found a more positive skeletal response (17,23,60,90,95,98).

Exercise intervention trials that included high-intensity progressive resistance training have found increases in hip and spine BMD in estrogen-deficient women (22,56,57,60,82,87) and in women on hormone therapy (HT) (35,82). Moderate-intensity resistance training has not been found to generate the same increases in hip BMD as high-intensity training (56,57). In one study, the increase in BMD was linearly related to the total amount of weight lifted in a progressive resistance exercise training program (22).

The osteogenic response to jumping exercise (i.e., performing vertical jumps from a standing position) appears to be less robust in postmenopausal women than in children and young adults. Jumping exercise that increased hip BMD of premenopausal women was not effective in postmenopausal women not on HT, even when the duration of the exercise program was extended (5). Although not significant, the response of postmenopausal women on HT was intermediate to that of the pre- and postmenopausal women not on HT. It should be noted that the exercise stimulus in the study was constant, rather than progressive as would typically be prescribed. In a 5-yr study of a small group of postmenopausal women, exercisers who wore weighted vests averaging 5 kg during jumping activity preserved hip BMD to a greater extent than control subjects (110). There is preliminary evidence that combining exercise with bisphosphonate therapy may be effective in preventing osteoporotic fractures (119).

Recent findings that estrogen receptor antagonists impair the response of bone cells to mechanical stress (15) have raised the possibility that a down-regulation of estrogen receptors as a consequence of postmenopausal estrogen deficiency decreases the sensitivity of bone to mechanical loading (49). Indeed, there is evidence that exercises that generate high-intensity loading forces are more effective in increasing BMD in postmenopausal women on HT than in women not on HT (61,62,82,90), although this is not a uniform finding (42). It is also not clear whether the effects of mechanical stress and HT are independent, or whether HT modulates the response of bone to mechanical stress.

The vast majority of osteoporosis prevention research has focused on women because the incidence of osteoporotic fractures does not increase markedly in men until the eighth or ninth decade (21). Research on the effectiveness of physical activity to preserve bone health of men is therefore sparse, but is becoming increasingly important due to the growing numbers of elderly men.

A strong association between BMD and jogging was observed in 4254 men, aged 20–59 yr (86). Men who jogged nine or more times per month had higher BMD levels than men who jogged less frequently. In a 5-yr prospective study of middle-aged and older runners (81), the rate of bone loss was attenuated in runners compared with controls. Among the runners, decreases in BMD were most pronounced in men who substantially decreased their running volume. The general conclusion from a meta-analysis of published exercise intervention studies was that exercise can improve or maintain BMD in men (53).

Several studies have evaluated the effects of resistance training on bone mass in older men (9,73,76,80,130). The duration of exercise ranged from 3 to 24 months and exercise intensity was moderate to high. All but one (76) of the studies found beneficial effects of resistance training on BMD, most commonly at the femur; the study that did not find a benefit used a moderate exercise intensity. In general, the improvements in BMD in response to exercise were of the same relative magnitude as has been observed in women, although much larger increases were observed in male heart transplant patients who performed 6 months of resistance exercise training (9). Thus, the types of exercise programs that help to preserve bone mass in older women also appear to be effective in men.

Physical activity and fracture risk

Osteoporotic fractures occur with minimal trauma in bones weakened because of low BMD or unfavorable geometry (e.g., length or angle of the neck region of the proximal femur). The most common sites of osteoporotic fractures are the distal radius, spine, and the neck and trochanteric regions of the femur. There have been no randomized, controlled trials of the effectiveness of exercise to reduce fractures, and such a trial would be extremely challenging to conduct, in part because of the large sample size and long period of observation that would be required. There is encouraging evidence from a study conducted on a small sample of postmenopausal women that a 2-yr trial of back strengthening exercises reduced the incidence of vertebral fractures over the subsequent 8 yr (106). However, little other evidence exists from prospective trials that physical activity reduces the incidence of vertebral or wrist fractures (36).

There is considerable evidence from epidemiologic studies that physical inactivity is a risk factor for hip fracture. The incidence of hip fracture has been found to be 20–40% lower in individuals who report being physically active than in those who report being sedentary (37,75). Elderly women and men who were chronically inactive (i.e., rare stair climbing, gardening, or other weight-bearing activities) were more than twice as likely to sustain a hip fracture as those who were physically active, even after adjusting for differences in body mass index, smoking, alcohol intake, and dependence in daily activities (18). A prospective study of more than 30,000 Danish men and women found that the incidence of hip fracture in active people who became sedentary was twice as high as in those who remained physically active (45). In the Finnish Twin Cohort, men who reported participation in vigorous physical activity had a 62% lower relative risk of hip fracture than men who indicated they did not participate in vigorous physical activity (64). The Nurses' Health Study of more than 61,000 postmenopausal women suggested that the relative risk of hip fracture was reduced by 6% for every 3 MET·h·wk^{-1} of physical activity, which is roughly equivalent to 1 h of walking per week (24). Interestingly, women who reported walking at least 4 h·wk^{-1} had a 41% lower risk of hip fracture compared with sedentary peers who walked less than 1 h·wk^{-1}. This suggests that even low-intensity weight-bearing activity, such as walking, may be beneficial in lowering fracture risk, even though minimal changes in BMD would be expected.

Regular physical activity may help to prevent fractures by preserving bone mass and/or by reducing the incidence of injurious falls. Many factors contribute to falling, including diminished postural control, poor vision, reduced muscle strength, reduced lower limb range of motion, and cognitive impairment, as well as such extrinsic factors as psychotropic medications and tripping hazards. Exercise interventions will be effective in reducing falls only if they are directed to individuals in whom the cause of falling involves factors that are amenable to improvement with exercise (e.g., poor muscle strength, balance, or range of motion). Reviews and meta-analyses of randomized trials (14,30,37) suggest that exercise trials that included balance, leg strength, flexibility, and/or endurance training effectively reduced risk of falling in older adults.

It must be noted that some studies have found little or no effect of exercise interventions on the incidence of falls (69,84). A recent Cochrane database review concluded that exercise alone does not reduce fall risk in elderly women and men (33). One reason forwarded for the lack of a positive effect was that studies frequently targeted very frail nursing home residents, who likely had multiple risk factors for falling that would not be expected to be ameliorated by exercise (e.g., poor vision). Further, if the exercise intensity is too low (common in studies of the frail elderly), only minimal gains in muscle strength that might help reduce falling risk are achieved. Lastly, it must be recognized that the opportunity for falling probably increases as people become more physically active, particularly in community-dwelling elderly (97,114).

The type of exercise regimen most likely to reduce falls remains unclear (14), because studies with positive and negative findings overlap a great deal in the type of activity utilized (i.e., oriented to strength, endurance, balance, or flexibility), duration of exercise, and frequency of training sessions (51). It appears that balance training is a critical component of these programs and should be included in exercise interventions for older individuals at risk of falling. Improving muscle strength has been posited as potentially one of the most effective means of reducing falls and fracture incidence in the elderly because of its beneficial effects on multiple risk factors for fracture, such as low BMD, slow walking speed, low levels of energy-absorbing soft tissue, and immobility (75). There is further evidence that the gains in functional abilities after a course of resistance training lead to an increase in voluntary physical activity in older adults (46) as well as in the very elderly living in nursing homes (25). The capacity of even frail elderly to exercise at relatively high intensities may be habitually underestimated, though the feasibility of establishing community programs that utilize the intensive training that has been found to increase muscle strength and improve functional ability (25) is likely limited by the challenges of implementing such programs outside a research setting.

CONCLUSIONS

Weight-bearing physical activity has beneficial effects on bone health across the age spectrum. There is evidence that physical activities that generate relatively high-intensity loading forces, such as plyometrics, gymnastics, and high-intensity resistance training, augment bone mineral accrual in children and adolescents. This is compatible with the findings from studies of animals that the osteogenic response to mechanical stress is maximized by dynamic loading forces that engender a high strain magnitude and rate. Further, there is some evidence that exercise-induced gains in bone mass in children are maintained into adulthood, suggesting that physical activity habits during childhood may have long-lasting benefits on bone health. It is not yet possible to describe in detail an exercise program for children and adolescents that will optimize peak bone mass, because quantitative dose-response studies are lacking. However, evidence from multiple small randomized, controlled trials suggests that *the following exercise prescription will augment bone mineral accrual in children and adolescents*:

Mode: impact activities, such as gymnastics, plyometrics, and jumping, and moderate intensity resistance training; participation in sports that involve running and jumping (soccer, basketball) is likely to be of benefit, but scientific evidence is lacking

Intensity: high, in terms of bone-loading forces; for safety reasons, resistance training should be $\leq$60% of 1RM

Frequency: at least 3 $\text{d}\cdot\text{wk}^{-1}$

Duration: 10–20 min (2 times per day or more may be more effective)

During adulthood, the primary goal of physical activity should be to maintain bone mass. Whether adults can increase BMD significantly through exercise training remains equivocal. When increases have been reported, it has been in response to relatively high intensity weight-bearing endurance or resistance exercise; gains in BMD do not appear to be preserved when the exercise is discontinued. Observational studies suggest that the age-related decline in BMD is attenuated, and the relative risk for fracture is reduced, in people who are physically active, even when the activity is not particularly vigorous. However, there have been no large randomized, controlled trials to confirm these observations, nor have there been adequate dose-response studies to determine the volume of physical activity required for such benefits. Animal research has demonstrated that mechanical loading generates improvements in bone strength (i.e., resistance to fracture) that are disproportionately larger than the increases in bone mass. This supports the concept that physical activity can reduce fracture risk even in the absence of changes in BMD. Confirmation of this in humans will require large randomized, controlled trials of the effects of physical activity on fracture incidence, although further advancements in technology to enable the *in vivo* assessment of bone strength will provide insight regarding whether this occurs. Evidence from multiple small randomized, controlled trials of the effectiveness of exercise to increase or maintain BMD suggests that the bone health of adults will be favorably influenced by the maintenance of a high level of daily physical activity, as recommended by the U.S. Surgeon General (117), if the activity is weight-bearing in nature. It is important to note that, although physical activity may counteract to some extent the aging-related decline in bone mass, there is currently no strong evidence that even vigorous physical activity attenuates the menopause-related loss of bone mineral in women. Thus, pharmacologic therapy for the prevention of osteoporosis may be indicated even for those postmenopausal women who are habitually physically active. Given the current state of knowledge from multiple small randomized, controlled trials and epidemiological studies, *the following exercise prescription is recommended to help preserve bone health during adulthood*:

Mode: weight-bearing endurance activities (tennis; stair climbing; jogging, at least intermittently during walking), activities that involve jumping (volleyball, basketball), and resistance exercise (weight lifting)

Intensity: moderate to high, in terms of bone-loading forces

Frequency: weight-bearing endurance activities 3–5 times per week; resistance exercise 2–3 times per week

Duration: 30–60 min·d^{-1} of a combination of weight-bearing endurance activities, activities that involve jumping, and resistance exercise that targets all major muscle groups

It is not currently possible to easily quantify exercise intensity in terms of bone-loading forces, particularly for weight-bearing endurance activities. However, in general, the magnitude of bone-loading forces increases in parallel with increasing exercise intensity quantified by conventional methods (e.g., percent of maximal heart rate or percent of 1RM).

The general recommendation that adults maintain a relatively high level of weight-bearing physical activity for bone health does not have an upper age limit, but as age increases so, too, does the need for ensuring that physical activities can be performed safely. In light of the rapid and profound effects of immobilization and bed rest on bone loss, and the poor prognosis for recovery of mineral after remobilization, even the frailest elderly should remain as physically active as their health permits to preserve skeletal integrity. *Exercise programs for elderly women and men should include not only weight-bearing endurance and resistance activities aimed at preserving bone mass, but also activities designed to improve balance and prevent falls.*

Maintaining a vigorous level of physical activity across the lifespan should be viewed as an essential component of the prescription for achieving and maintaining optimal bone health. Further research will be required to define the type and quantity of physical activity that will be most effective in developing and maintaining skeletal integrity and minimizing fracture risk.

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