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Physical Activity and Bone Health

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Individuals who cannot tolerate high-impact modes of exercise should consider lower impact activities or progressive weight training that involves upper and lower body muscle groups.


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Abstract

Osteoporosis and related fractures cause significant morbidity and mortality worldwide and result in enormous costs to affected individuals and society. Lifestyle choices across the lifespan impact osteoporosis and fracture risk. Physical activity is a viable strategy for the prevention and treatment of low bone mass.

Introduction: Osteoporosis

Osteoporosis, which is defined as "low bone mass and micro-architectural deterioration of bone tissue, leading to enhanced bone fragility and a consequent increase in fracture risk",[1] is the most prevalent bone disorder. Currently, more than 75 million people in the United States, Europe, and Japan are diagnosed with osteoporosis, and over 4.5 million fractures occur annually in the United States and Europe.[2] Due to the increase in the aging population and the rise in life expectancy in recent years, the incidence of osteoporosis and related fracture risks are expected to increase.[3] According to the World Health Organization, osteoporosis is defined as a bone mineral density (BMD) that is two-and-a-half standard deviations or more below the average value for a young adult (T-score < -2.5).[2] Osteopenia is characterized as low bone mass, and is defined as a BMD that is between one and two-and-a-half standard deviations below the young adult mean (T-score between -1 and -2.5).[2] Low BMD is associated with increased risk of non-traumatic fracture; fracture risk is increased 1.5 to 3-fold or greater for each standard deviation decrease in BMD.[4]

Hip fracture is responsible for most of the mortality and morbidity associated with osteoporosis, and it is the leading cause of disability in the elderly.[1] It is well-established that the risk of death post-hip fracture is increased during the first three to six months after the injury.[5] Compared with women, men have a significantly greater risk for complications after a hip fracture, including increased morbidity, mortality, loss of independence, and rate of institutionalization.[5,6] While hip fractures are associated with mortality, spine fractures are known to be a common source of pain, deformity, loss of height, and disability.[5] Among individuals with osteoporosis, a high proportion are bedridden with serious, life-threating complications.[2] Consequently, osteoporosis is a leading cause of mortality, morbidity, and medical expense worldwide,[2] as well as in the United States.[1]

Risk Factors for Fragility Fracture

Although BMD is an important determinant of fracture risk, non-traumatic fractures occur in individuals with normal BMD. In addition to BMD, there are other skeletal (e.g., abnormal rates of bone turnover) and non-skeletal (e.g., falling) risk factors for fragility fracture. Therefore, assessment of fracture risk should consider additional factors that predict risk independent of BMD.[7] Recently, a tool that evaluates fracture risk based on multiple clinical risk factors (See Table 1) was developed for assessment of fracture risk.[8, 9] FRAX® (www.shef.ac.uk/FRAX) computes the 10-year probability of hip fracture or a major osteoporotic fracture, which includes a clinical spine, hip, forearm or humerus fracture. The FRAX® tool more accurately predicts fracture risk than predictions based only on BMD.[8]

Table 1
Clinical Risk Factors for Fragility Fracture

- Age
- Sex
- Low body mass index
- Previous fragility fracture
- Parental history of fracture
- Glucocorticoid treatment
- Current cigarette smoking
- Alcohol use (>3 drinks/day)
- Rheumatoid arthritis
- Hypogonadism
- Physical inactivity, immobilization
- Thyroid disorders
- Diabetes

Treatment of Osteoporosis

There are two categories of drugs for the treatment of osteoporosis: anti-resorptives, which slow the rate of bone breakdown (resorption) and reduce fracture risk; and anabolics, which enhance bone formation, thereby lowering fracture risk. Although there is evidence supporting the efficacy of osteoporosis medications to improve bone health, the osteoporosis drugs are not without serious side effects. For example, the anti-resorptive bisphosphonates are associated with bone, joint or muscle pain, nausea, difficulty swallowing, heartburn, esophagitis, gastric ulcer, flu-like symptoms (intravenous bisphosphonates), osteonecrosis of the jaw, and spontaneous femur fractures (NOF). Estrogen therapy and estrogen plus progesterone therapy, which are used to prevent osteoporosis in women, may increase the risk of estrogen-sensitive cancers. In addition, some osteoporosis medications must be administered by injection or intravenously. Therefore, it is not surprising that drug treatments for osteoporosis have low rates of compliance and persistence, and most patients who stop taking their osteoporosis medication do not restart.[10]

Exercise-based interventions are an attractive alternative to medication due to the reduced cost, fewer serious side effects, and additional health benefits, including improved balance and fall reduction (See Figure 1).[11] Moreover, because osteoporotic fractures occur most frequently at the hip and spine, site-specific interventions to increase BMD are highly desirable. Physical activity allows for targeted strengthening of the hip and spine because sufficient skeletal loading stimulates net bone formation at the stressed skeletal sites.[12]

Prevention of Osteoporosis

Acquisition of at least 90% of peak bone mass occurs by age 18, with additional gains of 5% to 10% during young adulthood. Bone formation and bone resorption markers both decrease in pre-menopausal women and in men between the ages of 20 and 50, thus suggesting bone homeostasis.[13] Around age 50 in men and after menopause in women, bone resorption is significantly increased, thereby reducing bone mass.[13] Because bone mass declines with aging, maximization of peak bone mass has been recommended as one the most effective ways to prevent osteoporosis.[14] Nutrient deficiencies, endocrine disorders or physical inactivity during this critical period of skeletal growth can have lasting deleterious effects onbone health.[14] After acquisition of peak bone mass has occurred, minimizing the rate of age-related loss of bone mass and strength is the primary strategy for prevention of osteoporosis.

Figure 1
Exercise-based interventions are an attractive alternative to medication due to the reduced cost, fewer serious side effects, and additional health benefits, including improved balance and fall reduction.

Physical Activity

Physical inactivity is a modifiable risk factor for osteoporosis, and increasing physical activity at any point throughout the lifespan positively affects bone health,[15-19] while reductions in physical activity can result in bone loss.[20, 21] Cross-sectional and longitudinal studies have shown that the skeletal benefits of physical activity during adolescence persist into young adulthood, while activity-associated bone loading during young adulthood increases BMD in middle-age and older adulthood. In addition to increasing BMD, bone loading during adulthood increases bone size, cortical area and strength[22] and reduces hip fracture risk later in life.[18]

The American College of Sports Medicine recommends weight-bearing endurance activities, including those that involve jumping (such as tennis) and jogging, three to five times per week and resistance exercise two to three times per week to preserve bone health during adulthood.[23] Resistance training is recommended by the National Strength and Conditioning Association to increase BMD or to prevent age-associated reductions in BMD.[24] The Surgeon General's Report on Bone Health also recommends progressive resistance training, as well as daily jump-training and participation in weight-bearing recreational activities, for individuals who can tolerate high-impact activity.[1] However, there are no clinical trials that demonstrate the efficacy of these recommendations to decrease fracture incidence, and the effects of exercise-based interventions on BMD are mixed. Thus, the optimal exercise prescription (i.e., exercise mode, intensity, duration, and frequency) for bone health remains to be identified. The design of exercise prescriptions for bone health should be based on the mechanisms by which exercise affects bone and on the mechanical loading characteristics that result in the greatest increases in bone strength.

Exercise can affect bone via multiple mechanisms, including: muscle contraction forces, gravitational loading, and endocrine/paracrine effects. During physical activity, bone is subjected to mechanical forces exerted by muscle contraction and gravitational loading. At the cellular level, bone cells (osteocytes) perceive these mechanical forces as cell deformation, changes in extracellular fluid shear stress, pressure gradients and electric fields.[12] The osteocytes communicate with osteoblasts and osteoclasts to modulate bone formation and resorption thereby changing bone geometry and material properties.[25] Because most modes of physical activity involve both muscle contraction and gravitational loading, it is difficult to determine their relative effects on bone.

Muscle Contraction Forces

It is well accepted that bone adapts to the mechanical demands it is subject to, and muscle contractions contribute a portion of those demands.[26, 27] The importance of skeletal muscle contraction forces to bone mass is supported by the parallel changes in bone mass and muscle strength throughout the lifespan.[26, 28] Similarly, in states of muscular disuse that result in muscle atrophy, such as disease, inactivity, or paralysis, muscle contraction forces are severely reduced and there are site-specific reductions in bone mass and bone strength.[27] Infants born with intrauterine-onset neuromuscular paralysis exhibit normal bone length, but impaired cortical thickness and bone mass.[26] Because a fetus is exposed to a weightless environment in utero, the low bone mass and increased bone fragility observed in these infants can be attributed entirely to the absence of muscle contraction forces.

Site-specific differences in the relationship between skeletal muscle mass and BMD demonstrate the importance of muscle contraction to the preservation of bone mass. Studies of tennis players, in which the BMD of the dominant (i.e., racket) arm is compared to the non-dominant arm, demonstrate that the dominant arm has greater muscle and bone mass than the non-dominant arm.[28] Resistance training of the major muscle groups of the upper and lower body exerts muscle contraction forces on the arm and leg bones. In resistance-trained athletes, skeletal muscle mass is positively associated with BMD of the arms, legs, hip and lumbar spine.[29] In particular, the positive relationship between skeletal muscle mass and BMD of the arm—a non-weight-bearing skeletal site—suggests that muscle contraction forces make a significant contribution to skeletal muscle mass-associated increases in BMD. Cycling, unlike whole-body resistance training, results in repetitive exertion of muscle contraction forces on only the leg bones. Consequently, in cyclists, skeletal muscle mass is positively associated only with leg, but not arm, hip or spine, BMD.[29] Resistance-training intervention studies of either the upper body or unilateral resistance training of the lower body that resulted in increased muscular strength have shown mixed effects on BMD.[28, 30, 31]. However, we found that after 12 months of progressive, periodized resistance training, changes in arm skeletal muscle mass were positively associated with changes in upper body BMD.[31] Thus, there is considerable evidence that muscle contraction forces are important for bone strength.

Gravitational Loading

Gravitational loads are reactive loads resulting from contact between a weighted body (i.e., human) and a substrate (i.e., ground).[32] Gravitational loads are measured via ground reaction forces, which are determined by body mass and the acceleration/deceleration of the activity.[32] During high-impact activities, such as gymnastics, the ground reaction forces can be between 10 and 20 times body weight,[32] while low-impact, weight-bearing, activities

Figure 2
Athletes who play sports, which exert high-impact loading on the skeleton, such as soccer, volleyball, and gymnastics, have greater BMD and stronger bones.[2]

such as walking have ground reaction forces approximately equivalent to body weight.

Gravitational loading has a powerful influence on skeletal health,[32] which is evident by the marked loss of bone that occurs in a weightless environment. For example, during space flight, astronauts lose bone at a rate of up to 1% per week.[33] Although the astronauts are still actively using their muscles during everyday activities, the elimination of gravity and impact forces results in a dramatic loss of bone mass, which is greatest in weight-bearing skeletal sites.[33] Likewise, exercise in a weightless environment cannot prevent that bone loss that occurs in the absence of gravity.[34] Similarly, there is an accelerated rate of bone loss during bed rest.[35] Therefore, the findings from space flight and bed rest studies indicate that gravitational loading is necessary to preserveBMD at weight-bearing sites.[36]

As mentioned above, most modes of physical activity increase both muscle contraction forces and gravitational loading of the skeleton. Consequently, it is very difficult to isolate the effects of muscle contraction forces from those of gravitational loading, and it remains to be determined whether muscle contraction forces or gravitational loading is the dominant osteogenic stimulus.[32] Studies that compare athletes in sports that are non-weight-bearing, but load the skeleton via muscle contraction forces, with athletes in high-impact sports provide some insight into the relative importance of muscle contraction forces and gravitational loading to bone health.

Sports such as cycling and swimming involve muscle contraction forces on skeleton, but because body weight is supported, lack a gravitational loading component. Studies that have compared BMD of cyclists and swimmers to non-athlete controls and to weight-bearing-athletes consistently report that cyclists and swimmers have reduced BMD[37-42] and that differences persist when controlling for differences in body weight or lean body mass.[29, 37] A study comparing runners, cyclists, weight lifters, and non-athlete controls, showed that the cyclists and controls had similar BMD at all sites; whereas the weight lifters and runners had significantly higher BMD.[43]

Athletes who play sports, which exert high-impact loading on the skeleton, such as soccer, volleyball, and gymnastics, have greater BMD and stronger bones (See Figure 2).[27] Similarly, athletes who participate in the highest-impact sports (i.e. basketball and volleyball) have the highest concentrations of serum bone formation markers, as well as the greatest BMD when compared to athletes in moderate-impact sports (i.e. soccer and track), no-impact sports (i.e. swimming), and sedentary controls.[36] Athletes involved in non-impact sports have reduced hip BMD compared with athletes in high- and moderate-impact sports and did not differ from sedentary controls.[36] Thus, the stress associated with high-impact, weight-bearing sports may induce bone formation and enhance osteogenesis at weight-bearing skeletal sites.

Mechanical Loading Characteristics that Optimize Gains in Bone Strength

For well-over a century, it has been known that the stresses placed upon the bone determine its strength and architecture.[44] According to Wolff's Law, "Every change in the form and function of bone…is followed by certain definite changes in the internal architecture, and equally definite alteration in their external conformation in accordance with mathematical laws."[45] In other words, the structural and material properties of bone change in response to mechanical loading. Studies in animal models allow identification of the characteristics of mechanical loading that induce the largest increases in bone strength. Mechanical loading, whether due to muscle contraction or gravitational loading, causes bone deformation. Strain is a measure of the magnitude of bone deformation in response to application of force. Strain magnitude, frequency, rate, and direction all impact bone's response to the applied force, as do the number of loading cycles and "recovery" between application of force.

Strain magnitude (i.e., amount of deformation) affects bone formation, with larger applied forces resulting in greater rates of bone formation. In the middle of the twentieth century, Frost determined that the stresses exerted on a bone must achieve a minimum effective strain before adaption occurs.[46] Thus, the bone deformation must reach a certain point before bone is added; likewise, if the stresses fall below a certain point, bone is lost.[27] Less than a decade later, it was found that the strain had to be dynamic (i.e., cyclic application and removal of external force), as opposed to static (i.e., constant application of external force), to induce an increase in bone strength.[44] More recently, it was determined that the frequency of the dynamic loading also influenced bone adaptions, with higher frequencies resulting in greater bone formation.[47, 48] The strain rate (i.e., the amount of deformation divided by time), which is related to strain magnitude and frequency, also affects the skeletal response to mechanical loading.[49]

Strain rates greater than habitual strain rate result in bone formation, while disuse-associated reductions in strain rate result in bone resorption. The strain direction also affects bone response, such that bone adapts to become stronger in the direction of applied force. For example, bones that are loaded in compression become stronger in compression, while those that are loaded in torsion are more resistant to fracture by application of torque. Thus, the skeletal response is specific to the strain direction, and the greatest bone adaptations happen with dynamic strains, at a magnitude or frequency that can be detected by the bone cells.[48]

In addition to strain characteristics, insertion of "rest" periods between loading cycles, bouts, and blocks enhances bone formation for a given number of loading cycles at a constant strain magnitude and frequency. For example, insertion of a 14-second rest between loading cycles resulted in a two-fold greater increase in bone formation compared with the response to loading with shorter rest intervals.[50] Longer bone-loading exercise bouts (i.e., more loading cycles) do not proportionally increase the bone formation response.[44] The detection of the mechanical signal requires that the bone cells be in a sensitive, receptive state.[48] After as few as 40-100 loading cycles, bone cells are desensitized to mechanical stimuli, such that additional loading, at a strain magnitude and frequency which would normally be osteogenic, has no effect on bone formation.[48] It appears that bone cells regain sensitivity to mechanical loading after ~ two hours and are fully sensitized after eight hours.[51] Likewise, insertion of a one-week rest block in a three-week "training" block resulted in nearly a two-fold greater increase in bone strength compared to three continuous loading blocks.[52]

Atypical stresses applied to bone drive adaptive changes.[44] The stresses that induce osteogenesis are not the numerous cycles of normal stresses that the bone experiences on a day-to-day basis; rather, the strains that induce bone formation are the atypical stresses to which the bone is not habituated.[44, 53] Thus, the bone cells become accustomed to the strains associated with repetitive activities, such as walking or running. However, activities, such as multi-directional jumping, that produce strains to which the bone is not habituated, enhance the bone formation response to increase bone strength.

Based on the our current understanding of the characteristics of mechanical loading that result in the greatest increases in bone strength, the "ideal" exercise prescription for bone health should include the following: load the skeletal sites of interest, high-impact activity, result in dynamic strain, be "unusual" and include rest between loading cycles (10-15 seconds), sessions (eight hours), and blocks (several days). In addition, when it comes to skeletal benefits of exercise, it is important to remember that more is not better—as few as 40-100 loading cycles per day is sufficient.

Practical Applications

The existing data from experimental animals, cross-sectional studies of athletic populations and from exercise-intervention studies support the exercise prescription of weight-bearing endurance exercise, activities that involve jumping, and resistance exercise that targets all major muscle groups for the preservation of bone mass. Ideal modes of activity are those that involve jumping and multi-directional movements, e.g., basketball or plyometrics. Thus, individuals who participate primarily in non-weight-bearing physical activities, such as cycling, swimming, or rowing, should be encouraged to add bone-strengthening activities, including resistance training or jumping, to their training regimes. A simple, ten-minute program of physical activity that incorporates 50 three-inch, multi-directional jumps per day would meet these parameters.[1]

Likewise, resistance training, which increases skeletal muscle mass and strength, may benefit individuals whose primary mode of exercise does not involve impact forces. Individuals who cannot tolerate high-impact modes of exercise should consider lower impact activities or progressive weight training that involves upper and lower body muscle groups. For older adults, for whom falls are a significant contributor to fracture risk, physical activity should aim to improve muscle strength and balance. It is important to note that the maximal benefits of physical activity on bone health depend on adequate nutrient intake, in particular calcium and vitamin D intake, and on normal hormonal status.

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Disclosure

None reported.

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