The Importance of Childhood Physical Activity for Optimal Lifelong Bone Health

Introduction

Physical activity is an important behavior for children’s biological and psychosocial development and as such plays a major role in pediatric health promotion and disease prevention. Some children’s physical activity-related health outcomes are immediately evident; for example, levels of adiposity and blood glucose are objective measures that can be altered in a short time period. Others, like the prevention of osteoporosis, are less obvious since the benefit occurs much later in life. In part, the delayed benefit might be attributable to physically active lifestyles developed during childhood continuing through to adulthood. In addition to the possibility that a physically active lifestyle tracks throughout the lifespan, emerging evidence suggests that pediatric activity-related bone health benefits are sustained even in the absence of continued physical activity.

“Osteoporosis is a disease in which the density and quality of bone are reduced. As the bone becomes more porous and fragile, the risk of fracture greatly increases” (www.iofbonehealth.org/health-professionals/about-osteoporosis.html). Figure 1 shows images of normal and osteoporotic bone. Osteoporotic fractures are considered pathologic fractures because the conditions under which they occur, such as a fall from a standing position, would not be expected to cause a fracture in healthy bone. Osteoporotic fractures have a significant impact on adult health including the loss of function, chronic pain, disfigurement, and loss of independence. About 30 to 50% of women and 15 to 20% of men currently 50 years of age will have an osteoporotic fracture in their remaining lifetime. This cumulative incidence rate is greater than breast cancer in women and prostate cancer in men. Women who sustain an osteoporotic hip fracture have a mortality rate that is 10 to 24% greater than their peers.¹
The risk of osteoporotic fracture is higher for women than for men due to sex-specific growth and aging patterns of bone and, perhaps, lifestyle differences. Pharmaceutical treatment reduces the fracture susceptibility in high-risk women (that is, older women with diagnosed osteoporosis). However, more than 50% of fractures occur in women and men at moderate risk, that is, younger adults or adults with only modest decreased bone mineral density. These data indicate the need for population-wide strategies to reduce osteoporotic fractures. Of the behavioral factors known to influence bone health, such as diet, tobacco consumption, and physical activity, it is physical activity, particularly during childhood and adolescence, that promises the greatest potential for efficient, safe, and accessible population-based interventions to reduce osteoporotic fracture risk later in life. This Research Digest article presents the current scientific understanding of the role of childhood physical activity in bone health and, ultimately, fracture risk. We include recommendations for promoting bone-enhancing physical activity among children and adolescents and conclude with new research suggesting a unique relationship between childhood physical activity and adult bone health.

**Figure 1.** (Left) normal bone, (right) osteoporotic bone. From International Osteoporosis Foundation at (http://www.iofbonehealth.org/health-professionals/about-osteoporosis.html).

**Physical Activity Influences Bone Mass and Structure**

Physical activity influences the amount of bone mass (quantity of bone mineral—primarily calcium and phosphorous) contained in a specific volume of bone, and where the bone mass is distributed. Bone mass distribution is an important characteristic of whole bone structure and is key to minimizing the amount of mineral needed in a cross-section to ensure lightness without decreasing strength. This is significant because the skeleton must be strong for load bearing but also light for mobility. Throughout life, but mainly during the growing years, periosteal apposition (bone gain to the outer surface of bone) increases the diameter of long bones and endocortical resorption (bone loss from the inner surface of bone) enlarges the marrow cavity (shown in Figure 2). The end result is displacement of the cortex (hard compact exterior of bone) away from the neutral axis (middle of the bone in cross-section). Even without an increase in cortical thickness, that is, more bone mineral mass, the displacement of the cortex increases bending strength because resistance to bending is proportional to the fourth power of the distance from the neutral axis. Figure 3 illustrates distribution differences in bones with the same mass. Boys and girls who are more physically active have more favorable bone mass distribution and, therefore, greater bone strength. Physical activity is particularly important during
prepuberty and early puberty, when periosteal apposition is the predominant bone response to increased mechanical loading. Physical activity-related increases in the periosteum during childhood are likely to help maintain the bone’s resistance to fracture with age because adult bone is predominately lost from the endosteal surface. The long-term health implication of this effect has been shown in animal models where exercise-induced alterations to bone structure in young animals persist throughout their lifespan, significantly reducing fracture risk in older age. Presently, there are no long-term longitudinal studies fully tracking this effect in humans.

In addition to improving whole bone structure, childhood physical activity results in more bone mass. During the growing years (when compared to adulthood), bone surfaces are covered with a greater proportion of active osteoblasts. These cells initiate bone formation when stimulated mechanically via the muscle- and weight-bearing forces associated with physical activity. Increase in bone mass rather than change in bone mass distribution appears to be the predominant response to loading with exercise interventions after puberty in females. This is because the onset of menarche and the associated increase in estrogen inhibits periosteal bone formation. Bone mass formation, therefore, occurs on the endosteal surface, which limits the diameter of bone. Although increased bone mass on the endosteal surface increases bone strength, its effect is less than if bone formation occurred on the periosteal surface.

Research supporting the differential effects of physical activity relative to maturity have been reported by Ducher et al. These researchers studied competitive female tennis players who were 10 to 17 years old using a 12-month prospective design. Players, initially stratified according to maturity, were evaluated for bone mass and structure of their playing and non-playing humeri (upper arm). Bone mineral content (the amount of bone mass per square centimeter of bone; BMC) was measured using dual energy X-ray absorptiometry (DXA). Total bone area, marrow area, and cortical area as well as muscle cross-sectional area were measured using magnetic resonance imaging (MRI). At baseline, BMC, total bone area, cortical area, and muscle cross-sectional area were 8 to 18% greater in the playing arm of all girls regardless of their maturity level. However, the post-pubertal girls exhibited a smaller marrow area in the playing versus non-playing arm. After 12 months, the relative side-to-side difference in total bone area, cortical area, and muscle cross-sectional area among the pre- and peri-pubertal players had increased. However, among the post-pubertal players, only BMC and total bone area increased. The 39% greater annual accrual in cortical area in the playing vs. non-playing arm of the pre- and peri-pubertal players was attributed to increased bone gain to the outer surface of bone and not to changes in the endocortical surface. The pre- and peri-pubertal girls also showed increases in muscle cross-sectional area (presumably caused by training) which accounted for ~32% of the variance associated with the exercise-induced bone benefits. This muscle-bone relationship was not observed in the older girls. These results suggest that hormonal changes associated with pubertal growth may override the influence of lean mass among post-pubertal girls. To date, the study by Ducher and colleagues provides some of the best evidence that activity-induced adaptations of bone mass distribution are maturity dependent. Using a targeted (jumping) intervention, Mackelvie et al. conducted a two-year randomized school-based trial to study bone mass and structural changes at the proximal femur in peri-pubescent boys. All of the boys were pre-pubertal at the start of the trial and most were in mid-puberty by the end of the study. DXA data were used to mathematically model the cross-sectional area of the bone and the distribution of the bone mass from the neutral axis. Compared to controls, boys in the intervention group had 4.3% greater bone mass and ~3% greater bone expansion on the periosteal and endosteal surfaces. These effects resulted in a 7.4% increase in bending strength when compared to controls.

The maturity- and sex-specific differences in bone formation draw attention to the importance of early physical activity exposure to optimize bone strength, particularly because girls are typically less active than boys and mature two years sooner (peak height velocity ~12 yr in girls and ~14 yr in boys). These sex-specific growth and maturation patterns explain the 25% difference in peak bone mass between males and females. They also contribute to making women, particularly after menopause, more vulnerable to fractures than men.

**Figure 3.**
Illustration of bone distribution differences for two long bones, each having the same (hypothetical) bone mass. Bone B would have greater bending strength than bone A because its mass is farther away from the neutral axis.


**Physical Activity and Peak Bone Mass**

Peak bone mass (PBM) is the greatest amount of bone mass achieved at the end of the growth period (late adolescence and early adulthood) and as such it is an important marker of future bone health. Bonjour and colleagues have estimated that a one standard deviation (10%) increase in population PBM would reduce fracture risk in older adults by as much as 50%. Although PBM is achieved at the end of the second or third decade, the greatest overall proportion of total bone mineral accrual occurs during the adolescent growth spurt (see Figure 4). On average, the highest PBM accrual occurs between ~11.5 and 13.5 yr in girls and between ~13 and 15 yr in boys. Longitudinal studies of bone development show that nearly 40% of PBM is achieved during the two years before and the two years after peak height velocity. The percentage of bone mineral content acquired during this time is similar to what is lost in the 30 years between 50 to 80 years of age.

Recent findings from exercise interventions conclusively show that impact exercise just prior to puberty leads to gains in bone mass. This speaks to the importance of using physical activity to optimize PBM. Further, if exercise is sustained over time, the benefits likely continue to accrue.

Similar results have also been seen in observational studies. For example, in the Saskatchewan Pediatric Bone Mineral Accrual Study (in which children were followed for six years from late childhood through adolescence), boys and girls who were more

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**Table 1. Physical activity intensity based on oxygen uptake and ground reaction forces.**

<table>
<thead>
<tr>
<th>Oxygen Uptake</th>
<th>Ground Reaction Forces</th>
<th>Criteria</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>4–8 METs</td>
<td>≥ 5 x BW</td>
<td>Activities including jumping actions</td>
<td>Volleyball, basketball, jumping (with or without counter movements, and drop jumps)</td>
</tr>
<tr>
<td></td>
<td>Moderate-high impact PA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7–8 METs</td>
<td>2–5 x BW</td>
<td>Activities including sprinting and turning actions and moderate impact actions</td>
<td>Tennis, jogging, running (general), jumping (lateral jumping, jumping jacks) Stepping</td>
</tr>
<tr>
<td></td>
<td>Weight-bearing PA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2–6 METs</td>
<td>1–2 x BW</td>
<td>Weight-bearing activities (repetitive) Low impact loading</td>
<td>Walking, dancing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4–8 METs</td>
<td>&lt; 1 x BW</td>
<td>Non impact activities</td>
<td>Cycling, aquatic activities for leisure</td>
</tr>
</tbody>
</table>

Information from Ainsworth et al for oxygen uptake and from Groothuesan et al; McKay et al for ground reaction forces. PA: physical activity; BW: body weight; MET: metabolic equivalent.
physically active than their peers had higher total body BMC (17% and 9%, respectively) one year following peak height velocity (PHV).11 In a recent follow-up of the Saskatchewan participants (who are now adults), Baxter-Jones and colleagues (2008) reported a difference of up to 10% BMC between participants who were physically active during adolescence versus those who were inactive.12 The effects were site-specific and gender-specific with benefits observed at the total hip and femoral neck for females and at the total body, total hip, and femoral neck in males. In general, studies indicate that BMC gains associated with physical activity before and during early puberty range from 1 to 6%, whereas gains are considerably smaller thereafter (0.3 to 2%).13 This time frame, just before and during early puberty, has become known as the “window of opportunity” for bone-health programming.

**Physical Activity Dose for Bone Mass and Structural Response**

Energy expenditure is the most important physical activity characteristic for metabolic health. However, when improvements in bone mass and structure are the desired health outcomes, the mechanical load applied to the skeleton is more critical than the metabolic load. The osteogenic potential of physical activity is determined by the dynamic nature of the mechanical load, the rate at which the load is applied, the duration of the loading session, and the magnitude of load. Generally, ground reaction forces expressed in body weight multiples serve as a proxy measure of the magnitude of load. Fortunately, during weight-bearing aerobic activities the magnitude of loading force generally increases in parallel with metabolic activity intensity quantified by the conventional MET method (see Table 1). This parallel increase is not seen in non-weight-bearing aerobic activity such as swimming and cycling. In short, when considering the relationship between physical activity and health, it is necessary to consider the mechanical loading aspect of the activity, which reflects the strain on the bone. When bone is subjected to a strain magnitude that surpasses a threshold (related to its habitual strain range), it responds by increasing bone mass and changing structure. The threshold level varies among individuals and also among bone sites. Inactive children may respond to low impact loading (ground reaction forces 1 to 2 times body weight), while others will need a higher mechanical load to promote a bone response. Importantly, the required frequency of loading decreases as the magnitude of mechanical load increases. In general, greater forces, delivered quickly (through activities such as jumping), appear to convey the greatest benefits to bone mass and structure in children and adolescents. However, bone can be influenced by a few high magnitude events or by several low magnitude events. For example, the accumulation of ~30 min/d of metabolically-vigorous-intensity physical activity, such as jogging, would be expected to lead to bone results equivalent to those produced by the accumulation of 10 to 15 min/d, 2 to 3 times/week of vigorous intensity activities with greater mechanical demands, such as jumping.14-16 This is why high mechanical load activities like jumping, hopping, skipping, and gymnastics do not have to be done daily to affect bone outcomes.

Based on the work of Gunter and colleagues and the available ground reaction force data from other bone loading intervention studies,13 activities with the most osteogenic potential have ground reaction forces greater or equal to 3.5 times body weight. Intervention studies using high impact loading exercises (approximately 100 impacts per session with ground reaction forces > 3.5 times body weight) show significant skeletal benefits when the exercise stimulus is delivered for a sufficient length of time.9,17,18 Research thus far indicates that at least 7 months of exercise is essential to induce a measurable change in bone mass in children.10,13,18 As mentioned earlier, the influence of exercise-

### Table 2.
Summary of physical activity for optimal bone health in children and adolescents.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Impact</th>
<th>Resistance</th>
<th>Aerobic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>≥ 3.5 times body weight</td>
<td>60% of 1 RM</td>
<td>Moderate to vigorous</td>
</tr>
<tr>
<td>Session duration</td>
<td>100 impacts</td>
<td>&gt; 30 minutes</td>
<td>30–40 minutes</td>
</tr>
<tr>
<td>Frequency</td>
<td>3 days per week</td>
<td>3 days per week</td>
<td>daily</td>
</tr>
<tr>
<td>Long-term duration*</td>
<td>≥ 7 months</td>
<td>&gt; 7 months</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Table 2 provides the evidence-based characteristics of an optimal exercise prescription targeted to improve bone health in growing children.  
1 RM = one repetition maximum; *Refers to the required program length in order to observe a measurable improvement in bone.
induced loading is also dependent on maturity status with prepuberty and early puberty as the time when bone's response to loading appears to be most sensitive. Studies examining the effects of everyday physical activity choices on children's bone mass and structure suggest that a daily accumulation of vigorous-intensity physical activity (measured by accelerometry) of approximately 30 to 40 minutes is needed. However, there is much room for further research in the area of dose-response, particularly as national priorities for increasing physical activity levels in youth are focused on combating childhood obesity. The recommended frequency, duration, and intensity for optimal metabolic health are not necessarily optimal for bone health; studies are needed to identify an exercise dose that encompasses both priorities.

At this time, activities with a high-intensity mechanical load (specifically, activities that include jumping), with a duration of 10 to 15 minutes per day, 2 to 3 times a week, or with lower mechanical intensity (activities that include jogging), 30 to 40 min per day, every day, seem to be effective for optimizing bone health. Table 2 shows key points for bone-related physical activity dose. When taking into account other ways in which physical activity impacts health, particularly obesity prevention, children and adolescents should accumulate 60 minutes per day of physical activity, of at least moderate intensity, as specified by the World Health Organization and the U.S. Department of Health and Human Services. Within this physical activity dose, high mechanical load activities should be done three times per week.

Children should also engage in muscle strengthening activities three times per week, which has further benefits for bone health. Muscle mass and muscle strength are positively associated with bone mass and structure. This is because strong muscles apply greater force to the skeleton, which adapts by increasing its own strength. In addition to providing a direct mechanical load, muscle, which is the largest internal body organ, secretes a variety of different substances, collectively known as myokines, that regulate bone mass. Some myokines are growth factors able to stimulate receptors in bone cells which, in turn, increase bone mass. Muscle mass and muscle strength are particularly important for bone health when exposure to weight-bearing loads is reduced, e.g., in children who use wheelchairs or children with osteoarthritis.

**Sustained Benefits of Childhood Activity on Lifelong Bone Health**

Recently the work of several research teams has provided evidence that physical activity during childhood can have a sustained effect on bone health. This suggests that even if children reduce their physical activity as they get older, bone mass and structure changes that occurred due to past physical activity might persist, thereby positively influencing adult bone health. We do not know yet whether these benefits continue into older adulthood when the likelihood of a fragility fracture is greatest. However, the sustained effect of childhood physical activity into adolescence and even young adulthood has been demonstrated in several observational studies. Janz and colleagues grouped young children (age 5) by their activity level and studied the effect of their age-5 physical activity on BMC at age 8 and age 11 yr. Children in the most active quartile at age 5 had adjusted BMC values at age 8 ranging between 6% and 14% greater than those in the lowest activity quartile at age 5. By age 11, those who were most active at age 5 still had 4 to 7% greater BMC (adjusted for age, height, weight, and current physical activity.) While the magnitude of the benefits dampened over time, the benefits of being highly active at age 5 positively affected bone mass into early adolescence. In another prospective, longitudinal study, Baxter-Jones et al. investigated whether children who were most physically active at study entry (age 8 to 15 yr) maintained higher BMC into young adulthood compared to their less active peers. Young adult BMC was evaluated after adjusting for other factors that would be expected to influence BMC, including current physical activity levels. Researchers found that males and females who were most active as children had approximately 8 to 10% more adjusted BMC at the hip as young adults.
Studies of former athletes also provide evidence as to the persistent beneficial effects of early childhood high intensity loading. Scerpella et al.\textsuperscript{25} studied ex-gymnasts who quit competitive gymnastics training around the time of menarche, compared to non-gymnasts. After adjusting for age at menarche, changes in growth, lean mass, and calcium intake, the ex-gymnasts had more BMC and larger bone size in young adulthood (4 to 9 years post-menarche). More evidence that physical activity during growth induces persistent changes comes from Erlandson and colleagues, who reported the results of a 14-year prospective study conducted to assess the persistent effects of gymnastic training on adult bone mass. In 1995, active pre-menarcheal gymnasts, ages 8 to 15 yr, were found to have significantly greater size and maturity-adjusted total body, lumbar spine, and femoral neck BMC compared to controls (15, 17, and 12%, respectively). Fourteen years later, gymnasts who had been retired from the sport for an average of 10 years had maintained similar size- and maturity-adjusted BMC differences (13, 19, and 13%, respectively, at the total body, lumbar spine, and femoral neck).\textsuperscript{26} Finally, Gunter et al. analyzed data from two randomized, controlled trials to show that young children (7 to 8 yr at baseline) participating in 7-month-long jumping interventions maintained a significant proportion of increased BMC (when compared to controls) years after the cessation of training.\textsuperscript{9,10} What is important about these studies is their suggestion that physical activity during childhood can have lasting effects. This highlights the potential for all children to achieve optimal skeletal health through physical activity and, perhaps, benefit from this effect later in life.

**Conclusions**

Optimal bone development is a key reason for promoting physical activity during the growing years—approximately 50% of the variability in bone mass in older adults is due to their degree of earlier bone mineralization. Bone mass and distribution appear to track through childhood, adolescence, and young adulthood.\textsuperscript{12} To achieve maximal benefits, intervention strategies aimed at reducing the incidence of osteoporosis should begin in childhood, when bone appears most sensitive to the effects of physical activity.


