How does Exercise Affect Bone Development during Growth?

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Abstract

It is increasingly accepted that osteoporosis is a paediatric issue. The prepubertal human skeleton is quite sensitive to the mechanical stimulation elicited by physical activity. To achieve the benefits for bone deriving from physical activity, it is not necessary to perform high volumes of exercise, since a notable osteogenic effect may be achieved with just 3 hours of participation in sports. Physical activity or participation in sport should start at prepubertal ages and should be maintained through the pubertal development to obtain the maximal peak bone mass potentially achievable. Starting physical activity prior to the pubertal growth spurt stimulates both bone and skeletal muscle hypertrophy to a greater degree than observed with normal growth in non-physically active children. High strain-eliciting sport like gymnastics, or participation in sports or weight-bearing physical activities like football or handball, are strongly recommended to increase the peak bone mass. Moreover, the increase in lean mass is the most important predictor for bone mineral mass accrual during prepubertal growth throughout the population. Since skeletal muscle is the primary component of lean mass, participation in sport could have not only a direct osteogenic effect, but also an indirect effect by increasing muscle mass and hence the tensions generated on bones during prepubertal years.
Osteoporosis and related fractures are a considerable health concern worldwide. However, the idea that ‘senile osteoporosis is a paediatric disease’ is increasingly accepted. In fact, the WHO proposed that prevention is the most powerful way to fight against the non-communicable diseases, i.e. osteoporosis.

Physical activity, specifically sporting participation during growth, seems to be effective in reducing the prevalence of osteoporosis-related fractures. However, an increased sedentarism in children has also been described, which is even more alarming in girls because they are usually less active than boys. For that reason, it is important to know how sport activities specifically affect bone development, what are the mechanisms involved in the exercise-bone relationship, what is the optimal kind and duration of exercise to stimulate osteogenesis, and when should the participation in sports start to maximise the bone mineral peak attained during growth. All this information could help to design effective, simple, economical and safe physical activity programmes against osteoporosis and its related social and economic costs.

Sport participation during growth seems to increase the peak bone mineral density (BMD) in the weight-loaded bones of the active subjects by between 10% and 20% compared with non-physically active counterparts. This effect could be greater when exercise starts before the pubertal growth spurt. In addition, it is clear that at least 25% of the adult total bone mineral content (BMC) is attained in just a 2-year period of fast bone mineral accrual during growth (11–13 years in girls and 12–14 years in boys). It is also likely that sport participation during this period acts synergistically with the growth-related bone mass accumulation leading to a higher bone mass at the pubertal period.

The body’s soft tissue components (lean and fat masses) have been shown to be related to bone mass. Skeletal muscle development precedes bone mass development in such a way that it has been suggested that the increase of muscle strength accompanying muscle development allows for a greater generation of forces on bone attachment, which stimulate bone growth. Although it was reported that sport participation hardly elicits muscle hypertrophy at a prepubertal age, more recent studies have provided evidence of the opposite, i.e. intensive sport participation is associated with increased acquisition of muscle mass during growth. Then, apart from the direct effect of exercise on bone accrual, exercise could also increase bone acquisition indirectly by increasing muscle mass and, hence, the forces generated on the bones where the hypertrophied muscles attach.

The aim of this article is to summarise current knowledge on the interplay between biological maturation, body composition and exercise on bone mass development during growth.

1. Definitions and Context

Many terms are often used when discussing children and adolescents. ‘Growth’ refers to the dominant biological activity for approximately the first 20 years of human life, through changes in size underlying three cellular processes: (i) increase in cell number (hyperplasia); (ii) increase in cell size (hypertrophy); and (iii) increase in intercellular substances (accretion). All these processes occur during growth; however, the predominance of one or another varies with age and the tissue involved. Bone growth is brought about by hyperplasia, hypertrophy and accretion.

These cellular processes are also involved in maturation. ‘Maturation’ is the progress toward the mature stage, referring to the timing and tempo of the progress. Maturity thus varies with the biological system considered. Skeletal maturity is then a fully ossified adult skeleton. ‘Timing’ refers to when specific maturation event appears, e.g. age at
maximum growth during growth spurt; and ‘tempo’ refers to the rate at which maturation progresses. Timing and tempo vary largely among individuals; this is why sexual development is more consistent than, for example, chronological age.

Finally, pubertal growth spurt can be defined as a 2- to 3-year period of rapid increase in height and weight related to the change in the activity of the hypothalamus with a gradual increase in the secretion of pulses of gonadotrophin-releasing hormone. An increase in gonadotrophin secretion stimulates gonadal growth and sex steroid secretion, and secondary sexual characteristics appear as the concentrations of sex steroids rise.\[32\] For more details, the excellent book by Malina et al.\[33\] is recommended.

2. Biological Maturation, Exercise and Bone Mass

The male has a longer prepubertal period of growth,\[34\] as their pubertal growth spurt occurs 1–2 years later than in girls,\[35,36\] contributing to the sex differences in skeleton proportions,\[34\] e.g. longer lower extremities in males than females. BMC increases linearly, with no sex differences until the onset of the pubertal growth spurt.\[37\] Additionally, boys BMC continues to increase through late adolescence,\[37\] while the girls BMC barely increases after the onset of puberty.\[37\] Specifically, sex differences in bone size and strength are established in puberty as a result of the greater endocortical and periosteal expansion during prepubertal years and the minimal endocortical contraction in males compared with the high endocortical contraction and the inhibition of periosteal apposition in females after the pubertal growth spurt.\[36,38\] As a result, while volumetric density remains constant during growth and similar in both sexes,\[39,40\] BMC is around 20% higher in males compared with females at the age of 16–17 years, simply because their bones are bigger.\[41\] Thus, sex differences in bone strength are the result of the differences in shape and geometry.\[41\]

The question we would like to approach is whether sport participation could affect the normal development of bone during growth. The highest body of knowledge on bone development and exercise has been acquired using dual energy x-ray absorptiometry (DXA) techniques. DXA is a suitable method to study children because of its low irradiation and time needed to perform the scans.\[42\] However, data from DXA must be interpreted carefully because the areal density measured is the amount of BMC per cm\(^2\), so bigger bones have higher areal BMD with a similar real volumetric BMD (g/cm\(^{-3}\)).\[36\] This limitation may be circumvented if areal BMD data are combined with bone- and body size-adjusted BMC.\[37\]

Weight-bearing sport activities generate compressive forces that have been generally proposed as essential stimuli for bone formation and growth.\[42\] Thus, the intermittent compression of the growth plates elicited by the weight-bearing physical activity or exercise is apparently essential for bone growth.\[33\] Additionally, the strains generated on bones before puberty may produce higher cortical bone expansion,\[15,43\] increasing bone strength.\[41\]

Correlational studies suggest a positive relationship between habitual physical activity or sport participation and bone mineralisation, the amount of BMC being higher with higher amounts of physical activity.\[5,17,44,45\] A few years ago, it became clear that the peak of bone mass accumulation velocity occurs around the age of 12–14 years, and that BMC accumulation is greater in more active children.\[5,44,46\] Other studies also indicated that adult athletes who started their sport careers before puberty benefit not only from enhanced BMD but also from enlarged bones,\[12-16\] which are more resistant to fractures.\[41\]

Evidence was lacking, however, on whether sport participation at prepubertal age may elicit a physiologically relevant effect on bone accrual. Additional studies have shown that prepubescent physically
active boys\(^{12,17,47}\) and girls\(^{48-50}\) have higher lumbar spine and/or femoral BMD than their non-physically active peers. Later, controlled trials and longitudinal studies confirmed the prior cross-sectional studies showing that, during the prepubertal years, sport helps bones to accumulate more mineral\(^{30,31,51-54}\). Moreover, the participation in sport elicits structural, shape and size changes in prepubertal children\(^{11,13}\). Vicente-Rodriguez et al.\(^{17}\) reported that prepubertal footballers have 10% larger osseous area at the trochanteric zone than their age-matched non-active controls. Likewise, prepubertal boys involved in a school-based, high-impact circuit intervention (12 minutes, three times a week) for 20 months had greater bone expansion on both the periosteal (+2.6%, \(p = 0.1\)) and endosteal (+2.7%, \(p = 0.2\)) surfaces\(^{55}\). This resulted in a 7.5% increase in bone bending strength, after adjusting for change of height and Tanner Stage (an indicator of sexual development degree regarding to the pubic hair and gonads size as secondary sex characteristics) at the end of the study, and baseline bone values\(^{55}\). Similar results have also been recently observed in prepubertal girls\(^{56}\). These changes in shape and structure are very positive for bone health because they may endure throughout life, in contrast to BMC or BMD changes that may be lost over time with reduced physical activity\(^{57}\).

Thus, there is enough scientific evidence to suggest that sport participation should start before the pubertal growth spurt, given the fact that immature bones are more responsive to mechanical stress\(^{12,17,31,47,51-55,58}\). Testosterone, growth hormone and insulin-like growth factor-1 increase during the pubertal period\(^{42}\), enhancing bone growth and turnover through osteoblastic stimulation\(^{59}\). Estrogen production is low in premenarcheal girls, which makes their bones more responsive to exercise loading\(^{60}\) and increases their size\(^{36,38}\). But, for how long should children be active? Cross-sectional and longitudinal data suggest that it should be possible to elicit a greater enhancement in BMC and BMD if the exercise period extends over a longer period than just the 2-year period of fast bone mineral accrual (11–13 years in girls and 12–14 years in boys\(^{5,16,17,19,31}\)).

An important question is how long the benefits achieved will last if children stop exercising. Some authors have suggested that the gains in bone mass are retained after an equivalent period of detraining\(^{61}\) and even longer\(^{11,62}\). In contrast, it has also been reported that there is a fast BMD loss at the femoral neck after a reduction of sport activity in young men\(^{57}\). However, we lack conclusive data to provide a definitive answer to this question, which will remain pending until longer longitudinal data are available.

### 3. Type and Duration of Sport Participation and Bone Development

The skeleton adapts just to the prevalent level of exercise intensity required and no further\(^{63}\), depending on the mechanical stress that bone must support (for a specific review see Heinonen\(^{64}\)). Previous knowledge suggests that the intensity rather than the duration of the sport activity is the main determinant of BMD\(^{65,66}\). Karlsson et al.\(^{63}\) studied adult male football (soccer) players with different levels and duration (6 vs 8 vs 12 hours/week) of participation in football, and sedentary controls. The footballers, as a group, showed enhanced BMD compared with the controls. However, differences in the amount of participation in football were not paralleled by corresponding difference in bone adaptation\(^{63}\). In fact, exercising for >6 hours/week does not appear to add extra BMD increase in men\(^{63}\). Most of the investigations communicating great sport benefits on bone density have been performed with gymnasts who usually train for many hours per week (>15)\(^{11,48-50,67-71}\). However, in contrast to what has been seen in adults\(^{63}\), it has recently been observed that recreational premenarcheal
gymnasts, having noticeably higher values of BMD than controls, did not reach the percentage differences communicated by other authors in gymnasts with higher volumes of exercise. The latter suggest that the higher the exercise volume the higher the BMD accumulation. Where is the limit? It is not yet known.

Although the most suitable sporting activity for maximal bone growth remains unknown, compelling evidence has accumulated to suggest that participation in weight-bearing sports is fairly efficient in promoting bone acquisition even in prepubertal children. For example, similar osteogenic benefits have been reported with just 3 hours/week of football or handball. Controlled trial jumping interventions have also shown significant increases in bone mass, even with a really low time intervention such as 12 minutes, three times a week. Gymnastics elicits huge strains but the number of impacts is lower than in other sports. Thus, a beneficial effect for bone may be achieved with two different strategies: (i) enrolling children in a high strain-eliciting sport such as gymnastics; or (ii) promoting participation in sports such as football or handball, or weight-bearing physical activities, where the growing skeleton is submitted to frequent strains in different directions, without the need for a volume of exercise >3 hours/week.

Mechanical loads need certain strain magnitude, rate and frequency to be effective to stimulate osteogenesis. For example, Dorado et al. observed that professional golfers have enhanced muscle mass in the playing arm compared with the non-playing arm, as previously reported in tennis players. Despite the fact that both sports elicit muscle hypertrophy in the dominant arm, only the tennis players show an increase of BMD in the dominant compared with the non-dominant arm. Despite similar muscular effects of golf and tennis, the effects on bone are remarkably different, probably due to the greater number of impacts sustained by the dominant arm in the tennis players compared with the golf players. It also seems that high loads have a critical roll in bone mass acquisition during and before puberty. During growth, after the first mineralisation, the bone matrix remains in a dynamic state to allow the bone tissue to reorganise and grow to withstand the new mechanical tensions and load conditions. The mechanostat theory proposes that bone strength is regulated by modelling and remodelling processes depending on forces acting on bones. Bone modelling is a regional response to a loading condition, which increases mechanical bone resistance through the osteoblastic deposit and mineralisation of bone, as well as improving the cortical and the trabecular (internal) architecture with a net gain of bone mass. Thus, actions in sport that involve tensile, compressive, shear, bending and torsion stresses on bones that can elicit mechanostat-related mechanisms during growth have an osteogenic potential.

4. Soft Tissue Development and Bone Mass

Total body mass has for a long time been identified as the best predictor for bone mass in children. The appearance of DXA has facilitated the analysis of the separate influence that fat and lean masses may have on bone mass and density.

4.1 Muscle-Bone-Exercise Relationship

Previous studies documented cross-sectional associations between lean mass (equivalent to muscle mass in the extremities and a surrogate measure of muscle force) and BMC and areal density. Longitudinal studies have confirmed a close relationship between the change in lean mass and bone mass during growth. In 1990, Young et al. started an 8-year longitudinal study of 286 female twins aged 8–26 years at baseline. They concluded that the change in BMC was strong.
ly correlated with the change in lean mass during linear growth (at least 4 years before the onset of menarche). More recently, Forwood et al. observed that the greater increase in lean body mass and the consequent related mechanical loadings that lean mass imposes, accounted for the sexual dimorphism in bone structure. Additionally, Rauch et al. have reported that the peak BMC accrual for the whole body, upper and lower extremities occurred between 0.36–0.66 and 0.22–0.71 years after the maximal increase in total lean mass in boys and girls, respectively. Recent longitudinal studies have found lean mass development to be the best predictor for BMC and areal density accrual during prepubertal growth in children, independent of the physical activity level. Although the latter studies do not exclude the fact that both bone and lean mass (muscle) development could be independently determined by genetic mechanisms, the muscle-bone relationship during growth could presumably be explained by the mechanostat theory as bigger muscles exert higher tensile forces on the bones they attach.

Despite these strong relationships between muscle mass and bone mass, it has been remarked that loading-related factors, i.e. sport, could have a greater influence on bone development than just the enhancement of muscle mass. In fact, in physically active boys, the increase of total and regional BMD per unit of lean mass is between 22% and 42% higher than observed in age-, height- and body mass-matched sedentary controls. The latter combined with the fact that bone mass increased more in the active boys than in the sedentary, after accounting for changes in lean mass, further emphasizes the independent role of exercise (mechanical strain) in bone mass acquisition during growth.

Since active boys also increased their physical fitness more than the sedentary controls, the lean (muscle)-bone association may arise because mechanical loadings exerted by exercise stimulate both muscle and bone development. Therefore, exercise could drive a direct osteogenic effect and following the mechanostat theory, an indirect osteogenic effect by increasing muscle size and strength and hence tensions generated on bones.

### 4.2 Fat-Bone-Exercise Relationship

Fat mass has also been independently associated with bone mass, although to a lesser extent than lean mass in cross-sectional studies in children. Longitudinally, it has been shown that fat mass is also related to bone mass 4 years after the menarche and thereafter, but it has a weaker predictive value than lean mass, suggesting a low effect on bone mass. However, no relationship has been found between the changes in fat mass on one side and bone masses on the other during prepubertal growth. The results of these studies imply that the longitudinal changes in fat mass do not appear to contribute significantly to the accumulation in bone mass with growth.

### 5. Conclusion

The prepubertal human skeleton is rather sensitive to mechanical stimulation elicited by physical activity, i.e. sport participation. To achieve the physical activity benefits on bone, it is not necessary to perform high volumes of exercise, since a remarkable osteogenic effect may be achieved with just 3 hours of participation in sports. Physical activity or sport should start at prepubertal ages and should be maintained through the pubertal development to obtain the maximal peak bone mass potentially achievable. Starting physical activity prior to the pubertal growth spurt stimulates both bone and skeletal muscle hypertrophy to a greater degree than observed with normal growth in non-physically active children. Participation in high strain-eliciting sports such as gymnastics, or weight-bearing physical ac-
tivities, such as football or handball, is strongly recommended to increase the peak bone mass.

The increase in lean mass is the most important predictor for bone mineral mass accrual during prepubertal growth at a population level. Since skeletal muscle is the principal component of lean mass, sport participation could have not only a direct osteogenic effect, but also an indirect effect by increasing muscle mass and hence the tensions generated on bones during prepubertal years.

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