REVIEW ARTICLE

Sports Med 2006; 36 (7): 561-569
0112-1642/06/0007-0561/$39.95/0

How does Exercise Affect Bone Development during Growth?

German Vicente-Rodríguez[1,2]

1 Department of Physical Education, University of Las Palmas de Gran Canaria, Canary Island, Spain
2 Faculty of Health and Sport Science, University of Zaragoza, Zaragoza, Spain

Contents

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.[1] However, the idea that 'senile osteoporosis is a paediatric disease'[2] is increasingly accepted.[3-5] In fact, the WHO proposed that prevention is the most powerful way to fight against the non-communicable diseases, i.e. osteoporosis.[6]

Physical activity, specifically sporting participation during growth, seems to be effective in reducing the prevalence of osteoporosis-related fractures.[4,7] However, an increased sedentarism in children[8,9] has also been described, which is even more alarming in girls because they are usually less active than boys.[10] 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.[4]

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.[11] This effect could be greater when exercise starts before the pubertal growth spurt.[12-17] 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).[18] 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.[18,19]

The body's soft tissue components (lean and fat masses) have been shown to be related to bone mass.[20-26] Skeletal muscle development precedes bone mass development[27] 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.[27,28] Although it was reported that sport participation hardly elicits muscle hypertrophy at a prepubertal age,[29] more recent studies have provided evidence of the opposite, i.e. intensive sport participation is associated with increased acquisition of muscle mass during growth.[30,31] 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.[17,55] 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.[30] 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[17,31] or handball.[31] Controlled trial jumping interventions have also shown significant increases in bone mass,[51-55,58] even with a really low time intervention such as 12 minutes, three times a week.[55] 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.[64,72] For example, Dorado et al.[73] observed that professional golfers have enhanced muscle mass in the playing arm compared with the non-playing arm, as previously reported in tennis players.[74] 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.[74,75] 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.[75] It also seems that high loads have a critical roll in bone mass acquisition during and before puberty.[30,48-50,67-71] 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.[42,76] The mechanostat theory proposes that bone strength is regulated by modelling and remodelling processes depending on forces acting on bones.[21,27,77,78] 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.[42,76,79] 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.[64]

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.[47,80] The appearance of DXA has facilitated the analysis of the separate influence that fat and lean masses may have on bone mass and density.[24]

4.1 Muscle-Bone-Exercise Relationship

Previous studies documented cross-sectional associations between lean mass (equivalent to muscle mass in the extremities[81] and a surrogate measure of muscle force[27]) and BMC and areal density.[17,30,47,82-84] Longitudinal studies have confirmed a close relationship between the change in lean mass and bone mass during growth.[27,31,85-87] In 1990, Young et al.[86] started an 8-year longitudinal study of 286 female twins aged 8–26 years at baseline. They concluded that the change in BMC was strongly correlated with the change in lean mass during linear growth (at least 4 years before the onset of menarche).[86] More recently, Forwood et al.[87] 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.[27] 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.[20,31] Although the latter studies do not exclude the fact that both bone and lean mass (muscle) development could be independently determined by genetic mechanisms,[88] the muscle-bone relationship during growth could presumably be explained by the mechanostat theory,[27,78] 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[31,85] 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.[20,31] 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 emphasises the independent role of exercise (mechanical strain) in bone mass acquisition during growth.[20,31]

Since active boys also increased their physical fitness more than the sedentary controls,[20,31] 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.[26] 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.[86] However, no relationship has been found between the changes in fat mass on one side and bone masses on the other during prepubertal growth.[20,31] 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 activities, 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 primary 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.

Acknowledgements

The study was supported by Ministerio de Educación, Cultura y Deportes (AP2000-3652), Universidad de Las Palmas de Gran Canaria, Gobierno de Canarias (PI2000/067), Consejo Superior de Deportes (27/UNI10/00) and Ministerio de Ciencia y Tecnología (BFI2003-09638 and FEDER). The authors thank José Navarro de Tuero for his excellent technical assistance. The author has no conflicts of interest that are directly relevant to the content of this review.

References

1. Kanis JA, Melton LJ, Christiansen C, et al. The diagnosis of osteoporosis. J Bone Miner Res 1994; 9: 1137-41
2. Dent CE. Keynote address: problems in metabolic bone disease. In: Frame B, Parfitt AM, Duncan H, editors. International symposium on clinical aspects of metabolic bone disease. Detroit (MI): Henry Ford Hospital, 1972: 1-7
3. Bonjour JP, Chevalley T, Ammann P, et al. Gain in bone mineral mass in prepubertal girls 3.5 years after discontinuation of calcium supplementation: a follow-up study. Lancet 2001; 358: 1208-12
4. Seeman E. An exercise in geometry. J Bone Miner Res 2002; 17: 373-80
5. Bailey DA, McKay HA, Mirwald RL, et al. A six-year longitudinal study of the relationship of physical activity to bone mineral accrual in growing children: the university of Saskatchewan bone mineral accrual study. J Bone Miner Res 1999; 14: 1672-9
6. World Health Organization. Statement by Dr Gro Harlem Brundtland, Director-General of the World Health Organization on World Health Day, 7 April 2002 [online]. Available from URL: http://www.who.int/docstore/world-health-day/2002/dg_statement.pdf [Accessed 2006 May 26]
7. Nordstrom A, Karlsson C, Nyquist F, et al. Bone loss and fracture risk after reduced physical activity. J Bone Miner Res 2005; 20: 202-7
8. Andersen RE, Crespo CJ, Bartlett SJ, et al. Relationship of physical activity and television watching with body weight and level of fatness among children: results from the Third National Health and Nutrition Examination Survey. JAMA 1998; 279 (12): 938-42
9. Woodring BC. Relationship of physical activity and television watching with body weight and level of fatness among children: results from the Third National Health and Nutrition Examination Survey. J Child Fam Nurs 1998; 1 (2): 78-9
10. Lindquist CH, Reynolds KD, Goran MI. Sociocultural determinants of physical activity among children. Prev Med 1999; 29: 305-12
11. Bass S, Pearce G, Bradney M, et al. Exercise before puberty may confer residual benefits in bone density in adulthood: studies in active prepubertal and retired female gymnasts. J Bone Miner Res 1998; 13: 500-7
12. Bradney M, Pearce G, Naughton G, et al. Moderate exercise during growth in prepubertal boys: changes in bone mass, size, volumetric density, and bone strength: a controlled prospective study. J Bone Miner Res 1998; 13: 1814-21
13. Kannus P, Haapasalo H, Sankelo M, et al. Effect of starting age of physical activity on bone mass in the dominant arm of tennis and squash players. Ann Intern Med 1995; 123: 27-31
14. Haapasalo H, Kannus P, Sievanen H, et al. Effect of long-term unilateral activity on bone mineral density of female junior tennis players. J Bone Miner Res 1998; 13: 310-9
15. Kontulainen S, Sievanen H, Kannus P, et al. Effect of long-term impact-loading on mass, size, and estimated strength of humerus and radius of female racquet-sports players: a peripheral quantitative computed tomography study between young and old starters and controls. J Bone Miner Res 2002; 17: 2281-9
16. Calbet JA, Dorado C, Diaz-Herrera P, et al. High femoral bone mineral content and density in male football (soccer) players. Med Sci Sports Exerc 2001; 33: 1682-7
17. Vicente-Rodriguez G, Jimenez-Ramirez J, Ara I, et al. Enhanced bone mass and physical fitness in prepubescent footballers. Bone 2003; 33: 853-9
18. Bailey DA, Martin AD, McKay HA, et al. Calcium accretion in girls and boys during puberty: a longitudinal analysis. J Bone Miner Res 2000; 15: 2245-50
19. Gustavsson A, Thorsen K, Nordstrom P. A 3-year longitudinal study of the effect of physical activity on the accrual of bone mineral density in healthy adolescent males. Calcif Tissue Int 2003; 73: 108-14
20. Vicente-Rodriguez G, Ara I, Perez-Gomez J, et al. Muscular development and physical activity are major determinats of femoral bone mass acquisition during growth. Br J Sports Med 2005; 39: 611-6
21. Doyle F, Brown J, Lachance C. Relation between bone mass and muscle weight. Lancet 1970; I: 391-3
22. Ferretti JL, Cointry GR, Capozza RF, et al. Bone mass, bone strength, muscle-bone interactions, osteopenias and osteoporoses. Mech Ageing Dev 2003; 124: 269-79
23. Reid IR, Ames R, Evans MC, et al. Determinants of total body and regional bone mineral density in normal postmenopausal women: a key role for fat mass. J Clin Endocrinol Metab 1992; 75: 45-51
24. Lohman T, Going S, Pamenter R, et al. Effects of resistance training on regional and total bone mineral density in premenopausal women: a randomized prospective study. J Bone Miner Res 1995; 10: 1015-24

25. Faulkner RA, Bailey DA, Drinkwater DT, et al. Regional and total body bone mineral content, bone mineral density, and total body tissue composition in children 8-16 years of age. Calcif Tissue Int 1993; 53: 7-12
26. Pietrobelli A, Faith MS, Wang J, et al. Association of lean tissue and fat mass with bone mineral content in children and adolescents. Obes Res 2002; 10: 56-60
27. Rauch F, Bailey DA, Baxter-Jones A, et al. The 'muscle-bone unit' during the pubertal growth spurt. Bone 2004; 34: 771-5
28. Frost HM. Muscle, bone, and the Utah paradigm: a 1999 overview. Med Sci Sports Exerc 2000; 32: 911-7
29. Ramsay JA, Blimkie CJR, Smith K, et al. Strength training effects in prepubescent boys. Med Sci Sports Exerc 1990; 22: 605-14
30. Vicente-Rodriguez G, Dorado C, Ara I, et al. Artistic versus rhythmic gymnastics: effects on bone and muscle mass in young girls. Int J Sports Med. In press
31. Vicente-Rodriguez G, Ara I, Perez-Gomez J, et al. High femoral bone mineral density accretion in prepuberal football players. Med Sci Sports Exerc 2004; 33: 1789-95
32. Krisman-Scott MA, Buzby M, Weill V, et al. Working with adolescents: a time of opportunity [online]. Available from URL: http://www.nursingworld.org/mods/archive/mod500/ceadabs.htm [Accessed 2006 May 26]
33. Malina RM, Bouchard C, Bar-Or O. Growth, maturation, and physical activity. Champaign (IL): Human Kinetics, 2004
34. Cameron N, Tanner JM, Whitehouse RH. A longitudinal analysis of the growth of limb segments in adolescence. Ann Hum Biol 1982; 9: 211-20
35. Tanner JM. Foetus into man: physical growth from conception to maturity. Rev. ed. Cambridge (MA): Harvard University Press, 1990
36. Seeman E. Clinical review 137: sexual dimorphism in skeletal size, density, and strength. J Clin Endocrinol Metab 2001; 86: 4576-84
37. Molgaard C, Thomsen BL, Prentice A, et al. Whole body bone mineral content in healthy children and adolescents. Arch Dis Child 1997; 76: 9-15
38. Zhang XZ, Kalu DN, Erbas B, et al. The effects of gonadectomy on bone size, mass, and volumetric density in growing rats are gender-, site-, and growth hormone-specific. J Bone Miner Res 1999; 14: 802-9
39. Lu PW, Briody JN, Ogle GD, et al. Bone mineral density of total body, spine, and femoral neck in children and young adults: a cross-sectional and longitudinal study. J Bone Miner Res 1994; 9: 1451-8
40. Schoenau E. The development of the skeletal system in children and the influence of muscle strength. Horm Res 1989; 49: 27-31
41. Schoenau E, Neu CM, Rauch F, et al. The development of bone strength at the proximal radius during childhood and adolescence. J Clin Endocrinol Metab 2001; 86: 613-8
42. Bailey DA, Faulkner RA, McKay HA. Growth, physical activity, and bone mineral acquisition. Exerc Sport Sci Rev 1996; 24: 233-66
43. Kontulainen S, Sievanen H, Kannus P, et al. Effect of long-term impact-loading on mass, size, and estimated strength of humerus and radius of female racquet-sports players: a peripheral quantitative computed tomography study between young and old starters and controls. J Bone Miner Res 2003; 18: 352-9
44. Ilich JZ, Skugor M, Hangartner T, et al. Relation of nutrition, body composition and physical activity to skeletal development: a cross-sectional study in preadolescent females. J Am Coll Nutr 1998; 17: 136-47
45. Slemenda CW, Reister TK, Hui SL, et al. Influences on skeletal mineralization in children and adolescents: evidence for varying effects of sexual maturation and physical activity. J Pediatr 1994; 125: 201-7
46. Jiménez Ramírez J, López Calbet JA. Influencia de la actividad física extraescolar en la masa ósea durante el crecimiento. Rev Entrenamiento Deportivo 2001; 15: 37-42
47. Lima F, De Falco V, Baima J, et al. Effect of impact load and active load on bone metabolism and body composition of adolescent athletes. Med Sci Sports Exerc 2001; 33: 1318-23
48. Lehtonen-Veromaa M, Mottonen T, Irjala K, et al. A 1-year prospective study on the relationship between physical activity, markers of bone metabolism, and bone acquisition in peripubertal girls. J Clin Endocrinol Metab 2000; 85: 3726-32
49. Courteix D, Lespessailles E, Peres SL, et al. Effect of physical training on bone mineral density in prepubertal girls: a comparative study between impact-loading and non-impact-loading sports. Osteoporos Int 1998; 8: 152-8
50. Nurmi-Lawton JA, Baxter-Jones AD, Mirwald RL, et al. Evidence of sustained skeletal benefits from impact-loading exercise in young females: a 3-year longitudinal study. J Bone Miner Res 2004; 19: 314-22
51. Morris FL, Naughton GA, Gibbs JL, et al. Prospective ten-month exercise intervention in premenarcheal girls: positive effects on bone and lean mass. J Bone Miner Res 1997; 12: 1453-62
52. Mackelvie KJ, McKay HA, Khan KM, et al. A school-based exercise intervention augments bone mineral accrual in early pubertal girls. J Pediatr 2001; 139: 501-8
53. MacKelvie KJ, Khan KM, Petit MA, et al. A school-based exercise intervention elicits substantial bone health benefits: a 2-year randomized controlled trial in girls. Pediatrics 2003; 112: e447
54. MacKelvie KJ, McKay HA, Petit MA, et al. Bone mineral response to a 7-month randomized controlled, school-based jumping intervention in 121 prepubertal boys: associations with ethnicity and body mass index. J Bone Miner Res 2002; 17: 834-44
55. MacKelvie KJ, Petit MA, Khan KM, et al. Bone mass and structure are enhanced following a 2-year randomized controlled trial of exercise in prepubertal boys. Bone 2004; 34: 755-64
56. Valdimarsson O, Linden C, Johnell O, et al. Daily physical education in the school curriculum in prepubertal girls during 1 year is followed by an increase in bone mineral accrual and bone width: data from the prospective controlled Malmo Pediatric Osteoporosis Prevention study. Calcif Tissue Int 2006; 78: 65-71
57. Gustavsson A, Olsson T, Nordstrom P. Rapid loss of bone mineral density of the femoral neck after cessation of ice hockey training: a 6-year longitudinal study in males. J Bone Miner Res 2003; 18: 1964-9

58. Heinonen A, Sievanen H, Kannus P, et al. High-impact exercise and bones of growing girls: a 9-month controlled trial. Osteoporos Int 2000; 11: 1010-7

59. Hock JM, Centrella M, Canalis E. Insulin-like growth factor I has independent effects on bone matrix formation and cell replication. Endocrinology 1988; 122: 254-60

60. Jarvinen TL, Kannus P, Pajamaki I, et al. Estrogen deposits extra mineral into bones of female rats in puberty, but simultaneously seems to suppress the responsiveness of female skeleton to mechanical loading. Bone 2003; 32: 642-51

61. Fuchs RK, Snow CM. Gains in hip bone mass from high-impact training are maintained: a randomized controlled trial in children. J Pediatr 2002; 141: 357-62

62. Rizzoli R, Bonjour J-P. Determinants of peak bone mass and mechanisms of bone loss. Osteoporos Int 1999; 9 Suppl. 2: 17-23

63. Karlsson MK, Magnusson H, Karlsson C, et al. The duration of exercise as a regulator of bone mass. Bone 2001; 28: 128-32

64. Heinonen A. Biomechanics. In: Khan K, McKay H, Kannus P, et al., editors. Physical activity and bone health. 1st ed. Champaign (IL): Human Kinetics, 2001: 23-34

65. Fehling PC, Alekel L, Clasey J, et al. A comparison of bone mineral densities among female athletes in impact loading and active loading sports. Bone 1995; 17: 205-10

66. Block JE, Friedlander AL, Brooks GA, et al. Determinants of bone density among athletes engaged in weight-bearing and non-weight-bearing activity. J Appl Physiol 1989; 67: 1100-5

67. Helge EW, Kanstrup IL. Bone density in female elite gymnasts: impact of muscle strength and sex hormones. Med Sci Sports Exerc 2002; 34: 174-80

68. Cassell C, Benedict M, Specker B. Bone mineral density in elite 7- to 9-yr-old female gymnasts and swimmers. Med Sci Sports Exerc 1996; 28: 1243-6

69. Dyson K, Blimkie CJ, Davison KS, et al. Gymnastic training and bone density in pre-adolescent females. Med Sci Sports Exerc 1997; 29: 443-50

70. Nickols-Richardson SM, O'Connor PJ, Shapses SA, et al. Longitudinal bone mineral density changes in female child artistic gymnasts. J Bone Miner Res 1999; 14: 994-1002

71. Nickols-Richardson SM, Modlesky CM, O'Connor PJ, et al. Premenarcheal gymnasts possess higher bone mineral density than controls. Med Sci Sports Exerc 2000; 32: 63-9

72. Bass SL, Eser P, Daly R. The effect of exercise and nutrition on the mechanostat. J Musculoskelet Neuronal Interact 2005; 5: 239-54

73. Dorado C, Sanchis Moysi J, Vicente G, et al. Bone mass, bone mineral density and muscle mass in professional golfers. J Sports Sci 2002; 20: 591-7

74. Calbet JA, Moysi JS, Dorado C, et al. Bone mineral content and density in professional tennis players. Calcif Tissue Int 1998; 62: 491-6

75. Dorado C, Sanchis J, Vicente G, et al. Isokinetic strength and arm bone mass in postmenopausal tennis players. In: Miller S, editor. Tennis science and technology. London: International Tennis Federation, 2003: 237-43

76. Boskey AL. Mineralization, structure, and function of bone. In: Seibel MJ, Robins SP, Bilezikian JP, editors. Dynamics of bone and cartilage metabolism. San Diego (CA): Academic Press, 1999: 153-64

77. Frost HM. Vital biomechanics: proposed general concepts for skeletal adaptations to mechanical usage. Calcif Tissue Int 1988; 42: 145-56

78. Schoenau E, Frost HM. The 'muscle-bone unit' in children and adolescents. Calcif Tissue Int 2002; 70: 405-7

79. Khan K, McKay H, Kannus P, et al. Physical activity and bone health. Champaign (IL): Human Kinetics, 2001

80. Faulkner RA, Bailey DA, Drinkwater DT, et al. Bone densitometry in Canadian children 8-17 years of age. Calcif Tissue Int 1996; 59: 344-51

81. Kim J, Wang Z, Heymsfield SB, et al. Total-body skeletal muscle mass: estimation by a new dual-energy x-ray absorptiometry method. Am J Clin Nutr 2002; 76: 378-83

82. Ferretti JL, Capozza RF, Cointry GR, et al. Gender-related differences in the relationship between densitometric values of whole-body bone mineral content and lean body mass in humans between 2 and 87 years of age. Bone 1998; 22: 683-90

83. Young D, Hopper JL, Nowson CA, et al. Determinants of bone mass in 10- to 26-year-old females: a twin study. J Bone Miner Res 1995; 10: 558-67

84. Vicente-Rodriguez G, Dorado C, Perez-Gomez J, et al. Enhanced bone mass and physical fitness in young female handball players. Bone 2004; 35: 1208-15

85. Daly RM, Saxon L, Turner CH, et al. The relationship between muscle size and bone geometry during growth and in response to exercise. Bone 2004; 34: 281-7

86. Young D, Hopper JL, Macinnis RJ, et al. Changes in body composition as determinants of longitudinal changes in bone mineral measures in 8 to 26-year-old female twins. Osteoporos Int 2001; 12: 506-15

87. Forwood MR, Bailey DA, Beck TJ, et al. Sexual dimorphism of the femoral neck during the adolescent growth spurt: a structural analysis. Bone 2004; 35: 973-81

88. Parfitt AM. The attainment of peak bone mass: what is the relationship between muscle growth and bone growth? Bone 2004; 34: 767-70

Correspondence and offprints: *German Vicente-Rodríguez*, Departamento de Educación Física, Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Canary Island, Spain.
E-mail: gvicente@arrakis.es

