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Review article

Exercise and bone mineral accrual in children and adolescents

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Abstract
Osteoporosis is a serious skeletal disease causing an increase in morbidity and mortality through its association with age-related fractures. Although most effort in fracture prevention has been directed at retarding the rate of age-related bone loss and reducing the frequency and severity of trauma among elderly people, evidence is growing that peak bone mass is an important contributor to bone strength during later life. Indeed, there has been a large emphasis on the prevention of osteoporosis through the optimization of peak bone mass during childhood and adolescence. The prepubertal human skeleton is sensitive to the mechanical stimulation elicited by exercise and there is increasing evidence that regular weight-bearing exercise is an effective strategy for enhancing bone mineral throughout growth. Physical activity or participation in sports needs to start at prepubertal ages and be maintained through pubertal development to obtain the maximal peak bone mass achievable. High strain eliciting sports like gymnastics, or participation in sports or weight bearing physical activity like soccer, are strongly recommended to increase peak bone mass. Many other factors also influence the accumulation of bone mineral during childhood and adolescence, including heredity, gender, diet and endocrine status. However, this review article will focus solely on the effects of physical activity and exercise providing a summary of current knowledge on the interplay between activity, exercise and bone mass development during growth. Due to the selection bias and other confounding factors inherent in cross-sectional studies, longitudinal and intervention studies only will be reviewed for they provide a greater opportunity to examine the influence of mechanical loading on bone mineral accretion over time.

Key words: Puberty, loading, growth, osteoporosis, exercise .

Introduction

Osteoporosis is a skeletal disorder characterised by low bone mass and microarchitectural deterioration of bone tissue with a consequent increase in bone fragility and susceptibility to fracture (Cooper, 2003). Osteoporosis and related fractures represent a major societal health burden (Kanis et al., 1994), with figures suggesting that 1 in 3 women and 1 in 5 men will experience an osteoporotic fracture at some point in their lifetime (Kanis and Johnell, 2005). These figures are set to rise exponentially over the next 50 years as the population ages, and by 2050 the total direct costs of hip fracture in Europe are projected to be £51 billion (Kanis and Johnell, 2005). Thus, there needs to be a large emphasis on preventative measures to combat or offset this rise in osteoporosis and fracture. Physical inactivity contributes substantially to osteoporosis risk (Kannus et al., 1999) and although manifest in older people, osteoporosis has antecedents in childhood (Bailey et al., 1999). Bone mass is an established determinant of bone strength, and the bone mass of an individual in later life depends upon the peak attained during skeletal growth and the subsequent rate of bone loss. It has been suggested that a major strategy to prevent osteoporosis is to optimise peak bone mass. Peak bone mass reflects the maximal lifetime amount of bone mineral accrued in individual bones and the whole skeleton and is a consequence of net accrual of bone during childhood and the balance between accrual and resorption during adulthood (Bass et al., 1998). Theoretically, because bone loss occurs with aging, people who acquire maximal bone mass in their early years should be at a reduced risk of skeletal fragility and fracture in later life. One strategy to increase peak bone mass is regular, weight-bearing exercise. Weight-bearing exercise can include aerobics, circuit training, jogging, jumping, volleyball and other sports that generate impact to the skeleton. There is evidence to suggest that the years of childhood and adolescence represent an opportune period during which bone adapts particularly efficiently to such loading (Bass et al., 2000; Khan et al., 2000). Evidence supporting the role of weight-bearing exercise in bone accrual has accumulated from cross-sectional, longitudinal and intervention studies. However, due to the selection bias and other confounding factors inherent in cross-sectional studies, only longitudinal and intervention studies will be reviewed in this paper as they provide a greater opportunity to examine the influence of mechanical loading on bone mineral accretion over time (Table 1). This review will address the role of physical activity and exercise in promoting peak bone mass in boys and girls in two maturational categories namely, pre-puberty and puberty/adolescents. The largest amount of knowledge to date on bone development and exercise has been acquired using dual energy x-ray absorptiometry techniques (DXA) and thus this review will concentrate on these DXA studies. However, the reader should keep in mind the limitations with DXA and interpret the results accordingly (Wren and Gilsanz, 2006). For detailed information on bone biology, maturation or osteoporosis in general the reader is refereed to some excellent texts on these topics (Currey, 2002; Malina and Bouchard, 2004; Cooper et al., 2006).

Prepuberty

Sports participation during growth has been shown to increase bone mineral density (BMD) in the weight loaded limbs of active subjects by 10-20 % (Bass *et al.,* 1998), which is greater if the exercise precedes pubertal growth (Bradney *et al.,* 1998; Calbet *et al.,* 2001; Vicente-Rodriguez *et al.,* 2003). A study Bradney *et al.* (1998) looked at moderate exercise during growth and assessed changes in areal BMD (aBMD) over an 8 month

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games program in prepubertal boys (Table 1). The study reported increases in aBMD of 2.6 % in the total body, 4.3 % in the lumbar spine and 9.3 % in the femoral mid-shaft in the exercise group compared to the controls. In addition, volumetric BMD increased, suggesting that the increases in bone mass were greater than the increases in body size due to growth, and thus the growing skeleton was responsive to moderate exercise. Bradney et al. (1998) used after schools clubs for the exercise intensity, but two later studies in 2006 assessed the effect of moderate exercise on bone mass in children using school curriculum based exercise programs. Valdimarsson et al., (2006) assessed whether a general, moderate exercise program within a school (consisting of ball games, running and jumping) could increase bone accrual in girls over a 1 year period (Table 1). They reported positive effects on bone accretion at the lumbar spine (Bone mineral content (BMC) + 4.7 %; aBMD + 2.8 %). These results were taken further when Linden et al. (2006) published the two year results of the same study (Table 1), reporting further increases in total body and lumbar spine BMC and aBMD. However, caution needs to be taken with these results as the studies were not randomized at the start increasing the risk of selection bias, the intensity of the exercise undertaken was not assessed directly, and there was a high drop out in the second year in the control group.

Mackelvie et al. in 2001 and 2002 conducted similar studies (Table 1), looking at school-based exercise interventions, but quantified the exercise loading as a ground reaction force (GRF) between 3.5-5 times body weight. In addition, the studies were randomized and well controlled over a period of 7 months. The 2002 study showed a significant effect of the school based jumping program on bone mineral change in the total body and proximal femur in boys. Although the bone effect was small for the boy's intervention, body mass index at baseline was significantly related to bone mineral accrual and may have played a role in dampening the effect of the jumping intervention. There was no gain in bone mineral in girls over the same time period (2001). These results suggest a sex, as well as site, specific effect of moderate exercise on bone mineral accrual. Indeed, Petit et al. (2002) conducted a similar trial over 7 months using jump and circuit based training (GRF = 3.5-5 times body weight), in girls and found no significant increases in BMC or aBMD at any skeletal site measured (Table 1). In contrast, Van Langendonck et al. (2003) conducted a unique twin study assessing the influence of weight bearing exercise on bone acquisition in prepubertal, monozygotic female twins (Table 1). The study allowed for the control of several parameters that influence bone mass that had not been able to be controlled previously. The study reported positive effects for girls bone mineral accrual at the proximal femur, but only in those girls who were not previously active. Therefore, it may be that exercise loading is beneficial for prepubertal girls, but only those without a loading history prior to the exercise intervention.

The previous studies were completed over relatively short periods of time for bone remodeling. Mackelvie et al. (2004) completed a longer 20-month randomized controlled trial of exercise in prepubertal boys to compare changes in proximal femur BMC in exercisers compared to controls (Table 1). The same exercise intervention was utilised as in the 2001 and 2002 studies. However, the results were different, with no significant change in BMC at the total body, proximal femur or lumbar spine in boys. The only skeletal site to respond to the exercise intervention was the femoral neck (+ 4.3 % BMC). Although there was an imbalance between the maturity stages in the exercise and control group, this study does suggest that minimal changes to the physical education curriculum can influence bone accrual at specific skeletal sites.

Another long duration study was undertaken by Laing et al. (2005), who assessed the effect of recreational gymnastics training on bone mineral accrual in 4-8 year old girls (Table 1). These girls had no history of athletic participation prior to the study and those in the exercise group reported a greater rate of increase in lumbar spine aBMD compared to controls. This increase was only seen at the lumbar spine, with other sites increasing equally between the exercisers and controls. Therefore, it seems from these results that moderate exercise loading is beneficial in prepubertal boys. It is also beneficial in prepubertal girls, although previous exercise history may influence the amount of benefit gained. The gains are also site specific.

The question arises though that if moderate exercise has beneficial effects on bone mineral accrual, would high intensity exercise have additional positive effects on bone mineral accretion? Mckay et al. (2000) conducted a study in boys and girls to assess whether school physical education classes could be modified to augment BMD (Table 1). The study introduced high intensity exercises into the curriculum, such as tuck jumps, hopping and skipping for 8 months, and found a 4.4 % increase in trochanteric bone mineral density. This study found that an easily implemented school based jumping intervention augments aBMD. A similar study assessing the effects of a high intensity jumping intervention on hip and lumbar spine BMC was conducted by Fuchs et al. (2001) in girls and boys over a period of 7 months (Table 1). The prescribed high impact jumping exercises elicited GRF of 8.8 times body weight and produced increases in BMC and aBMD at the lumbar spine and femoral neck. These studies were randomized, provided GRF data to quantify the loading on the skeleton and controlled for pubertal stage. Thus, they provide convincing evidence that prepubertal boys and girls are able to participate in vigorous exercise programmes and appear to respond positively to this through prepubertal growth.

Puberty and adolescents

The pubertal growth spurt can be defined as the 2-3 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 gonadotrophic releasing hormone (GnRH). The increase in GnRH stimulates gonadal growth and sex steroid secretion; secondary sexual characteristics appear as the sex steroid concentration rises. Testosterone, growth hormone and insulin-like growth factor-1 increase during the pubertal period (Bailey et al., 1996) enhancing bone growth and turnover through osteoblastic stimulation (Hock et al., 1988). Estrogen production is low in premenarcheal girls, which makes their bones more responsive to exercise loading (Jarvinen et al., 2003) and increases their size (Zhang et al., 1999; Seeman, 2001).

Blimkie et al. (1996) performed a prospective study on resistance training in adolescent girls to determine the effect of 26 weeks of progressive resistance training on total body and lumbar spine BMC and aBMD (Table 1). The girls performed a variety of exercises on hydraulic machines, and although one may expect to find a significant change in bone mineral accrual due to strength exercises, only trends towards increases in lumbar spine bone mineral during the first 13 weeks of training were found. No changes in lumbar spine or total body bone mineral after 26 weeks of training were reported. However, the girl's enthusiasm for the exercise intervention decreased during the latter part of the study resulting in poor compliance. This may therefore explain the lack of significant results from this study. However, Witzke and Snow (2000) also conducted a resistance intervention in girls during adolescence and reported non-significant results (Table 1). Trends were seen towards increases in BMC at the total body, femoral neck, femoral shaft, greater trochanter and lumbar spine, but the control group also reported such changes. The authors concluded that these trends may suggest a longer training period was required (above 9 months) to see significant results. Nicholas et al. (2001) conducted a resistance training study in girls over 15 months and found significant improvements in femoral neck aBMD in the order of 2.3 % (Table 1). However, the girls in this study were adolescents, postmenarchal and thus direct comparisons cannot be made.

Blimkie et al. (1996) and Witzke and Snow (2000) are two of the few studies, which have used resistance training as the exercise intervention. Most studies conducted in this maturity group have utilised jumping interventions (Table 1). All of the studies utilising jumping interventions have shown positive results, and therefore it may not necessarily be the length of the study that produces non-significant results, but the choice of intervention. Morris et al. (1997) conducted a 10 month, prospective exercise intervention in premenarcheal girls, utilising after school clubs of activities such as aerobics, dance and ball games, and reported 3.5 %-12 % increases in BMC and aBMD across skeletal sites (Table 1). This study provided direct evidence that this type of exercise enhances bone mineral accrual in the premenarchal skeleton. Other studies assessing the effect of exercise have also reported positive effects. Mackelvie et al. (2001) conducted a 7 month jumping and circuit exercise intervention in early pubertal girls and found that the girls gained significantly more bone at the femoral neck and lumbar spine than maturity matched controls (Table 1). This study was the first to suggest that exercise for girls at 10.5years and older provided a 'window of opportunity' for exercise induced bone gain. The gains were site specific and only significant in early pubertal girls (the prepubertal girls reported no bone mineral changes – refer to prepubertal section for details). Petit et al. (2002) conducted a study looking into exercise (GRF between 3.5-5 times body weight) in premenarcheal girls and found that femoral neck aBMD and intertrochanteric aBMD increased by 2.6 % and 1.7 % respectively (Table 1). The bone adaptation was at these sites only and thus site specific, which agrees with the findings of Mackelvie et al. (2003). Mackelvie et al. (2003) conducted a jumping intervention over a longer period of time (20 months compared to 7 months in the other trials) and found a 5 % increase in bone mineral accrual in girls at the schools randomised to the exercise intervention compared to those girls in the control schools (Table 1). This study was an extension of the Mackelvie et al. (2001) study, with the 20-month results indicating an accumulation of bone with the bone mineral accrual in those girls in the exercise schools doubling from 7 – 20 months.

Such a bone effect is also seen for exercises performed for very short durations throughout the day and at very low GRF. Iuliano-Burns et al. (2003) conducted a study in girls aged 8.8 years, using low-moderate impact exercises such as skipping, hopping and jumping (GRF between 2-4 times body weight) and reported a 7.1 % increase in femoral neck BMC (Table 1). Whilst, Mckay et al. (2005) conducted a study into girls and boys aged 10.1 years who were randomised to a novel intervention called "Bounce at the Bell" (Table 1). This intervention only took the children 3 minutes, 5 times a day to complete, but still resulted in 2 % increase in proximal femur BMC and a 27 % increase in trochanteric BMC. Thus, these studies indicate that the exercise intervention can be of a low intensity (in terms of GRF), and short in duration, but still provide an osteogenic response in girls and boys during early puberty.

Kontulainen et al. (2002) assessed girls at 12.8 years to determine the effect of a jumping intervention on subsequent bone mineral accrual (Table 1). The study utilised step aerobics and jumping programs and lasted for 20 months. The study reported lumbar spine BMC increases of 4.9 % which were maintained at least a year after the end of training. This study was well controlled, but the observational nature of the follow up means caution should be taken over the findings.

Stear et al. (2003) conducted a study investigating the effect of exercise to music on BMC in girls aged 17.3 years (Table 1). The study was conducted over 15.5 months and reported significant improvements in BMC at the total body, lumbar spine and hip regions. These findings were supported in another dance intervention study. Matthews *et al.* (2006) assessed whether, in a non-athletic population, ballet dancing over 3 years promoted bone mineral accrual (Table 1). The girls, aged 8-11 years all experienced increases in BMC at the total body, lumbar spine and femoral neck sites. The strength of these studies is that they are longitudinal in nature. However, the exact amount and type of dancing each girl took part in were not controlled and thus a variety of dance regimes may have been actively taken part in so the exact exercise loading cannot be quantified.

Exercise intervention programs aimed at increasing bone mass or strength in pubertal or adolescent children have involved diverse activities of moderate to high impact such as jumping or running. The majority of trials have reported positive skeletal effects from the exercise interventions, the magnitude of which varies according to the skeletal site measured. The evidence suggests that early puberty may be particularly optimal for bone adaptation to loading. Reasons for why this may be an opportune period for bone adaptation to exercise may be due to the velocity of bone growth and the endocrine changes at this age. It has been estimated that around 30 % of total body adult bone mass is accrued during this time (Mauras et al., 1996). However, whilst the evidence suggests that a window of opportunity exists in children at this pubertal stage, the studies to date are of insufficient number to arrive at a definitive conclusion.

Studies spanning pubertal stages

There is a lack of well-controlled, intervention studies over a period of time and thus multiple pubertal stages, due to the logistics and costs of completing such trials. However, Bailey et al. (1999) reported the result of the 6 year University of Saskatchewan Pediatric Bone Mineral Accrual Study. This study followed boys and girls for a period of 6 years to evaluate the relationship between every day physical activity and peak bone accrual in children passing through adolescents. The study demonstrated a greater peak bone mineral accrual rate and a greater bone mineral accumulation for 2 years around the peak growth spurt for children in the highest quartile of physical activity, compared to the children in the lowest quartile of physical activity. The effect was site specific and in the range of 9 % for boys and 17% for girls. Sundberg et al. (2001) also completed a long-term study over 4 years and aimed to determine if an increase of moderate exercise in the school curriculum would have anabolic effects on bone. The study reported positive effects on aBMD and BMC at the total body, lumbar spine and femoral neck regions – the weight loaded sites. However, this effect was only significant in boys. In addition, the boy’s effect was stronger at 4 years than at 3 years. Although this study was conducted over a long period of time, the control group was only assessed cross-sectionally at baseline and thus limits the validity of these results. Lastly, Heinonen et al. (2000) conducted a study over 9 months in growing girls to assess high impact exercise. The study found that in the growing girls, the benefit of the mechanical loading was only present before, rather than after menarche. It showed a clear and large additional bone gain could be obtained in exercising premenarcheal girls, but not in exercising postmenarchal girls, suggesting that exercise is more beneficial to bone during the growth spurt.

Long term benefits of exercise on osteoporosis risk

Pediatric bone gain associated with any intervention must be long lasting if it is to influence adult risk of osteoporotic fracture. In adults, it seems quite clear that beneficial effects on bone observed when an exercise program is initiated are lost during detraining (Dalsky et al., 1988) but whether this also occurs in response to exercise undertaken during growth is unclear. As bone can substantially change its shape during growth, via the process of modeling, it is not inconceivable that long-term benefits from childhood activity are realised (Forwood and Burr 1993; Haapasalo 1998).

Some evidence suggests that higher levels of bone mineral in childhood are maintained in gymnasts (Kirchner et al., 1996; Bass et al., 1998), elite ballet dancers (Khan et al., 1998) and for short term follow up intervention studies in children at some, but not all, sites (Fuchs et al., 2001; Kontulainen et al., 2002). In contrast, well designed animal studies show benefits of activity during growth are not maintained with complete cessation of training (Pajamaki et al., 2003), although some benefit is maintained with moderate loading (Jarvinen et al., 2003). A loss of aBMD by DXA does not necessarily translate into a decrease in bone bending strength. In fact, increased bone area would show up as a decrease in aBMD. Following pediatric groups beyond the length of the intervention itself using bone bending strength outcomes in future studies to clarify this important question is required.

Conclusion

The studies to date have involved a variety of maturity groups and span from 6.5 months – 6 years. Although there have been a number of limitations to the studies (due to the difficult nature of controlling trials over a prolonged period of time in children whilst accounting for growth), the data to date show that exercise is beneficial to bone mineral accrual throughout growth. Moderate exercise (3.5-5 times body weight) is beneficial to prepubertal boys and is site specific. Moderate exercise for prepubertal girls may be beneficial, but only if the girls do not have a prior history of loading, and the benefits would be site specific. High intensity exercise seems to be beneficial for both boys and girls pre-puberty. Resistance exercise may not be the best intervention for promoting bone mineral accrual in pubertal and adolescent girls. However, jumping interventions utilising a range of GRF (low-high impact) may promote bone mineral accrual in girls and boys, particularly in girls over 10.5 years and around the 2 years growth spurt. Both long and short duration exercise sessions may be beneficial and the longer the intervention, the greater the bone mineral accrual.

The majority of studies have used school-based exercise interventions involving 3-20 minutes per day of weight bearing impact activities with three or more sessions per week. The prescription of 3 days of exercise per week may potentially advance osteogenic responses in children and adolescents. However, longitudinal studies are required to ascertain the sustainability of gains in bone mineral. Bone can become accustomed to constant loading of a similar magnitude and will not increase in strength until a higher magnitude load is applied (Frost, 1990). Therefore, the progression of exercise (a well-known training principle) should be used to ensure continuous positive effects. Differences in exercise-generated forces can be quantified by GRF, which are linearly associated with the strain generated in bone. GRF between 2 to 9 times body weight strains greater than those produced during everyday activities would result in positive bone adaptations, although the higher the intensity the greater the osteogenic response.

Maximising peak bone mass is likely to offset future development of osteoporosis and bone fragility. More well designed and controlled investigations are required. The specific type of exercise, intensity and duration that will provide the optimal stimulus for peak bone mineral accretion still requires further investigation. In addition, the measurement of bone quality parameters and volumetric BMD would provide a greater insight into the mechanisms implicated in the adaptation of bone to exercise.

References

Bailey, D.A., Faulkner, R.A. and McKay, H.A. (1996) Growth, physical activity and bone mineral acquisition. *Exercise and Sport Sciences Reviews* **24,** 233-266.

Bailey, D.A., McKay, H.A., Mirwald, R.L., Crocker, P.R.E. and Faulkner, R.A. (1999) 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. *Journal of Bone Mineral Research* **14,** 1672–1679.

Bass, S., Pearce, G, Bradney M et al., Hendrich, E., Delmas, P.D., Harding, A. and Seeman E. (1998) Exercise before puberty may confer residual benefits in bone density in adulthood: studies in active prepubertal and retired gymnasts. *Journal of Bone Mineral Research* **13,** 500-507.

Bass, S., Bradney, M., Pearce, G., Hendrich, E., Inge, K., Stuckey, S., Lo, S.K. and Seeman, E. (2000) Short stature and delayed puberty in gymnasts: influence of selection bias on leg length and the duration of training on trunk length. *Journal of Pediatrics* **136,** 149-155.

Blimkie, C.J., Rice, S., Webber, C.E., Martin, J., Levy, D. and Gordon, C.L. (1996). Effects of resistance training on bone mineral content and density in adolescent females. *Canadian Journal of Physiology and Pharmacology* **74,** 1025–1033.

Bradney, M., Pearce, G., Naughton, G., Sullivan, C., Bass, S., Beck, T., Carlson, J. and Seeman, E. (1998). Moderate exercise during growth in prepubertal boys: changes in bone mass, volumetric density and bone strength: a controlled prospective study. *Journal of Bone Mineral Research* **13,** 1814–1821.

Calbet, J.A., Moysi, J.S., Dorado, C., and Rodriquez, L.P. (2001). Bone mineral content and density in professional tennis players. *Calcified Tissue International* **62,** 491-496.

Cooper, C. (2003) Epidemiology of osteoporosis. In: *Primer on the metabolic bone diseases and disorders of mineral metabolism.* Ed: Favuus, M.J. 5 th edition. American Society of Bone and Mineral Research, 307-313.

Cooper, C., Westlake, S., Harvey, N., Javaid, K., Dennison, E. and Hanson, M. (2006) Review: developmental origins of osteoporotic fracture. *Osteoporosis International* **17,** 337-347.

Currey, J.D. (2002) Bones: Structure and mechanics. Princeton University Press, Oxford.

Dalsky, G.P., Stocke, K.S., Ehsani A.A., Slatopolsky, E., Lee, W.C. and Birge, S.J., Jr. (1988) Weight-bearing exercise training and lumbar bone mineral content in postmenopausal women. *Annals of Internal Medicine* **108,** 824-828.

Forwood, M.R. and Burr, D.B. (1993). Physical activity and bone mass: exercise in futility? *Bone Mineral* **21,** 89-112.

Frost, H.M. (1990) Structural adaptations to mechanical usage (SATMU): 1. Redefining Wolff's law: the bone remodelling problem. *Anatomy Records* **226,** 403–413.

Fuchs, R.K., Bauer, J.J. and Snow, C. (2001) Jumping improves hip and lumbar spine bone mass in prepubescent children: a randomised controlled trial. *Journal of Bone Mineral Research* **16,** 148–156.

Haapasalo, H., Kannus, P., Sievanen, H., Pasanen, M., Uusi-Rasi, K., Heinonen, A., Oja, P. and Vuori, I. (1998) Effect of long-term unilateral activity on bone mineral density of female junior tennis players. *Journal of Bone Mineral Research* **13,** 310–319.

Heinonen, A., Sievanen, H., Kannus, P., Oja, P., Pasanen, M. and Vuori, I. (2000) High impact exercise and bones of growing girls: a 9-month controlled trial. *Osteoporosis International* **11,** 1010–1017.

Hock, J.M., Centrella, M. and Canalis, E. (1988) Insulin-like growth factor I has independent effects on bone matrix formation and cell replication. *Endocrinology* **122,** 254-260.

Iuliano-Burns, S., Saxon, L., Naughton, G., Gibbons, K. and Bass, S.L. (2003) Regional specificity of exercise and calcium during skeletal growth in girls: a randomised controlled trial. *Journal of Bone Mineral Research* **18,** 156–162.

Jarvinen, T.L., Kannus, P., Pajamaki, I., Vuohelainen, T., Tuukkanen, J., Jarvinen, M. and Sievanen, H. (2003) 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* **32,** 642-651.

Kanis, J., Melton, L.J., Christiansen, C., Johnston, C.C. and Khaltaev, N. (1994) The diagnosis of osteoporosis. *Journal of Bone Mineral Research* **9,** 1137–1141.

Kanis, J.A., Johnell, O. (2005) Requirements for DXA for the management of osteoporosis in Europe. *Osteoporosis International* **16,** 229.

Kannus, P., Niemi, S., Parkkari, J., Palvanen, M., Vuori, I. and Jarvinen, M. (1999) Hip fractures in Finland between 1970 and 1997 and predictions for the future. *Lancet* **353 (9155),** 8002-8055.

Khan, K.M., Bennell, K.L., Hopper, J.L., Flicker, L., Nowson, C.A., Sherwin, A.J., Crichton, K.J., Harcourt, P.R. and Wark, J.D. (1998) Self-reported ballet classes undertaken at age 10–12 years and hip bone mineral density in later life. *Osteoporosis International* **8,** 165-173.

Khan, K., McKay, H.A., Haapasalo, H., Bennell, K.L., Forwood, M.R., Kannus, P. and Wark, J.D. (2000) Does childhood and adolescence provide a unique opportunity for exercise to strengthen the skeleton? *Journal of Science and Medicine in Sports* **3,** 150-64.

Kirchner, E., Lewis, R. and O'Connor, P. (1996) Effects of past gymnastics participation on adult bone mass. *Journal of Applied Physiology* **80,** 226-232.

Kontulainen, S., Kannus, P., Pasanen, M., Sievanen, H.T., Heinonen, A.O., Oja, P. and Vuori, I. (2002). Does previous participation in high impact training result in residual bone gain in growing girls? One year follow up of a 9 month jumping intervention. *International Journal of Sports Medicine* **23,** 575-581.

Laing, E.M., Wilson, A.R., Modlesky, C.M., O'Connor, P.J., Hall, D.B. and Lewis, R.D. (2005). Initial years of recreational artistic gymnastics training improves lumbar spine bone mineral accrual in 4-to 8-year-old females. *Journal of Bone Mineral Research* **20,** 509–519.

Linden, C., Ahlborg, H.G., Besjakov, J., Gardsell, P. and Larlsson, M.K. (2006) A school curriculum based exercise program, increases bone mineral accrual and bone size in prepubertal girls: two year data from the Pediatric Osteoporosis Prevention (POP) study. *Journal of Bone Mineral Research* **21,** 829-835.

Mackelvie, K.J., McKay, H.A., Khan, K.M. and Crocker, P.R.E. (2001) A school-based exercise intervention augments bone mineral accrual in early pubertal girls. *Journal of Pediatrics* **139,** 501–508.

Mackelvie, K.J., Khan, K.M. and McKay, H.A. (2002). Is there a critical period for bone response to weight-bearing exercise in children and adolescents? A systematic review. *British Journal of Sports Medicine* **36,** 250–257.

Mackelvie, K.J., Khan, K.M., Petit, M.A., Janssen, P.A. and McKay, H.A. (2003) A school based exercise intervention elicits substantial bone health benefits: a 2-year randomised controlled trial in girls. *Pediatrics* **112,** e447–452.

Mackelvie, K.J., Petit, M.A., Khan, K.M., Beck, T.J. and McKay, H.A. (2004) Bone mass and structure are enhanced following a 2-year randomised controlled trial of exercise in prepubertal boys. *Bone* **34,** 755–764.

Malina, R.M., Bouchard, C. and Barr-Or, O. (2004) Growth, maturation and physical activity. Human Kinetics, Illinois.

Matthews, B.L., Bennell, K.L., McKay, H.A., Khan, K.M., Baxter-Jones, A.D.G., Mirwald, R.L. and Wark, J.D. (2006) Dancing for bone health: a 3-year longitudinal study of bone mineral accrual across puberty in female non-elite dancers and controls. *Osteoporosis International* **17,** 1043-1054.

Mauras, N., Rogel, A.D., Haymond, M.W. and Veldhuis, J.D. (1996) Sex steroids, growth hormone, insulin-like growth factor-1: neuroendocrine and metabolic regulation in puberty. *Hormonal Research* **45,** 74–80.

McKay, H.A., Petit, M.A., Schutz, R.W., Prior, J.C., Barr, S.I. and Khan, K.M. (2000) Augmented trochanteric bone mineral density after modified physical education classes: a randomised school-based exercise intervention study in prepubescent and early pubescent children. *Journal of Pediatrics* **136,** 156–162.

McKay, H.A., MacLean, L., Petit, M., Mackelvie, K., O'Brien, K., Janssen, P., Beck, T. and Khan, K.M. (2005) 'Bounce at the bell': a novel program of short bouts of exercise improves proximal femur bone mass in early pubertal children. *British Journal of Sports Medicine* **39,** 521–526.

Morris, F.L., Naughton, G., Gibbs, J.L., Carlson, J.S. and Wark, J.D. (1997). Prospective ten month exercise intervention in premenarchal girls: positive effects on bone and lean mass. *Journal of Bone Mineral Research* **12,** 1453–1462.

Nichols, D.L., Sanborn, C.F. and Love, A.M. (2001) Resistance training and bone mineral density in adolescent females. *Journal of Pediatrics* **139,** 494–500.

Pajamaki, I., Kannus, P, Vuohelainen, T., Sievanen H., Tuukkanen, J., Jarvinen, M. And Jarvinen, T.L. (2003) The gain induced by exercise in puberty is not preserved through a virtually life-long deconditioning: a randomized controlled experimental study in male rats. *Journal of Bone Mineral Research* **18,** 544-558.

Petit, M.A., McKay, H.A., Mackelvie, K.J., Heinonen, A., Khan, K.M. and Beck, T.J. (2002) A randomized school-based jumping intervention confers site and maturity specific benefits on one structural property in girls: a hip structural analysis study. *Journal of Bone Mineral Research* 17, 363–372.

Seeman, E. (2001) Clinical review 137: Sexual dimorphism in skeletal size, density and strength. *Journal of Clinical Endocrinology and metabolism* **86,** 4576-4584.

Stear, S.J., Prentice, A., Jones, S.C. and Cole, T.J. (2003) Effect of a calcium and exercise intervention on the bone mineral status of 16-18 year old adolescent girls. *American Journal of Clinical Nutrition* **77,** 985-992.

Sundberg, M., Gardsell, P., Johnell, O., Karlsson, M.K., Ornstein, E., Sandstedt, B., Sandstedt, B. and Sernbo, I. (2001) Peripubertal moderate exercise increases bone mass in boys but not in girls: a population-based intervention study. *Osteoporosis International* **12,** 230–238.

Valdimarsson, O., Linden, C., Johnell, O., Gardsell, P. And Karlsson, M.K. (2006) Daily physical education un the school curriculum in prepubertal girls during 1 year is followed by an increase in bone mineral accrual and bone width: data form the prospective controlled Malmo Pediatric Osteoporosis Prevention Study. *Calcified Tissue International* **78,** 65-71.

Van Langendonck, L., Claessens, A.L., Vlietinck, R., Derom, C. and Beunen, G. (2003). Influence of weight-bearing exercises on bone acquisition in prepubertal monozygotic female twins: a randomised controlled prospective study. *Calcified Tissue International* **72,** 666–674.

Vicente-Rodriguez, G., Jimennez-Ramirez, J., Ara I.,Serrano-Sanchez, A., Dorado, C. And Calbert, A. (2003). Enhanced bone mass and physical fitness in prepubescent footballers. *Bone* **33,** 853-859.

Witzke, K.A. and Snow, C.M. (2000) Effects of plyometric jump training on bone mass in adolescent girls. *Medicine and Science in Sports and Exercise* **32,** 1051–1057.

Wren, T.A. and Gilsanz, V. (2006) Assessing bone mass in children and adolescents. *Current Osteoporosis Reports* **4 (4),** 153-158.

Zhang, X.X., Kalu, D., Erbas, B. Hopper, L.. and Seeman, E. (1999) The effects of gonadectomy on bone size, mass and volumetric density in growing rats are gender, site and growth hormone specific. *Journal of Bone Mineral Research* **14 (5),** 802-809.

Key points

- Pre-pubertal children's ability to thermoregulate when exposed to hot and humid environments is deficient compared to adults.
- Research into the severity of heat-related illness in pre-pubertal children is inconclusive.
- Discretion should be used in applying findings from indoor studies to outdoor activities due to the influence of the velocity of circulating air on thermoregulation.

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Table 1. **Exercise intervention studies in children and adolescents.**

	Reference	Participants	Design	Intervention	Results*
Prepubertal	Bradney *et al.,* 1998	Boys. White. Age 10.4±0.2yrs	Randomized by school Con = 20; Ex = 20	After school clubs of aerobics, soccer, volleyball, dance, gymnastics, basketball and weight training; 3 times/week; 30mins/session; 8 months duration	TB + 2.6% aBMD LS + 4.3% aBMD FS + 9.3% BMC FS + 9.1% vBMD
	Mckay *et al.,* 2000	Girls & boys. White & Asian. Age 8.9±0.7yrs	Randomized by school Con = 81; Ex = 63	10 tuck jumps prior to class, 3 times/week Jumping, skipping, hopping 2 times/week 10-30mins/session; 8 months duration	GT + 4.4% aBMD
	Fuchs *et al.,* 2001	Girls & boys. White. Age 7.5±0.2yrs	Randomized within school Con = 44; Ex = 45	100 two footed drop jumps off 61cm box; GRF = 8.8 bw; 3 times/week; 10mins/session; 7 months duration	LS + 2% aBMD FN + 1.4% aBMD LS + 3.1% BMC FN + 4.5% BMC
	Mackelvie *et al.,* 2001	Girls. White & Asian. Age 10.1±0.5yrs	Randomized by school Con = 26; Ex = 44	50-100 jumps and circuit training GRF = 3.5-5 bw; 3 times/week; 10-12mins/session; 7 months duration	NS
	Mackelvie *et al.,* 2002	Boys. White & Asian. Age 10.3±0.6yrs	Randomized by school Con = 60; Ex = 61	50-100 jumps and circuit training GRF = 3.5-5 bw; 3 times/week; 10mins/session; 7 months duration	PF + 1.6% aBMD TB + 1.6% BMC
	Petit *et al.,* 2002	Girls. White & Asian. Age 10.0±0.6yrs	Randomized by school Con = 25; Ex = 43	50-100 jumps and circuit training GRF = 3.5-5 bw; 3 times/week; 10mins/session; 7 months duration	NS
	Van Langendonck *et al.,* 2003	Girls. Age 8.7±0.7yrs	Twin study Con = 21; Ex = 21	Hopping and jumping exercises; 3 times/week; 10mins/session; 9 months duration	PF + 2.5% BMC
	Mackelvie *et al.,* 2004	Boys. White & Asian. Age 10.2±0.5yrs	Randomized by school Con = 33; Ex = 31	50-100 jumps and circuit training GRF = 3.5-5 bw; 3 times/week;12mins/session; 20 months duration	FN + 4.3% BMC
	Laing *et al.,* 2005	Girls. White, Asian & black. Age 6.0±1.6yrs.	No randomization Con = 78; Ex = 65	Recreational gymnastics; 1 hour/week; 24 months duration	LS+11.6% aBMD
	Linden *et al.,* 2006	Girls. Age 7.8±0.6yrs	No randomization Con = 50; Ex = 49	PE - Ball games, running and jumping; 200mins/week; 2 years duration	TB + 0.6% aBMD LS + 1.2% aBMD LS + 3.8% BMC
	Valdimarsson *et al.,* 2006	Girls. Age 7.8±0.6yrs	No randomization Con = 50; Ex = 53	PE - Ball games, running and jumping; 5 times/week; 40mins/session; 1 year duration	LS + 2.8% aBMD LS + 4.7% BMC
Pubertal and adolescent	Blimkie *et al.,* 1996	Girls. Age 16.2±0.2yrs	Randomized within school Con = 16; Ex = 16	Resistance training, hydraulic machines; 13 exercises x 4 sets; 10-12 reps; 3 times/week; 6.5 months duration	NS
	Morris *et al.,* 1997	Girls. Age 9.5±0.9yrs	No randomization Con = 33; Ex = 38	After school clubs of aerobics, step aerobics, soccer, dance, ball games and weight training; 3 times/week; 30mins/session; 10 months duration	TB +3.5% aBMD LS +4.8% aBMD PF + 4.5% aBMD FN + 12% aBMD PF + 4.5% aBMD TB + 12% BMC LS + 7% BMC FN + 10.4% BMC PF + 11.9% BMC
	Witzke and Snow 2000	Girls. White. Age 14.6±0.5yrs	No randomization Con = 28; Ex = 25	Resistance training and plyometrics; 3 times/week; 30-45mins/session; 9 months duration	NS

	Mackelvie *et al.,* 2001	Girls. White & Asian. Age 11.0±0.9yrs	Randomised by school Con = 64; Ex = 43	50-100 jumps and circuit training GRF = 3.5-5 bw; 3 times/week; 10-12mins/session; 7 months duration	LS + 8.2% aBMD FN + 6.7% aBMD LS 16.5% BMC FN + 11.3% BMC FN + 3.6% vBMD
	Nichols *et al.,* 2001	Girls. Age 15.9±0.1yrs	Group randomized Con = 21; Ex = 46	15 resistance exercises; 3 times/week; 30-45mins/session; 15 months duration	FN + 2.3% aBMD
	Kontulainen *et al.,* 2002	Girls. Age 12.8±1.5yrs	Group randomised Con = 49; Ex = 50	Step aerobic and jumping program; 2 times/week; 50mins/sessions; 20 months duration.	LS + 4.9% BMC
	Petit *et al.,* 2002	Girls. White & Asian. Age 10.5±0.6yrs	Randomized by school Con = 63;Ex = 43	5 diverse jumping exercises GRF = 3.5-5 bw; 3 times/week; 10mins/session; 7 months duration	FN + 2.6% aBMD IR + 1.7% aBMD
	Iuliano-Burns *et al.,* 2003	Girls. White & Asian Age 8.8±0.1yrs	Randomized by group 4 groups of 16	Moderate impact skipping, hopping and jumping GRF = 2-4 bw; 3 times/week; 20mins/session; 8.5 months duration	FN + 7.1% BMC
	Mackelvie *et al.,* 2003	Girls. White & Asian. Age 9.9±0.6yrs	Randomized by school Con = 43;Ex = 32	100 jumps and circuit training GRF = 3.5-5 bw; 3 times/week; 10mins/session; 20 months duration	LS + 41.7% BMC FN + 24.8% BMC
	Stear *et al.,* 2003	Girls. White. Age 17.3±0.3yrs	Randomized by group Con = 66; Ex = 65	Exercise to music; 3 times/week; 45 mins/session; 15.5 months duration	TB + 0.8% BMC LS + 1.9% BMC FN + 2.2% BMC HIP + 2.7% BMC TR + 4.8% BMC
	Mckay *et al.,* 2005	Girls and boys. White & Asian. Age 10.1±0.5yrs	Randomized by school Con = 71;Ex = 51	Bounce at the Bell; 10 CMJ GRF = 5 bw; times/day; 3mins/session; 8 months duration	PF + 2.0% BMC TR + 27% BMC
	Matthews *et al.,* 2006	Girls. White & Asian. Age 8-11 yrs	Randomized by school Con = 61;Ex = 82	Ballet dancing; 4.5 hours/week to 7.0/hours week; 3 years duration	TB + 1% BMC LS + 0.6% BMC FN + 4% BMC
Multiple maturity groups	Bailey *et al.,* 1999	Girls and boys. Age 8–14yrs	53 girls; 60 boys	Daily physical activity measured via questionnaire; 6 years duration	Active boys had 9% and girls 17% > TB BMC
	Heinonen *et al.,* 2000	Girls. White. Age 13.7±0.9yrs	No randomization Con = 33;Ex = 25 Con = 29;Ex = 39	100-220 jumps, one and two footed from 30cm; 2 times/week; 20mins/sessions; 9 months duration	LS +8.6% BMC FN + 9.3% BMC
	Sundberg *et al.,* 2001	Girls and boys. Age 16.0±0.3yrs	Randomized by school Con =148;Ex = 80	Weight loaded activities such as running, jumping, gymnastics; 4 x 40mins/week PE in school; 4 years duration	TB +3% aBMD LS + 3% aBMD FN + 9% aBMD TB + 4% BMC LS + 9% BMC FN + 8% BMC

* % gained over exercise intervention in exercise group (after any statistical adjustments). Only significant results reported. Age reported as mean ± SD. Abbreviations: aBMD – areal bone mineral density; ANCOVA – Analysis of covariance; ANOVA – Analysis of Variance; BMC – Bone mineral content; bw – Body weight; CMJ – Counter movement jump; Con = Controls; Ex = Exercise; FN – Femoral neck; FS – Femoral shaft; GRF – Ground reaction force; GT – Greater trochanter; IT – Intertrochanteric region; LS – Lumbar spine; NS – Non significant findings; PE – Physical education; PF – Proximal femur; reps – repetitions; TB – Total body; TR – Trochanter; vBMD – Volumetric bone mineral density.