Review

Physical activity increases bone mass during growth

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Abstract

Background: The incidence of fragility fractures has increased during the last half of the 1900's. One important determinant of fractures is the bone mineral content (BMC) or bone mineral density (BMD), the amount of mineralised bone. If we could increase peak bone mass (the highest value of BMC reached during life) and/or decrease the age-related bone loss, we could possibly improve the skeletal resistance to fracture.
Objective: This review evaluates the importance of exercise as a strategy to improve peak bone mass, including some aspects of nutrition.
Design: Publications within the field were searched through Medline (PubMed) using the search words: exercise, physical activity, bone mass, bone mineral content, bone mineral density, BMC, BMD, skeletal structure and nutrition. We included studies dealing with exercise during growth and young adolescence. We preferably based our inferences on randomised controlled trials (RCT), which provide the highest level of evidence.
Results: Exercise during growth increases peak bone mass. Moderate intensity exercise intervention programs are beneficial for the skeletal development during growth. Adequate nutrition must accompany the exercise to achieve the most beneficial skeletal effects by exercise.
Conclusion: Exercise during growth seems to enhance the building of a stronger skeleton through a higher peak bone mass and a larger bone size.

Keywords: *bone mass*; *bone mineral content, BMC*; *bone mineral density, BMD*; *exercise*; *growth*; *nutrition*; *physical activity*; *skeletal structure*

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One of the major medical problems in society during the latter part of the last century is the increasing incidence of fragility fractures (1–15). During their lifetime, half of all women and one-third of all men will suffer a fracture (1, 3). The fractures cause increased morbidity, mortality and costs for society (16). The increase in fracture incidence is to some extent attributed to an increased prevalence of osteoporosis, predominantly due to an increased aging population (15, 17, 18).

Peak bone mass is defined as the highest level of bone mineral density (BMD) or bone mineral content (BMC) or bone mass (BM) reached during life. These are all estimations of the amount of mineralised bone. BM is a more generalized term when describing the amount of mineral, BMC the amount of mineral measured within the scanned skeletal region and BMD the amount of mineral measured within the scanned skeletal region but partially adjusted for the bone size. If growing children built a skeleton with a lower peak bone mass than 50 years ago, then the fracture risk ought to have increased during the same period. It seems possible that this has occurred, as today we live a more sedentary life than some decades ago, although no long-term studies are available to support this assumption (4). If we could implement changes in the current lifestyle by increasing levels of physical activity, we could possibly also increase the accrual of bone mineral so that young individuals of today reach a high peak bone mass. A higher peak bone mass would then probably reduce the number of fractures, as 50% of the BMD in old age is attributed to the peak bone mass (19).

Epidemiological studies have convincingly shown that BMC and BMD are closely associated with the risk of sustaining a fracture (20). A 10% decrease in BMD (corresponding to one standard deviation; SD) is associated with a doubled fracture risk (20). However, even if BMD seems to be an excellent tool when evaluating fracture risk at a group level, it is a less reliable predictor when evaluating the individual fracture risk. Many other

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risk factors influence the risk of suffering a fracture (3, 17, 20, 21). Bone structure is such a trait that, independently of BMD, influences the bone's resistance to trauma (22). Although recent studies have suggested to shift the focus from BMD to interventions that reduce the number of falls as a more efficient fracture prophylactic tool approach (23), this review focuses on data that support or oppose the view that exercise during growth may influence the accrual of bone mineral and gain in bone structure. Some aspects of nutrition are covered as well.

Method

The search for papers to be included in the review was done in Medline (PubMed). The search words: exercise, physical activity, bone mass, bone mineral content, BMC, bone mineral density, BMD, skeletal structure and nutrition were used. Only papers or abstracts published in the English language and studies that evaluate exercise and the skeleton during growth and adolescence were included in the review. From the relevant papers included in the Medline search, a further search was undertaken by choosing the connection 'related manuscripts'. Preferably, prospective, randomised controlled trials (RCT) were then included in this overview, as this is the highest ranked study design in evidence-based systems (24). All published RCTs in pre-pubertal (Tanner stage I), early pubertal (Tanner stage II and III) and pubertal (Tanner stage IV and V) children were evaluated. If no RCTs were found, the next level of evidence in the evidence-based hierarchy was scrutinised, i.e. non-randomised controlled studies, then retrospective and prospective observation cohort studies, and finally case-control studies. As there exists an enormous amount of publications with these study designs, we aimed to include those with the largest sample size and the longest follow-up period. But, it must be emphasised that this is not a systematic review with pre-specified inclusion criteria or a meta-analysis. Neither did we intend to include all papers published within this topic since Nilsson et al. first wrote their article in 1970 'bone density in athletes' (25). Instead, we tried to interpret the enormous amount of data within the field in order to summarize the current view within this topic, to evaluate if exercise and nutrition during growth are of biological significance for the skeleton.

Results and discussion

Physical activity on competitive level and the skeleton

Today, there is compelling evidence indicating that physical activity affects the skeleton and the BMC and BMD in an anabolic way (26). The first study that addressed this hypothesis showed that athletes subjected to high load activities had 10–20% higher BMD compared to the controls (25). Further cross-sectional studies supported this view when comparing the dominant and non-dominant arm in racket players, a study design that controlled for the genetic regulation of the BMC. The BMC was 25–35% higher among professional tennis players in the dominant arm compared to the non-dominant arm (27). Furthermore, life-long tennis players aged 70–84 years had 4–7% higher BMC in the dominant compared to the non-dominant forearm (28). Later studies have verified these findings (29) and also defined at what age period physical activity has the most pronounced anabolic effects (30). After adjustment for different training history, the dominant and non-dominant arm difference were two to four times higher if the training was started before than after menarche (30) (Fig. 1).

If exercise is performed at a high level of activity, as in competitive athletes, a 10–20% gain in BMC can be expected (31–35) (Fig. 2). Both male and female gymnasts, soccer players, weight-lifters and ballet dancers are reported to have a 10–25% higher BMC compared to non-exercising controls (31–39). It is important to emphasise that the increase in BMC is only found in loaded skeletal parts and not in unloaded parts (Fig. 2). Thus, male weight lifters had a 10–20% higher BMC compared to the controls in the arms, which are highly loaded skeletal regions, during weight lifting (31, 40). On the contrary, male soccer players had no different BMC in the arms compared to the controls (34, 35), but in the lower legs BMC was higher in the soccer players at the same magnitude as in the arm of the male weight lifters, i.e. 10–20% higher than in the controls (32, 34, 35) (Fig. 2). Other athletes, training endurance exercise do not have higher BMC than controls (25). Moreover, exercise, on both more moderate and elite level confers

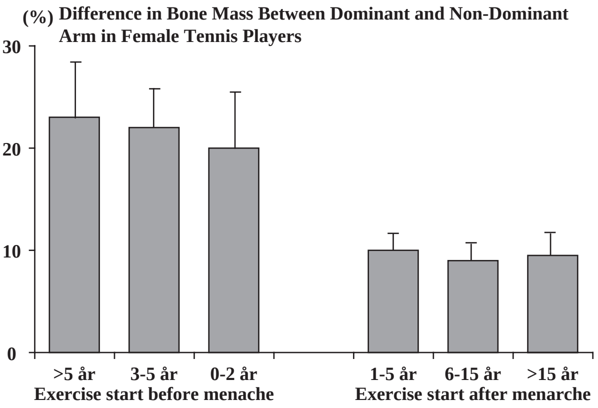

Fig. 1. The mean playing-to-non-playing arm difference in the bone mineral content of the humeral shaft (percentage difference of bone mineral content) according to the biological age at which training was started, that is, according to the starting age of playing relative to the age at menarche. Bars represent 95% CIs. Adapted from Kannus et al. (30).

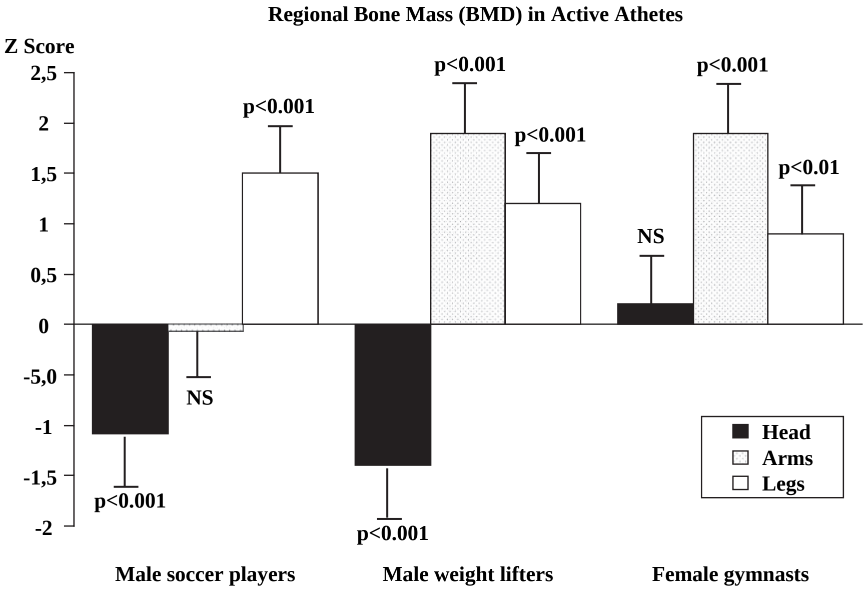

Fig. 2. Bone mineral density (BMD) of the head, the arms and the legs, in active male soccer players, male weight lifters and female gymnasts expressed as *Z* scores (number of standard deviations (SD) above or below age predicted mean). Adapted from Karlsson et al. (31, 34) and Bass et al. (39).

increased BMC. But, this type of exercise also induces benefits in bone size and skeletal structure that increase bone strength independently of the BMC (22, 29, 41, 42).

Which types of exercise provide skeletal benefits?

Exercise studies have also shown which type of exercise confers maximal anabolic effects on the skeleton. Skeletal load that includes a dynamic load, a load with a high magnitude, a high frequency load, a fast load and a load with unusually distributed strains provide the most pronounced osteogenic stimuli (43–46). The required mechanical load necessary to stimulate osteogenesis decreases as the strain magnitude and frequency increases (47, 48). A most important fact is that the osteogenic response to high magnitude loading becomes saturated after a few loading cycles (44), whereafter additional loading has limited benefits (49). That is, the duration of exercise is of much less importance because a short duration of load or a small number of repetitions is enough to achieve the maximal anabolic effect (43–46, 50). Bone cell mechano-sensitivity seems to recover following a period without loading. Thus, separating loading into short bouts with periods of rest optimises the osteogenic response to loading (51–53), even to low magnitude stimuli (54, 55). In animal studies, 4 h of rest doubled the response and the sensitivity was almost completely restored after 8 h of recovery (51).

With this knowledge, it seems as if high intensity sports like squash, tennis, soccer, ice-hockey, badminton, volleyball and weight-lifting performed on several different occasions during the week are most effective if the aim is to improve the skeletal strength (25, 30–35, 39) (Fig. 2). In contrast, endurance exercise is less beneficial for the skeleton. Long-distance running, not a high impact activity but at least promoting weight-bearing activity, produces minor skeletal benefits (25, 56), while non-weight-bearing activities, such as cycling and swimming, do not seem to produce any skeletal benefits of biological significance (24, 25).

Physical activity and the accrual of bone mineral during growth

Randomised and non-randomised prospective controlled exercise intervention studies with 6–24 months' duration infer that moderate physical activity in the pre- and peri-pubertal period could enhance BMC accrual with a magnitude that, if retained into old ages, would actually reduce the number of fragility fractures (42, 57–76) (Table 1). Few of these trials, however, follow the children with intervention beyond 1 year (66, 67, 77, 78). MacKelvie et al. (65–68) followed pre-pubertal girls in Tanner stage I (classification of pubertal stage) for 20 months and reported that an exercise intervention programme including specific osteogenic activities for 12 min, three times per week in 10-year-old girls led to 4% higher gain in femoral neck and lumbar spine BMC in the intervention group ($n = 32$) than in the control group ($n = 43$) (65). In 64 boys involved in the same programme (31 in the intervention group and 33 in the control group), there was a difference in the BMC of the femoral neck only, but of the same magnitude as in the girls (68).

The other long-term trial, the prospective Paediatric Osteoporosis Prevention (POP) study, included a moderate intense school-based exercise intervention program

Table 1. The skeletal response to exercise seen in randomized and non-randomized prospective controlled exercise intervention studies in pre- and peri-pubertal children and in post-pubertal girls

Reference	Age of participants	Type of exercise intervention	Duration of intervention	Increase higher in cases versus controls
Pre-pubertal (Tanner stage I)				
Fuchs et al. (2001) (61)	99 children; 7.6 ± 0.2 years	High impact jumping 10 min three times a week	7 months	BMC: +4.5% FN, +3.1% LS BMD: +2.0% LS BA: +2.5% FN
Petit et al. (2002, part a) (73)	68 girls; 10.0 ± 0.6 years	High impact 10–12 min three times a week	7 months	No effect
MacKelvie et al. (2001, part a) (66)	70 girls; 10.1 ± 0.5 years	High impact 10–12 min three times a week	7 months	No effect
McKay et al. (2000) (70)	144 girls	Moderate impact 10–30 min three times a week	8 months	BMD: +1.1% Tr
Bradney et al. (1998) (59)	40 boys; 10.4 ± 0.2 years	Weight bearing 30 min three times a week	8 months	BMD: +1.2% TB, +2.8% LS, +5.6% legs vBMD: +5.6% FM
Van Langendonck et al. (2003) (75)	42 twin girls; 8.7 ± 0.7 years	High impact three times a week	9 months	BMC: +2.5% PF, +2.0% FN BMD: +1.3% PF, +2.4% FN
Lindén et al. (2006) (82)	138 boys; 7.8 ± 0.6 years	Daily school physical educational classes	12 months	BMC: +5.9% LS BMD: +2.1% LS BA: +2.3% LS
Valdimarsson et al. (2006) (81)	103 girls; 7.7 ± 0.6 years	Daily school physical educational classes	12 months	BMC: +4.1% LS, 16.0% Tr BMD: 2.8% LS BA: 2.9% LS
Specker et al. (2003) (42)	178 girls; 3.9 ± 0.6 years	High impact 30 min five times a week with or without calcium	12 months	BMC: +9.7% leg
MacKelvie et al. (2004) (68)	64 boys; 10.2 ± 0.5 years	High impact 10–12 min three times a week	20 months	BMC: +4.3% FN
Laing et al. (2005) (64)	143 girls; 6.0 ± 1.5 years	Gymnastics 1 h once a week	24 months	BMC: TB, PF BMD: TB, PF BA: TB, PF
Alwis et al. (2008) (78)	137 boys; 7.8 ± 0.6 years	Daily school physical educational classes	24 months	BMC: +3.0% LS BA: +1.3% LS
Lindén et al. (2006) (77)	99 girls; 7–9 years	Daily school physical educational classes	24 months	BMC: 3.8% LS, 3.0% legs BMD: 0.6% TB, 1.2% LS, 1.2% legs BA: 1.8% LS, 0.3% FN
Early pubertal (Tanner stage II–III)				
Petit et al. (2002 part b) (73)	106 girls; 10.5 ± 0.6 years	High impact 10–12 min three times a week	7 months	BMD: +1.7% Tr, +2.6% FN
MacKelvie et al. (2001, part a) (66)	107 girls; 10.5 ± 0.6 years	High impact 10–12 min three times a week	7 months	BMC: +1.8% LS BMD: +1.7% LS, +1.6% FN vBMD: FN
McKay et al. (2005) (69)	124 girls and boys; mean 10.1 years	Jumping 3*3 min 5 days a week	8 months	BMC: +2.0% PF, +2.7% Tr

Table 1 (*Continued*)

Reference	Age of participants	Type of exercise intervention	Duration of intervention	Increase higher in cases versus controls
Iuliano-Burns et al. (2003) (63)	64 girls; 8.8 ± 0.1 years	Moderate impact 20 min three times a week with or without calcium	8.5 months	BMC: +2.1% LS, +3.0% lower leg
Heinonen et al. (2000, part a) (62)	58 girls; 11.0 ± 0.9 years	High impact 20 min two times a week	9 months	BMC: +3.3% LS, +4.0% FN
Morris et al. (1997) (71)	71 girls; 9.5 ± 0.9 years	Moderate impact 30 min three times a week	10 months	BMC: +5.5% TB, +5.5% LS, +4.5% FN, +8.3% PF BMD: +2.3% TB, +3.6% LS, +10.3% FN, +3.2% PF vBMD: +2.9% LS
Courteix et al. (2005) (60)	Girls; 8–13 years	Exercise 7.2 h/week; controls 1.2 h/week	12 months	BMD: +6.3% TB, +11.0% LS, +8.2% FN
MacKelvie et al. (2003) (65)	75 girls; 9.9 ± 0.6 years	High impact 10–12 min three times a week	20 months	BMC: +4.6% FN, +3.7% LS
Pubertal (Tanner stage IV–V)				
Blimkie et al. (1996) (58)	36 girls; 16.3 ± 0.3 years	Weight training three times a week	6 months	No effect
Witzke et al. (2000) (76)	53 girls; 14.6 ± 0.5 years	Resistance exercise 30–45 min three times a week	9 months	No effect
Heinonen et al. (2000, part b) (62)	58 girls; 13.3 ± 0.9 years	High impact 20 min two times a week	9 months	No effect
Nichols et al. (2001) (72)	17 girls; 15.9 ± 0.1 years	Resistance exercise three times a week	15 months	BMC: +2.3% FN, +3.2% WT
Stear et al. (2003) (74)	144 girls; 17.3 ± 0.3 years	Moderate impact 45 min three times a week with or without calcium	15.5 months	BMC: +0.8% TB, +1.9% LS, +2.2% FN, +2.2% PF, +4.8% Tr

Bone mineral content (BMC), bone mineral density (BMD), volumetric bone mineral density (vBMD) and bone area (BA) compared between cases and controls in total body (TB), proximal femur (PF), femoral neck (FN), wards triangle (WR) trochanter (Tr), legs, femoral midshaft (FM) and lumbar spine (LS).

comprising 40 min of general physical activity per school day (200 min per week), while the controls were subjected to the general Swedish school curriculum of 60 min per week (77, 78). Eighty boys aged 7–9 years were included in the intervention program with 57 age-matched boys as controls. The mean annual BMC gain in the third lumbar vertebra was 3% ($p < 0.01$) and in L3 width 1.3% ($p < 0.01$) greater in the intervention than in the control group. The weekly duration of exercise estimated through the questionnaire correlated with a gain in BMC in the third lumbar vertebra ($r = 0.25$, $p = 0.005$) and was also related to vertebra width ($r = 0.20$, $p = 0.02$) (78). Forty-nine girls aged 7–9 years were included in the intervention group while 50 served as controls (77). All girls were premenarchal and in Tanner stage I during the study. The annual gain in BMC was greater in the intervention group than in the controls, in the second to fourth lumbar vertebrae (L2–L4) mean 3.8% ($p = 0.007$), in the L3 vertebra mean 7.2% ($p < 0.001$) and the legs mean 3% ($p = 0.07$). There was also a greater mean annual gain in bone size, in the L3 vertebra mean 1.8% ($p < 0.001$) and in the femoral neck mean 0.3% ($p = 0.02$) in the intervention group (77). Three- and four-year data have also been presented from the POP study in abstract form, showing that the benefits remain with 3 and 4 years of extra school training at a similar magnitude as after 2 years' intervention (79, 80).

The rest of the cited RCTs in this review have followed the children for a shorter follow-up period than 16 months. Most of the studies include children that on a voluntary basis wanted to participate in an exercise study, a fact that increases the risk of selection bias. One study reported that exercises including jumping up and down a small step 30 min per day, three times per week, increased BMD in the greater trochanter by 1.4% over a period of 8 months (70). Most of the studies in pre- and peri-pubertal children have used specifically designed osteogenic intervention programmes, such as jumping up and down a small height, or high intense short-term programs and provide similar data (57, 59, 61, 62, 70, 71, 81, 82) (Table 1). These repetitive types of exercise have been shown to be effective in the short-term perspective, but involve the risk of boring the children, leading to high dropout frequencies (83). There are fewer RCTs in post-pubertal children (Table 1). No increase in BMC or BMD could be demonstrated after a 6–9 months' intervention period in these girls (58, 62, 76). On the other hand, two 15-month trials in post-pubertal girls indicate that physical training may insert skeletal effects also during this period (72, 74). However, these data should be interpreted with caution as there were only 17 girls in one study (72) and in the second, additional calcium support of 1000 mg per day was given (74).

In summary, available prospective controlled exercise intervention studies support the hypothesis forwarded by Kannus et al. more than 10 years ago (30), that training in the late pre- and early pubertal period seems to be more effective when trying to enhance the BMD, than providing the same type of training after puberty (Fig. 1, Table 1).

Effects of physical activity on skeletal structure during growth

In addition to the increased accrual of bone mineral, exercise during growth is important because of the associated changes in bone geometry that translate to greater increases in bone strength than provided by an increase in BMC alone (22). Bone size was approximately 10% larger when comparing the upper limbs of young pre-pubertal gymnasts and normally active children (84, 85), or the playing and non-playing arms of young pre-pubertal tennis players (29, 86). This beneficial effect seems to have occurred due to an exercise-induced periosteal expansion. Alternatively, bone mineral may be deposited on the endosteal surface, producing a thicker cortical shell without a wider bone. For example, cortical cross-sectional area was 5–12% greater in the lower limbs of young runners or young gymnasts compared to controls (84, 87, 88). The enlargement of bone cross section in response to loading has been reported to increase from pre- to peri-puberty in male but not in female tennis players (29, 86). Apposition of bone on the periosteal surface of cortical bone is a more effective means of increasing the bending and torsion strength of bone than acquisition of bone on the endosteal surface (89).

The complexity of the skeletal response to loading is also illustrated by the heterogeneity of the geometrical adaptations along the length of a bone (52, 53). For instance, in young tennis players, loading has been shown to induce endosteal apposition at the distal humerus but not at the mid humerus. Periosteal expansion has been reported to occur differently in the proximal, mid-diaphyseal and distal parts as well as in the medio-lateral and anterior-posterior directions within the same bone (27, 90).

Some but not all of the cited RCTs in pre-pubertal children have also inferred that bone structure, evaluated as bone area or bone size, in both boys and girls may be influenced in a beneficial way even by moderate intense intervention programs (38, 57, 61, 77, 82, 91) (Table 1). As already mentioned, the osteogenic benefits achieved by exercise during growth are also maturity- and sex-dependent (92), with exercise interventions being most effective for both BMC and bone structure when initiated during pre- or early puberty. It is thought that exercise may preferentially affect the surface of bone that is undergoing apposition during growth (93). Accordingly, the pre-pubertal skeleton demonstrates the capacity to respond to loading by adding more bone on the periosteal surface than would normally occur through growth-induced periosteal apposition (29, 85, 86). Several studies also mentioned exercise-induced endosteal apposition in pre-pubertal boys (84, 86, 94), whereas such a response is not seen in pre-pubertal girls observed under the same conditions (29, 84). Further studies are needed to determine the sex- and maturity-dependent osteogenic response to loading.

Adverse effects of exercise

Most skeletal changes associated with physical activity are beneficial and there are only sparse descriptions of adverse effects. If the physical level is increased, normally the skeleton responds with an increased BMC (31–39). However, in some individuals the BMC remains unchanged or even decreases, something that has been seen as a factor behind both stress fracture and shin splints (95). But the most serious adverse skeletal side effect from exercise is seen in individuals with a very high intensity activity. Menstrual and hormonal alterations are frequently connected with dieting, low body mass and eating disorders – in addition to strenuous training. A long duration of hard training can lead to decreased oestrogen levels and a training-induced amenorrhoea, often accompanied by reduced BMC (96). Several studies in females within different sports have verified that this menstrual dysfunction leads to lowered BMC, even lower than in controls (96). If the menstrual dysfunction is normalised, the BMC slowly increases but is not fully restored (97). Interestingly, a similar negative metabolic effect after very hard exercise has also been seen in men (98).

Effect of nutrition on exercise-induced skeletal benefits

There are few studies that specifically evaluate how nutritional parameters may modify exercise-induced skeletal effects. Observational studies infer that energy and protein malnourished children have reduced bone size and BMC (99). Furthermore, prospective studies suggest that there is a positive association between dietary protein intake in children over 4 years and bone size and BMC (100).

Several studies have shown that the beneficial exercise-induced skeletal effects are seen only if the calcium intake is high, around 1300 mg per day in growing individuals and 1000 mg per day in adults (101–103). Prospective controlled exercise intervention trials also infer that extra calcium supplement interacts with increased exercise, resulting in a higher BMC and more advantageous skeletal structure (42). However, after cessation of the trial, all BMC benefits were lost after 12 months while the structural benefits remained (104). The exercise–nutrition interaction has been verified in several other trials (42, 60, 63, 74, 101, 103, 105). The underlying mechanisms for the exercise and nutritional interaction are poorly understood. Even fewer studies have evaluated the importance of Vitamin D, protein intake and energy intake. In summary, even if the literature is sparse, available data support that optimal beneficial skeletal effects are dependent on adequate nutrition.

Conclusions

Activity at a level that most individuals can perform increases the accrual of bone mineral during growth. Adequate nutrition must accompany the exercise to achieve the strongest possible skeleton. These data support the importance of community and health care interventions towards the young generation. A physically active lifestyle that includes skeletal mechanical load and an adequate nutrition seems to increase peak bone mass and in a longer perspective, possibly reduce the numbers of fragility fractures.

Recommendations

Based on current scientific knowledge, we should recommend a physically active lifestyle and an adequate nutritional intake for growing children, as one prevention strategy to reduce the current high incidence of fractures.

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Conflict of interest

No conflicts of interest exist.

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