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Influence of rapid growth on skeletal adaptation to exercise

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Abstract

During rapid growth, increased body weight and muscle strength result in increased loads on bone. Bone adapts to these increased strains by increasing bone modeling and remodeling. As the growth rate decreases, bone that was formed as a result of these adaptations continues to mineralize and "catch up", and bone modeling and remodeling decreases. Bone benefits of exercise in childhood are reported in some studies, although we observed less BMC gain at trabecular-rich sites during the peri-pubertal period in children who jumped than those who did not. Data from 13 existing pediatric exercise studies were compiled to determine whether similar patterns of age-related bone changes could be identified, and whether the bone benefit of exercise differed depending upon pubertal stage. The benefit of exercise on total body BMC gains occurred across all ages, whereas greater exercise-induced gains at the spine and hip were observed in younger children compared to older children. The majority of studies found a positive effect of exercise on bone, but typically this involved limiting the analysis to specific sub-populations (i.e., higher calcium intake, lower baseline activity levels, smaller body size). Limitations of the studies published to date are discussed.

Keywords: Bone, Pediatric, Exercise, Obesity, Growth

Bone growth

During growth, there are gains in both bone length and width. The increase in bone length is a result of endochondral ossification. Endochondral ossification involves the formation of cartilage at the ends of the long bones in the growth plate region, which is then transformed into bone tissue in the adjacent metaphysis.

Modeling and remodeling are distinctly different. Modeling is a result of osteoblasts depositing bone matrix on the periosteal surface, while osteoclasts resorb bone on the endosteal cortical surface. Remodeling occurs in bone formed both through endochondral ossification and by modeling, and is the result of successive cycles of bone resorption and formation on the same surface. Bone modeling leads to an increase in bone width or circumference, while increased

bone remodeling leads to increased cortical "porosity." This increase in cortical porosity explains in part the increased fracture risk that is observed at the time of peak height velocity. Bone adapts to increased strains during growth, and as the growth rate decreases the bone that was formed as a result of these adaptations continues to mineralize and "catch up", and bone modeling and remodeling decreases.

Exercise during rapid bone growth

During rapid growth spurts, increased body weight, muscle strength and longitudinal bone growth result in increased loads on bone. According to the "mechanostat" theory, proposed by Harold Frost in 1987¹, the skeleton will adapt to these loads by increasing its strength. There are numerous studies reporting an association between bone and lean mass, and this association is often used as evidence supporting the "mechanostat" theory^{2,3}. However, genetic factors also may explain the association between bone and lean mass, as well as between bone and body weight, with leaner or larger individuals "programmed" to have larger skeletons. Recent findings by Rauch and co-workers show that increased muscle growth precedes increased bone mass accretion and the authors suggest that these data support the "mechanostat" theory that bone is driven by muscle development⁴.

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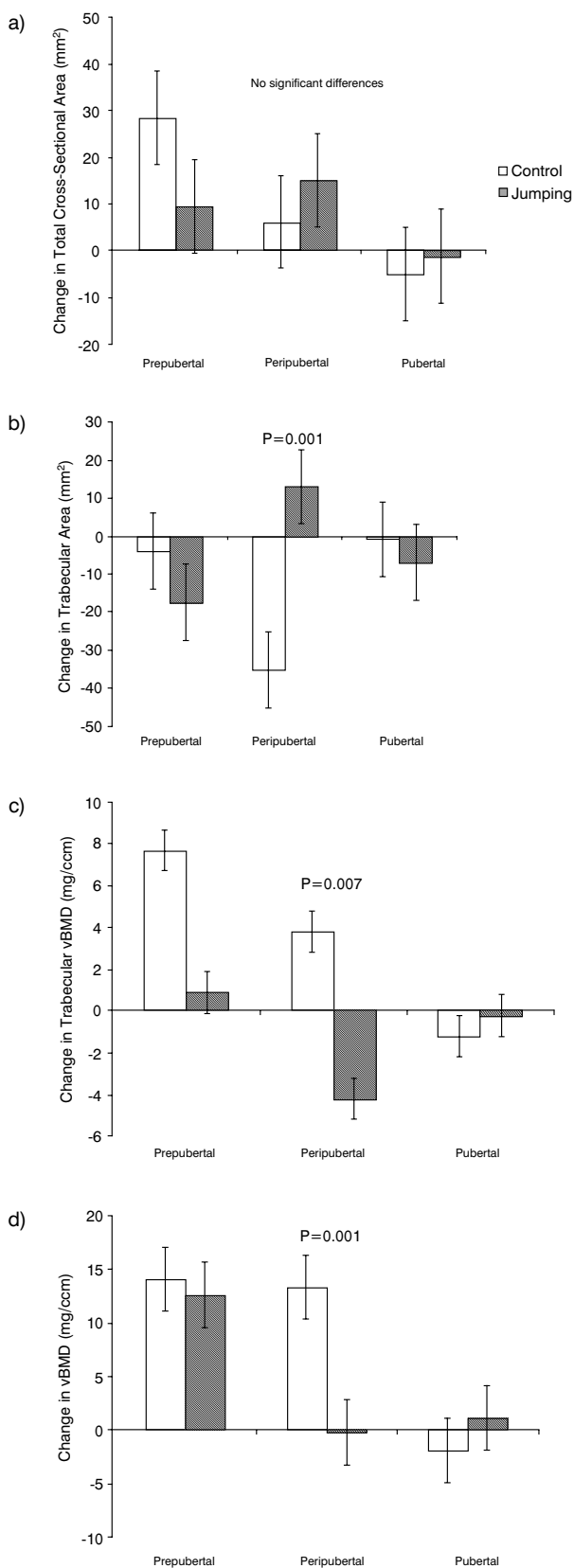


Figure 1. The effect of jumping in pre-pubertal, peri-pubertal, and pubertal children on changes at the: a) total cross-sectional area, b) trabecular bone area, c) trabecular vBMD and d) total vBMD at the 4% distal tibia.

In general, it is thought that periods of growth are the best time to influence bone through increased loading due to the high rates of bone modeling and remodeling that are occurring⁵. Structurally, the most efficient way for bone to increase strength is by increasing bone diameter. Exercise during early adolescence may affect the periosteal surface, which is rapidly growing due to the high rates of modeling that are occurring. Exercise later in adolescence may affect endosteal surfaces. This is a time when endocortical apposition is occurring and cortical thickness is increasing. Findings from randomized exercise trials, on the other hand, are not always consistent with the general belief that increased bone loading during growth will lead to increased bone mass accrual.

Findings from a preliminary randomized trial of jumping in 54 pre-, peri-, and post-pubertal children did show bone benefits in children who were randomized to jump (25 times per day off a 45 cm box, 5 days per week for 12 weeks) compared to controls who did not jump⁶. Bone measures included DXA scans of the total body and spine and pQCT scans at the 4% (trabecular) and 20% (cortical) distal tibia at baseline and 12 weeks. Children who jumped had significantly greater increases in total body and leg BMC compared to control children, but jumping led to significantly less BMC gain at trabecular-rich sites during the peri-pubertal period (group-by-puberty interactions, $p<0.05$). Further investigation of differences in pQCT measurements at the 4% trabecular bone site found no difference in total cross-sectional bone area, but greater trabecular bone area with lower trabecular and total volumetric bone mineral density (vBMD) in peri-pubertal children who jumped than control children (Figure 1). These results suggest that loading leads to a greater increase in endosteal resorption and expansion of the trabecular bone area during the peri-pubertal period. It is likely that the relatively small sample size contributed to the lack of significant difference in total cross-sectional area between children who jumped and controls. A further disadvantage of this study was that pubertal status was self-reported and significant hormonal changes occur during the peri-pubertal period. The findings of this study led to a review of pediatric exercise trials, in order to determine whether other studies report similar findings during this period of rapid growth.

Review of pediatric exercise trials

Upon the initial reading of the pediatric intervention trials, it was difficult to come to a single conclusion regarding the effect of exercise on bone changes and whether or not puberty or different periods of growth modify the skeletal effect of loading. The intervention trials reported a variety of bone sites, various techniques were used, the exercises were varied in their approach, and the length of the studies also differed significantly. Therefore, a review of pediatric exercise trials was conducted to attempt to synthesize results of previous trials to determine whether consistent patterns could be identified.

There were 13 pediatric exercise trials that were reviewed

Reference	Unit *	Gender	Age	Number	Length	Intervention
Morris et al., 1997 ⁷	S	Girls	10 y	71	10 mo	High impact + weight training: 30min 3d/wk
Bradney et al., 1998 ⁸	S	Boys	10 y	40	8 mo	High impact + weight training: 30min 3d/wk
Heinonen et al., 2000 ⁹	I	Girls	12 y	126	9 mo	High impact: 50min 2d/wk
Witzke et al., 2000 ¹⁰	S	Girls	15 y	53	9 mo	High impact + strength training: 30min 3d/wk
McKay et al., 2000 ¹¹	S	Mix	9 y	144	8 mo	High impact: 10min 3d/wk
MacKelvie et al., 2001 ¹² & Petit et al., 2002 ¹³	S	Girls	10 y	177	7 mo	High impact: 20 min 3d/wk
Fuchs et al., 2001 ¹⁴	S	Mix	8 y	89	7 mo	100 jumps/d 3d/wk
MacKelvie et al., 2002 ¹⁵	S	Boys	10 y	121	7 mo	High impact: 10min 3d/wk
Specker et al., 2003 ¹⁶	I	Mix	4 y	178	12 mo	High impact: 30min 5d/wk
Stear et al., 2003 ¹⁷	I	Girls	17 y	131	16 mo	High impact: 45min 3d/wk
Iuliano-Burns et al., 2003 ¹⁸	I	Girls	9 y	66	9 mo	Moderate impact: 20 min 3d/wk
Johannsen et al., 2003 ⁶	I	Mix	11 y	54	3 mo	25 jumps/d 5d/wk
VanLangendonck et al., 2003 ¹⁹	I	Girls	9 y	21	9 mo	High impact: 10 min 3d/wk

* Unit that was assigned or randomized: I=individual; S=school or classroom

Table 1. Summary of pediatric exercise trials.

(Table 1)⁶⁻¹⁹. Trials conducted in infants^{20,21} or done as a follow-up^{22,23} were excluded. The mean *annual* percentage changes were calculated for both exercise and control groups, as well as the difference in percentage change between the two groups. The changes were annualized in order to allow for comparisons among studies. The mean annual changes and differences between percentage change in the exercise and control groups were plotted against age to determine whether bone response varied by age. The results for different bone regions are illustrated in Figures 2 to 7.

The majority of studies using dual energy X-ray absorptiometry (DXA) found gains in total body BMC at all ages studied, and annual percentage gains were greater in younger children (Figure 2a). A greater gain in total body BMC among the exercise group than the control group was found in some of the trials and the effect appeared to be similar for all ages (Figure 2b). Overall, greater spine BMC gains occurred around the time of puberty (Figure 3a), with a greater benefit of exercise among pre-pubertal children (Figure 3b). The percentage change in spine BMC was greater among the exercise than control groups, except around the peri-pubertal period. As expected, greater gains in femoral neck BMC also were observed in the pre- and peri-pubertal periods than during post-puberty (Figure 4a). The benefit of exercise on femoral neck BMC gain also was fairly consistent across the studies among pre-pubertal children, but not post-pubertal children (Figure 4b).

The use of peripheral quantitative computed tomography (pQCT) or hip structural analysis (HSA) in some of the studies allowed for the investigation of changes in bone geometry. pQCT also provides estimates of changes in trabecular and cortical volumetric density (vBMD), although measures

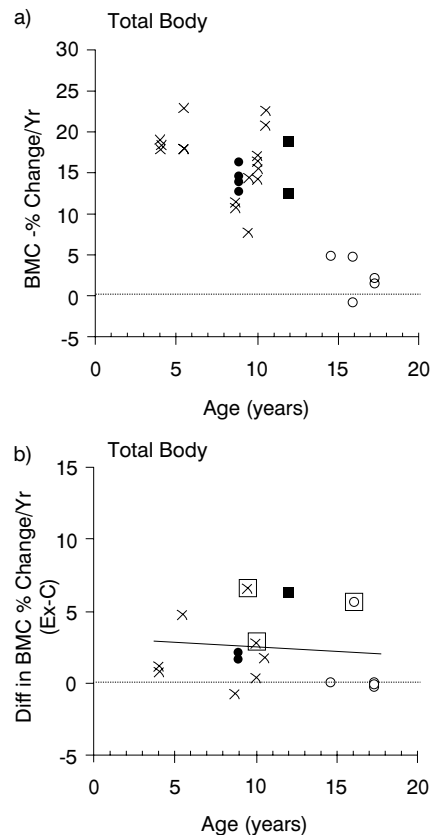


Figure 2. Total body BMC. a) Annualized mean changes by pubertal status for both exercise and control groups, and b) differences in BMC percentage change between exercise and control groups. Statistically significant findings among single studies are shown inside a square. x=pre-pubertal; •=pre- + early puberty combined; ■=early or peri-pubertal; ○= post-pubertal.

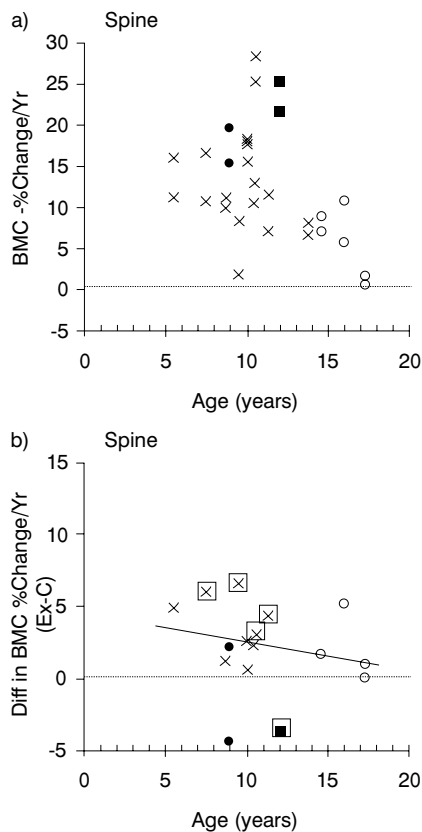


Figure 3. Spine BMC. a) Annualized mean changes by pubertal status for both exercise and control groups, and b) differences in BMC percentage change between exercise and control groups. Statistically significant findings among single studies are shown inside a square. x=pre-pubertal; •=pre- + early puberty combined; ■=early or peri-pubertal; o=post-pubertal.

of cortical vBMD may be underestimated in smaller bones due to a partial volume effect²⁴. Overall, an increase in periosteal expansion with lower endosteal expansion occurred around the time of puberty, leading to a greater increase in cortical thickness (Figure 5). There was no consistent effect of exercise on any of the bone geometric properties, although one study did report a greater decrease in endosteal circumference leading to a greater cortical thickness among children who exercised compared to those children who did not exercise⁸ (Figure 6). There was a slight decline with age in the bone differences that were observed with exercise. Greater increases in cortical vBMD were observed around the time of puberty, and the gains in vBMD were not different between exercise and control groups (Figure 7).

It is likely that there are environmental factors that may modify the bone response to activity. There has been speculation that greater exercise-induced changes occur in individuals with greater calcium intake than what is seen in individuals with lower calcium intake²⁵. Four of the 13 trials

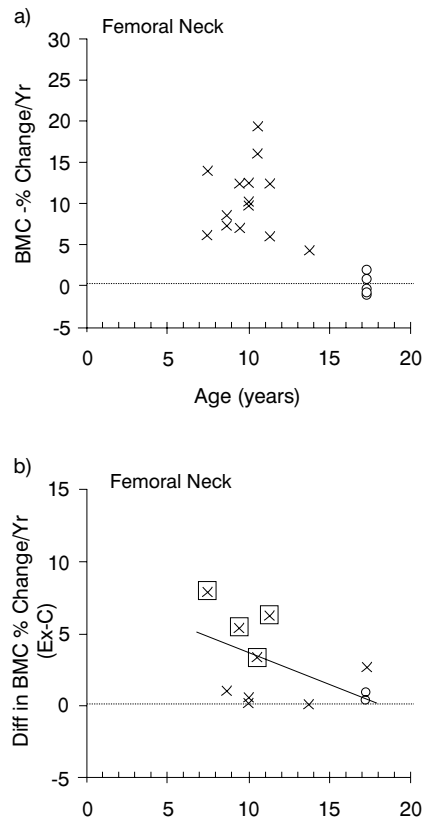


Figure 4. Femoral neck BMC. a) Annualized mean changes by pubertal status for both exercise and control groups and b) differences in BMC percentage change between exercise and control groups. Statistically significant findings among single studies are shown inside a square. x=prepubertal; o=post-pubertal.

shown in Table 1 reported results consistent with this speculation^{6,16-18}.

An exercise program also may only have bone benefits if the loads that are placed on the skeleton are greater than what the bone normally senses. Several of the studies found results that would support this. Positive effects of exercise were observed in the study by MacKelvie and co-workers only if the analysis was limited to boys with low or average body mass index¹⁵. Van Langendonck et al. found an exercise benefit on bone if they limited their analysis to girls with minimal weight-bearing activity during their leisure time¹⁹.

Compliance with the exercise program also is important since the less compliant individuals are likely not to have sufficient loads to observe a bone effect. This was observed by Stear et al. who reported a significant effect of exercise on size-adjusted BMC, but only when the analysis was limited to girls who attended at least 50% of the exercise classes¹⁷.

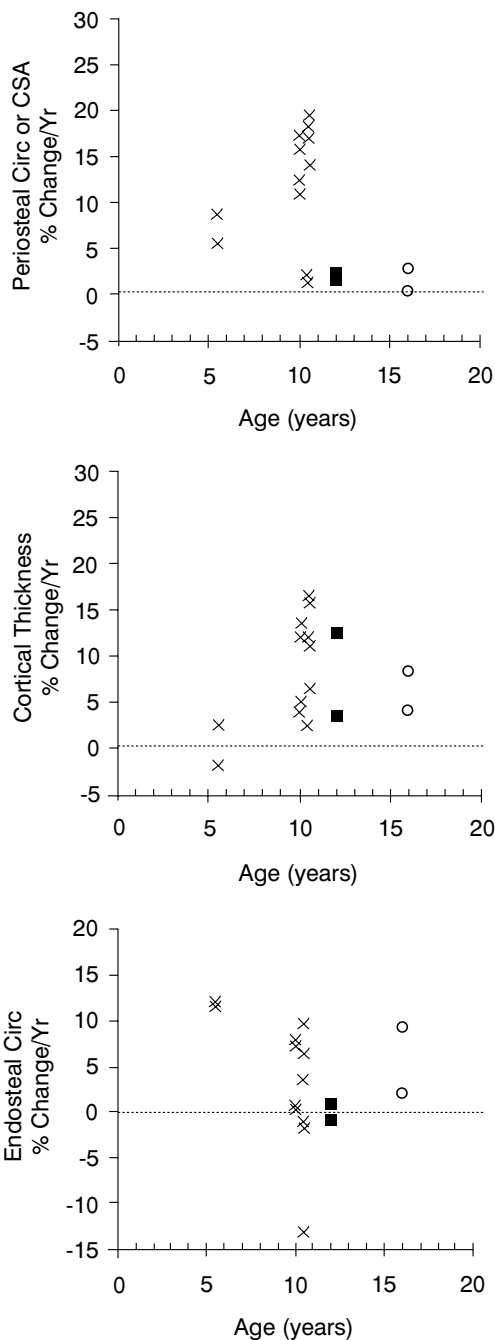


Figure 5. Annualized mean changes by pubertal status in periosteal and endosteal circumferences and cortical thickness. x=pre-pubertal; ■=early or peri-pubertal; ○=post-pubertal.

Study limitations

There are many difficulties in comparing the pediatric exercise trials that have investigated bone health. Many of these studies involved randomization of the schools rather than the individual, and other differences may exist between

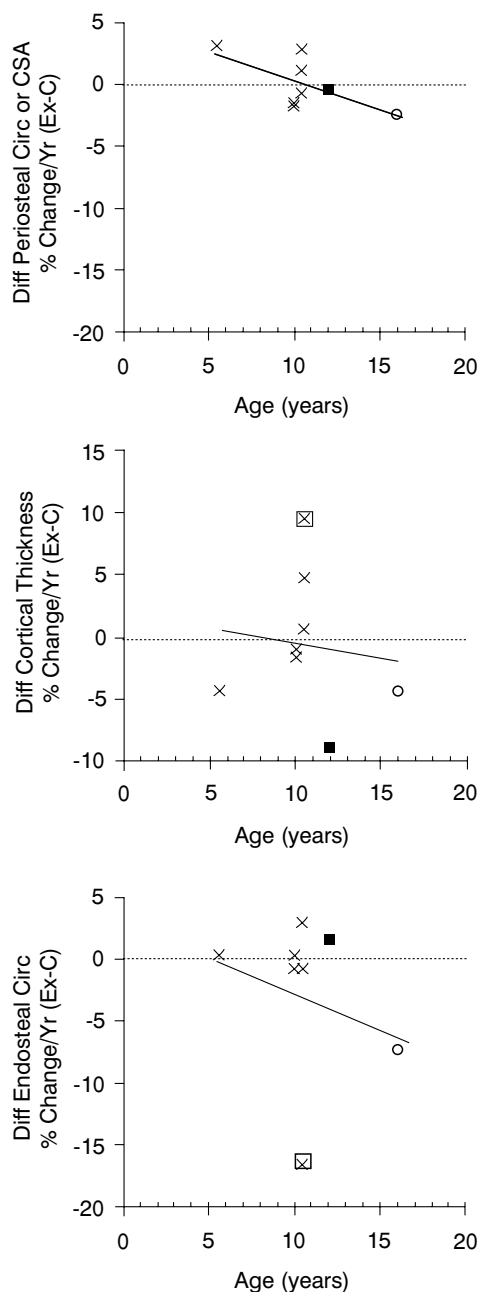


Figure 6. Differences (exercise - control) in annualized mean percentage changes by pubertal status in periosteal and endosteal circumferences and cortical thickness. Statistically significant findings among single studies are shown inside a square. x=pre-pubertal; ■=early or peri-pubertal; ○=post-pubertal.

schools that could influence bone changes. In addition, randomized trials are expensive and the majority of studies tend to be relatively small.

Different methods for assessing bone and the outcomes that are presented vary from one study to another. Bone measures that are typically reported include areal measures of BMD, while more important measures of BMC and bone

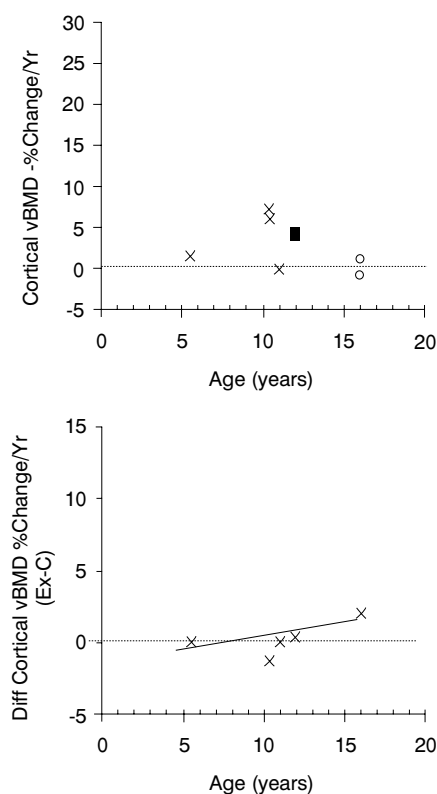


Figure 7. Cortical vBMD. a) Annualized mean changes by pubertal status for both exercise and control groups, and b) differences in vBMD percentage change between exercise and control groups. x=pre-pubertal, ■=early or peri-pubertal; ○=post-pubertal.

area are often not provided. Measures of bone geometry include those obtained by pQCT or estimated from HSA that is performed using the hip DXA scan. There are likely to be site-specific changes that occur in bone geometry and few studies have measured similar bone sites. Often only the unadjusted or adjusted means are given, making comparisons among studies difficult. The intriguing results of our original study were changes that occurred at trabecular bone sites. However, when conducting the review of existing studies it was apparent that the majority of studies using pQCT measured primarily cortical bone sites, making it difficult to compare results with changes observed at a trabecular bone site.

While trying to investigate the effect of rapid growth on bone changes resulting from increased loading, it is difficult to identify pubertal status in many of the studies. Often study populations were described simply as pre-pubertal or post-pubertal, yet this is a continuum that will change over the period of the trial and the majority of studies did not take changes in pubertal status over the study period into account.

The trials conducted different types of interventions over varying lengths of time. The majority of trials involved high impact activities only and few reported actual increases in lean mass or strength. Muscle generates significant forces on

the skeleton and exercises that involve a combination of impact and strength training exercises are likely to have more of a bone benefit than exercises involving only impact activities. The length of the trials ranged from 3 to 15.5 months. Errors in estimates of bone changes over the shorter study periods will be greater when they are annualized for comparison purposes.

Due to the small number of trials that have been completed, it was not possible to present sex-specific results. There are significant sex differences in bone changes, especially around the time of puberty, and it is possible that the response to exercise may differ among boys and girls at different ages. Eight of the studies were conducted in girls, 2 in boys and three presented the bone results for both boys, and girls combined.

Summary

Although it is widely believed that exercise during childhood leads to significant bone benefits, the results of randomized controlled trials are not consistent and there are many unanswered questions. It appears that some bone sites are more responsive to exercise than others and this responsiveness varies by age. The benefit of exercise on gains in total body BMC occurred across all ages, whereas greater exercise-induced gains at the spine and hip were observed in younger children compared to older children. The majority of studies found a positive effect of exercise on bone, but typically this involved limiting the analysis to specific sub-populations (i.e., higher calcium intake, lower baseline activity levels, smaller body size). These findings suggest specific populations may benefit from increased exercise more than others.

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