Adequate dietary calcium and bone-stimulating exercise during growth are known to affect skeletal development, but the combined effects of dietary calcium and osteogenic exercise have received scant attention. Animal research has showed a compensatory effect of impact loading on calcium-deprived bones, while various human studies have suggested compensatory, additive, or possibly synergistic effects in certain skeletal locations. Current evidence suggests that the best strategy for strong bones by the end of childhood may be either high-impact exercise with a moderate or greater calcium intake or a combination of moderate-impact exercise and adequate calcium during growth.

Key words: dietary calcium, exercise, growth, bone

INTRODUCTION

Sufficient dietary calcium and weight-bearing exercise are accepted factors in the formation of a strong skeleton. They both represent realistic opportunities for skeletal improvement because they are relatively easy and inexpensive to modify. Dietary intake of calcium can be increased through school lunch programs, fortified foods, and indirectly through nutritional education. Similarly, both the quality and quantity of physical activity that children undertake can be improved through school curricula, community programs, sports clubs, and greater awareness of its importance. Both calcium consumption and exercise have improved surrogates for bone strength in children. However, little research has explored the relative or combined merits of diet and exercise to the skeletons of children. Do calcium and exercise work independently, perhaps in different fractions of the bone? Can exercise be efficacious on nearly any diet, or does sufficient calcium need to be consumed for exercise to exert its rewards? Can exercise on a low-calcium diet be harmful? The aims of this paper were: 1) to review separate and combined effects of dietary calcium and exercise on growing bone, and 2) to reach pragmatic conclusions about the relative merits of exercise and calcium during growth, both separately and as combined factors.

MEASUREMENT OF DIETARY CALCIUM

Comparisons of the effects of diet and exercise are often complicated by differences in the methodology employed in the fields of nutrition and the exercise sciences to assess treatment outcomes. Calcium research in children has focused on dietary interventions that either maximize calcium retention or peak bone mass. Short-term calcium studies typically examine whole-body calcium balance by using actual dietary intake plus urinary, fecal, and sometimes sweat output to measure retention.1-3 These studies often employ calcium kinetics using stable isotopes3,6 sometimes in conjunction with bone markers.1,7 The use of calcium radioisotopes is not usually considered ethical in children. Longer-term calcium studies have used dual-energy x-ray absorptiometry (DXA) to measure changes in bone mineral content (BMC) or areal bone mineral density (aBMD) derived from planar measurements. Only two dietary calcium studies that investigated the effects of dietary calcium in children employed peripheral quantitative computed tomography (pQCT),8,9 which measures three-dimensional spatial and densitomic parameters of both cortical and trabecular bone at scan sites.

Pediatric exercise research also commonly utilizes DXA. Most studies on the effects of exercise or sports on children’s skeletons have been either cross-sectional or longitudinal in design, with longitudinal studies lasting a minimum of 7 months. To our knowledge, acute or short-term exercise studies on children in a controlled environment using isotopes or bone markers have not been performed. Recent pediatric exercise research has also seen limited employment of pQCT.8,10,11...
tive ultrasound,12-15 and magnetic resonance imaging (MRI).16,17

When animal models are employed, both the nutrition and exercise-related fields typically measure outcomes by mechanical testing, histomorphometry, and sometimes DXA. However, nutritional researchers using animal models are more apt to use radioisotopes and kinetic modeling to measure calcium balance, absorption, and retention in the whole body18-20 or calcium accrual in a selected bone.21 Researchers who examine the effects of mechanical loading using animal models emphasize the actual mechanical strength, as well as parameters closely correlated with strength, such as geometry and cross-sectional moments of inertia that can be determined through the use of three-dimensional pQCT22,23 and microcomputed tomography imaging.24 Although rodent bones have been examined by microscopic MRI25 and synchrotron computed tomography,26 neither system has yet been used for dietary or exercise-related studies in growing animal models.

**EFFECTS OF DIETARY CALCIUM**

Calcium is a primary constituent of bone, but if metabolic needs for it are not met by the diet, calcium is removed from the skeleton to fulfill those needs. Calcium requirements are greater during growth, so if insufficient calcium is consumed, the strength of the skeleton both during growth and in later adult years may be compromised. Calculations of Adequate Intake (AI) for calcium during growth were based on the amount of calcium at which maximal retention was minimally improved by additional calcium intake.27 Maximal calcium retention in adolescent girls plateaued at intakes of approximately 1300 mg/d.28,29 Diminished fractional retention with additional dietary calcium is due to both decreased fractional absorption and increased calcium excretion.28 In 1997, the Standing Committee on the Scientific Evaluation of Dietary Reference Intakes reported that the median calcium intake of adolescent females in United States was 889 mg/d for girls 9 to 13 years and 713 mg/d for girls 14 to 18 years, which equated to only 68% and 55% of their AI, respectively.27 Of even greater concern are the girls who consume less than the 10th percentile of calcium (Table 1).

The effects of a low-calcium diet on the human skeleton are not clear. Children consuming low-calcium diets may have other nutritional deficiencies or health problems that obscure the effects of calcium in their diets. Additionally, this question is difficult to investigate through human intervention trials, as ethical concerns prevent randomizing children to low-calcium diets for a sufficiently long period to obtain bone differences, or placing children in extremely low-calcium groups for shorter periods to measure surrogate parameters of bone change. Rodents have therefore been used as models to examine the effects of diets deficient in calcium on the growing skeleton, and extremely low-calcium diets depressed body weight20,30-32 and bone ash weight.32,33 In diaphyseal areas, the periosteal surface remained smooth, while the endosteal surface displayed a scalloped resorption surface32,34 with a two- to three-fold increase in resorption surface and an approximately 50% depression in the formation surface.34 In addition, new lacunae were two to three times larger and more plentiful33,34 thereby contributing to greater porosity. In bone ends, severe calcium deficiency resulted in reduced amounts of trabecular bone and decreased both trabecular thickness and number.33 It also produced alterations in the morphology of both osteoblasts and osteoclasts.30

Diets absent in calcium are not consumed by humans except under circumstances of starvation. The effects of less severe diets, such as those containing calcium concentrations equivalent to the 1st to 10th percentile of that consumed by American children (Table 1), have also been investigated in growing rats. In some experiments, these diets, which contained 0.1% to 0.3% calcium, resulted in mild hypocalcemia,35,36 decreased body weight,20,37 and reduced bone strength and stiffness.36 Bone length,35,37 bone volume,20,35,40 bone volume,20,35,40,41 ash weight,20,38,40 and calcium content of bone36,38-40 were also lower than their calcium-replete

| Table 1. Dietary Adequate Intake (AI)27 and Corresponding Amounts of Calcium for Girls Who Consume Fractions of their AI Compared with Rat Equivalents |
|----------------------------------|-------------------|------------------|-----------------|
|                                  | Calcium Intake     |                  |
|                                  | AI                | 1st Percentile | 10th Percentile | 50th Percentile |
| Girls                           |                  |                  |
| 4–8 yrs                         | 800              | 339 (42%)       | 524 (66%)       | 808 (101%)      |
| 9–13 yrs                        | 1300             | 361 (28%)       | 562 (43%)       | 889 (68%)       |
| 14–18 yrs                       | 1300             | 246 (19%)       | 413 (32%)       | 713 (55%)       |
| Rat Equivalents (% Ca)*         | 0.50             | 0.10–0.21       | 0.16–0.33       | 0.27–0.51       |

controls. Histological examination of the shaft region showed increased medullary area\textsuperscript{39} and endosteal circumference\textsuperscript{35} and decreased periosteal circumference\textsuperscript{35} and cortical thickness.\textsuperscript{36} The effects of a calcium-deficient diet were greater in the cortical than in the trabecular bone fraction.\textsuperscript{35,38} Nevertheless, effects on trabecular bone were generally undesirable, with decreased trabecular bone volume,\textsuperscript{36} trabecular number,\textsuperscript{40} trabecular thickness,\textsuperscript{35} and mineral apposition rate,\textsuperscript{39,41} and increased eroded surface\textsuperscript{40} and number of osteoclasts per bone surface.\textsuperscript{35} However, some studies reported no change in body weight,\textsuperscript{36,39,40} femur dry weight,\textsuperscript{42} trabecular thickness,\textsuperscript{40} trabecular space,\textsuperscript{35} or mineral apposition rate.\textsuperscript{35}

Whether the depreciating effects of a low-calcium diet are reversible through supplementation has been examined in rodents. Studies in growing rats showed that diets containing 20% or 50% of recommended calcium concentrations, fed from early puberty to beyond the onset of sexual maturity resulted in bone changes that were only partially reversible by a diet adequate in calcium.\textsuperscript{37,40} The reversibility of calcium deficiency in children may depend on age and pubertal stage, as greater benefits have been reported when supplemental calcium was administered before puberty.\textsuperscript{43,44}

Diets within the 1st to 10th percentiles of the AI for calcium are typical of intakes among children in parts of Asia\textsuperscript{45} and Africa.\textsuperscript{46} Lee et al.\textsuperscript{45,47} conducted two supplemental calcium studies on 7-year-old children, one in mainland China\textsuperscript{45} and the other in Hong Kong.\textsuperscript{37} At baseline, the Chinese children consumed 280 mg Ca/d,\textsuperscript{45} while the Hong Kong children consumed 567 mg Ca/d,\textsuperscript{47} which equates to 35% and 71% of the AI in the United States for 4- to 8-year-olds, respectively.\textsuperscript{27} Dibba et al.\textsuperscript{46} studied rural Gambian children 8 to 12 years old at baseline, whose habitual calcium intakes were 340 mg/d, which is 28% of the AI in the United States for 9- to 13-year-olds.\textsuperscript{27} The low-calcium diet consumed by the Gambian children was presented as a possible cause of their small stature, delayed puberty, and longer time to maximal height. The children in both of the Asian studies were provided with an additional 300 mg Ca/d for 18 months, while 1000 mg Ca/d was supplied as a supplement to the African children for 12 months. In all three studies, children in the supplemented groups gained more BMC or aBMD than did their controls. The benefits to the children most deficient at baseline, the Gambians, ranged from 2% to 6%, which the authors noted was similar to the increase reported in supplemented American and European children, who had much higher baseline calcium intakes.\textsuperscript{43,48} This is contrary to others, who concluded that benefits from calcium supplementation seemed to be greater in children with lower baseline intakes.\textsuperscript{44,49}

Many of the skeletal improvements were maintained in the Gambian children at the end of a 24-month follow-up period, but not in the Asian children after 18 months. The difference between these results could perhaps be attributable to the quantity of the supplementation, as the 1000 mg Ca/d that the African children received resulted in greater bone gains relative to controls than did the 300 mg Ca/d received by the Asians by the end of the supplementation periods. Race may also have contributed to the difference, as African-American girls have enhanced calcium retention compared with Caucasian American girls.\textsuperscript{3}

In developed countries, children enrolled in calcium supplementation trials are less deficient in their baseline intakes than Asians or Africans. However, calcium supplementation still increases bone mineral content or density,\textsuperscript{9,43,44,48,50-52} although only Bonjour et al.\textsuperscript{44} reported that the benefits were sustained through a follow-up period. Additionally, other studies reported that correlations between calcium intake and aBMD or BMC in prepubertal children disappeared when the children reached peri- or post-puberty.\textsuperscript{51,53}

It is possible that information about the effects of calcium deficiency and repletion in children’s bones were missed in the above studies, as the data for them were provided by DXA and single photon absorptiometry, neither of which can distinguish cortical from trabecular bone. An exercise study in postmenopausal women demonstrated that pQCT technology can distinguish changes to bone that are not apparent by DXA. The women did weight-training exercises in their forearms and this treatment resulted in gains in cortical bone concomitant with a reduction in trabecular bone.\textsuperscript{54} In the only longitudinal study using pQCT to measure nutritional treatments for which individual baseline data were used, Moyer-Mileur et al.\textsuperscript{9} investigated the effects of supplementing the diets of 12-year-old girls with 800 mg of calcium and 400 IU of vitamin D for 12 months. In the distal tibia, supplementation increased trabecular BMC by 4.1%.

The precision of DXA is generally acceptable and its measurement drift correctable with phantoms. However, the accuracy of DXA has been questioned.\textsuperscript{55} Studies examining adult bone show that differences in extra- and intra-osseous lipids at scan sites can cause over a 20% error in measurements if the fat is uniformly distributed\textsuperscript{56,57} and a 20% to 50% error if it is not.\textsuperscript{58} Additionally, the type or location of bone scanned can result in highly variable accuracy. The less than 2% inaccuracy in measurements if the fat is uniformly distributed\textsuperscript{56,57} and a 20% to 50% error if it is not.\textsuperscript{58} Discrepancies between true versus DXA-measured BMC or aBMD have not been reported in children’s bones.
It remains uncertain if the average calcium intake of American girls, although considered suboptimal, causes bone fragility. However, animal studies suggest that calcium intakes in the range consumed by the lowest 10% of American girls could result in bone weakness. Calcium supplementation trials delivered equivocal results, with most, but not all, of the benefits gained through additional calcium lost within a year or two post-supplementation. It is not known if maintaining a high calcium intake through skeletal maturity would result in a stronger skeleton. Examining the subjects with pQCT or other three-dimensional technology may elucidate changes not detected by DXA. Animal trials with QCT technology could further identify where and how growing bone is most affected by low calcium intakes that are equivalent in range to low calcium intakes in children, and if these specific effects can be negated or reversed by diet or exercise.

EFFECTS OF GROWTH AND PUBERTY

Bone turnover is rapid during growth, with formation exceeding resorption. During pre- and early puberty, appendicular bones increase in length and width. In cortical bone of the appendicular skeleton, high bone turnover rates in pre- and early puberty result in a rapid increase in both the periosteal and endosteal surfaces. A high bone formation rate drives increased periosteal apposition, while a high bone resorption rate increases resorption on the endosteal surface. Even as total skeletal mass increases with growth, cortical width is maintained.

Computed tomographic evaluation of the femoral shaft showed no change in cortical BMD throughout puberty. As early puberty progresses into mid- and then late puberty and the adolescent growth spurt slows, bone resorption declines. The endosteal envelope first ceases its expansion, then contracts as it is transformed from a resorption into an appositional surface. Cortical widths increase due to the differing rates and directions of change in the outer and inner surfaces of the bone.

Endocrine control of skeletal change through the pubertal period is complex and not entirely understood. In pre-puberty, bone growth remains gradual due to constant levels of growth hormone and IGF-1 (insulin-like growth factor-1) (Figure 1). Pulses of GnRH (gonadotropin-releasing hormone receptor) released into the circulation trigger production and release of sex steroids, which mark the onset of puberty. In turn, increased circulating estrogen triggers growth hormone and IGF-1 production and the pubertal growth spurt begins. Estrogen, growth hormone, and IGF-1 appear to interact to allow predetermined skeletal growth characteristics to be reached. The roles of growth hormone and IGF-1 in this process are not clear, and their suspected involvement is mostly based on their timing with growth events.

Growth hormone levels peak during the growth spurt, and free IGF-1 dissociates from IGFBP-1 and peaks during epiphyseal closure. The effects of estrogen on cortical bone appear to depend on concentration, with relatively low levels responsible for the pubertal growth spurt, and higher levels resulting in epiphyseal closure in both genders. In girls, the surge in estrogen at menarche abruptly arrests longitudinal growth through epiphyseal closure, and signals the rapid mineralization of the bones. In boys, estrogen levels gradually increase to levels thought to be responsible for epiphyseal closure. Boys achieve greater bone size than girls largely because they remain in the pre-pubertal stage for an additional 2 years, and remain pubertal for about a year longer than girls. The role of testosterone in adolescent bone growth and development is not clear. It can spur

![Figure 1. Hormonal factors involved in bone development.](https://academic.oup.com/nutritionreviews/article-abstract/63/11/361/2672712)
EFFECTS OF GROWTH PLUS MECHANICAL EXERCISE

There is some evidence that loading bones during growth may magnify the geometric changes produced by growth. Bone growth and mineral accrual immediately preceding menarche are rapid, and mechanical loading at that time might augment gains due to growth and maturation. This theory is consistent with the similar signal transduction pathways of mechanical strain and estrogen. Thus, the growing skeleton may be more readily influenced by mechanical stimulation during mid-puberty. Young female tennis and squash players who began tennis before menarche have greater periosteal size than either post-menarchial starters or non-playing controls. However, the endosteal contraction that occurs during puberty was not demonstrated in the shafts of racquet players in all studies. Bass et al. reported that post-pubertal female tennis players had smaller endosteal areas in one site of their humerus in their playing arms, but no effects were found at any other site or in either site in pre- and mid-pubertal girls. Kontulainen et al. reported no effect of tennis on the endosteal space in one site of their humerus in their playing arms, but no effects were found at any other site or in either site in pre- and mid-pubertal girls. Kontulainen et al. reported no effect of tennis on the endosteal space in one site of their humerus in their playing arms, but no effects were found at any other site or in either site in pre- and mid-pubertal girls.

In most studies, loading bones post-puberty has produced less benefit than during mid-puberty. However, one short jumping intervention reported increased BMC in the spine and distal tibia in pubertal but not pre- or peri-pubertal children. A study of female tennis players found that side-to-side differences became significant at Tanner stage 3, which occurs during the adolescent growth spurt. Moreover, Tanner stages 2 and 3 coincide with maximum levels of bone turnover, with gymnastics training doubling the resorption rate. Additionally, women in their 20s who started playing squash and tennis before or at menarche had 12% greater BMC in their humeral shaft as young adults compared with women who began the sport at least 1 year after menarche.

Mechanical strains during the early pubertal stages (Tanner stages 2 and 3) may affect bones more substantially than do similar strains before puberty and therefore may be supplementary to growth. Girls who completed a 7-month randomized jumping interventions while in early puberty demonstrated greater gains in aBMD and BMC at the femoral neck and lumbar spine and greater geometric changes that reflected improved bending strength in the proximal femur compared with prepubescent schoolmates. However, a discrepancy between exercise intervention results and sports effects is evident in prepubertal girls. Prepubertal girls training for competitive gymnastics had aBMDs that were 11% to 12% greater at the lumbar spine, 12% to 15% greater in the hip region, and 12% to 33% greater in the radius than non-gymnastic controls. Scerpella et al. provided evidence that this discrepancy is a function of training dose, with girls who trained half as many hours per week receiving an intermediate level of benefit. Overall, the skeleton appears most susceptible to modeling and remodeling in response to mechanical stimuli during the adolescent growth spurt, but the reason for this is unclear.

EFFECTS OF MECHANICAL EXERCISE

Effects of mechanical exercise on juvenile bone appear to hold promise in ultimately decreasing fracture rates. Exercise interventions investigating the effects of high-impact forces or strain rates on juvenile bone have demonstrated skeletal benefits. Several short-term randomized, controlled trials on prepubescent children have demonstrated that the growing skeleton is particularly responsive to impact exercise. Most of those trials used a short jumping protocol that was added to the curriculum for one 7- to 8-month school year, with DXA used to estimate bone parameters in the proximal femur and lumbar spine sites. Differences between the jumpers and controls in BMC, aBMD, and bone area tended to be small but significant. Differences in bone parameters due to gender were not found in prepubertal children. These trials were performed by entire classes of schoolchildren, with high compliance and without injury, which indicates that the protocols can be adapted for large-scale implementation.

Cross-sectional studies of young adult athletes show that those who train for sports involving high impact or torsion characteristics develop bones with geometric and mineral mass advantages that are strongly related to bone strength. Triple jump, a track and field event, is a particularly osteogenic sport. National-level Finnish athletes, men and women aged 22 who began triple jumping at age 14, had distal tibias 56% greater in cortical thickness, 52% greater in cortical area, and 18% greater in trabecular density than controls. The bone area and cortical thickness at midshaft sites in the tibia were 19% to 24% greater in jumpers than in non-jumpers. Young female gymnasts also appear to develop substantially stronger bones compared with children who are more...
sedentary. Although structural bone parameters have not yet been reported for gymnasts, DXA-derived bone strength parameters,\textsuperscript{95} aBMD, and BMC are substantially greater in young gymnasts than in matched controls,\textsuperscript{62,81,82,96-103} except in the skull.\textsuperscript{98,102} Results from competitive athletes may involve some amount of selection bias, as it can be argued that they may have begun their training with different bones or had an unusual genetic potential to develop such bones.

The problem of selection bias that is inherent in cross-sectional designs can be overcome by examining athletes who can be their own controls. The playing and non-playing arms of racquet sport players have been compared.\textsuperscript{85,103-105} Playing arms of tennis players gain BMD, BMC, and bone area in the trabecular fraction of the distal radius, and BMC and bone area in the midshaft of the radius.\textsuperscript{103} The midshaft of the radius and humerus of the dominant arm adapt to strains and strain rates by remodeling into shapes indicative of greater strength.\textsuperscript{16,71,103,105}

**COMBINED EFFECTS OF DIETARY CALCIUM AND EXERCISE**

Dietary calcium and physical exercise are factors that independently affect bone, but the relationship between them is controversial. Lanyon et al.\textsuperscript{106} and Anderson\textsuperscript{107} postulated that mechanical stimuli can compensate for insufficient dietary calcium. Specker\textsuperscript{108} theorized that enough calcium must be consumed for exercise to have an effect on the skeleton, and that “high activity levels in the presence of low calcium may be detrimental to bone.”\textsuperscript{109} Uusi-Rasi et al.\textsuperscript{110} suggested that both physical activity and calcium intake have similar but independent effects on bone, and that skeletal competence requires either factor.

A paucity of research has investigated how these factors, in combination, affect the growing skeleton. Many studies examining the effect of calcium intake and exercise on pediatric bone included both factors in multivariate analyses but did not report any examination of interactions between the two.\textsuperscript{111-118} Furthermore, it is difficult to interpret exercise effects on the skeleton in studies that present exercise data in terms of intensity, duration, and frequency of cardiovascular exercise.\textsuperscript{111,112,114-116,119-121} For example, Rowlands et al.\textsuperscript{119} quantified exercise in terms of cardiovascular intensity, expressed as metabolic equivalents, and correlated this with calcium intake in 9-year-old children. This could result in the inclusion of activities with low strain rates, such as walking, bicycling, and water sports, which are known to have little, no, or possibly adverse effects on bone.\textsuperscript{17,81,92,97,122-124} Studies examining the effects of exercise on bone are easier to interpret when physical activity is restricted to sports and organized physical activities,\textsuperscript{114} or sports only,\textsuperscript{117}; however, these studies usually still include non-weight-bearing sports. Welten et al.\textsuperscript{118} collected exercise data in metabolic equivalents but subsequently utilized only weight-bearing data. This research group further separated weight-bearing exercise into strata based on an estimate of ground reaction forces produced in each sport or activity, and the exercise was then termed “mechanical physical activity.”\textsuperscript{125} They reported a stronger correlation between bone parameters and mechanical physical activity than between bone and cardiovascular-type exercise (metabolic equivalents),\textsuperscript{125} which underlines the importance of selecting exercise known to specifically benefit bone rather than other physiological systems when determining the effects of exercise on bone.

Evidence of the lack of a synergistic relationship between calcium and exercise comes from children and adolescents involved in high-impact sports. Young gymnasts typically demonstrated greatly enhanced aBMD and BMC, yet had suboptimal calcium intakes.\textsuperscript{62,96,100,126} It therefore appears that, during growth, high magnitudes of mechanical stimuli can compensate for suboptimal calcium levels in the range of 60% to 90% of the dietary AI. However, this may be a function of calcium intake, as severe bone loss in rats fed diets nearly absent in calcium was not modified by exercise.\textsuperscript{31}

To our knowledge, only five intervention trials have examined dietary calcium and exercise interactions in children (Table 2). These studies were all conducted in prepubertal children, in whom the effects of exercise on bone tend to be more difficult to discern than in early puberty. Iuliano-Burns et al.\textsuperscript{127} conducted an 8.5-month calcium and exercise intervention using healthy 9-year-old girls who had habitual suboptimal calcium intakes. Girls assigned to exercise groups performed skipping and jumping, and those in supplemental calcium groups were provided with an additional 434 mg Ca/d. DXA was used to measure BMC in the humerus, forearm, lumbar spine, and femur. An interaction between calcium and exercise was reported for femoral BMC accrual, and the interaction appeared to be synergistic. They also reported an exercise but not a calcium effect in the lower leg, and a calcium but not an exercise effect in the forearm. In a parallel study by the same researchers, currently only available as an abstract, boys of similar age showed no calcium-exercise interactions at any site.\textsuperscript{128}

Two additional studies by Lappe et al.\textsuperscript{129} and Seip et al.\textsuperscript{130} examined the effects of supplemental calcium and exercise on girls who were approximately 9 years old at baseline. Both studies are currently only available as abstracts and therefore cannot yet be fully interpreted. Their designs were similar, with three treatment groups:


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<th>Study</th>
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<td>Iuliano-Burns et al., 2003</td>
<td>9-yr-old girls</td>
<td>8.5 mos</td>
<td>No supplementation (644 and 705 mg/d) vs. supplementation (958 and 1002 mg/d)</td>
<td>Hopping, skipping, jumping for 20 min 3×/week at 2 to 4 times body weight</td>
<td>Humerus, distal forearm, lumbar spine, proximal femur</td>
<td>DXA of BMC accrual</td>
<td>Interactions: synergistic in femur; positive exercise effect in tibia; positive calcium effect in humerus and radius; no effect in lumbar spine</td>
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<td>Bass et al., 2002</td>
<td>9-yr-old boys</td>
<td>9 mos</td>
<td>Supplementation (800 mg/d) vs. no supplementation</td>
<td>Hopping, skipping, jumping for 20 min 3×/week</td>
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<td>DXA of BMC accrual</td>
<td>No interactions; positive calcium effect in femur; positive exercise effect in femur and tibia; no effect in total body, lumbar spine, humerus, or radius</td>
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<tr>
<td>Lappe et al., 2001</td>
<td>9- to 10-yr-old girls</td>
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<td>DXA of BMC accrual</td>
<td>Interactions not tested; exercise plus calcium more positive effect than exercise alone or control in hip; no effect in total body, lumbar spine, or radius</td>
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<td>Specker and Binkley, 2003</td>
<td>4-yr-old girls and boys</td>
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<td>No supplementation (904 and 977 mg/d) vs. supplementation (1340 and 1367 mg/d)</td>
<td>Jumping, skipping, hopping for 20 min 5×/week vs. sedentary</td>
<td>DXA of total body partitioned to arm and leg; pQCT of tibia</td>
<td>DXA of BMC accrual and bone area; pQCT of cortical bone area, cortical thickness, endosteal and peripheral circumference of bone</td>
<td>Interaction (DXA): exercise plus calcium had a greater effect than exercise or calcium alone in tibia; DXA: no other effects; Interaction (pQCT): sedentariness with no calcium and exercise plus calcium had a greater effect than either treatment alone on cortical bone area and cortical thickness in tibia; positive exercise effect in tibia, peripheral and endosteal circumference of bone</td>
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BMC = bone mineral content; DXA = dual-energy x-ray absorptiometry; pQCT = peripheral quantitative computed tomography.
exercise, exercise plus calcium, and controls. Exercise-calcium interactions could not be assessed because neither trial included a group that received calcium but did not exercise. Lappe et al.\textsuperscript{129} reported greater effects on the rate of DXA-assessed BMC accrual in the hip after 1 year in the supplemental calcium plus exercise group than in the exercise-alone group. Girls in the study conducted by Seip et al.\textsuperscript{130} participated in a climbing and jumping intervention and received supplemental calcium for 7 months. Those in the exercise plus calcium group showed a significant benefit to pQCT-assessed cortical bone area in the shafts of forearms, but not in the tibial shafts.

Specker and Binkley\textsuperscript{8} investigated calcium intake and exercise interactions in 4-year-old children and reported a significant benefit to leg BMC from combining calcium supplementation with physical activity. Children either received supplemental calcium or not, and half were enrolled for 12 months in supervised exercise sessions in which they performed weight-bearing exercise. The non-exercise group performed sedentary activities. All of the children began the study with calcium intakes in excess of their AI, so it is not surprising that the main effect of calcium was not significantly related to any bone parameters. This exercise intervention did not provide ground reaction forces as substantive as those in trials using older children, so their finding that exercise had few effects was perhaps predictable. It is unclear why the linear growth of the children was significantly greater in the unsupplemented groups. Movement by the small children during their pQCT scans resulted in difficulty adhering to standard scan protocol, and unusable baseline measurements for half of the subjects. The lack of individual baseline data, coupled with the unexplained negative effect of calcium supplementation on growth, suggests that the results of this study\textsuperscript{8} need to be validated by additional studies.

Intervention trials investigating interactions between calcium intake and exercise in children have some inherent difficulties. Children in many Western countries consume adequate (or nearly adequate) calcium, which increases the difficulty in finding a calcium effect. Accuracy in quantifying calcium intake is difficult in children for a variety of reasons. The diet of each child can vary over the study, diets cannot be controlled in free-living children, and both the food record and dietary recall systems of calculating dietary intake only estimate intakes. Additionally, active children can vary considerably in mechanical exercise throughout the year due to the seasonal basis of many sports. Measurement of skeletal parameters can present serious ethical issues in child subjects due to excessive radiation from some methods of high-resolution imaging, especially if multiple sites or repeat measurements are needed. Also, unlike inbred rats, any cohort of children can vary dramatically in morphologic, racial, and growth characteristics, which results in a need for large sample sizes to improve the power to detect differences.

Animal models have also been used to examine the combined effects of calcium intake and exercise on the skeleton. Morimoto et al.\textsuperscript{31} examined the combined effects of calcium deficiency and endurance exercise on rapidly growing rats. However, calcium was essentially absent from the diet, which resulted in skeletal pathologies that were neither improved nor worsened by running. Lanyon et al.\textsuperscript{106} examined the effects of mechanical loading on adult turkey ulnas. Some of the birds received an extremely low-calcium diet, with or without experimentally induced unilateral limb disuse, and of the birds subject to disuse, some were also subjected to periodic mechanical loading on the affected ulna. Birds fed the deficient diet and subjected to disuse without additional loading lost bone both on the endosteal surface and throughout the cortex. Mechanical loading, without additional calcium, modified this loss. Inman et al.\textsuperscript{131} performed a similar experiment in adult rats and reported that calcium-deficient rats gained bone through periosteal apposition when an immobilized hind leg was subjected to mechanical loading.

**SUMMARY**

Low calcium consumption and the growing trend towards inactivity in children and adolescents may result in decreased skeletal competence. It does appear that impact exercise performed during growth can enhance skeletal strength, and a calcium intake of at least 1300 mg/d during pubertal growth results in optimal calcium retention. The combined effects of calcium and exercise on bone are not as clear, with various studies suggesting that calcium and exercise may function independently or interact in a compensatory or possibly even a synergistic fashion. Current evidence suggests that the best strategy for strong bones by the end of childhood may be either high-impact exercise with a moderate or adequate calcium intake, or a combination of moderate-impact exercise and adequate calcium during growth.

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