ELSEVIER

Bone 40 (2007) 14 – 27

BONE

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Review

Weight-bearing exercise and bone mineral accrual in children and adolescents: A review of controlled trials

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Received 16 February 2006; revised 6 July 2006; accepted 11 July 2006

Abstract

Introduction: Osteoporosis is a serious skeletal disease and as there is currently no cure, there is a large emphasis on its prevention, including the optimisation of peak bone mass. There is increasing evidence that regular weight-bearing exercise is an effective strategy for enhancing bone status during growth. This systematic review evaluates randomised and non-randomised controlled trials to date, on the effects of exercise on bone mineral accrual in children and adolescents.

Methods: An online search of Medline and the Cochrane database enabled the identification of studies. Those that met the inclusion criteria were included in the review and graded according to risk for bias.

Results: Twenty-two trials were reviewed. Nine were conducted in prepubertal children (Tanner I), 8 in early pubertal (Tanner II–III) and 5 in pubertal (Tanner IV–V). Sample sizes ranged from $n = 10$ to 65 per group. Exercise interventions included games, dance, resistance training and jumping exercises, ranging in duration from 3 to 48 months. Approximately half of the trials ($n = 10$) included ground reaction force (GRF) data (2 to 9 times body weight). All trials in early pubertal children, 6 in pre pubertal and 2 in pubertal children, reported positive effects of exercise on bone ($P < 0.05$). Mean increases in bone parameters over 6 months were 0.9–4.9% in prepubertal, 1.1–5.5% in early pubertal and 0.3–1.9% in pubertal exercisers compared to controls ($P < 0.05$).

Conclusions: Although weight-bearing exercise appears to enhance bone mineral accrual in children, particularly during early puberty; it remains unclear as to what constitutes the optimal exercise programme. Many studies to date have a high risk for bias and only a few have a low risk. Major limitations concerned selection procedures, compliance rates and control of variables. More well designed and controlled investigations are needed. Furthermore, the specific exercise intervention that will provide the optimal stimulus for peak bone mineral accretion is unclear. Future quantitative, dose–response studies using larger sample sizes and interventions that vary in GRF and frequency may characterise the most and least effective exercise programmes for bone mineral accrual in this population. 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.

Keywords: Bone mineral density; Children; Exercise; Peak bone mass

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doi:10.1016/j.bone.2006.07.006

Introduction

Osteoporosis is a systemic, skeletal disease characterised by low bone density and micro-architectural deterioration of bone tissue, with a consequent increase in bone fragility [1]. It is a serious disease that is increasing at an epidemic rate and it is predicted that osteoporosis and osteoporotic fractures will rise exponentially over the next 50 years, as the population ages [2]. Thus, there is a large emphasis on preventative measures to combat or offset osteoporosis and fracture. One major preventive measure is the optimisation of peak bone mass in the early years. *Peak bone mass* can be defined as the greatest amount of bone mass achieved during life at a given skeletal site and is based on observations that bone mass increases during childhood and puberty, consolidates during young adulthood and declines with age [3,4]. One strategy to increase peak bone mass is through regular, weight-bearing exercise [5–7]. The definition of *weight-bearing exercise* that has been adopted for this review is that of a structured, force-generating activity that provides loading to skeletal regions, above that provided by activities of daily living [8]. Weight-bearing exercises 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 [9,10].

Evidence supporting the role of weight-bearing exercise in bone health has accumulated from cross sectional, retrospective, prospective and intervention studies. Cross sectional studies report higher bone mass in athletes than non athletes [11,12], and in highly active children compared to those who are more sedentary [13,14]. Retrospective studies report greater bone mass in retired dancers compared to controls [15], and an increase in physical education (PE) within the school curriculum is associated with positive skeletal effects in children [16]. Prospective studies following children with different physical activity levels also report greater increases in the bone mass of active children compared to those who are less active [17–19]. Although such studies have contributed to the literature, they do not provide robust and causal inferences between exercise and bone mineral accrual. As such, there is a need to assess randomised controlled trials (RCT), which are regarded as the primary source for more valid and reliable evidence. The number of investigations has increased over the last 5 years [20–33] therefore the purpose of this review was to evaluate this literature to date.

Methods

Search strategy to identify relevant trials

The aim of the literature search was to identify all available RCTs and controlled studies concerning the effects of weight-bearing exercise on bone mineral accrual in children and adolescents, aged 8 and 17 years. To do so, a computerised search of the MEDLINE database was performed on articles published between the years 1964 and 2005. The keywords entered were: ‘exercise, children, girls, boys, adolescents, bone, bone mineral and bone mass’. A total of 573 articles were found, and their titles and abstracts (or complete papers when the abstracts contained insufficient information) were reviewed to see whether they met the inclusion criteria. Papers from all journals were considered and retrieved either online or by interlibrary loan. A search was also conducted using The Cochrane Controlled Trials Register (CENTRAL), using the following keywords: ‘exercise, bone and children’. An additional search using ‘Google’ was performed to identify any further trials that were currently underway.

Considered studies were reviewed according to a general criterion and graded through a quality assessment, based on bias risk. The risk for bias was based on the extent to which the study design may influence the results in such a way that may prejudice the conclusions.

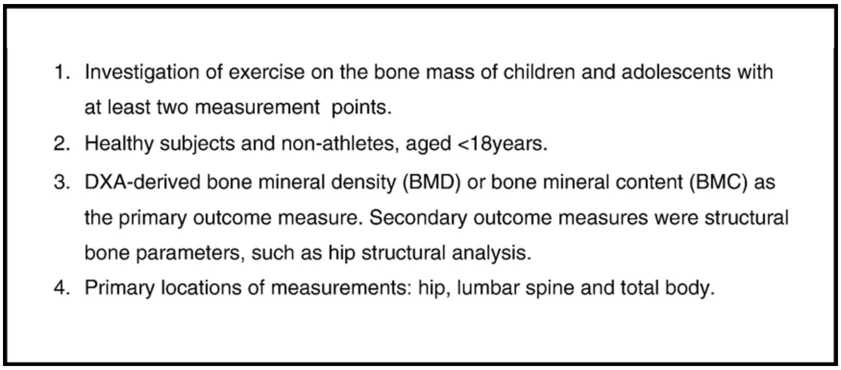
Nineteen studies met the inclusion criteria (Fig. 1), were graded according to the quality assessment categories described below (Table 1), and were reviewed in terms of their contribution to the literature. Studies were grouped according to the maturity status of the participants: prepubertal (Tanner I), early pubertal (Tanner II–III) and pubertal (Tanner IV–V). Three studies were divided into 2 parts (a and b) for analysis, as the authors provided results for both prepubertal and pubertal children [26,31,33]. Thus, 22 trials were reviewed. Studies using samples of mixed maturity subjects that did not provide separate analyses for each group, and which used small numbers (<10 per group), were not included.

Grading the trials

The 22 trials were graded according to bias risk. In exercise intervention trials, blinding of the investigators and of the participants is not feasible and thus, was not used as a criterion for validity. The grading system can be seen in Table 1. It is recognised that not all categories are equal in terms of influencing the bias of the study conducted, for example, the compliance rate might be more important than whether the ground reaction forces generated by the exercise intervention were measured or not. Although weighting the categories would have provided greater accuracy in the grading scheme, this was problematic to undertake. According to our criteria, the highest grade a study could be given was 21. For the purpose of this review, a grade of 19–21 indicates a low risk of bias; 16 and 18 indicates a moderate risk, and those at 15 or below, indicate a high risk.

Results

Table 2 summarises the design, execution and outcomes of the studies reviewed. These are grouped according to the participants’ Tanner Stage because maturity status is critical



1. Investigation of exercise on the bone mass of children and adolescents with at least two measurement points.
2. Healthy subjects and non-athletes, aged <18years.
3. DXA-derived bone mineral density (BMD) or bone mineral content (BMC) as the primary outcome measure. Secondary outcome measures were structural bone parameters, such as hip structural analysis.
4. Primary locations of measurements: hip, lumbar spine and total body.

Fig. 1. Criteria for inclusion in the review.

when evaluating the effects of exercise on growing bone [8,9]. Results are given as the percentage increase in bone mass parameters (bone mineral content (BMC), areal bone mineral density (aBMD) and volumetric BMD (vBMD) in exercisers compared to controls. When provided by the authors, absolute changes in bone mass have also been included in the discussion. It is now known that increases in areal BMD may actually reflect increases in bone size rather than actual bone density. A few studies included measures of projected bone area (BA). In addition, although the purpose of this paper was to review the evidence concerning exercise and bone mineral accrual, several studies also included assessments of bone geometry, an important component of bone strength and fragility risk. These data include cortical thickness and hip section modulus.

Studies varied in the exercise intervention duration from 6.5 months to 24 months. Therefore to enable comparisons between studies, the results have also been adjusted to effects on bone over 6 months duration (Table 2**), assuming that the exercise effect is linear over time.

Thirteen studies were conducted in girls [20,21,25–29,31,33,35–38], 2 in boys [24,34] and 4 in both girls and boys [22,23,30,32]. Nine were conducted in prepubertal, 8 in early pubertal and 5 in pubertal children (Table 2). Three trials included both exercise and calcium interventions [21,29,30]. Subject sample sizes were relatively small, from 10 [21] to 65 [20] per intervention group.

This paper reviewed randomised and non-randomised controlled trials to date, on the effects of exercise on bone mineral accrual in children and adolescents. Bone mineral accrual differs according to maturity status [9,10] because levels of secreted hormones and growth factors, as well as the sites and velocity of bone acquisition, vary by maturity stage [4,39]. For this reason, the trials have been evaluated according to the subjects' maturity status.

Table 1
Criteria and grading of the studies

Criteria	Grade	Description
Randomisation	1	Groups were not randomised and presence of discrepancies in baseline characteristics
	2	Groups not randomised but were well-matched
	3	Groups were randomised
Compliance to the study	1	Losses were greater than 30% or not reported
	2	Losses were between 21 and 30%
	3	Losses were 20% or less
Compliance to the exercise intervention	1	Less than 70% or not reported
	2	Between 71 and 80%
	3	81% or greater
Exercise intervention	1	No specific intervention: general physical activities and choices were given to participants. No measure of ground reaction force (GRF)
	2	Specific intervention but no measure of GRF
	3	Specific intervention and measurement of GRF
Confounding variables (Maturity status—peak height velocity or Tanner stage; age; height, weight; baseline physical activity and calcium intake; exercise history; calcium history; extra-physical exercise and calcium intake during trial).	1	Lack of control for confounding variables (≤3 variables)
	2	Control over some confounding variables (4–7 variables)
	3	Control over most confounding variables (8+ variables)
Duration of the trial	1	Less than 6 months
	2	6–12 months
	3	Greater than 12 months
Sample size	1	Less than 20 per group
	2	20–40 per group
	3	+40 per group

Maturity status

All studies estimated subject's maturity status using the five point scale Tanner stage assessments of pubertal development in both sexes, based on external characteristics. The technique is non-invasive and effective, although other maturity parameters do exist. Bone age is based on the development of bone maturation throughout childhood and adolescence, and can be accurately assessed by standard radiography of the hand-wrist. Several studies used this technique in addition to Tanner assessments [21,27,34]. However, due to the involvement of ionising radiation, the use of bone age is less common than that of Tanner assessments, and both appear to have a similar degree of accuracy [40]. Physical maturity can also be useful and is assessed according to peak height velocity (PHV). As this requires a collection of longitudinal data over at least 3 years, none of the studies reviewed had measured PHV.

Prepubertal children

Six out of 9 trials in prepubertal children (Tanner I), reported positive effects from exercise on bone mass. These trials were graded between 12 and 20 [23,24,27,30,32,34] indicating a high to low risk for bias, and effects ranged from 0.9% [27] to 4.9% [30] over 6 months depending on the study and the site measured.

The strongest study, with the lowest risk for bias (grade of 20), was conducted by Fuchs et al. [32] in boys and girls. Over 7 months, increases in (DXA-derived) femoral neck BMC, lumbar spine aBMD and BMC by 4.5% (0.09 g), 2% (0.011 g cm^{-2}) and 3.1% (0.71 g) respectively, were observed in exercisers compared to controls. Significant results were also reported by Bradney et al. [34] over 8 months in boys, whose study was graded at 16, indicating a moderate risk of bias. Increases in aBMD of 1.2% (0.008 g cm^{-2}) in the total body, 2.8% (0.016 g cm^{-2}) in the lumbar spine and 5.6% (0.08 g cm^{-2}) in the femoral mid-shaft, were observed in exercisers compared to controls. Over 1 month, increases in lumbar spine aBMD equated to 0.0016 g cm^{-2} in Fuchs's study and 0.002 g cm^{-2} in Bradney's study. There were differences in the exercise regimen between the two studies. Fuchs et al. [32] prescribed high impact jumping, eliciting ground reaction forces (GRF) of 8.8 times body weight. On the other hand, Bradney et al. [34] prescribed an exercise programme consisting of games such as football. Considering the duration of each trial, the resultant bone response was similar in both studies, to suggest that both high and moderate impact weight-bearing exercise can benefit bone mineral accrual in this population.

MacKelvie et al. [24] also reported increases in bone mass following their exercise intervention in boys. Over 20 months, increases in femoral neck BMC of 4.3% (0.11 g) were reported. The increase over 1 month in femoral neck BMC by DXA equated to less than half the increase reported by Fuchs et al. [32] (0.0055 g vs. 0.0129 g). The intervention consisted of circuit training 12 min, 3 times per week [24] and Fuchs et al. [32] prescribed their jumping exercises for 10 min, 3 times per week. However, GRF were lower than in Fuchs et al.'s study (3.5–5 vs. 8.8 × body weight). Section modulus was also measured using hip structural analysis (HSA), and greater increases in femoral neck bending strength were found in exercisers than controls [24]. Their study was graded at 16, indicating a moderate bias risk and it should be considered that study compliance was one of the lowest, at 33%.

Although significant results were reported in boys, they reported no positive skeletal effects in exercising prepubertal girls [26]. Similarly, although with a higher risk for bias (grade 15), Petit et al. [31] also reported no effects of exercise on bone mass in prepubertal girls. All studies [24,26,31] used identical interventions, generating GRF at 3.5–5 times body weight. Thus, differences in results between the studies could not be attributed to different exercise prescriptions. The only difference between the studies was the duration of the exercise regimens. MacKelvie et al. [24] observed a positive skeletal effect from exercise when their trial was over 20 months, whereas the earlier studies reporting no effects in prepubertal children, were over 7 months [26,31]. However, Fuchs et al. [32] and Bradney et al. [34], implemented exercise interventions of 7 and 8 months respectively, and reported substantial skeletal effects [32,34]. Results are conflicting, thus definitive conclusions cannot be drawn.

When percent increases were adjusted to effects over 6 months, the greatest increases were observed by Fuchs et al. [32] of 3.9% femoral neck BMC compared to the 1.3% increases observed by MacKelvie et al. [24] and Van Langenodonck et al. [27]. Fuchs et al. [32] also observed the greatest increases in lumbar spine BMC of 2.7% [32]. As stated earlier, this study had the lowest risk for bias and employed the highest impact exercise intervention [32]. From the research to date it is apparent that prepubertal boys and girls are able to participate in vigorous exercise programmes and appear to respond positively to this.

Early pubertal children

From the 8 studies conducted in early pubertal children, all reported significant effects from exercise on bone mass [21,25,26,29,31,33]. The studies were graded between 13 and 19, indicating a high to low risk for bias, but only one study had a low risk for bias [29]. All trials reported positive skeletal effects from the prescribed exercise, and success over 6 months ranged from increases of 1.1% [21] to 5.5% [25], depending on the intervention and the site measured (Table 2).

The strongest study (grade 19) was by Iuliono-Burns et al. [29] and included both an exercise and calcium intervention. Exercise programmes of either moderate intensity (20 min jumping exercises) or low intensity (stretching) were prescribed 3 times per week, with or without calcium supplementation (434 mg day^{-1}). No effects were found in the low intensity exercise group, with or without calcium; supporting the notion that non weight-bearing exercise, such as stretching, does not promote an anabolic bone response. BMC advantages of 3% in the legs and 7.1% (11.7 g overall; 1.35 g per month) at the femur

Table 2
Randomised controlled trials and controlled studies of the effects of exercise on bone mineral accrual in children and adolescents

Reference	Subjects and design	Intervention	Measures	Results* and limitations to the results	Grade
Pre pubertal (Tanner stage I)					
Laing et al. (2005) [20]	Girls Asian, Black and White Ex: $n=65$, mean age 6.0±1.5 years; C: $n=78$, mean age 6.3±1.6 years No randomisation 80% compliance to the study Girls were beginner artistic gymnasts and non-gymnasts Ca and other pa were considered	24 months Gymnastics for 1 h/week Rotations on bars, vault, balance beam and floor exercises No GRF data 78.7 (10.9)% ex compliance	DXA TB aBMD LS aBMD TB BMC, BA LS BMC, aBMD, BA PF BMC, aBMD, BA Forearm BA BMC	$P<0.05$ NS, $P>0.05$ $P<0.05$ NS, $P>0.05$ $P<0.05$ Gymnasts were shorter and lighter than non-gymnasts at baseline and end of the study Self-selection bias, with genetic predisposition to gymnastics, a likely confounder Ex compliance not reported	14
MacKelvie et al. (2004) [24]	Boys Asian and White Ex: $n=31$, mean age 10.2±0.5 years; C: $n=33$, mean age 10.1±0.5 years Randomised by school (14 schools) 33% study compliance over 20 months Ca and other pa not reported	20 months 10–12 min, 3×week, impact exercises including circuit training+100 jumps. Additional to PE GRF=3.5–5×bw 99–100% ex compliance	DXA and HSA FN BMC SM: NN of FN	+4.3% $P<0.01$ 1.3%** +7.5% $P=0.02$ (increased bending strength) **2.3% More control boys stayed in Tanner Stage I, which may have affected the results	16
Specker and Blimkie (2003) [30]	Girls White Randomised 74% compliance to the study Group 1: Gross motor activities and Ca, $n=43$, mean age 3.9±0.6 years; Group 2: Gross motor activities and placebo, $n=45$, 3.8±0.5 years; Group 3: Fine motor activities and Ca, $n=45$, 4.0±0.6 years; Group 4: Fine motor activities and placebo, $n=45$, 4.0±0.6 years Ca and other pa considered	12 months 30 min, 5×week. Gross motor (jumping, hopping, skipping) or fine motor (sitting) activities Ca: 2×500 mg day^{-1}, 5×week 73.5% intervention compliance	DXA and QCT TB BMC Leg BMC Tibial peri and end circ	NS, $P>0.05$ +9.7% group 1 vs. 3, $P<0.05$ 6 months: 4.8% Group 1 vs. 3, $P<0.05$	17
Van Langendonck et al. (2003) [27]	Girls Ethnicity not given Mean age 8.7±0.7 years $n=21$ pairs of monozygotic twins Twin study, thus, controlling confounding by genetics Bone age and Tanner stage to assess and control for maturity Ca not reported	9 months 3×week, hopping, jumping from a box, all fours side-to-side movements Progression by removing shoes to increase impact and different stimulus 91% ex compliance No GRF data	DXA PF BMC PF aBMD FN BMC FN aBMD	+2.5%, $P<0.01$ **1.7% +1.3%, $P<0.01$ **0.9% +2%, $P<0.01$ **1.3% +2.4%, $P<0.05$ **1.6%	16

Table 2 (*continued*)

Reference	Subjects and design	Intervention	Measures	Results * and limitations to the results	Grade
Pre pubertal (Tanner stage I)					
	Other pa reported and considered when interpreting results			The significant effects were only found in twins who had not previously exercised to a high level ($n=12$)	
Petit et al. (2002) (part a) [31]	Girls Asian and White Mean age 10.0±0.6 years Ex: $n=43$; C: $n=25$ Randomisation (14 schools stratified by ethnic composition and randomised) Ca but not other pa, considered	7 months 10–12 min, 3×week. Additional to PE. 5×diverse jumping exercise stations GRF=3.5–5×bw	DXA and HSA TB aBMD LS aBMD TR aBMD PF aBMD PF cortical thickness, area and SM	NS, $P>0.05$ NS, $P>0.05$ NS, $P>0.05$ NS, $P>0.05$ NS, $P>0.05$ Compliance unclear	15
Fuchs et al. (2001) [32]	Girls and Boys Asian and White Mean age 7.6±0.2 years Ex: $n=45$; C: $n=41$ 90% study compliance Randomised (1 school) Ca and other pa considered	7 months Jumping ex 10 min, 3×week. Progressed from 50 to 100 2-footed jumps from 61 cm high boxes. Additional to PE 96% ex compliance GRF=8.8×bw	DXA LS BMC LS aBMD FN BMC FN aBMD FN BA	+3.1% $P<0.05$ ** 2.7% +2.0% $P<0.01$ **0.9% +4.5% $P<0.001$ **3.9% NS, $P>0.05$ +2.9% $P<0.001$ **2.5%	20
MacKelvie et al. (2001) (part a) [26]	Girls White and Asian. Mean age 10.1±0.5 years Ex: $n=44$; C: $n=26$ Randomisation of schools 80% study compliance Ca and other pa considered	7 months 10–12 min, 3×week Additional to PE 50–100 jumps and circuit training. Progression with jumps GRF=3.5–5 ×bw	DXA and estimated vBMD equation TB BMC, aBMD LS BMC, LS aBMD FN BMC FN aBMD FN vBMD	NS, $P>0.05$ NS, $P=0.640$ NS, $P=0.783$ NS, $P=0.979$ NS, $P=0.767$ NS, $P=0.179$ Compliance to the exercise intervention not reported	18
McKay et al. (2000) [23]	Girls and boys White and Asian Mean age Ex: $n=63$; C: $n=81$ Randomisation of schools	8 months 10–30 min, 3×week in PE classes. Games, dance, circuit training incorporating jumps	DXA TB aBMD LS aBMD PF aBMD FN aBMD TR aBMD	NS, $P>0.05$ NS, $P>0.05$ NS, $P>0.05$ NS, $P>0.05$ +1.4%, $P<0.05$ **1.1%	17
Bradney et al. (1998) [34]	Boys White Mean age 10.4±0.2 years Ex: $n=19$; C: $n=19$ 95% study compliance Randomisation decided by the school (1 school) Bone age, Biochemistry and Tanner Stage to assess maturity Ca and other pa not reported	8 months 30 min, 3×week Activities included aerobics, football, dance, gymnastics, volleyball, basketball, weight training. Additional to PE No GRF data	DXA and BMAD TB aBMD LS aBMD Femoral mid-shaft Cortical thickness	+1.2%, $P<0.01$ **0.9% +2.8%, $P<0.01$ **2.1% +5.6%, $P<0.05$ **4.2% +6.4%, $P<0.05$ **4.8% Influence of Ca not assessed and compliance to the exercise intervention not reported Potential selection bias arising from teachers' selection of pupils to groups	16
Early pubertal (Tanner Stages II–III)					
Courteix et al. (2005) [21]	Girls White Aged 8–13 years 75% study compliance	12 months Ex: 7.2 h/week Sed: 1.2 h/week Ca: 800 mg day^{-1}	DXA TB aBMD LS aBMD FN aBMD	+6.3%, $P<0.05$ **3.2% +11%, $P<0.05$ **5.5% +8.2%, $P<0.02$ **4.1%	14

(*continued on next page*)

Table 2 (*continued*)

Reference	Subjects and design	Intervention	Measures	Results * and limitations to the results	Grade
Early pubertal (Tanner Stages II–III)					
	Randomised and blinded trial Group 1: Ex+Ca, $n=12$; Group 2: Ex +placebo, $n=42$; Group 3: Sed+Ca $n=10$; Group 4: Sed+placebo, $n=21$ Bone age and Tanner stage to assess maturity Other pa not reported		WT aBMD	+9.3%, $P<0.01$ **4.7% Group 1 vs. group 4, all variables. Ex group had greater lean mass than non-ex at baseline and final stage ($P<0.05$). This may have confounded results	
McKay et al. (2005) [22]	Girls and boys Asian and White Mean age 10.1 years Ex: $n=51$; C: $n=73$ 100% study compliance No randomisation Controls from a previous study Ca and pa considered	8 months 3 min, 3 × day for each school day. 'Bounce at the Bell': 10 counter-movement jumps 60% ex compliance (ranging widely from 2–5 days per week). GRF = 5 × bw	DXA and HSA PF BMC TR BMC PF BA TR BA PF cortical thickness and area	+2.0%, $P=0.019$ **1.5% +2.7%, $P=0.017$ **2% +1.3%, $P=0.072$ **1% +2.0%, $P=0.065$ **1.5% NS, $P>0.10$ Controls had greater increases in TB BMC and BA ($P<0.05$) Ex group participated in more pa at baseline ($P<0.05$), thus this may have confounded results	15
MacKelvie et al. (2003) [25]	Girls Asian and White Ex: $n=33$, mean age 9.9±0.6 years; C: $n=43$, mean age 10.3±0.4) years 42% study compliance over 20 months Randomised (14 schools) Ca and other pa not reported (although varsity athletes were excluded)	20 months 10–12 min, 3 × week, including 100 jumps and circuit training GRF = 3.5–5 × bw	DXA LS BMC FN BMC	+3.7%, $P<0.05$ **1.1% +4.6%, $P<0.05$ **1.4% There was an imbalance in maturity status between Ex and C, with maturity more advanced in C Compliance to the ex intervention not reported	16
Iuliano-Burns et al. (2003) [29]	Girls White and Asian Mean age 8.8±0.1 years 88% study compliance Randomised Group 1: Moderate impact ex +Ca, $n=16$; Group 2: Moderate impact ex +placebo, $n=16$; Group 3: Low impact ex +Ca, $n=16$; Group 4: Low impact ex +placebo, $n=16$ Ca considered	8.5 months 20 min, 3 × week Moderate impact: skipping, hopping, jumping. Progression with hand weights in last 8 weeks GRF = 2–4× bw Low impact: stretching Ca: 434 mg day^{-1} 93% ex compliance	DXA Tibia–fibula BMC LS BMC Femur BMC	+3%, $P<0.05$, Moderate vs. low impact (main effect of moderate impact ex) **2.1% NS, $P>0.05$, all groups +7.1%, $P<0.05$, Moderate impact Ex+Ca vs. no Ca (main effect of ex/ca interaction) **5%	19
Petit et al. (2002) (part b) [31]	Girls White and Asian Mean age 10.5±0.6 years Ex: $n=43$; C: $n=63$ Randomisation of schools (14 schools stratified by ethnic composition and randomised) Ca but not other pa reported	7 months 10–12 min, 3 × week 5 × diverse jumping exercise stations. Additional to PE GRF = 3.5–5 × bw	DXA and HAS TR aBMD FN aBMD FN SM FN cortical thickness	+1.7%, $P=0.016$ **1.5% +2.6%, $P=0.027$ **2.2% +4.0%, $P=0.034$ **3.4% +3.2%, $P=0.032$ **2.7% Compliance unclear	15

Table 2 (*continued*)

Reference	Subjects and design	Intervention	Measures	Results * and limitations to the results	Grade
Early pubertal (Tanner Stages II–III)					
MacKelvie et al. (2001) (part b) [26]	Girls Asian and White Mean age 10.5±0.6 years Ex: $n=43$; C: $n=64$ 80% study compliance Randomisation of schools (14 schools) Ca and other pa considered	7 months 10–12 min, 3×week. 50–100 jumps and circuit training. Additional to PE Progression with jumps GRF=3.5–5×bw	DXA and estimated vBMD LS BMC LS aBMD FN BMC FN aBMD FN vBMD	 +1.8%, $P=0.016$ **0.9% +1.7%, $P=0.005$ **1.5% NS, $P=0.979$ +1.6%, $P=0.027$ **1.4% +3.1%, $P=0.019$ **2.7% Ex compliance not reported	18
Heinonen et al. (2000) (part a) [33]	Girls White Mean age 11.0±0.9 years Ex: $n=25$; C: $n=33$ 92.5% study compliance Selection to groups decided by teachers Ca and other pa not reported	9 months 20 min, 2×week. Jumping exercises, 100–200 jumps from box, two and one-footed 70% ex compliance No GRF data	DXA and pQCT LS BMC FN BMC TR BMC Tibial midshaft cortical area	 +3.3%, $P=0.0012$ **2.2% +4.0%, $P=0.014$ **2.7% NS, $P=0.202$ NS, $P=0.230$ Potential selection bias from teachers deciding groups	13
Morris et al. (1997) [35]	Girls Ethnicity not given but 4 schools stratified by ethnic composition Mean age 9.5±0.9 years Ex: $n=38$; C: $n=33$ 97% study compliance Groups decided by teachers Ca and other pa considered	10 months 30 min, 3×week. Aerobics, skipping, dance, weight training, ball games. Progression in weight training. Additional to PE 92% ex compliance No GFR data	DXA and BMAD TB BMC TB aBMD LS BMC LS aBMD LS BMAD FN BMC FN aBMD FN BMAD PF BMC PF aBMD	 +5.5%, $P=0.001$ **3.3% +2.3%, $P=0.001$ **1.4% +5.5%, $P=0.05$ **3.3% +3.6%, $P=0.04$ **2.2% +2.9%, $P=0.05$ **0.6% +4.5%, $P=0.001$ **2.7% +10.3%, $P=0.01$ **6.2% NS, $P=0.76$ +8.3%, $P=0.01$ **5% +3.2%, $P=0.001$ **1.9% Selection bias likely Drop-outs resulted in maturity status being more advanced in the ex group than in controls, which may have contributed to their greater bone mass increases	15
Pubertal (Tanner Stages IV–V)					
Stear et al. (2003) [28]	Girls White Mean age 17.3±0.3 years; $n=144$ Group 1: Ca+ex, $n=37$; group 2 Ca+no ex, $n=28$; group 3: placebo+ex, $n=38$; group 4: placebo+no ex, $n=28$. Randomised and double-blinded 91% study compliance Ca and other pa considered	15.5 months Ex: 45 min exercise to music, 3×week No GRF data Ca: 1000 mg day^{-1} 36% exercise compliance	DXA TB BMC LS BMC FN BMC HIP BMC TR BMC	 +0.8%, $P<0.01$ **0.4% +1.9%, $P<0.001$ **0.7% +2.2%, $P<0.001$ 0.9% +2.7%, $P<0.001$ **1% +4.8%, $P<0.05$ **1.9% All group 1 vs. group 4	16
Nichols et al. (2001) [29]	Girls Ethnicity not given Mean age 15.9±0.1 years. Ex: $n=5$; C: $n=11$ Menarche status not given	15 months 30–45 min, 3×week Ex: 15 resistance exercises to stress all muscle groups. Some machine-assisted.	DXA TB aBMD LS aBMD	 NS, $P>0.05$ NS, $P>0.05$	13

(*continued on next page*)

Table 2 (*continued*)

Reference	Subjects and design	Intervention	Measures	Results* and limitations to the results	Grade
Pubertal (Tanner Stages IV–V)					
	15% study compliance Randomised Ca considered	Progression by increasing weight. 73% ex compliance No GRF data	WT aBMD TR aBMD FN aBMD	+3.2%, $P<0.01$ **1.3% NS, $P>0.05$ +2.3%, $P<0.01$ **0.4% Large drop-out rate, which resulted in small group numbers	
Witzke and Snow. (2000) [37]	Girls White Mean age 14.6±0.5 years Ex: $n=25$; C: $n=28$ All postmenarchal at baseline No randomisation	9 months Ex: 30–45 min, 3×week, resistance training and plyometrics, increasing in intensity over 9 months No GRF data	DXA TB BMC LS BMC FN BMC TR BMC	+0.1%, NS, $P>0.05$ +1.3%, NS, $P>0.05$ +2.1%, NS, $P>0.05$ +1.2%, NS, $P>0.05$ Potential self-election bias. Compliance rates not given	11
Heinonen et al. (2000) (part b) [33]	Girls White Mean age 13.7±0.9 years Ex: $n=39$; C: $n=29$ 92.5% study compliance Selection to groups decided by teachers. Ca and other pa not reported	9 months 20 min, 2×week. Jumping exercises, 100–200 jumps from box, two and one-footed 65% ex compliance	DXA and pQCT LS BMC FN BMC Tibial midshaft cortical area	NS, $P=0.325$ NS, $P=0.573$ Potential selection bias NS, $P=0.548$	13
Blimkie et al. (1996) [38]	Girls, all postmenarcheal Ethnicity not given Ex: $n=16$, mean age 16.3±0.3 years; C: $n=16$, mean age 16.1±0.2 years Randomisation (1 school)	6.5 months 3×week. Machine-assisted weight training, 4sets of 12 reps each Progression every 6 weeks No GRF data	DPA TB BMC, aBMD LS BMC, aBMD	NS, $P<0.05$ NS, $P<0.05$ Duration of each session unclear, as was compliance	12

Ex: exercise group; C: control group; BMC: bone mineral content; aBMD: areal bone mineral density; vBMD: volumetric BMD; BA: bone area; BMAD: bone mineral apparent density (BMD adjusted for bone area); TB: total body; LS: lumbar spine; FN: femoral neck; NN: narrow neck; PF: proximal femur; WT: wards triangle; TR: trochanter; peri: periosteal; end: endosteal; circ: circumference; DXA: dual energy X-ray absorptiometry; DPA: dual photon absorptiometry; QCT: qualitative computed tomography; pQCT: peripheral QCT; HSA: hip structural analysis; SM: section modulus; Ca: calcium; pa: physical activity; GRF: ground reaction force; RCT: randomised controlled trial; bw: body weight; PE: physical education.

* % greater increase in Ex v C.

** % increase averaged over 6 months.

were observed over the 8.5 months intervention duration, in the moderate-intensity and calcium group. This increase represented a calcium–exercise interaction, highlighting the importance of monitoring calcium intake in exercise and bone mineral studies.

Graded at 15 to 18, indicating a high to moderate bias risk, 3 studies in early pubertal children by the same research group, incorporated identical exercise programmes, eliciting GRF of 3.5–5 times body weight [25,26,31]. Over 20 months, MacKelvie et al. reported greater BMC increases in exercising girls than controls, by 3.7% (1.6 g overall; 0.08 g per month) at the lumbar spine and 4.6% (0.11 g overall; 0.0055 g per month) at the femoral neck [25]. Their earlier study [26] conducted over 7 months, revealed greater increases of 1.7% and 1.8% in lumbar spine aBMD and BMC respectively, in exercisers than controls (absolute bone mass values were not reported). There were also greater increases at the femoral neck in exercisers of 1.6%, 1.9% and 3.1% in aBMD, BMC and vBMD, respectively. The greater increase in vBMD suggests that increases in bone size may characterise the positive bone changes. However, the same study had found no differences in bone mineral accrual in prepubertal girls [26] (Table 2). Similarly, over 7 months, Petit et al. [31] (grade 15) found no skeletal effects of exercise in prepubertal girls (Table 2), but observed greater increases by 2.6% (0.025 g cm^{-2} overall; 0.004 g cm^{-2} per month) in femoral neck and 1.7% (0.016 g cm^{-2} overall; 0.002 g cm^{-2} per month) in trochanter aBMD, in early pubertal intervention girls compared to controls.

Using a novel exercise intervention, McKay et al. [22] prescribed only 3 min of jumping exercises, 3 times a day on each school day in early pubertal girls and boys. The '*Bounce at the Bell*' intervention, involved a 3 min jumping session at each school bell throughout the day (3 per day). Over 8 months, greater increases by 2% (0.4 g overall; 0.05 g per month) in proximal femur BMC and 2.7% (0.3 g overall; 0.04 g per month) in intertrochanteric BMC were found in intervention compared to control children. However, there are a number of limitations with the study (grade 15). Firstly, there was no randomisation or grouping of the subjects and although matched, the control group were from a previous study. Compliance to the exercise intervention ranged from 2 to 5 days per week, thus it was not possible to determine the efficacy of the complete trial. Furthermore, whilst the intervention group showed increases in BMC and bone area at the proximal femur and intertrochanteric regions; the control group showed greater increases of total body BMC and bone area, leading to conflicting results. McKay et al.'s [22] exercise intervention offers a novel and time-efficient programme to target BMC in children during school time, but its effectiveness in increasing bone mineral accrual is unclear.

Heinonen et al. [33] incorporated specific jumping exercises, but prescribed only two 20 min sessions per week. Following the 9 month intervention, they reported greater BMC changes in exercisers than in controls, at the lumbar spine (3.3%) and femoral neck (4%). Absolute BMC values were not reported. In one of the earliest studies, Morris et al. [35], unlike Heinonen et al. [33], McKay et al. [22], MacKelvie et al. [25] and Petit et al. [31], did not incorporate specific jumping exercises. Their intervention comprised of ball games and aerobics, 3 times per week, yet positive results were also reported (Table 2). Over 10 months, the exercisers gained more total body, lumbar spine, femoral neck and proximal femur BMC and aBMD (2.3–10.4%). However, it should also be considered that the results from both Morris et al.'s and Heinonen et al.'s study were potentially confounded by selection bias due to the group selection, decided by the teachers of the participating schools.

The adjustment of effects to 6 months resulted in the largest improvement in bone mass observed by Morris et al. [35] with the highest increase of 6.2% in femoral neck BMD, although this study had a relatively high risk for bias (15). Large increases in bone mass averaged over 6 months were also observed by Iuliano-Burns [29] (lowest risk for bias, 19) of 5% in femoral neck BMC and Courteix et al. [21] of 4.1% in femoral neck BMD and 5.5% in lumbar spine BMD. Both groups reported their positive effects from an exercise–calcium interaction, although the latter was found to have a higher risk for bias (14) [21].

The evidence suggests that early puberty may be particularly optimal for bone adaptation to loading, particularly when coupled with sufficient calcium intake. Reasons for why this may be an opportune period for bone adaptation to exercise may be due to the velocity of bone growth and with the endocrine changes at this age. It has been estimated that around 30% of total body adult bone mass is accrued during this time [39], and in parallel, bone enhancing hormones such as oestrogens, androgens, growth hormone and insulin-like growth factor 1 increase at this time, due to a change in the amplitude of the hypothalamic gonadostat [39]. Such a sudden change may lead to an improved skeletal response to loading through the new quantities of bone-active hormones. It is also known that the effects of calcium on bone are synergistic with oestrogen, as without oestrogen, the intestinal absorption of calcium has been shown to diminish [41]. To summarise, whilst the evidence suggests that a *window of opportunity* [8] exists in children at this pubertal stage, the studies to date are of insufficient quality and number to arrive at a definitive conclusion. Thus, further studies of greater quality in design and execution, are required.

Pubertal children

Five studies were conducted in pubertal children and 2 reported positive effects, ranging from 0.3% [28] to 1.9% [28] over 6 months depending on the site of measurement. Studies in this section had the highest risk for bias graded at 11 to 16; only one had a moderate risk for bias [28].

Only 2 studies reported positive effects of bone mineral from exercise [28,29]. The first, by Stear et al. [28], included both an exercise and calcium intervention and bone mineral advantages were observed at a number of sites, including the femoral neck, lumbar spine and total body. This was a double-blinded, placebo controlled trial and was graded at 16. Without a calcium intervention, Nichols et al. [29] reported BMD increases at the femoral neck and Ward's triangle in exercisers compared to controls. However, this study had the lowest level of compliance, with only 15% of participants completing the intervention. When adjusted for effects over 6 months, Stear et al. [28] observed the larger improvements in bone mass compared to Nichols et al. [29], although increases were small (0.4% to 1.9%).

Two investigations of the effects of resistance exercise on bone mineral accrual in pubertal girls, failed to significantly augment bone mineral in exercisers compared to controls [37,38]. In the earlier study conducted by Blimkie et al. [38], girls participated in machine-assisted resistance training 3 times per week for 6.5 months, yet no significant changes in bone mineral were observed. Exercises were machine-assisted, which may have resulted in an insufficient stress exerted through muscle to bone. However, Witzke and Snow [37] implemented a more intensive resistance exercise programme as it consisted of plyometric training (particularly high impact) as well as exercises with and without machines. Yet no significant effects on bone mass were detected.

Studies in more mature children are few and poorly conducted. Although the skeletal response to exercise may be blunted here, evidence indicating no effects, may reflect poor study design. Further research is required, using well controlled studies.

Discussion

Optimal exercise intervention for bone mineral accrual

It is known that the skeletal response to weight-bearing exercise is site-specific and studies to date support this, reporting the most significant effects at the femoral neck (Table 2). However, a major question arising from this review is what constitutes the optimal exercise programme to improve bone mineral accrual in children?

Intervention trials that have achieved successful results have used a range of exercise protocols. These have included (a) activities such as aerobics, football and gymnastics [34,35]; (b) resistance training [36–38]; (c) plyometrics [37]; (d) circuit training [23–26]; (e) jumping exercises [22,24–27,29,31–33] or a combination of both ‘b’ and ‘c’ [37], or ‘d’ and ‘e’ [24–26]. However, there have been no quantitative, dose–response studies, thus it is difficult to ascertain what type and level of exercise program would be optimal to have a positive effect on peak bone mass accrual. Results from the exercise interventions reviewed in this paper have varied. Yet comparison between studies is complex due to differences in design, control of variables, duration of the interventions, the frequency at which exercises were performed and the GRF generated.

The studies reviewed in this paper varied in the duration of the exercise intervention employed. Adjusting results to 6 months enabled a comparison of effects between studies. Increases in bone mass (BMC and areal BMD), averaged over 6 months, were 0.9 to 3.9% for studies conducted in prepubertal children; 0.9 to 6.2% in early pubertal children and 0.4 to 1.4% in pubertal children. Increases tended to be greater at the femoral neck than at the lumbar spine or proximal femur. Most exercise interventions comprised largely of jumping exercises and those which generate impact forces through the lower limbs. This would exert a greater magnitude of loading at the hip than at the spine. In addition, changes may first be observed at the femoral neck region of the hip rather than the proximal femur as it is largely comprised of trabecular bone, which has a higher rate of bone turnover. Increases in bone area, and bone structural parameters such as cortical thickness and section modulus were also reported by several studies. Over 6 months, estimated increases in bone area in prepubertal children at the femoral neck were 2.5% [32], and in early pubertal children at the trochanter and proximal femur were 1.5% and 1% respectively [22]. Both interventions involved high-impact jumping exercises. Increases in femoral cortical thickness averaged over 6 months were 4.8% in prepubertal children from weight-bearing activities such as football and aerobics 3 times per week [34], and 2.7% in early pubertal children from jumping exercises and circuit training 3 times per week [31]. In the latter study, structural changes also resulted in an increase in hip section modulus of 3.4% [31].

The majority of studies have prescribed exercise sessions 3 times per week [24–29,31,32,34,35,38]. McKay et al.’s jumping intervention was implemented only 3 min, 3 times every school day [22]. Over the 8 months intervention duration, jumpers gained 1.3 to 2.7% more BMC than controls at the trochanter and proximal femur. Averaged over 6 months, these increases ranged from 1 to 2%. However, in comparison, Heinonen et al. [33] implemented jumping exercises that were performed by children only twice per week but for 20 min per session. Over 9 months, the exercisers gained 3.3 to 4% more BMC than controls at the lumbar spine and femoral neck. Averaged over 6 months these increases ranged from 2 to 3%, greater than those reported by McKay et al. [22].

It is possible that bone adaptation is more likely to occur with interspersed rest periods that are greater than those prescribed by McKay et al. [22]. Indeed, animal research indicates that bone responds more to alternate-day loading rather than consecutive daily loading [43,44]. It is also possible that in McKay et al.’s study [22], the children’s skeletons may have become accustomed to the loading, as this was the same every day, without progression, although it should also be considered that the exercise compliance rates in this trial ranged widely. Bone can become accustomed to constant loading of a similar magnitude and will not increase in strength until a higher magnitude load is applied [42], and the progression of exercise is a well-known training principle and was used by a number of research groups, most of which reported positive effects [26,27,29,32,33,35].

Differences in exercise-generated forces can be quantified by GRF, which are linearly associated with the strain generated in bone [43]. Studies have reported GRF at between 2 to 9 times body weight [24,29,32]. Indeed, such strains are greater than those produced during everyday activities [43], and were found to result in positive bone adaptations. MacKay et al. [43] conducted an important study of GRFs in a variety of childhood activities. They found that simple jumps requiring minimal equipment such as those used in the author’s own recent intervention study [23] and those by MacKelvie et al. [24–26], generated GRFs of 3.5 to 5 times body weight. Fuchs et al. [32], used GRF at around 8.8 times body weight, and this resulted in more bone mineral accrual than interventions used by McKay et al. [23] and McKelvie et al. [24–26], suggesting that higher GRF may result in larger osteogenic responses. However, even moderate impact exercise may be effective, as illustrated by Morris et al. [35] and Bradney et al. [34]. GRF were lower than in Fuchs et al.’s [32] and MacKelvie et al.’s [24] study, yet the authors observed significant increases in bone mass.

Unfortunately, the majority of studies have not provided information regarding GRF therefore it is difficult to quantify what loading is optimal for bone mineral accrual. Furthermore, no studies have used more than one variant of exercise programme. Thus, it remains unclear as to what constitutes the optimal exercise programme for improving bone mineral accrual in children.

Optimal exercise for promoting bone health is important, but it is also important to have an optimal dietary intake of nutrients and energy essential for normal growth processes and for bone metabolism. Few studies examined the contribution of diet, and those that did found positive exercise–calcium interactions for improvements in bone mass [21,28,29]. The importance of maintaining a diet rich in calcium for bone health is recognised and most studies have controlled for calcium intake throughout the exercise intervention. However, the focus of more recent research has shifted from an emphasis on calcium to energy intake for bone health. Evidence indicates that insufficient energy intake is detrimental to bone health via an impaired secretion of GnRH leading to a state of hypoestrogenism and a reduced synthesis of growth factors such as insulin-like growth factor-1 (IGF-1) [45]. None of the trials reviewed controlled for energy intake over the intervention durations. This variable should be included in future studies.

Clinical and public health significance of the results

BMC and aBMD were the major outcomes evaluated in the intervention trials reviewed. Adjusted over 6 months, increases ranged from 0.9 to 5% for femoral neck BMC; 1.4 to 6.2% femoral neck aBMD; 0.9 to 3.3% lumbar spine BMC; and 0.9 to 5.5% lumbar spine aBMD. Depending on the duration of the trial and the subjects maturity status, the largest increases reported were 7.1% femoral neck BMC over 8.5 months [29]; 10.3% femoral neck aBMD over 10 months [35]; 5.5% lumbar spine BMC over 10 months [35] and 11% lumbar spine aBMD over 12 months [21]. Although an inverse relationship between increasing BMD and fracture risk reduction has not yet been demonstrated in clinical trials, the findings of the reviewed trials have a degree of clinical significance as a 10% decrease in BMD has been linked to a 1.5-fold increase in fracture risk [46]. Furthermore, the increases reported at the femoral neck and spine, are particularly significant as these are the most common skeletal sites for osteoporotic fracture.

There is increasing recognition that bone fragility is caused not only by low BMD but by diminished bone quality and structure. Bone structural changes were assessed in several studies, and increases were reported for cortical thickness (femoral neck and proximal femur) and section modulus (femoral neck) [22,31,32,34]. Increases in cortical thickness, as observed in a few studies [31,34], may be of clinical relevance, as a greater cortical thickness may offset future bone fragility that is caused by age and menopausal-related endocortical bone resorption. In addition, several studies found increases in hip section modulus [24,31]. This is a parameter to assess the bending strength of the bone in that region, and is obtained using conventional DXA images of the geometrical properties of the bone in that region. Poor resistance to bending can increase the likelihood of bone fracture, thus any increases in section modulus are viewed as positive.

Whilst bone mineral accrual and certain indices of bone structure appear to be promoted by exercise during the growing years, it is not possible to determine whether these benefits are maintained into and throughout adulthood. It is not known whether there is a causal relationship between exercise during childhood and fracture prevention. This would require many years of follow-up and it is unlikely that fracture in adulthood can be used as an end point from which to assess this. However, as a modifiable determinant of peak bone mass, weight-bearing exercise during childhood and adolescence offers a valuable, cost effective strategy to potentially reduce the burden of osteoporosis and osteoporotic fractures in later life. The potential for such a public health implication warrants further research into this area.

Common limitations and considerations

Although most studies reported positive skeletal effects in exercisers, several confounders, limitations and considerations were evident. These mainly concerned selection procedures, compliance rate and control of variables.

Many studies were open to a degree of bias arising from methods of group selection procedures [20,22,33–35,37]. Two studies allowed children to self-select into their preferred group [20,37], and in several studies, teachers decided upon intervention and control groups [33–35]. Some studies randomised groups by school [23–26,31] and others were individually randomised [21,28–30,32,38]. These were associated with the lowest bias according to group selection methods.

Compliance rates varied between studies. In prepubertal children, study compliance ranged from 33% [24] to 95% [34], and exercise compliance ranged from 91% [27] to 100% [24]. With early pubertal children, study compliance ranged from 42% [25] to 100% [22], and exercise compliance from 60% [22] to 93% [25]. In pubertal children, study compliance was between 15% [29] and 92.5% [33], and exercise compliance between 65% [33] and 73% [29]. A number of studies did not report exercise compliance [21,25,26,31,34]. Most interventions took place in schools, although there were no differences in compliance rates with those which took place outside of school [20,21,27].

Genetics is a major confounder, particularly in studies that are open to self-selection bias. It is difficult to control, although this was achieved by Van Langendonk et al. [27] whose sample comprised of identical twin girls.

This study [27] also highlighted the importance of monitoring previous physical activity in participants. Significant skeletal effects were only found in twins who had not previously exercised to a high level. No positive skeletal effects from their intervention were observed in their total sample [27]. Thus, a more osteogenic effect may be gained from those who previously have no history of exercise compared to those who do. Bone adapts to new and unusual loading and once accustomed to this loading, will not further adapt until the stimulus has increased [42]. Thus, in those who are active at baseline, a more intense or different exercise regimen may deliver a more positive effect on bone, and should be considered when designing interventions for children who are already moderately or highly active. A number of studies did not assess previous physical activity undertaken by their participants [24,25,29,31,33,34,37].

Calcium intake is another important variable to control throughout the intervention period, as calcium may optimise the effect of exercise on bone mass. This was illustrated in several studies that reported significant interactive effects between calcium intake and exercise [21,29,30]. However, a number of trials did consider calcium intake before or throughout the intervention [24,25,27,33,34,37]. No studies controlled or monitored energy intake which is also now recognised as having a pivotal role in bone metabolism [45].

Considerations should also be made with concern to the techniques used to assess bone and the outcomes in which the changes were reported. DXA was the main bone measurement technique, and BMC and aBMD the main outcomes in which changes were observed. Although DXA is currently the gold standard technique for osteoporosis assessment, it cannot determine whether changes in BMD are due to changes in bone mineral or in bone geometrical parameters. All studies used 2-dimensional measures of BMD and very few used 3-dimensional measures.

Although DXA-derived HSA was also used in several studies to estimate geometrical qualities of bone, this is associated with a degree of error, as it attempts to estimate a 3-dimensional structure with a 2-dimensional imaging technique. It is especially limited in studies of children, as the assumptions for the estimation of cortical thickness, section modulus and endosteal diameter are derived from work in adults and have not been validated in children. Future studies would benefit from the evaluation of changes in parameters that can assess the quality of bone, for example, bone size, trabecular and cortical bone architecture, trabeculae size and trabeculae number, in addition to 3-dimensional BMD. Techniques such as quantitative computed tomography (QCT) or magnetic resonance imaging (MRI) would enable this. Specifically, the latter is preferred for use on children as it does not involve ionising radiation. The rationale for assessing bone quality is that individuals who fracture do not always have low BMD as measured by DXA, and that bone fracture may occur due to inherent weaknesses in bone structure.

Conclusions

To conclude, positive skeletal effects from weight-bearing exercise can be attained in girls and boys. The long term effects are unknown, but maximising peak bone mass is likely to offset future development of osteoporosis and bone fragility. The evidence indicates that early puberty potentially represents an opportune maturity stage to augment bone mineral accrual through exercise, although definitive conclusions cannot yet be made. Many studies to date have a high risk for bias, with only a few having a low risk. Major limitations of the reviewed studies concerned selection procedures, compliance rates and control of variables such as other or previous physical activity and calcium. It is clear that 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 is unclear and requires 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.

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