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Title:

Eight months of regular in-school jumping improves indices of bone strength in adolescent boys and girls: The POWER PE study

Running Title:

Jumping for bone strength in adolescents

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The POWER PE study was an eight-month, randomized, controlled, school-based exercise intervention designed to apply known principles of effective bone loading to practical opportunities to improve life long musculoskeletal outcomes.

A total of 99 adolescents (46 boys, 53 girls) with a mean age of 13.8 ± 0.4 years (peri-post pubertal) volunteered to participate. Intervention subjects performed ten minutes of jumping activity in place of regular physical education (PE) warm up. Control subjects performed usual PE warm-up activities. Bone mass (DXA and QUS) was assessed at baseline and follow-up along with anthropometry, maturity, muscle power, and estimates of physical activity and dietary calcium. Geometric properties (such as FN moment of inertia) were calculated from DXA measures.

Boys in the intervention group experienced improvements in calcaneal BUA (+5.0%), and fat mass (-10.5%), while controls did not (+1.4%, and –0.8% respectively). Girls in the intervention group improved FN BMC (+13.9%) and LS BMAD (+5.2%), more than controls (+4.9% and +1.5% respectively). Between group comparisons of change revealed intervention effects only for WB BMC (+10.6% vs +6.3%) for boys. Boys in the intervention group gained more lean tissue mass, TR BMC, LS BMC, and WB BMC and lost more fat mass than girls in the intervention group ($p < 0.05$).

Ten minutes of jumping activity twice a week for eight months during adolescence appears to improve bone accrual in a sex-specific manner. Boys increased whole body bone mass and BUA, and reduced fat mass, while girls improved bone mass at the hip and spine.

Key words: bone strength; children; exercise; jumping; peak height velocity.

INTRODUCTION

An analysis of the osteogenic efficacy of exercise suggests that strategic intervention during childhood which maximizes peak bone mass is likely to be more fruitful than attempts to rehabilitate an osteoporotic skeleton. As hormones modulating puberty are known to exert strong influence on bone, it is unsurprising that the effect of exercise on children and adolescents appears to vary according to pubertal status. Although a growing number of controlled pediatric exercise trials have been reported, relatively little is known about the response of the adolescent skeleton to targeted exercise, nor the influence of gender on that response.

Pre-pubertal children as young as seven years old who regularly participate in weight-bearing activities exhibit bone mass that is significantly greater than those who do not [(1)]. Side-to-side differences of adult tennis and squash player arm and forearm bone mineral content (BMC) are reportedly two to four times greater in women who start playing before or at menarche than those who begin after menarche [(2)]. Intervention studies typically support such observational findings, reporting positive effects of moderate to high-intensity exercise on bone mass in pre-pubertal children at the hip and spine [(3,4)]. The duration of exercise required to stimulate these positive effects may be as low as ten minutes per day and only a few days per week [(4)]. In older children, however, exercise intervention may be a less effective bone stimulus [(5,6)]. While there is currently a lack of very long-term follow-up data, preliminary evidence [(7,8)] forms the basis for hope that relatively insubstantial amounts of targeted exercise during youth may help protect the skeleton to a clinically significant extent in later life.

The aim of the Preventing Osteoporosis With Exercise Regimes in Physical Education (POWER PE) study was to determine the effect of a practical, evidence-based exercise regime (ten minutes of jumping activity twice per week for eight months) on parameters of bone and muscle strength in healthy adolescent boys and girls in comparison with age- and sex-matched controls. We hypothesized that (1) adolescents participating in jumping activities would have greater gains in parameters of bone and muscle strength than controls, (2) boys and girls would experience similar effects, and (3) changes in bone mass would be related to changes in lean tissue mass, other daily physical activity level and dietary calcium.

MATERIALS AND METHODS

Ethical approval

Approval to perform the study was obtained from the Griffith University Human Research Ethics Committee and Education Queensland (Queensland Government Department for Education, Training and the Arts).

Study Design

POWER PE was a prospective eight-month, randomized, controlled, school-based, exercise intervention examining the musculoskeletal effects of brief, twice-weekly, novel jumping exercise on adolescent boys and girls. Exercise sessions took place every week of the school year with the exception of school holidays and study testing periods. Baseline testing occurred at the beginning of the school year. Follow up testing was completed in the final weeks of the school year.

Subjects and subject selection

A total of 46 adolescent boys (mean age 13.8 ± 0.4 years at baseline) and 53 adolescent girls (mean age 13.7 ± 0.4 years at baseline) enrolled in the ninth grade of a local high school (Gold Coast, Australia) consented to participate in the POWER PE trial. Subjects were included if they were of sound general health, fully ambulatory, and had the written consent of a parent or guardian. Subjects were excluded from the study if they had a metabolic bone disease, endocrine disorder or chronic renal pathology, were taking medications known to affect bone, were recovering from lower limb fracture or other immobilized injury, or were affected by any condition not compatible with physical activities likely to raise the heart rate for up to ten minutes.

The 99 adolescents were randomized to either control or intervention groups. Eighteen students were lost prior to follow up testing, leaving 81 adolescents (43 intervention, 38 control) in the final analysis at eight months (Figure 1). Baseline characteristics of those lost to follow up did not differ from the remaining cohort.

Intervention activities

Participants allocated to the intervention group participated in ten minutes of directed jumping activity at the beginning of every physical education (PE) class, that is, twice per week for eight months, excluding holidays. Activities were designed to apply loads to the skeleton at high strain magnitude, frequency, and rate; characteristics that were determined by ground reaction force analysis [(9)]. Although activities varied from session to session to maintain participant interest, each bout included at least some of the following: jumps; hops; tuck-jumps; jump-squats; stride jumps; star jumps; lunges; side lunges; and skipping (Table 1).

Most of the jumps were performed at a frequency of 1-3 Hz and at a height of 0.2-0.4 metres. An entire ten-minute jumping session included approximately 300 jumps, although this figure was achieved gradually in order to reduce the risk of injury and apply progressive overload. A single instructor (BW) described and led all jumping activities and announced changes to the routine during each session. Jumps were occasionally supplemented with upper body strengthening activities, including push-ups and exercises with resistive latex bands (AusBand, Ausmedic Australia, Pty. Ltd.).

Participants completed the exercise regime twice per week to coincide with regularly scheduled PE classes. Given recent reports of osteogenic effects of short duration jumping [4,10], the ten minute intensive sessions could be expected to deliver a sufficient number of loading cycles to our subjects. We were particularly interested in ascertaining whether merely incorporating bone-specific loading into existing PE classes would have a measurable effect on the skeletons of adolescents. Replacing the usual warm up with the intervention was considered a test of minimum effective dose. The eight-month duration of the study was chosen as it coincided with one school year and has previously been sufficient to detect positive changes in younger children [3,11].

Control activities

In a separate location, control group subjects undertook regular PE warm-ups and stretching directed by their usual PE teacher at a time that corresponded with intervention group activities, that is, at the beginning of every PE class, twice per week for a period of eight months, excluding holidays. Control activities were focused on improving flexibility and general preparedness for physical activity without specifically loading the skeleton at higher rates than normal. Activities typical of the usual PE warm-up included brisk walking, light jogging, and stretching. All subjects regrouped for normal PE activities directly after the diverse warm ups had been completed.

Both intervention and control children engaged in 80 minutes of normal PE activities following the initial ten-minute warm up period. These activities followed the Queensland School Curriculum Council Health and Physical Education Syllabus and included 3-6 weeks blocks of theory and practical activities relating to health and physical activity. Activities within the curriculum include swimming, team sports, dance, fitness assessment, and track and field.

Testing

Students were tested at baseline and follow-up, including anthropometrics, Tanner staging, assessment of muscle strength and power, quantitative ultrasonometry of the heel and bone mass measurements with dual energy x-ray absorptiometry (DXA). Physical activity and diet questionnaires were completed during PE classes in the same week as testing.

Anthropometrics

Subject height and sitting height were measured to the nearest millimetre using the stretch stature method with a portable stadiometer (HART Sport & Leisure, Australia). Weight was measured to the nearest 0.1 kilogram using the mean of measures from two sets of digital scales (Soehnle Co., Switzerland). Body mass index (BMI) was determined from measures of height and weight per the accepted method (BMI = $weight \cdot height^{-2}$, $kg \cdot m^{-2}$).

Assessment of maturity

Maturity was determined using two methods. The first involved self-determination of Tanner stage using standard diagrams of pubic hair growth (and breast development for females). Tanner Stage I represents the prepubertal child, Stages II and III describe the peripubertal child, while Stages IV and V represent the postpubertal child. Privacy was maintained from other subjects and investigators by providing booths for completing forms and placing them in sealed, coded envelopes.

The second method was that of Mirwald and colleagues [12] who formulated an algorithm using data from a large paediatric longitudinal trial [13] to predict years from peak height velocity (PHV) based on the single measurement of several anthropometric parameters. These gender-specific predictive equations incorporate the interactions between height, weight, sitting height and limb length to determine a maturity offset that is added to chronological age to give PHV. The ability of these equations to predict actual PHV have been reported as $R^2 = 0.890$ and $R^2 = 0.891$ for boys and girls respectively [12].

Muscle power

Muscle power was determined using a vertical jump test. The Yardstick (Swift Sports Equipment, Lismore, NSW, Australia) was used to determine vertical jump height as the difference between the height of a standing reach and total jump height. The subject stood with feet shoulder width apart, preferred arm raised and non-preferred arm kept to the side of the body. A jump for maximum height was made in a countermovement fashion without arm swing. The best of three attempts was recorded to the nearest centimetre.

Bone parameters

The QUS-2 Ultrasound Densitometer (Quidel Corporation, CA, USA) was used to evaluate broadband ultrasound attenuation (BUA) of the non-dominant calcaneus. A recent report of the validity of the QUS-2 in pubertal children [14] indicated that calcaneal BUA is comparable to DXA and pQCT in its ability to monitor bone densitometric change in this population. The same investigator (BB) performed all ultrasound assessments. Calibration quality control was accomplished via an automated verification process that involved the scanning of a phantom model of known BUA on each day of testing. Repeat scans in this cohort (n = 20) with repositioning determined short-term BUA measurement precision (CV) of 2.8%.

Measures of bone mineral content (BMC), bone mineral density (BMD), and bone area (BA) of the femoral neck (FN), trochanter (TR), lumbar spine (LS), and whole body (WB) were made with an XR-36 Quickscan Densitometer (Norland Medical Systems, Inc., USA) using host software, version 3.9.4, and scanner software version 2.0.0. The non-dominant hip was used for measurements at the FN and TR. Size-adjustment was accomplished by calculating bone mineral apparent density (BMAD), and other mechanical characteristics such as cortical wall thickness (CWT), cross-sectional moment of inertia (MI), and index of bone structural strength (IBS) were estimated using formulae described by Sievanen and colleagues [15]. Measures of lean tissue and fat mass were determined from WB scans. The same investigator (BW) performed and analyzed all DXA measurements. Short-term precision for repeated measures with repositioning on a sub-sample of the cohort (n = 35) for FN, LS, and WB BMC was 1.3%, 1.1%, and 1.4% respectively.

Physical activity

A physical activity score was derived for each subject, from responses to a bone-specific physical activity questionnaire (BPAQ), using a custom-designed LabVIEW program (National Instruments, Texas, USA). The program ran an algorithm that accounted for frequency of exercise bouts, and years of participation in past (whole of life) and current (previous 12 months) exercise involvement, as well as an impact rating of each type of exercise. Details of the BPAQ system are to be reported elsewhere. Recent analyses indicate that, in contrast to the inability of traditional measures of physical activity to reflect bone loading history, BPAQ score has the ability to predict up to 60% of the variance in indices of bone strength at the FN and LS [9].

Calcium intake

Dietary calcium consumption was estimated from a calcium-focused food questionnaire. Subjects were asked to indicate the type and amount of each food item they consume on average over a period of one day, one week, or one month. The average daily intake of dietary calcium was calculated using *Calcium Calculator*^{SM}, an internet-based java applet program obtained from *CALCIUMinfo.com* [16].

Statistical analyses

In order to obtain sufficient statistical power to examine effect size in all dependent variables we calculated the sample size required for 80% power for the measure with the most variability (i.e. BUA). To observe a mean difference of 10 ±15 dB/MHz in BUA between groups based on repeated measures ANCOVA with an alpha level of 0.05 we determined a minimum group size of 36 (n = 72 total) should be enrolled. Allowing for an attrition rate of 10%, a minimum of 80 participants was required.

All statistical analyses were performed using SPSS version 12.0 for Windows (SPSS, Chicago, IL, USA). Two-tailed Pearson correlation analyses were employed to observe relationships between physical/lifestyle characteristics and eight-month change in bone parameters. A repeated measure ANCOVA was used to determine main effects for dependent variables. Height, weight, and age at PHV (APHV) were entered as covariates to account for the known influence of growth and maturity on bone and to align subjects on a common maturational milestone per the recommendation of Baxter-Jones and colleagues [17]. The preponderance of subjects falling in only two of the Tanner categories, prevented categorical analysis of data according to Tanner stage. As differences in physical and maturational characteristics existed between sexes, data were further analyzed in a sex-specific manner. Forward stepwise multiple regression analysis was employed to investigate the influence of physical, lifestyle, and dietary factors. Differences in baseline data between those who dropped out of the study and those who remained were analyzed using independent t-tests. Statistical significance was set at $p < 0.05$.

RESULTS

Subject characteristics at baseline

Ninety-nine adolescents (46 boys and 53 girls) volunteered for the study. Fifty-two were randomized to the intervention group and 47 to control.

Considerable differences were observed between male and female subjects. Boys were heavier, taller, and had greater vertical jump performance than girls ($p < 0.05$). Boys had significantly greater lean mass (37380 ± 8390 g vs 30585 ± 3736 g; $p < 0.002$), lower percent body fat (22.0 ± 8.6 vs 27.7 ± 5.7; $p < 0.002$), and consumed more dietary calcium than girls (1143 ± 92 $mg.day^{-1}$ vs 826 ± 57 $mg.day^{-1}$, $p = 0.004$). There were no sex differences in bone-specific physical activity (BPAQ) scores.

Boys recorded a significantly older APHV (13.8 ± 0.1 years) than girls (12.3 ± 0.1 years). As male and female volunteers were of similar age, males were significantly fewer years from APHV (0.0 ± 0.1 years) than females (1.5 ± 0.1 years). All Tanner stages were represented in both boys and girls (Table 2); however, most (53 %) were Tanner IV. Average age of menarche for girls in the study cohort was 12.5 ± 0.7 with eleven premenarcheal and 42 post-menarcheal at the time of baseline testing.

Given the physical and maturational differences observed between male and female subjects, sex-specific analyses were conducted. At baseline there were no significant differences between groups for any physical characteristic for boys (Table 3). For girls, however, sitting height was significantly greater in the intervention group than the control group (0.852 ± 0.026 m vs 0.828 ± 0.030 m; $p = 0.02$) and FN area was greater in controls than intervention girls (4.72 ± 0.29 cm^2 vs 4.33 ± 0.59 cm^2; $p = 0.04$). No differences existed for any other baseline parameters (Table 3).

Eight-month change in physical and lifestyle characteristics

Eight-month change in physical and lifestyle characteristics for boys and girls are presented in Table 4. Boys in both groups experienced significant increases in weight, height, and vertical jump ($p < 0.05$). There were no between-group differences. No changes were detected for body mass index, other physical activity level or dietary calcium intake for either male group.

After eight months, all girls experienced significant gains in weight, height, and body mass index ($p < 0.05$). Girls in the control group increased their physical activity level significantly (+28.9%, $p = 0.003$), while girls in the intervention did not (-13.6%, NS), a between-group difference that was significant ($p = 0.008$). No significant differences were observed for eight-month change in vertical jump or dietary calcium intake for girls.

Eight-month between-group change in bone and lean tissue parameters

Intention-to-treat analysis revealed several differences between intervention and control groups (Table 5). Lean tissue mass, calcaneal BUA, FN BMC, TR BMC, LS IBS and WB BMC improved more for intervention subjects than controls. Per protocol analysis of group data revealed treatment effects for change in WB BMC only, whereby children in the intervention group gained significantly more bone mineral than controls (185.4 ± 91.9 g vs 110.4 ± 96.1 g, $p = 0.009$). No other differences in eight-month change in parameters of bone or muscle strength reached significance.

Eight-month sex-specific between-group change in bone and lean tissue parameters

Eight-month changes in bone and lean tissue parameters for boys and girls are presented in Table 6. After eight months, boys in both groups experienced significant improvements in bone mass and geometric parameters at the proximal femur and lumbar spine ($p < 0.05$). Significant improvements were recorded for calcaneal BUA (+5.0%), FN area (+3.8%), and fat tissue mass (-10.5%) for boys in the intervention group ($p < 0.05$), but not the control group (+1.4%, +2.7%, and –0.8% respectively). Intervention group boys increased WB BMC significantly more than control group boys (+10.6% vs +6.3%, $p = 0.03$).

At eight months, girls in the intervention group significantly improved FN BMC, and LS BMAD while the control group did not (+13.9%, $p = 0.05$ vs +4.9%, NS; +5.2%, $p = 0.04$ vs +1.5%, NS, respectively). Both groups experienced significant gains in LS BMC, LS IBS, WB BMC, and lean tissue mass ($p < 0.05$). LS area was found to improve for girls in the control group (+4.9%, $p = 0.001$), while the improvement in girls of the intervention group did not reach significance (+2.0%, NS). Between-group differences in eight-month percent changes for girls did not reach significance.

Eight-month between-sex change in bone and lean tissue parameters

When eight-month changes in bone and lean tissue parameters were compared between boys and girls in the control group, no significant differences were evident. Changes in lean tissue mass, fat mass, TR BMC, LS BMC, and WB BMC, however, were found to differ between boys and girls of the intervention group. Boys gained more lean tissue mass ($p = 0.001$) and lost more fat mass ($p = 0.02$) than girls. Likewise, improvements in TR BMC ($p = 0.007$), LS BMC ($p = 0.028$), and WB BMC ($p = 0.007$) in the intervention group were greater in boys than in girls. Changes in all other parameters of bone and lean tissue were similar between sexes in both groups.

Relationships between bone, lean tissue, and lifestyle parameters

Significant relationships were observed for eight-month change in lean tissue mass and bone strength parameters for all subjects. Change in lean tissue mass of the control group showed a moderate to strong positive relationship with change only in TR BMC ($r = 0.62$, $p = 0.01$). Change in lean tissue mass of intervention children, however, displayed moderate positive relationships with changes in FN BMC ($r = 0.59$, $p = 0.001$), TR BMC ($r = 0.52$, $p = 0.004$), LS BMC ($r = 0.50$, 0.006), and WB BMC ($r = 0.63$, $p = 0.001$). No significant relationships existed between dietary calcium intake and parameters of bone strength for either group.

Results of the multiple regression analyses conducted on grouped data demonstrated that change in lean tissue mass of subjects in the intervention group was predictive of improvements in BMC at the FN ($R^2 = 0.35$, $p = 0.001$), LS ($R^2 = 0.25$, $p = 0.006$), and WB ($R^2 = 0.40$, $p = 0.001$), however, no significant bone mass predictors emerged for children in the control group. Neither daily physical activity level (BPAQ), nor dietary calcium intake, or vertical jump were able to predict intervention effects for either group.

Compliance

Overall study drop out rate was 18% and was due to student relocation or absence from school on the days of follow-up testing. Mean compliance for the intervention was 80% and was a direct reflection of absence from school. There were no differences in baseline physical characteristics or bone and lean tissue parameters between those who dropped out and those who remained in the program.

DISCUSSION

Our goal was to determine the effect of ten minutes of jumping activity twice per week for eight months on parameters of bone and muscle strength in healthy adolescent boys and girls. Group analysis revealed that jumpers experienced significant improvements over controls for bone mass at the femoral neck, trochanter, whole body and calcaneus, as well as lean tissue mass. Specifically, we found that boys who participated in the jumping regime improved calcaneal and whole body bone mass and lowered fat tissue mass, while girls in the intervention enhanced bone mass at the femoral neck and lumbar spine. We also discovered that changes in lean tissue mass accounted considerably for improvements in parameters of bone strength for intervention participants, but not for controls, while lifestyle factors such as dietary calcium intake or baseline level of physical activity did not influence changes in bone.

Numerous previous studies have concluded that physical activity prior to puberty is more beneficial to the skeleton than activity undertaken during puberty [2,5,6,18]. Heinonen and colleagues [6], for example, observed significant bone mass gains at the femoral neck for premenarcheal, but not post-menarcheal girls in response to a lengthy protocol (approximately 50 min) of aerobics and drop jumping. Wang and colleagues [19] reported that maturational status of girls accounts for more variation in bone mass than physical activity history. Tanner Stages II to V are associated with increasing levels of circulating sex steroids, while peak concentrations of insulin-like growth factor I (IGF-I) and growth hormone are reached in Tanner Stage III and IV [20]. MacKelvie and colleagues [20] postulated that the reduction in concentration of hormonal factors such as growth hormone and IGF-I following menarche might account for a less mechanically-sensitive skeleton in girls at this stage. As 79% of the girls were postmenarcheal at baseline and 90% at follow-up, it could be postulated that growth hormone and IGF-I concentrations were largely post peak in our female cohort, such that the mechanosensitivity of their skeletons was indeed suboptimal.

Some evidence exists, however, to suggest that the optimal timing of exercise for bone in relation to puberty is not a simple matter. For example, while BMD change in response to thrice weekly, ten-minute, school-based jumping was not different between pre and postmenarcheal girls, BMD change at the hip was 2.6% greater than controls only in the postmenarcheal girls [21]. Furthermore, others have reported much shorter duration (three months) jumping (25 jumps per day, five days per week) by children aged 3-18 years increased whole body and leg BMC more than controls in all age-groups, but that BMC at the spine and distal tibia increased only in post-pubertal subjects [22]. The authors proposed that loading may increase bone mass, but not at predominantly trabecular sites during rapid growth (i.e. around PHV).

While a pre/post comparison was not possible in our study (only eleven girls were premenarcheal at commencement of the program), we observed a more substantial FN BMC gain (9% greater) in intervention group girls (who were on average slightly older than subjects in the above reports), compared with controls. Our data would support the contention that loading may effect non-trabecular sites during rapid growth, as boys in our cohort (mostly at peak height velocity at the time of the study) primarily improved whole body bone mass (reflecting considerable cortical bone mass), while girls (who were further past PHV) improved bone mass at the hip and spine (i.e. predominantly trabecular regions).

The greater improvement in calcaneal BUA of boys than in girls that we observed might reflect an interaction of strain magnitude with maturation. That is, the largely unattenuated strain signals at the calcaneus during jumping (from a combination of ground reaction forces and muscle traction via the Achilles) may be large enough to override any confounding effect of rapid growth at this primarily trabecular site.

Although a few studies have focused on the effect of exercise on the bones of children during puberty [(6,7,18,23,24)], to our knowledge, the effectiveness of a very simple, regular, brief, high intensity program on the bones of both adolescent boys and girls has not previously been examined by a randomized, controlled, intervention trial. That we report positive, albeit site- and sex-specific responses to an exercise stimulus in our cohort suggests worthwhile skeletal benefits may indeed be achieved beyond the prepubertal years.

Per protocol analyses indicated that greater improvement in whole body bone mass occurred in the intervention versus control group. Although the observation could be explained by a more vigorous cortical bone response during PHV as described above, it may also reflect a systemic bone response to a supplemental exercise regime. That is, our loading regime may have stimulated endocrine factors, such as growth hormone or insulin-like growth factor. Enhanced growth hormone release is known to occur during both aerobic and resistance exercise and is observed to follow a positive linear relationship with increasing exercise intensity [(25)]. The reverse of this effect is evident in studies of skeletal unloading whereby suppression of the growth-promoting action of insulin-like growth factor (IGF) results in the systemic inhibition of bone formation in rats [(26)]. Alternatively, the lack of regional site-specific effect might reflect the variety of movements strategically incorporated into the jumping sessions (including upper extremity activity) and associated muscle-induced loading at a range of sites within the skeleton.

We did not detect the improvement in WB bone mass in girls that has been reported previously [24,27,28]. The latter studies were longer in duration (ten months and longer) and involved girls who were either much younger or much older than our cohort. The lack of intervention effect on female whole body bone, muscle and fat mass, in comparison with controls, suggests that girls responded to the intervention in a more localized or site-specific manner, versus the systemic response of the boys. The considerable mineralization lag during rapid growth of up to one year [13] may explain our inability to detect site-specific change in boys (closer to PHV than the girls). Only one previous study has reported the improvement in WB bone mass that we observed in our male subjects in response to exercise intervention; it involved prepubertal boys [11]. Interestingly, boys in our intervention gained significantly more lean tissue mass and lost more fat mass than girls in the intervention group. Improvement in lean tissue mass mirrored the positive bone effect and was predictive of bone mass at the hip, spine and whole body in jumpers. The observation reflects the known influence of muscle force on the skeleton [29].

Of note, there was no significant change in vertical jump height for girls in the intervention. On occasion the girls were somewhat more difficult to motivate than the boys during intervention sessions and it is therefore possible (although not apparent at the time), that they performed the activities at a lower intensity. In the authors' experience, such behavior is common in girls of this age in the PE environment, including during regular warm ups, and so is not necessarily a reflection of the acceptability of the activities themselves. The observation, however, may warrant the development of sex-specific strategies to maximize the success of wider implementation. For example, it is possible the addition of music to the intervention activities may further engage female participants.

Although reductions in differences detected between control and exercise intervention groups can be expected in adult cohorts with time, there is reason to be optimistic that bone gains made in childhood will be sustained [7]. Follow up measures of the current cohort would provide valuable information in this regard, and are planned. Ongoing participation in the intervention activities in ensuing school years would likely limit a detraining effect, and similarly warrants further examination.

The fact that girls in the control group increased their level of unrelated physical activity (28.9%) over the course of the study may have reduced our ability to detect a between-group treatment effect. That is, increased daily bone-specific loading may have improved parameters of bone strength in controls despite non-participation in the jumping intervention. Despite this confound, girls in the intervention group gained more BMC at the femoral neck and BMAD at the lumbar spine compared with controls.

Surprisingly, we found no relationship between parameters of bone strength and calcium consumption for boys and girls in the study. It has been suggested that physical activity can counteract deficiencies in calcium intake during growth [30,31]. Although average subject calcium consumption (900 mg per day) was lower than recommended (1300 mg per day) [32], the 'deficiency' was not large enough to interact with the bone response in this healthy cohort of adolescents.

Broadband ultrasound attenuation (BUA) has been shown to reflect bone strength, primarily as a function of bone mass [33]. Very few pediatric studies have examined the response of ultrasound-derived indices of bone strength to exercise interventions. One short duration (four month) rope-jumping study monitored changes in stiffness index (SI) for post-pubescent girls performing low (50 skips per minute for five minutes, four times per week) and high volume (50 skips per minute for ten minutes, four times per week) jumping compared with controls [23]. Although there was no difference in SI between high and low volume jumpers, high volume jumpers had significantly greater SI than controls. More pronounced in boys, we found that BUA at the calcaneus improved in both boys and girls in the intervention group.

The contribution of bone geometry to bone strength is well known. Furthermore, the strengthening effect of exercise loading on bone via geometric adaptation may be considerable. For both sexes, the positive change in bone strength parameters (IBS, CSMI, and BUA) was consistently greater in both boys and girls in the intervention group compared with controls. The ability to reach significance in the combined analysis likely reflects the considerably larger sample size than the sex-specific analyses. Bone geometry is best evaluated using three-dimensional technology, such as magnetic resonance imaging (MRI) or computed tomography (CT). Our logistics prevented such direct measurement of bone geometry, thus we utilized DXA-derived indices of bone geometry developed and validated by Sievanen and colleagues [(15)] as surrogate 'measures'. We recognize this compromise limits our ability to fully report the effects of our intervention on bone strength changes.

In conclusion, our simple, practical exercise intervention improved indices of bone and muscle strength in healthy adolescent boys and girls in the high-school physical education setting without the need for additional staffing or equipment. Large-scale, longitudinal studies are necessary to determine if such effects achieved around the time of puberty can optimize peak bone mass and/or persist into later life in order to meaningfully reduce the risk of fracture. Until such time, it is reasonable to assume that the osteogenic sensitivity of the pediatric skeleton remains an appropriate target for the management of osteoporosis, being amenable to exercise prescription and easily incorporated into school-based activity.

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Table 1

TABLE 1: DESCRIPTIONS OF INTERVENTION ACTIVITIES

Activity	Description
Jumps	Two-leg take off, followed by a two-leg landing
Hops	Single-leg take off, followed by a single-leg landing on the same side
Tuck-jumps	Double-leg jump whereby hips and knees are further flexed during flight such that the knees achieve close proximity to the chest
Jump-squats	Double-leg jump whereby participants perform the double-leg landing in the squat position with knees and hips flexed to approximately 90 degrees
Stride jumps	Take off with one foot in front of the other, i.e. stride stance, landing with foot position reversed
Star jumps	Continuous double-leg jumps, where each alternate jump has both shoulders and hips in a slightly abducted position
Lunges	Starting with feet together, the participant takes a large step forward so that the front knee is flexed to approximately 90 degrees before returning to the starting position
Side lunges	Starting with feet together, the participant takes a large step to the side so that the knee is flexed to approximately 90 degrees before returning to the starting position
Skipping	A variety of repetitive jumps using a skipping rope

Table 2

TABLE 2: TANNER STAGE REPRESENTATION AND CORRESPONDING YEARS FROM AGE AT PEAK HEIGHT VELOCITY (YAPHV) AT BASELINE FOR ADOLESCENT BOYS AND GIRLS (N = 99)

Tanner Stage	**I**		**II**		**III**		**IV**		**V**	
Sex	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls
Number	1	1	3	2	8	14	23	29	11	7
YAPHV (years)	-1.4	0.6	-0.5	0.8	-0.2	1.4	0.1	1.5	0.4	1.8

Abbreviations: YAPHV = years from age of peak height velocity.

Table 3

TABLE 3: BASELINE CHARACTERISTICS FOR ADOLESCENT BOYS AND GIRLS (N = 99). MEAN VALUES (± SD).

Characteristic	Boys (n = 46)			Girls (n = 53)		
	Control (n = 24)	Intervention (n = 22)	p value	Control (n = 23)	Intervention (n = 30)	p value
Age (years)	13.8 (0.4)	13.8 (0.4)	NS	13.7 (0.5)	13.7 (0.4)	NS
YAPHV (years)	0.0 (0.8)	-0.1 (0.8)	NS	1.4 (0.4)	1.6 (0.5)	NS
Age of menarche (years)	-	-	-	12.4 (0.8)	12.6 (0.8)	NS
Weight (Kg)	58.6 (16.7)	55.0 (13.8)	NS	50.0 (6.4)	51.6 (10.5)	NS
Standing height (m)	1.640 (0.086)	1.637 (0.098)	NS	1.602 (0.058)	1.621 (0.060)	NS
Sitting height (m)	0.845 (0.049)	0.841 (0.056)	NS	0.828 (0.030)	0.852 (0.026)	0.02
Body mass index ($kg{\cdot}m^{-2}$)	21.5 (5.1)	20.3 (3.6)	NS	19.5 (2.1)	19.5 (3.5)	NS
Vertical jump (cm)	31.8 (8.9)	32.7 (6.0)	NS	27.6 (7.4)	29.7 (5.9)	NS
BPAQ score	3.55 (1.20)	3.84 (1.50)	NS	3.43 (1.39)	2.58 (1.73)	NS
Calcium intake ($mg{\cdot}day^{-1}$)	1006 (385)	1253 (779)	NS	873 (498)	776 (342)	NS
BUA ($dB{\cdot}MHz^{-1}$)	79.1 (16.2)	76.2 (10.0)	NS	83.6 (12.5)	79.3 (11.4)	NS
FN BMC (g)	4.39 (0.85)	4.25 (0.82)	NS	4.09 (0.55)	3.68 (0.67)	NS
FN Area (cm^2)	4.67 (0.42)	4.81 (0.34)	NS	4.72 (0.29)	4.33 (0.59)	0.04
LS BMC (g)	33.2 (7.2)	31.5 (8.5)	NS	36.4 (7.0)	35.6 (7.6)	NS
LS Area (cm^2)	40.6 (4.4)	39.9 (5.6)	NS	41.1 (3.4)	40.3 (3.8)	NS
WB BMC (g)	2139 (418)	2142 (456)	NS	2301 (196)	2094 (414)	NS
Lean Mass (g)	36945 (7598)	35885 (8938)	NS	30740 (2875)	30719 (4472)	NS
Fat Mass (g)	14531 (9543)	15532 (8116)	NS	20630 (4693)	18930 (8132)	NS

Abbreviations: BMAD = bone mineral apparent density; BMC = bone mineral content; BPAQ = bone specific physical activity questionnaire; BUA = broadband ultrasound attenuation; CSMI = cross sectional moment of inertia; IBS = index of bone structural strength; FN = femoral neck; LS = lumbar spine; NS = not significant, p > 0.05; TR = trochanter; WB = whole body; YAPHV = years from age of peak height velocity.

Table 4

TABLE 4: EIGHT-MONTH CHANGE (± SD) IN PHYSICAL AND LIFESTYLE CHARACTERISTICS FOR ADOLESCENT BOYS AND GIRLS (N = 81).

Parameter	Boys (n = 37)								Girls (n = 44)							
	Control (n = 15)				Intervention (n = 22)				Control (n = 23)				Intervention (n = 21)			
	Baseline	Follow up	%	p	Baseline	Follow up	%	p	Baseline	Follow up	%	p	Baseline	Follow up	%	p
Weight (kg)	58.6 (16.7)	63.0 (18.6)	+7.5	0.001	55.0 (13.8)	58.6 (13.1)	+6.5	0.001	50.0 (6.4)	52.6 (6.3)	+5.2	0.001	51.6 (10.5)	54.4 (10.5)	+5.4	0.001
Standing height (m)	1.640 (0.086)	1.687 (0.083)	+2.9	0.001	1.637 (0.098)	1.679 (0.100)	+2.6	0.001	1.602 (0.058)	1.621 (0.058)	+1.2	0.001	1.621 (0.060)	1.635 (0.055)	+0.8	0.001
Sitting height (m)	0.845 (0.049)	0.872 (0.047)	+3.2	0.001	0.841 (0.056)	0.862 (0.057)	+2.5	0.001	0.828 (0.030)	0.844 (0.026)	+1.9	0.001	0.852 (0.026)	0.862 (0.029)	+1.2	0.004
Body mass index ($kg{\cdot}m^{-2}$)	21.5 (5.1)	21.9 (5.6)	+1.9	NS	20.3 (3.6)	20.6 (3.3)	+1.5	NS	19.5 (2.1)	20.0 (2.0)	+2.6	0.002	19.5 (3.5)	20.3 (3.5)	+4.1	0.001
Vertical jump (cm)	31.8 (8.9)	34.4 (8.2)	+8.2	0.01	32.7 (6.0)	35.6 (6.7)	+8.9	0.001	27.6 (7.4)	29.4 (6.0)	+6.5	NS	29.7 (5.9)	30.5 (5.6)	+2.7	NS
BPAQ score	3.55 (1.20)	3.27 (2.13)	-7.9	NS	3.84 (1.50)	3.24 (1.60)	-15.6	NS	3.43 (1.39)	4.42 (2.36)	+28.9	0.003	2.58 (1.73)	2.23 (1.63)	-13.6	NS
Calcium intake ($mg{\cdot}day^{-1}$)	1006 (385)	862 (289)	-14.3	NS	1253 (779)	1162 (485)	-7.3	NS	873 (498)	827 (397)	-5.3	NS	776 (342)	805 (380)	+3.7	NS

Abbreviations: BPAQ = bone specific physical activity questionnaire; NS = not significant, $p > 0.05$.

Table 5

TABLE 5: EIGHT-MONTH CHANGE (± SD) IN BONE AND LEAN TISSUE PARAMETERS FOR HEALTHY ADOLESCENT BOYS AND GIRLS (GROUPED INTENTION-TO-TREAT ANALYSIS, N = 81).

Parameter	Eight-month Change				p value
	Control (n = 38)	%	Intervention (n = 43)	%	
BUA ($dB \cdot MHz^{-1}$)	0.71 (5.79)	+0.9	3.49 (4.26)	+4.3	0.01
FN BMC (g)	0.23 (0.32)	+5.6	0.47 (0.70)	+11.6	0.03
FN Area (cm^2)	0.12 (0.14)	+2.6	0.21 (0.43)	+4.5	NS
FN BMAD ($g \cdot cm^{-3}$)	0.005 (0.020)	+1.4	0.007 (0.020)	+1.9	NS
FN CSMI (cm^4)	0.29 (0.35)	+10.6	0.50 (0.72)	+18.8	NS
TR BMC (g)	0.4 (0.9)	+4.6	1.1 (1.1)	+14.9	0.001
LS BMC (g)	3.9 (1.3)	+11.3	4.3 (2.0)	+12.6	NS
LS Area (cm^2)	1.7 (0.9)	+4.1	1.4 (1.4)	+3.5	NS
LS BMAD ($g \cdot cm^{-3}$)	0.004 (0.006)	+3.2	0.007 (0.007)	+5.5	NS
LS IBS ($g^2 \cdot cm^{-4}$)	0.131 (0.064)	+14.4	0.165 (0.079)	+17.9	0.02
WB BMC (g)	110 (59)	+5.0	185 (72)	+8.6	0.001
Lean Mass (g)	2685 (1260)	+8.4	3718 (1574)	+10.7	0.001
Fat Mass (g)	-69 (1408)	-0.4	-699 (2061)	-3.9	NS

Abbreviations: BMAD = bone mineral apparent density; BMC = bone mineral content; BUA = broadband ultrasound attenuation; CSMI = cross sectional moment of inertia; IBS = index of bone structural strength; FN = femoral neck; LS = lumbar spine; NS = not significant, $p > 0.05$; TR = trochanter; WB = whole body.

Table 6

TABLE 6: EIGHT-MONTH CHANGE (± SD) IN BONE AND LEAN TISSUE PARAMETERS FOR ADOLESCENT BOYS AND GIRLS (PER PROTOCOL ANALYSIS, N = 51).

Parameter	Boys (n = 24)								Girls (n = 27)							
	Control (n = 8)				Intervention (n = 16)				Control (n = 13)				Intervention (n = 14)			
	Baseline	Follow up	%	p	Baseline	Follow up	%	p	Baseline	Follow up	%	p	Baseline	Follow up	%	p
BUA ($dB{\cdot}MHz^{-1}$)	79.1 (16.2)	80.2 (13.6)	+1.4	NS	76.2 (10.0)	80.0 (9.3)	+5.0	0.01	83.6 (12.5)	84.4 (11.5)	+1.0	NS	79.3 (11.4)	81.1 (11.2)	+2.3	NS
FN BMC (g)	4.39 (0.85)	4.74 (0.72)	+7.8	0.01	4.25 (0.82)	4.69 (1.00)	+10.3	0.001	4.09 (0.55)	4.29 (0.57)	+4.9	NS	3.68 (0.67)	4.20 (1.24)	+13.9	0.05
FN Area (cm^2)	4.67 (0.42)	4.80 (0.52)	+2.7	NS	4.81 (0.34)	4.99 (0.30)	+3.8	0.001	4.72 (0.29)	4.83 (0.32)	+2.3	NS	4.33 (0.59)	4.58 (0.51)	+5.8	NS
FN BMAD ($g{\cdot}cm^{-3}$)	0.392 (0.098)	0.402 (0.097)	+2.6	NS	0.349 (0.040)	0.355 (0.041)	+1.7	NS	0.349 (0.058)	0.351 (0.062)	+0.6	NS	0.369 (0.063)	0.377 (0.064)	+2.2	NS
FN CSMI (cm^4)	2.79 (0.88)	3.20 (1.16)	+14.6	0.02	2.96 (0.93)	3.49 (1.09)	+18.0	0.001	2.81 (0.68)	3.03 (0.45)	+8.0	NS	2.26 (0.76)	2.58 (1.03)	+14.3	NS
TR BMC (g)	8.9 (3.6)	10.1 (3.9)	+13.0	0.007	9.2 (3.0)	11.0 (3.0)	+18.9	0.001	7.2 (1.8)	7.1 (2.2)	-0.3	NS	7.3 (2.2)	7.7 (2.5)	+6.2	NS
LS BMC (g)	33.2 (7.2)	37.2 (8.5)	+12.1	0.001	31.5 (8.5)	36.7(10.1)	+16.5	0.001	36.4 (7.0)	40.3 (7.3)	+10.7	0.001	35.6 (7.6)	38.8 (7.9)	+9.0	0.001
LS Area (cm^2)	40.6 (4.4)	41.7 (4.6)	+2.7	0.007	39.9 (5.6)	41.7 (6.0)	+4.6	0.001	41.1 (3.4)	43.1 (3.9)	+4.9	0.001	40.3 (3.8)	41.1 (4.2)	+2.0	NS
LS BMAD ($g{\cdot}cm^{-3}$)	0.120 (0.016)	0.128 (0.018)	+6.7	0.001	0.115 (0.013)	0.123 (0.013)	+7.0	0.001	0.131 (0.019)	0.133 (0.016)	+1.5	NS	0.135 (0.021)	0.142 (0.022)	+5.2	0.04
LS IBS ($g^2{\cdot}cm^{-4}$)	0.856 (0.238)	1.018 (0.297)	+18.9	0.001	0.787 (0.223)	0.973 (0.281)	+23.6	0.001	1.003 (0.255)	1.112 (0.252)	+10.9	0.001	1.011 (0.319)	1.152 (0.333)	+13.9	0.001
WB BMC (g)	2139 (418)	2274 (417)	+6.3	0.001	2142 (456)	2368 (515)	+10.6	0.001	2301 (196)	2393 (172)	+4.0	0.002	2094 (414)	2230 (393)	+6.5	0.001
Lean Mass (g)	36945 (7598)	40652 (8047)	+10.0	0.001	35885 (8938)	40881 (9576)	+13.9	0.001	30740 (2875)	32682 (3674)	+6.3	0.001	30719 (4472)	32864 (4168)	+7.0	0.001
Fat Mass (g)	14531 (9543)	14409 (10710)	-0.8	NS	15532 (8116)	13896 (7139)	-10.5	0.02	20630 (4693)	20598 (4875)	-0.2	NS	18930 (8132)	19384 (8646)	+2.4	NS

Abbreviations: BMAD = bone mineral apparent density; BMC = bone mineral content; BUA = broadband ultrasound attenuation; CSMI = cross sectional moment of inertia; IBS = index of bone structural strength; FN = femoral neck; LS = lumbar spine; NS = not significant, $p > 0.05$; TR = trochanter; WB = whole body.

Figure 1

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