Effects of rope-jump training on the os calcis stiffness index of postpubescent girls

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ABSTRACT

MARK G. ARNETT and BOB LUTZ. Effects of rope-jump training on the os calcis stiffness index of postpubescent girls. *Med. Sci. Sports Exerc.*, Vol. 34, No. 12, pp. 1913–1919, 2002. **Purpose:** The specific aims of the study were to 1) determine what effects dose-dependent rope jumping had on os calcis stiffness index (OCSI) and 2) determine whether OCSI values measured by quantitative ultrasound (QUS) were dependent or independent of the values of bone mineral content (BMC) determined by dual energy x-ray absorptiometry (DXA) at the lumbar spine and proximal femur (femoral neck; greater trochanter). **Methods:** Upon study entry, girls were randomly assigned to either one of two treatment groups (high volume; low volume) or a control group. Thirty-seven high school girls were recruited to participate in the study. QUS and DXA measurements were made at baseline and at 4-month follow-up. Students in the high-volume and low-volume groups jumped rope for 10 and 5 min, respectively. **Results:** The follow-up mean OCSI values for the high-volume, low-volume, and control conditions were 103.95 ± 12.55, 102.09 ± 12.70, and 99.05 ± 9.84, respectively. A statistically significant difference ($P = 0.033$) was identified between the high-volume and control groups. Baseline and follow-up OCSI values were significantly correlated with baseline and follow-up BMC measures of the femoral neck ($r = 0.60$, $r = 0.59$), greater trochanter ($r = 0.47$, $r = 0.40$), and lumbar spine ($r = 0.56$, $r = 0.56$). **Conclusions:** High-volume rope jumping increases the OCSI more than the control condition in postpubescent girls. Furthermore, the OCSI measured by QUS is moderately related to proximal femur and lumbar spine BMC measured by DXA. **Key Words:** BONE MASS, ADOLESCENT GIRLS, MECHANICAL LOADING, BONE MINERAL CONTENT, QUANTITATIVE ULTRASOUND

Bone strength later in life may rely on the acquisition of bone during the first two decades of life (2,25). A majority of the adult bone mass will be accumulated before an individual reaches the age of 20 (2,5,26). It has been demonstrated with animals that mechanical loading on bone will increase bone mass (9,16). Therefore, it is critical to investigate mechanical loads that impact bone formation during the years when bone formation is greatest.

Dual energy x-ray absorptiometry (DXA) is used to measure bone mineral density (BMD) and bone mineral content (BMC) in adolescents (12,18,20,30). DXA is the gold standard; however, its cost, limited availability, and need for technical staff required to complete a total body scan presents some limitations. These factors have led to increasing interest in other measurement techniques. In recent years, the quantitative ultrasound technique (QUS), which measures the transmission of ultrasound waves through the heel, has been proposed for the assessment of bone density and bone structure (19,22). QUS is portable, requires 5–10 min to complete, and the costs per use are one third of the DXA. Furthermore, QUS may not only measure bone density but also bone elasticity and bone microarchitecture, which are determinants of bone strength (14). It maybe that QUS provides independent information from DXA.

There is a lack of consensus on whether QUS assess a response to an intervention. Intervention studies to date have examined older women (6,23). Rosenthall et al. (23) and Brooke-Wavell et al. (6) compared changes in os calcis QUS with changes in BMD variables in women on antiresorptive therapy and a walking intervention, respectively. Rosenthall et al. (23) reported increases in BMD values but not os calcis stiffness index (OCSI) values. Furthermore, the values were not significantly correlated. Brooke-Wavell et al. (6) reported increases in QUS values after 12 months of walking, but BMD values did not increase due to treatment. The authors in both studies (6,23) concluded that QUS and BMD values were independent of each other. Furthermore, few data are available in the literature about the quantification of bone mass in postpubescent girls by using QUS. Two studies have shown that QUS measured at the os calcis predicts DXA BMD measurement at the lumbar spine, femoral neck, and total body (17,27).

The overall purpose of the present study was to determine whether QUS measurements could be used to assess a response to an intervention in postpubescent girls. To date, no published studies have used QUS to measure a physical activity intervention effect in children or adolescents and specifically to compared os calcis QUS values after a rope-jumping intervention in postpubescent girls. Therefore, this study could provide significant knowledge to a limited database. Furthermore, if QUS can assess an intervention

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response, its portability, time-saving capability, and low cost could be used in large-scale school interventions. The specific aims of our study were to 1) determine what effects dose dependent rope jumping had on os calcis stiffness index (OCSI) and 2) determine whether OCSI values measured by QUS were dependent or independent of the values of BMC determined by DXA at the lumbar spine and proximal femur (femoral neck; greater trochanter).

METHODS

Approach to the Problem and Experimental Design

Results of physical activity interventions that have included postpubescent girls and measured bone status with DXA are mixed (12,18,20,30). In total, the studies noted above highly suggest the bone mineral measured with DXA in postpubescent girls can be enhanced by loading factors associated with physical activity. The present study set out assess whether QUS a new and promising technique for prediction of bone strength change could also measure bone strength change in the os calcis after a physical-activity intervention in postpubescent girls. We were specifically interested in whether different doses of rope jump training for 4 months would increase the OCSI as measured by QUS in postpubescent girls. The parameter for ultrasonometry was the stiffness index which is an empirical Lunar proprietary parameter defined as $(0.28 \times \text{SOS}) + (0.67 \times \text{BUA}) - 420$ (broadband ultrasound attenuation: BUA; decibels per MHz, speed of sound: SOS; $\text{m}\cdot\text{s}^{-1}$). The OCSI has been found to be a better predictor of fracture risk than either BUA or SOS alone (24). We hypothesized that after 4 months of rope-jump training, OCSI would increase in postpubescent girls and that a dose response would be evident. Furthermore, we were interested in whether OCSI values were independent or dependent of lumbar spine and proximal femur BMC values measured by DXA. BMC was evaluated because BMD in the growing skeleton does not accurately correct for changing bone geometry. BMC is a good measure of the structural properties of bone, capturing both the material and geometric properties. We hypothesized that OCSI values would be dependent of lumbar spine and proximal femur BMC values.

To test our hypotheses, we conducted a randomized control trial consisting of randomization of the girls to groups, baseline measurements, training, and follow-up measurements. The unit of randomization was the girls. Upon study entry, the girls were randomly assigned to either one of two treatment groups (low-volume: 5-min rope jumping; and high-volume: 10-min rope jumping) or a control group. Before beginning the rope jump training and within 1 wk of completion of the training measurements for the primary outcome variables (OCSI) and (BMC) as well as the secondary variables of height, weight, peak muscle torque, and percent body fat (%BF) were made. Peak muscle torque, %BF, height, and weight were measured to confirm positive effects of the interventions and to detect confounding changes in the control group. All measurements occurred at the University of Arizona. All technicians were blind to group assignment; furthermore, the same technician completed baseline and follow-up measurements. After the baseline measurement, the girls completed the 4-month rope-jump training in their regular physical education classes. Randomization was stratified by physical education class so each class had approximately the same number of girls assigned to each condition. To vary the dose of the rope jump training for the low- and high-volume conditions, magnitude of strain, rate of strain, and abnormal strain were controlled and the number of cycles of strain (volume) was manipulated. In this study a total of 64 jump-rope sessions were conducted. Attendance averaged 90% for all participants in the three conditions (range, 78–96%). All volunteers completed baseline and follow-up assessments.

Participants

Thirty-seven high school girls (aged 14.7 ± 0.7; 24.2 ± 10.8 months past menarche) were recruited from three local high schools. All participants were apparently healthy, postpubescent girls and maintained an elementary calcium intake of 1500 mg either through diet or supplementation (Os-Cal 500 mg, Vitamin D 200 IU). Postpubescent girls with the following conditions were excluded: 1) a history of hypoparathyroidism, hyperparathyroidism, or other metabolic bone disorders; 2) pregnancy; or 3) limited physical activity. The Human Subjects Committee of the University of Arizona approved the study. Informed consent was obtained from all students and their parents.

Assessment

Bone measurement. The Achilles ultrasonometer (Lunar Corp., Madison, WI) was used for ultrasonometry through the right os calcis. The parameter for ultrasonometry was the stiffness index which is an empirical Lunar proprietary parameter defined as $(0.28 \times \text{SOS}) + (0.67 \times \text{BUA}) - 420$ (broadband ultrasound attenuation: BUA; decibels per MHz, speed of sound: SOS; $\text{m}\cdot\text{s}^{-1}$). Quality assurance was performed daily. Measurements were made in triplicate with repositioning of the foot between each measurement. The mean of the three measurements was calculated. The precision for the stiffness index using phantoms was 2.2% *in vitro*. We assessed reproducibility of the ultrasound measurement in 25 normal high school girls over five consecutive determinations in 30 min: the *in vivo* precision was 2.2%. Other published studies are in agreement with these values (1,23).

DXA measurements of the proximal femur (femoral neck and greater trochanter) and lumbar spine (L2–4) BMC and soft tissue composition, including total fat and lean mass, was acquired and analyzed on a Lunar DPX-L densitometer (Lunar Corp., Madison, WI). DXA scans were completed one time on all girls at baseline and follow-up. The precision of DXA as evaluated *in vitro* was $< 1\%$ while the reproducibility by repeat scans separated by 1 wk produced a precision that varied 2–3% by site. %BF was computed as the ratio of total fat mass to the mass of all tissue (sum of fat, lean, and BMC). Lean and fat mass were obtained from the total body scan. The reproducibility by repeat scans separated by 1 wk produced a precision that varied 2%. These values are consistent with those described in the literature (7,13,28). All assessments (QUS and DXA) were performed and analyzed by the same person who was blind to group assignment.

Ancillary measurements. Peak muscle torque of the right knee extensors was measured using a Biodex Isokinetic Dynamometer (Biodex System, Shirley, NY). Each participant received 10 warm-up trials, followed by five maximal knee extensions and flexions at a speed of $180^\circ \cdot \mathrm{s}^{-1}$. Peak muscle torque was the mean of repetition number 2, 3, and 4. The measurements were performed and analyzed by the same person who was blinded to group assignment. The dynamometer has been shown to provide valid measure for knee extension at $180^\circ \cdot \mathrm{s}^{-1}$ (29). Reliability of the dynamometer was calculated using 10 normal high school girls over two determinations. Each trial was separated by 24 h. An intraclass correlation coefficient of 0.92 was calculated from the two repeated measures. These values are in agreement with previous studies (21,30).

Height was measured to the nearest 0.005 m using a free-standing stadiometer. Body mass was measured to the nearest 0.05 kg (Detecto Balance Scales, Webb City, MO). All measures were made in duplicate, and the average of these was used.

Activity measurement. To assess the volume of physical activity, the girls wore a SW-200 Digiwalker (New Lifestyles, Kansas City, MO) for 3 d: one school day that included jumping rope, one school day that did not, and one weekend day. The Digiwalker was secured on the waistband and placed at hip level with the front edge at the right mid-axillary line. Each student wore the same Digiwalker for all assessments. Validity and reliability of the SW-200 Digiwalker has been supported (3).

Ground reaction forces. Forces were recorded as the summed vertical forces from the four cells of a Kistler force plate, at a sampling rate of 500 Hz, using Quattro Jump software (Kistler, Amherst, NY). Recordings were made of 10–20 rope-jump trials performed on the force plate by a subsample of 10 girls enrolled in the study. Representative data were obtained from each girl by using the mean of the 10 middle values for peak landing force. An intraclass correlation coefficient of 0.98 was calculated for the 10 measures.

Exercise Intervention

All intervention participants jumped or stretched four times per week at the beginning of their regular physical education classes. Students in the high-volume (HV) and low-volume (LV) conditions jumped rope at a rate of 50 jumps per minute for 10 and 5 min, respectively. The LV students stretched for 5 min after rope jumping so that both groups completed the intervention at the same time. The rope jumping pace was controlled using a metronome. The average rope jumps for the HV and LV conditions were 472 ± 88 and 252 ± 38, respectively. The rope jumping consisted of repeated two-foot jumps with the take-off and landing occurring on the balls of the feet. Each rope jump was at least 8.5 cm in height. The average ground reaction force for each rope jump was 3.2 ± 0.2 times the girls' body weight. During the baseline week, students were instructed on proper rope jumping techniques. The regular class teacher supervised the rope jumping. Three teachers were used to control for teacher effects. Over time, participants from both intervention groups added weighted vests and progressively added weight to maintain overload. For the first month, students did not wear a weighted vest. For the second month, students wore a 1-kg weighted vest. During the third and fourth months, students wore a 2- and 3-kg weighted vest, respectively. The control group walked for 5 min and then stretched for 5 min at the beginning of class. Students followed the regular curriculum established by the teacher during the remainder of the physical education class.

Data Analyses

The first primary aim suggested analysis for the primary end point of the OCSI. The analysis evaluated evidence for an intervention effect at the end of 4 months of rope jumping. We used an ANCOVA at the end of 4 months of rope-jumping data with regression adjustment for the baseline level of the dependent variable. ANCOVA is a more

TABLE 1. Baseline and follow-up participant characteristics.[a]

Characteristics	HV (*N* = 13)		LV (*N* = 12)		Control (*N* = 12)	
	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up
Age (yr)	14.9 ± 0.6	15.2 ± 0.6	14.6 ± 0.7	14.8 ± 0.7	14.8 ± 0.9	15.0 ± 0.9
Months past menarche	25.4 ± 13.0	29.4 ± 13.0	23.0 ± 9.5	27.0 ± 9.5	24.0 ± 10.2	28.0 ± 10.2
Height (cm)	164.3 ± 5.8	164.5 ± 5.7	164.5 ± 9.8	164.8 ± 9.6	162.9 ± 5.2	163.3 ± 5.4
Weight (kg)	57.1 ± 11.7	57.0 ± 11.2	58.7 ± 8.2	58.4 ± 8.1	57.5 ± 8.7	57.5 ± 8.7
Lean mass (kg)	36.7 ± 3.8	36.7 ± 3.6	37.2 ± 5.4	37.7 ± 5.3	35.7 ± 2.7	36.0 ± 3.5
% body fat	28.4 ± 7.7	28.3 ± 7.2	28.9 ± 10.5	28.8 ± 9.9	27.0 ± 4.6	26.8 ± 4.0
OCSI	98.54 ± 11.52	104.46 ± 12.55[b]	100.17 ± 11.75	104.25 ± 12.70	98.03 ± 9.04	101.76 ± 12.08
LS BMC (g)	43.52 ± 9.50	44.55 ± 9.66	43.70 ± 4.97	44.54 ± 4.79	45.91 ± 9.47	46.39 ± 9.36
FN BMC (g)	4.52 ± 0.88	4.71 ± 0.90[b]	5.11 ± 0.57	5.26 ± 0.60	4.60 ± 0.62	4.66 ± 0.55
GT BMC (g)	9.50 ± 2.10	9.96 ± 2.11[b]	10.37 ± 2.86	10.72 ± 2.80	9.89 ± 1.74	10.07 ± 1.70
Peak torque (N·m)	91.5 ± 25.8	103.2 ± 20.7	92.6 ± 29.8	103.4 ± 32.3	89.8 ± 17.6	94.5 ± 15.7
Mean PA (step·day^{-1})		9008 ± 3134		9476 ± 3342		10831 ± 3756

[a] Mean ± SD.

[b] Significant difference from control conditions.

[c] OCSI, os calcis stiffness index; LS, lumbar spine; FN, femoral neck; GT, greater trochanter.

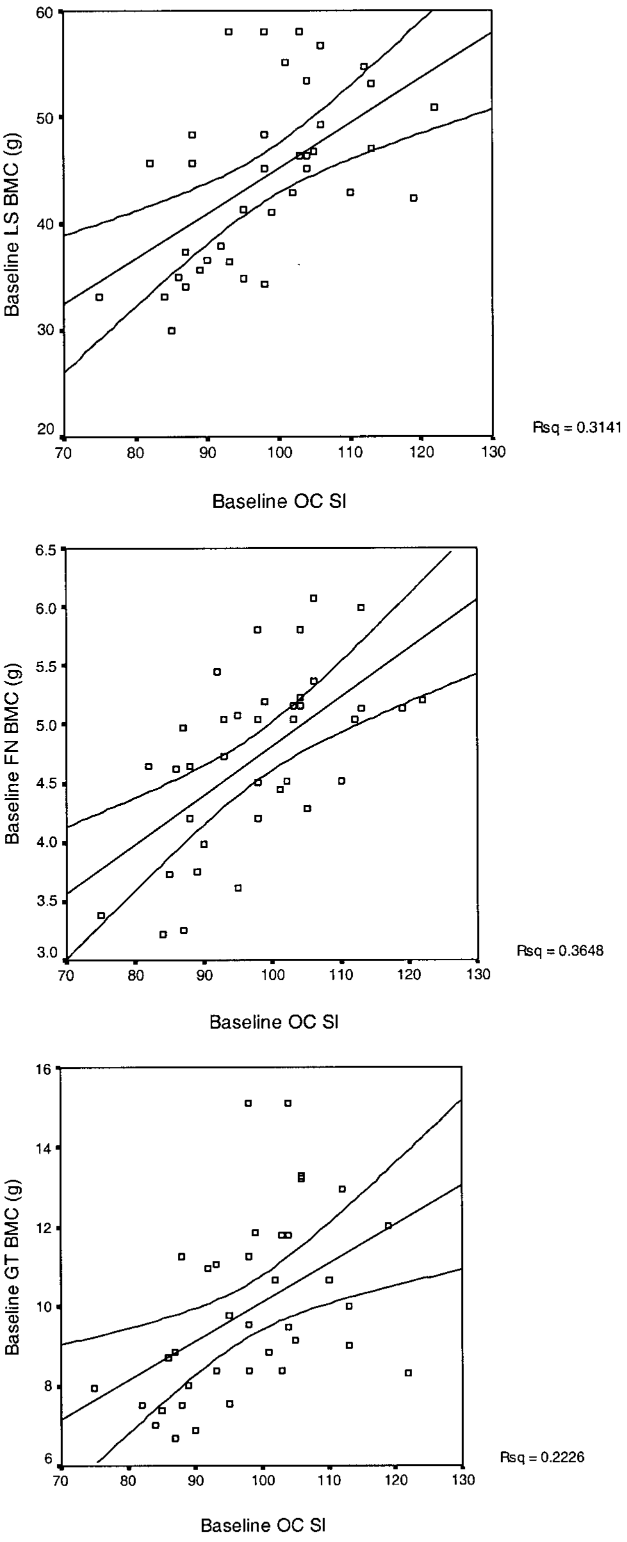

FIGURE 1—Correlation between baseline lumbar spine (LS) BMC and baseline os calcis stiffness index (OC SI) values (A), baseline femoral neck (FN) BMC and baseline OC SI values (B), and baseline greater trochanter (GT) BMC and baseline OC SI values (C) in 37 postpubescent girls. The graphs show individual data points, the regression lines, and 95% confidence limits for the regression lines.

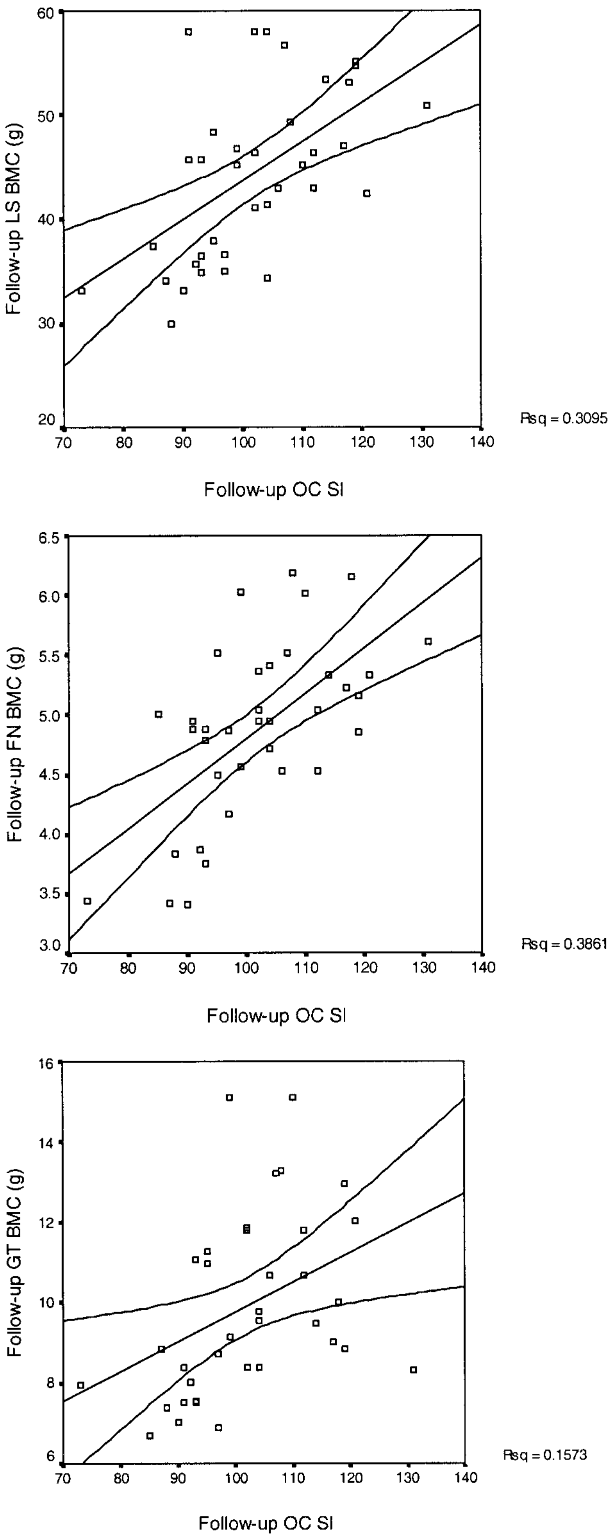

FIGURE 2—Correlation between follow-up lumbar spine (LS) BMC and follow-up os calcis stiffness index (OC SI) values (A), follow-up femoral neck (FN) BMC and follow-up OC SI values (B), and follow-up greater trochanter (GT) BMC and follow-up OS SI values (C) in 37 postpubescent girls. The graphs show individual data points, the regression lines, and 95% confidence limits for the regression lines.

powerful test of the treatment effects than ANOVA if follow-up and baseline OCSI values are highly correlated within each group (11). Baseline and follow-up OCSI values were highly correlated with each of the three groups (HV: $r_{xy} = 0.90$, LV: $r_{xy} = 0.97$, control: $r_{xy} = 0.91$). In this model, the intervention effect was estimated as the differ-

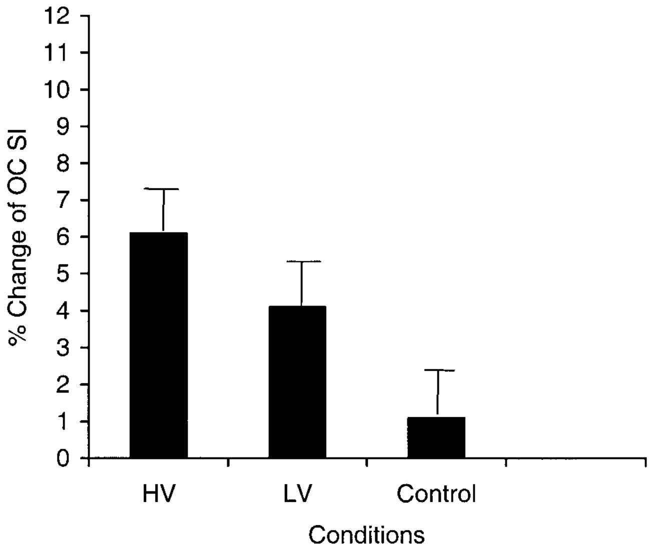

FIGURE 3—Mean percentage change ± SEM of the os calcis stiffness index (OCSI) after 4 months of jumping rope four times per week.

ence between the three adjusted condition means. The null hypothesis was that the difference was zero. Due to the expense of the DXA, the sample size in this study was relatively small. Accepting these constraints, we used a conservative Bonferroni *post hoc* test to determine differences among groups. *Post hoc* power analyses for the OCSI revealed a power of 0.65 for the intervention effect. However, the small sample size of the present study increased likelihood of committing a Type II error in the evaluation of OCSI for the three conditions.

The second primary aim suggested analysis of the relationship between OCSI and BMC. The analysis evaluated evidence of the dependence or independence between OCSI and BMC. The relationship between OCSI and BMC as a function of weight, height, body composition, and peak muscle torque was determined by linear regression analysis with the interaction term. The statistical software program SPSS version 10.0 (Chicago, IL) was used for all data analyses. For the analysis, the significance level was set at $P < 0.05$.

RESULTS

Participant characteristics for the three conditions are presented in Table 1. One-way ANOVA revealed no differences between conditions at baseline for any characteristic.

The mean stiffness indices corrected for baseline values for the HV, LV, and control conditions were 103.95 ± 12.55, 102.09 ± 12.70 and 99.05 ± 9.84, respectively (Table 1). An ANCOVA of OCSI revealed a significant difference between conditions (F (2,33) = 3.774, P = 0.033). Bonferroni pairwise comparison adjusted for multiple comparisons revealed a significant estimated marginal mean difference between the HV and control conditions (mean difference stiffness index = 4.895, P = 0.030). The estimated marginal mean differences between the HV and LV, and LV and control conditions were not significant.

The average volume of physical activity regularly performed was similar in all three conditions (HV: 9008 ± 3134; LV: 9476 ± 3342; and control: 10831 ± 3756 step·d^{-1}). A one-way ANOVA of the average volume of physical activity revealed no significant differences between conditions. The ground reaction force from rope jumping was approximately 3.2 ± 0.2 times the girls' body weight. These values were obtained without the girls wearing weighted vests.

Baseline OCSI values were significantly correlated with baseline measures of femoral neck BMC (r = 0.60, $P <$ 0.0001), greater trochanter BMC (r = 0.47, P = 0.003), and lumbar spine BMC (r = 0.56, $P < 0.0001$) (Fig. 1, A–C). Follow-up OCSI values were significantly correlated with follow-up BMC measures of the femoral neck (r = 0.59, P < 0.0001), the greater trochanter (r = 0.40, P = 0.015), and the lumbar spine (r = 0.56, $P < 0.0001$) (Fig. 2, A–C). The relationships between the OCSI and femoral neck, greater trochanter, and lumbar spine BMC were not affected by height, weight, percent body fat, or peak torque.

DISCUSSION

The aim of the present study was to assess whether QUS could be used to assess skeletal changes over a period of 4 months in postpubescent girls. There is limited information regarding whether QUS can assess a response to an intervention. Studies to date have examined older women (6,23). The Rosenthall et al. (23) and Brooke-Wavell, et al. (6) studies do not support the findings of the present study. Furthermore, the authors in both studies concluded that QUS and BMD values were independent of each other.

The finding of the present study indicated that postpubescent girls in the HV group who jumped rope for 10 min obtained QUS stiffness index values that were significantly greater than the control group values after 4 months of treatment (Table 1, Fig. 3). The OCSI of the HV group increased by 6.1% ± 1.3 after 4 months of treatment. The 4-month rope-jump training produced parallel results in the three groups' proximal femur BMC measured by DXA (Table 1). Furthermore, baseline and follow-up OCSI measurements correlated with baseline and follow-up lumbar spine, femoral neck, and greater trochanter BMC measurements. These observed values were moderately correlated (Table 2). Our results suggest that OCSI measurements and lumbar spine, femoral neck, and greater trochanter BMC measurements are dependent.

Major methodology differences could explain the difference in findings. The Rosenthall and Brooke-Wavell studies used women whereas our study used postpubescent girls. Our correlation results are similar to a study that compared OCSI measurements and lumbar spine, femoral neck, and total body BMD DXA measurements of 280 healthy children aged 11–16 yr (27). Correlations between OCSI measurements and lumbar spine, femoral neck, and total body BMD measurements of the girls were 0.61, 0.58, and 0.67, respectively. Our OCSI values (Table 1) are comparable to the 14- and 15-yr-old girls' OCSI values (102.4 ± 14.8 and 99.8 ± 13.9, respectively) reported by Sandberg et al. (27). Furthermore, Lum et al. (17) reported

TABLE 2. Correlation between baseline and follow-up BMC and QUS variables.

QUS Os Calcis	BMC Lumbar Spine	BMC Femoral Neck	BMC Greater Trochanter
Baseline	0.56***	0.60***	0.47**
Follow-up	0.56***	0.59***	0.40*

* $P < 0.05$
** $P < 0.001$
*** $P < 0.0001$

moderate correlations (r = 0.23–0.58) between os calcis QUS and DXA measurements of the lumbar spine, femoral neck, and total body BMD of 125 youths 9–25 yr of age. OCSI values reported in postmenopausal women were lower (range, 48–72) (10). The present study also used a jump rope intervention. Rosenthall et al. (23) used antiresorptive therapy and Brooke-Wavell et al. (6) used a walking intervention, thus making comparisons difficult. Animal models have indicated that bone adaptation is driven by dynamic, high-impact activity. Studies using controlled external loading in animal models have found that osteogenesis is maximal with high-magnitude strains applied at a high rate, involving abnormal patterns of stress (8,15,16). The jumping intervention was dynamic: impact from jumping rope without a weighted vest was approximately 3.2 ± 0.2 times the girls' body weight, and jumping rope would not be a normal activity for most of these girls. In contrast, walking has been shown to create a ground reaction force of approximately 2.0 times a woman's body weight and is a normal pattern of stress (4).

Although a significant difference was not seen between the HV and LV conditions and the LV and control conditions, the percent change from baseline to follow-up revealed a dose response trend for OCSI, (HV: 6.1%; LV: 4.1%; control: 1.1%; Fig. 2). This dose response trend was also seen in proximal femur BMC values. Bassey and Ramsdale (4) reported a dose effect on hip BMD among premenopausal women who participated in high-impact exercises (jumping and skipping) compared with women in low impact activities. However, no reported studies have assessed whether a dose-response relationship exists for modifying os calcis bone mass in postpubescent girls.

If bone formation is greatest at the point of impact, then the rope jumping protocol used in the present study could have a positive effect on the OCSI. Changes in proximal femur (femoral neck and greater trochanter) BMC were greater than lumbar spine bone formation in the HV group (5.0%, 4.4%, and 2.5%, respectively) and in the LV group (3.9%, 3.0%, and 2.0%, respectively). Although we cannot compare changes in DXA and QUS measurements, change in the OCSI value of the HV group was 6.1%. Therefore, bone sites closest to the point of impact appear to be most affected. Other studies using jumping interventions (4,18,30) have reported similar findings.

An important limitation of the present study was the low power in distinguishing between doses of rope jumping and the increased likelihood of committing a Type II error. A follow-up study to establish a dose-dependent relationship should increase the sample size.

The use of QUS for assessing intervention effects has received little attention. Evidence to support its use, however, would reduce the cost and need to technical staff compared with DXA assessments. The findings provide preliminary evidence for the use of QUS as a technique for estimating bone strength in postpubescent girls. However, the evidence has limitation and requires further investigation.

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