Increased training loads do not magnify cancellous bone gains with rodent jump resistance exercise

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Swift JM, Gasier HG, Swift SN, Wiggs MP, Hogan HA, Fluckey JD, Bloomfield SA. Increased training loads do not magnify cancellous bone gains with rodent jump resistance exercise. J Appl Physiol 109: 1600–1607, 2010. First published October 7, 2010; doi:10.1152/japplphysiol.00596.2010.—This study sought to elucidate the effects of a low- and high-load jump resistance exercise (RE) training protocol on cancellous bone of the proximal tibia metaphysis (PTM) and femoral neck (FN). Sprague-Dawley rats (male, 6 mo old) were randomly assigned to high-load RE (HRE; n = 16), low-load RE (LRE; n = 15), or sedentary cage control (CC; n = 11) groups. Animals in the HRE and LRE groups performed 15 sessions of jump RE during 5 wk of training. PTM cancellous volumetric bone mineral density (vBMD), assessed by in vivo peripheral quantitative computed tomography scans, significantly increased in both exercise groups (+9%; P < 0.001), resulting in part from 130% (HRE; P = 0.003) and 213% (LRE; P < 0.0001) greater bone formation (measured by standard histomorphometry) vs. CC. Additionally, mineralizing surface (%MS/BS) and mineral apposition rate were higher (50–90%) in HRE and LRE animals compared with controls. PTM bone microarchitecture was enhanced with LRE, resulting in greater trabecular thickness (P = 0.03) and bone volume fraction (BV/TV; P = 0.04) vs. CC. Resorption surface was reduced by nearly 50% in both exercise paradigms. Increased PTM bone mass in the LRE group translated into a 161% greater elastic modulus (P = 0.04) vs. CC. LRE and HRE increased FN vBMD (10%; P < 0.0001) and bone mineral content (~20%; P < 0.0001) and resulted in significantly greater FN strength vs. CC. For the vast majority of variables, there was no difference in the cancellous bone response between the two exercise groups, although LRE resulted in significantly greater body mass accrual and bone formation response. These results suggest that jumping at minimal resistance provides a similar anabolic stimulus to cancellous bone as jumping at loads exceeding body mass.

bone formation; bone biomechanics; microarchitecture; histomorphometry; osteoblast

It has been well established that bone responds to increased and reduced mechanical loading in opposing manners. Lack of gravitational loading, as encountered during bed rest or microgravity, results in significant reductions in cancellous bone mass and strength (10, 17, 18, 34) and results in reduced estimated femoral neck strength (15). In humans, bone responds to increased mechanical stress, evidenced during high-impact and resistance exercise (RE), by increasing lumbar and femoral neck bone mass and strength (7, 14, 19). RE can effectively provide the necessary load to increase bone mass in healthy individuals (20, 27, 29, 38). Furthermore, high-impact exercise (31) and jumping (7) elicit a greater anabolic response on bone than lower-impact activities like running or walking (16).

Animal studies demonstrate similar results, as high-intensity RE and jump training provide greater anabolic stimulus to bone than repetitive, low-load, high-frequency exercise (i.e., running) (22, 23). Drop training (a variation of jump training) results in greater proximal tibia total and cancellous volumetric bone mineral density (vBMD), [as a consequence of greater trabecular thickness (Tb.Th) compared with ambulatory controls] (35, 36). Jump exercise in rats and mice leads to greater bone volume (BV/TV) and osteoblast activity [mineral apposition rate (MAR)] at cancellous-rich bone sites (22, 23) as well as increased cortical bone mass and strength (32, 33). To our knowledge, however, no published studies have been designed to assess the effects of two intensities of jump RE on weight-bearing cancellous bone. Additionally, there are very limited data about changes in cancellous bone remodeling, microarchitecture, and mechanical properties in skeletally mature animals with voluntary jump RE (3, 37).

The exercise paradigm utilized in this study closely resembles progressive overload RE training as performed by humans, incurring the integrated physiological response to exercise (e.g., increased sympathetic nervous system outflow, blood flow, and IGF-1 production) (4, 25, 27, 28). Additionally, unlike other frequently used bone-loading paradigms (i.e., ulnar and tibial compression, 4-point bending), our jump RE model produces significant lower leg muscle hypertrophy and increased skeletal muscle protein synthesis (5, 6, 8), and the exercise is completed on a voluntary basis by unanesthetized, conscious rodents. Previously published data verified that 6 wk of this jump RE training can increase Tb.Th, trabecular number (Tb.N), and bone volume in the proximal tibia, but data on underlying changes in bone formation were not available (37).

The purpose of our investigation was to evaluate the effects of high- and low-load voluntary rodent jump RE in mature male rats on changes in mechanically sensitive cancellous bone mass, structure, and mechanical properties at both the proximal tibia metaphysis (PTM) and femoral neck. Furthermore, we sought to define the effects of these two RE training protocols on PTM bone formation and microarchitecture. We hypothesized that increased load during jump RE would result in a significantly greater osteogenic response, leading to enhanced cancellous bone formation and microarchitecture and improved cancellous bone mechanical properties compared with changes with low-load jump RE.
MATERIALS AND METHODS

Animals

Forty-two male Sprague-Dawley rats (6 mo old) were obtained from Harlan (Houston, TX) and individually housed in a climate-controlled room (23 ± 2°C) with a 12-h light (0600–1800) and dark cycle (1800–0600) in an American Association for Accreditation of Laboratory Animal Care-accredited animal care facility. Rats were fed ad libitum an experimental diet (Purina Test Diet, 5001) that comprised 24% protein, 12% fat, 54% carbohydrate, 7% ash, 5% fiber, and vitamins and, after 1 wk of acclimation, were block-assigned by body weight to high-load jump RE (HRE, n = 16), low-load jump RE control (LRE, n = 15), or sedentary cage control (CC, n = 11) groups. Daily food consumption for each animal was calculated by subtracting the mass of food pellets remaining in the cage from the previous days total feeding (in g). Food intake was averaged over the 35 days of the experiment to calculate an average for each animal. All experimental procedures were approved by the Institutional Animal Care and Use Committee of Texas A&M University.

Calcine injections (25 mg/kg body mass) were given subcutaneously at 9 and 2 days before the animal was euthanized in order to label mineralizing bone for histomorphometric analyses. At the end of the study (day 35), animals were anesthetized with a ketamine/xylazine cocktail (ketamine 50 mg/kg, medetomidine 0.5 mg/kg). After decapitation, right tibia and femur were removed, cleaned of soft tissue, and stored at −80°C in PBS-soaked gauze for ex vivo peripheral quantitative computed tomography (pQCT) scans and/or mechanical testing, whereas left tibia were stored in 70% ethanol at 4°C for histology.

Operant Conditioning

Before the actual training began, the HRE and LRE animals were operantly conditioned to jump and depress an illuminated bar located high on a transparent polymethylmethacrylate exercise cage as previously described (6, 8, 21, 37). Negative reinforcement via a brief electrical foot shock (1 mA, 60 Hz) from an electrical grid they were standing on was used to train the rats to perform the desired vertical jumping movement. The lever above the animal’s head was illuminated and the animal was encouraged to jump off of its hindlimbs and depress the lever, thus extinguishing the light in the lever. This “operant conditioning” of the animals was continued over the course of four sessions on alternate days (over 8 days). After the animals were conditioned to depress the illuminated lever with minimal or no applied shock, an 80-g Velcro vest (to which weighted packs were later strapped during the exercise sessions to provide additional load) was strapped over the scapulae for two additional sessions (6 days) (8). Animals in the CC group were allowed normal cage activity and remained single-housed over the course of the study.

Voluntary Jump RE Paradigm

The HRE and LRE rats performed 15 training sessions (3 sessions/wk separated by at least 48 h of rest) over a 5-wk period as previously reported by Gasier et al. (8). In brief, the HRE group completed a progressive resistance training program with a starting weight of 80 g (Velcro vest only) for 50 repetitions on session 1 and increasing to 410 g (Velcro vest plus 330 g added mass) for 16 repetitions on session 15. Training volume for each session was computed by multiplying the total number of repetitions times the added weight (in excess of body mass). The intent of this progressive resistance training paradigm was to overload skeletal muscle of the lower body during each successive training session, thereby, in theory, providing anabolic stimulus to musculoskeletal tissue. As a result, after the first 2 wk of training (6 sessions), the total exercise volume in the HRE group was decreased (increased added resistance to the weighted pack and decreased number repetitions/jumps) by ~7%/wk for a total of 20% over the final 3 wk (9 sessions) of the training period (Fig. 1). The LRE rats performed the same number of repetitions as the HRE group, receiving the same number of electrical foot shocks, with only a 30-g vest attached to their backs (~8% body mass). Few, if any, shocks were necessary to elicit a positive response during the training sessions; a minimum of 5–10 s of inserted rest was given between each repetition. For training session 1, HRE rats’ exercise volume (g lifted × repetitions) was 2.7-fold greater than that of LRE rats. Throughout the remainder of the experiment, HRE rats completed a greater exercise volume than the LRE group. This resulted in a 13.7-fold greater exercise volume in the HRE compared with the LRE group by training session 15 (Fig. 1).

Dual-Energy X-Ray Absorptiometry

One day before both initiation (day −1) and cessation (day 34) of the investigation, all animals were anesthetized with ketamine/me-detomidine cocktail to perform dual-energy x-ray absorptiometry (DEXA; GE Lunar Prodigy small animal program) scans to assess changes in body composition (lean mass, fat mass). In vivo coefficients of variation for lean mass and fat mass are 1.07 and 2.99%, respectively, as determined from repeat scans on each of the adult male rats (n = 6).

pQCT

PTM. To assess longitudinal changes in proximal tibia bone mass and geometry attributable to the exercise paradigms, in vivo pQCT scans were performed on days 1 and 35 of the study at the proximal metaphysis and mid-diaphysis of the left tibia with a Stratec XCT Research-M device (Norland, Fort Atkinson, WI), using a voxel size of 100 μm and a scanning beam thickness of 500 μm. All animals were anesthetized with isoflurane gas (~2.5%) mixed with oxygen to perform in vivo pQCT scans. Daily calibration of this machine was performed with a hydroxyapatite standard cone phantom. Transverse images of the left tibia were taken at 5.0, 5.5, and 6.0 mm from the proximal tibia plateau. A standardized analysis for either metaphyseal bone (contour mode 3, peel mode 2, outer threshold of 0.214 g/cm³, inner threshold of 0.605 g/cm³) was applied to each section using the Stratec XCT Analysis System, Version 6 (Norland).

Femoral neck. Thawed femora were placed in a PBS-filled vial to maintain proper hydration during the course of the scan, after which they were returned to the −80°C freezer. Femoral neck scanning was performed while bones were placed on a platform and wrapped in PBS-soaked gauze, with only the neck exposed, to scan slices (2 images, 0.5 mm apart) perpendicular to the femoral neck’s long axis.

Fig. 1. Graphical representation of exercise training paradigm for low- and high-load resistance exercise (LRE, HRE) groups during the 15 sessions. Exercise volume was calculated by multiplying g of mass lifted by total no. of repetitions per exercise session.
Femoral neck sections were analyzed using contour mode 3, peel mode 5, and attenuation threshold 0.214 g/cm³. Scan speed was set at 2.5 mm/s with a voxel resolution of 70 × 70 × 500 μm.

Values of total vBMD, total bone mineral content (BMC), total bone area, cancellous vBMD, and marrow area were averaged across multiple slices at the mixed bone sites (3 slices for proximal tibia, 2 for femoral neck) to yield a mean value. Machine precision (based on manufacturer’s data) is ±3 mg/cm³ for cancellous vBMD and ±9 mg/cm³ for cortical vBMD. Coefficients of variation were ±0.6, 1.6, 1.9, and 2.13% for in vivo proximal tibia total vBMD, total BMC, total area, and cancellous vBMD, respectively, as determined from repeat scans on each of six adult male rats.

**Histomorphometry Analysis**

Undemineralized proximal left tibia were subjected to serial dehydration and embedded in methylmethacrylate (Aldrich M5, 590 –9). Histomorphometric analyses were performed by using the OsteoMeasure Analysis System, Version 1.3 (OsteoMetrics, Atlanta, GA). A defined region of interest was established 1 mm from the growth plate and within the endocortical edges encompassing 8 –9 mm/day (50). Total bone surface (BS), single-labeled surface (SLS), double-labeled surface (DLS), interlabel distances, bone volume, and ostoid/osteoclast/osteoblast surfaces were measured at ×200 magnification. MAR (μm/day) was calculated by dividing the average interlabel width by the time between labels (7 days), and mineralizing surface (MS) for cancellous bone surfaces (BS) was calculated by using the formula %MS/BS = ([(SLS/2) + DLS]/surface perimeter) × 100. Bone formation rate (BFR) was calculated as (MAR × MS/BS). All nomenclature for cancellous histomorphometry follows standard usage (24).

**Biomechanical Testing**

**Femoral neck biomechanical testing.** Femoral necks were tested by placing the distal portion of the proximal half of the femur perpendicularly into a metal fixture and loading the femoral head in vertical direction, parallel to the long axis of the femur (26). Loading of the femoral head in this fashion creates a combination of bending, shear, and compression in the femoral neck. Quasi-static loading was applied at a rate of 2.54 mm/min to the femoral head with a force recorded by a 1,000-lb load cell calibrated to 100-lb maximum load.

**Metaphyseal reduced platen compression testing.** Proximal tibiae were tested for changes in cancellous bone properties using reduced platen compression (RPC) test as previously described (9). Briefly, a 2-mm-thick cross section was cut from the proximal tibia just distal to the primary spongiosa of the metaphysis. Each specimen thus consists of a central core of cancellous bone encompassed by the surrounding cortical shell. Contact radiographs were made of each specimen to determine the appropriate specimen-specific size (~75% of the inner radius of the bone) for the loading platens such that the platens contact only the cancellous bone and not the cortical shell. Quasi-static loading was applied at 2.54 mm/min to compress the specimen until failure occurred using an Instron 1125 load frame (Norwood, MA). Load and displacement were recorded digitally in real time at 10 Hz. Load-displacement data were analyzed to determine the stiffness (slope of linear loading portion) and the ultimate load (maximum force during test). Cancellous bone material properties [elastic modulus (EM) and ultimate stress (US)] were estimated assuming uniaxial compression of the cancellous bone material only, that is, assuming an “effective” specimen with a height equal to the specimen thickness and a cross-sectional area equivalent to that of the platen surface area. The equations used are EM = (stiffness × specimen thickness)/platen surface area, and US = ultimate load/platen surface area.

**Statistical Analyses**

All data were expressed as means ± standard error of the mean (SE), and their statistical relationships were evaluated using the statistical package SPSS (v.15). In vivo pQCT, DEXA, and body mass data were presented as change scores (pre-post) and analyzed using a one-factor ANOVA (exercise). Paired t-tests were used to compare pre- and postvalues of in vivo pQCT and DEXA scans to determine if the change scores presented in graphs represented a significant difference between day 1 and day 35 values. Mechanical testing, ex vivo pQCT, and histomorphometry data were analyzed using a one-factor ANOVA (exercise). When a significant main effect was found, Duncan’s post hoc analyses were performed for pairwise comparisons. For all data, statistical significance was accepted at P < 0.05.

**RESULTS**

Increased body mass during low-load jump RE is attributed to both lean tissue and fat mass accretion. Normal aging controls (CC) significantly increased total body mass (+9%; P < 0.001), which was due to a 60% increase in fat mass (P < 0.0001) but not lean mass (Fig. 2). High-load jump RE (HRE) appeared to suppress age-related increases in body mass, but LRE did not. The 9% increase in total body mass (P < 0.001) in LRE animals was associated with concomitant increases in lean (7%; P = 0.012) and fat mass (11%; P = 0.027). The LRE group exhibited significant increases in lean mass during the experiment, whereas the CC and HRE groups’ lean mass remained unchanged.

Unexpected suppression of normal weight gain evidenced in the HRE group was associated with significantly lower average food intake over the course of the experiment (HRE = 20.88 ± 0.45 g) compared with both CC (24.07 ± 0.41 g) and LRE (22.27 ± 0.57 g) groups (P < 0.001 and P = 0.039, respectively). Average food consumption in the LRE group was also reduced compared with CC animals (P = 0.046), suggesting an exercise-induced suppression in appetite.

Cancellous bone mass is increased during jump RE regardless of load. Although both training paradigms resulted in...
greater PTM bone mass and increased geometry, HRE did not produce any additional gains in these variables. Both LRE and HRE training protocols significantly increased proximal tibia cancellous vBMD by 9% \((P < 0.001)\) and 8% \((P < 0.001)\), respectively (Fig. 3). Compared with ambulatory controls, \(\Delta vBMD\) for the training groups was 1.7-fold (HRE) and 2.7-fold (LRE) greater. LRE increased PTM total bone area \((19%; P < 0.001)\) and total BMC \((11%; P < 0.001)\), whereas only total BMC \((10%; P < 0.001)\) was increased with HRE (data not shown). Neither of these variables was affected in the CC group.

Both RE protocols increased bone mass at the femoral neck, although no additional gains were evidenced in the HRE animals. LRE and HRE training resulted in greater femoral neck total vBMD \((10%; P < 0.0001)\) compared with aging controls (Table 1). Total bone area was unaffected \((HRE, P = 0.001)\) at the femoral neck endocortical surface. Femoral neck net bone apposition (increased formation and/or decreased resorption, resulting in improved cancellous bone microarchitecture. Dynamic histomorphometric analysis of the proximal tibia revealed that bone formation activity was increased by both low- and high-load jump RE (Fig. 4). LRE training resulted in greater MAR \((90%; P < 0.0001)\) and %MS/BS \((71%; P = 0.001)\) vs. the CC group. Additionally, MAR \((P = 0.014)\) and %MS/BS \((P = 0.011)\) were 50–55% greater in the HRE group compared with controls (Fig. 4, A and B). Cancellous bone formation rate was greatest in the LRE group \((+213% vs. CC; P < 0.0001)\) in the final week of these training paradigms, with a less robust increase observed in HRE \((130% vs. CC; P = 0.003)\). Contrary to our expectations, the greater BFR was observed in the LRE rather than in the HRE rats \((P = 0.02)\).

Unexpectedly, HRE did not produce any additional gains in proximal tibia microarchitecture, as the only significant effects were evidenced in LRE rats. Proximal tibia bone volume \((%BV/TV)\) and Tb.Th were significantly greater in the LRE-trained group \((30%; P = 0.041\) and \(P = 0.036\), respectively) vs. controls (Fig. 5, A and C), with nonsignificant effects observed in HRE animals. There were no differences between any of the groups in Tb.N (Fig. 5B) or Tb.Sp (not shown).

Greater bone formation was coupled with repressed osteoclast surface \((-50% vs. CC)\) in both RE groups \((HRE, P = 0.033; LRE, P = 0.024)\). Osteoblast surface (Fig. 5E) and osteoid surface (not shown) values were similar to those in aging controls, and no differences between exercising groups was found.

Mechanical properties of hindlimb cancellous bone are enhanced with both LRE and HRE. To determine whether changes in cancellous bone microarchitecture resulted in improved material properties with the two jump RE regimes, RPC testing of the proximal tibia was performed. Contrary to our hypothesis, a significant increase in elastic modulus of proximal tibia cancellous bone was measured only in the LRE group \((+161% vs. cage controls; P = 0.041)\) (Table 2). No effect of jump RE was detected on ultimate stress of cancellous bone.

The effects of RE training on changes in femoral neck strength yielded similar significant effects for both training protocols. Maximal force of LRE and HRE femoral necks with our testing paradigm was \(30% (P = 0.011)\) and \(37% (P = 0.001)\) higher, respectively, than in the CC group, and no difference between the training groups was detected (Table 2).

**Table 1. Effects of low- and high-load resistance exercise (LRE, HRE) on structural and geometric properties of the femoral neck as taken by ex vivo peripheral quantitative computed tomography scans**

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<th>CC</th>
<th>LRE</th>
<th>HRE</th>
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<tr>
<td>Total vBMD, mg/cm²</td>
<td>1.036.77 ± 13.15*</td>
<td>1.139.98 ± 8.14b</td>
<td>1.138.18 ± 12.30b</td>
</tr>
<tr>
<td>Total BMC, mg</td>
<td>5.29 ± 0.13*</td>
<td>6.18 ± 0.08b</td>
<td>6.34 ± 0.15b</td>
</tr>
<tr>
<td>Total bone area, mm²</td>
<td>5.11 ± 0.17</td>
<td>5.43 ± 0.09</td>
<td>5.58 ± 0.15</td>
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<tr>
<td>Cancellous vBMD, mg/cm²</td>
<td>477.65 ± 17.24</td>
<td>503.52 ± 4.46</td>
<td>504.47 ± 5.69</td>
</tr>
<tr>
<td>Marrow area, mm²</td>
<td>0.66 ± 0.08a</td>
<td>0.39 ± 0.05b</td>
<td>0.27 ± 0.03b</td>
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Values are group means ± standard error of the mean (SE). CC, sedentary cage control; vBMD, volumetric bone mineral density; BMC, bone mineral content. Those groups not sharing the same letter for each variable are significantly different from each other \((P < 0.05)\). Group means with no labels are not significantly different.

**Fig. 3.** Effects of low- and high-load resistance exercise (LRE, HRE) on cancellous bone mineral density (vBMD) of the proximal tibia metaphysis (PTM) as taken by in vivo peripheral quantitative computed tomography scans. There were no significant differences among the 3 delta vBMD group means. CC, sedentary cage control. *\(P < 0.05\) vs. Pre value.
load (~8% increase in body mass) during jump exercises. To help elucidate this, we sought to determine the effects of both low-load and high-load jump RE training (LRE, HRE) on cancellous bone mass, biomechanical properties, microarchitecture, and bone remodeling activity. We hypothesized that HRE would provide greater benefits for proximal tibia metaphysis and femoral neck bone than LRE.

Although both LRE and HRE resulted in greater cancellous bone accretion compared with CC, contrary to our original hypothesis, these effects were not similar between the loading groups. Most strikingly, cancellous bone formation in the LRE group was more than threefold greater than in control rats; bone formation was elevated in HRE rats as well but was significantly lower than BFR in LRE rats (Fig. 4C). This more pronounced increment in bone formation in the LRE animals resulted in improved proximal tibia metaphysis cancellous bone microarchitecture compared with controls. Furthermore, unlike the LRE group, HRE animals did not experience significantly greater proximal tibia bone volume (BV/TV) or trabecular thickness (Fig. 5). Finally, both training groups exhibited greater femoral neck bone mass, resulting in increased strength, although differences between exercising par-

![Fig. 4.](image1)

**Fig. 4.** Effects of low- and high-load resistance exercise (LRE, HRE) on dynamic histomorphometry analyses measured at the proximal tibia metaphysis. A: mineral apposition rate (MAR). B: mineralizing surface (%MS/BS). C: bone formation rate (BFR). Values are group means ± SE. Those groups not sharing the same letter for respective surface measures are significantly different from each other ($P < 0.01$).

![Fig. 5.](image2)

**Fig. 5.** Effects of low- and high-load resistance exercise (LRE, HRE) on cancellous bone microarchitecture and histomorphometry indexes of osteoblast activity at the proximal tibia metaphysis. A: bone volume (BV/TV). B: trabecular number (Tb.N). C: trabecular thickness (Tb.Th). D: osteoclast surface (OcS/BS). E: osteoblast surface (ObS/BS). Values are group means ± SE. Those groups not sharing the same letter for respective surface measures are significantly different from each other ($P < 0.01$). Group means with no labels are not significantly different.
adipose were not detected. Contrary to our hypothesis, minimal applied loads added to jump exercise (LRE group) resulted in similar and sometimes greater gains in cancellous bone properties as loads doubling body mass (HRE group). To our knowledge, this is the first jump RE study to demonstrate absolute increases in cancellous bone vBMD in skeletally mature (not growing) rodents using in vivo longitudinal measures.

The effects of loading on weight-bearing bone have been investigated using a variety of different models; most of these utilize external loading of bone in anesthetized animals and are involuntary. Similar to axial compression (ulnar and tibial), four-point bending relies on brief periods of anesthesia during the loading period, which can have significant and prolonged cardiovascular effects with sustained exposure (11). Most notably, these external loading models provide precise levels of bone deformation but, unlike our model of jump RE, do not have any effect on the surrounding skeletal muscle, nor do they induce integrated responses to exercise (e.g., increased sympathetic neural outflow). Although potential shared mechanisms of growth between the muscular and skeletal systems are not yet well defined, engaging only one of these systems is less than optimal for studying the physiological effects of exercise. Therefore, while traditional loading paradigms may be useful for studying site-specific changes in bone, they are not characteristic of typical RE paradigms, whereas the model used in this study more closely resembles that of human exercise programs.

In the LRE and HRE groups, we observed a significant increase in proximal tibia cancellous vBMD (Fig. 3), but femoral neck cancellous vBMD was not affected by jump RE (Table 1). Although total bone area of the femoral neck was similar, marrow area was significantly reduced in both HRE and LRE groups, suggesting that increased total femoral neck total vBMD (summing cancellous core and cortical shell contributions) resulting from jump RE training was likely the product of endocortical apposition (due to enhanced formation and/or reduced resorption) combined with a lack of significant periosteal expansion. These increases in femoral neck bone mass associated with low- and high-load jump RE translated into significantly greater bone strength (Table 2) compared with controls, although no difference in femoral neck strength was evidenced between the two RE groups. However, cancellous bone material properties at the proximal tibia were not affected to the same degree in both exercise groups. Compression testing of cancellous bone at this metaphyseal region demonstrated significantly greater elastic modulus (+161% vs. CC) only in the LRE group (compared with controls). Although we hypothesized that increased training loads during jump RE would further enhance the skeletal response to jumping, these results directly contradict our hypothesis. Our data imply that increasing training loads during jump RE did not produce additional benefits to either the proximal tibia or femoral neck beyond those observed in the LRE group.

Jumping intensity and the rodents’ ability to land on their feet may be potential explanations for the differences in cancellous bone formation and microarchitecture with low- vs. high-load RE. Although only observational evidence, animals in the LRE group, jumping only against 30 g or ~8% of their body mass, were able to jump off the floor much more explosively than HRE animals jumping with 310 g or more of additional mass. We noticed that animals encountered more difficulty jumping at loads of 310 g or greater but were able to jump with ease when the added resistance was equal to or less than 260 g. Furthermore, we noted that the incidence of animals landing squarely on their feet decreased during jumping loads at the upper threshold of the experiment. Some would land on their side instead and thus not provide as much direct impact loading to the leg. We measured bone formation during the final 9 days of the investigation, when the HRE group was training with loads of 360, 360, and 410 g during those last three exercise sessions. Therefore, it is possible that the HRE group experienced fewer impacts/session during the time frame that bone formation was measured compared with the LRE group.

Low-load jump RE training provides an attractive therapy to prevent age-related bone disorders characterized by reduced cancellous bone mass and strength. While the high impacts associated with even “low-load” resistance jumping would not be optimal for osteoporotic patients with increased fracture risk, a moderate volume of jumping RE begun before reaching the level of osteopenia may help retard, or even prevent, further reductions in clinically relevant bone mass sites. This type of exercise has previously demonstrated significant alterations in cortical and cancellous bone compartments of the femoral neck and lumbar spine in children (7, 12) and premenopausal women completing jumps from heights as low as 8.5 cm (1, 2, 13). Snow and colleagues (30) reported significant improvement in femoral neck BMD with a low number of weighted jumps from a height of 20.3 cm in postmenopausal women. Our present data suggest that as few as 16 jumps with minimal applied load would provide sufficient strains to cancellous bone of the proximal tibia to induce significant osteogenic effects.

There were a few limitations to the present study that should be noted. First, animals in the ambulatory control group (CC) were not subjected to the same stressors as the exercise groups (LRE, HRE) and were never placed in the exercise training box. We did not measure corticosterone levels in any of the groups, which, if a change were detected, might help explain differences between the LRE and HRE groups’ bone and lean mass outcomes at the end of the study. In addition, it is possible that young adult female rats would respond differently than did our adult male rats to this jump resistance training paradigm, but given the consistent results in studies testing bone mass responses in both girls and boys to jump training (7, 12), this appears unlikely. Finally, assessment of ground reaction forces during the landing phase of

Table 2. Effects of low- and high-load resistance exercise (LRE, HRE) on changes in mechanical properties of cancellous bone at the proximal tibia metaphysis and femoral neck

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<tr>
<td>Proximal tibia metaphysis</td>
<td></td>
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<tr>
<td>Ultimate stress, MPa</td>
<td>1.3 ± 0.4</td>
<td>2.5 ± 0.5</td>
<td>2.2 ± 0.3</td>
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<tr>
<td>Elastic modulus, MPa</td>
<td>86.1 ± 26.2</td>
<td>224.1 ± 42.5</td>
<td>206.8 ± 41.2ab</td>
</tr>
<tr>
<td>Femoral neck</td>
<td></td>
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<tr>
<td>Maximal force, N</td>
<td>92.7 ± 8.5a</td>
<td>120.2 ± 4.5b</td>
<td>127.2 ± 4.0b</td>
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Values are group means ± SE. Those groups not sharing the same letter for each variable are significantly different from each other (P < 0.05). Group means with no labels are not significantly different.
JUMP RESISTANCE EXERCISE EFFECTS ON CANCELLOUS BONE

RE jumps at the variant loads would have enabled us to gain insight into the potential contributions that peak impact forces had on differences in bone formation activity associated with LRE and HRE.

In summary, our data demonstrate that jump exercises completed with only modest load levels (~8% increase in body mass) were just as osteogenic as jumps using loads exceeding twice that of body mass for most outcome variables. Thus our global hypothesis was false: higher loads did not lead to a more potent bone response. In fact, the opposite was true for a few variables. Specifically, only the low-load level jumping generated significant beneficial effects for proximal tibia cancellous vBMD, trabecular thickness, and estimated cancellous bone elastic modulus. These results suggest that jumping, even at minimal resistance, provides sufficient mechanical loading to incur absolute gains in cancellous bone mass in skeletally mature rodents.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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