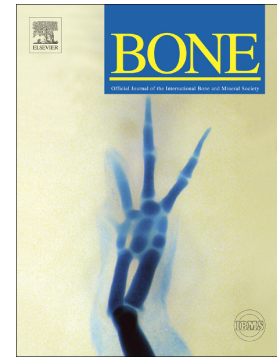# Journal Pre-proof

Regional changes in indices of bone strength of upper and lower limbs in response to high-intensity impact loading or high-intensity resistance training

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Title:

Regional changes in indices of bone strength of upper and lower limbs in response to high-intensity impact loading or high-intensity resistance training

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ABSTRACT

It is well known that the bone response to physical activity is highly dependent on the nature of the loads imposed. Despite this, few direct comparisons of the effect of impact-style loading and resistance training on bone have been made. We therefore aimed to compare the effects of 10-month, twice-weekly, high-impact loading and 10-month, twice-weekly, high-intensity resistance training on indices of bone strength of both the upper and lower limbs of young adult women. Physically inactive, otherwise healthy, young adult women (18-30 years) with below average bone mass (T-score ≤ 0) were recruited as part of the OPTIMA-Ex trial. Testing included DXA- and pQCT-derived measures of bone mass and indices of bone strength and QUS-derived measures of bone quality of the dominant (D) and non-dominant (ND) upper (radius) and lower limbs (femoral neck, tibia, calcaneus). The present study examined those participants who completed the impact training (IT; n = 10) and resistance training (RT; n = 12) arms of the trial. Age differed between groups at baseline (IT = 23.2 ± 3.8 years, RT = 20.5 ± 1.8 years; p = 0.042). Compliance with the training programs did not differ (IT = 61.4 ± 15.1%, RT = 66.4 ± 11.2%, p = 0.381). Age and baseline differences in bone outcomes served as covariates for repeated measures and univariate ANCOVA conducted for dependent variables and percent change respectively. IT improved distal pQCT-derived bone mineral density (BMD) of the upper limb (ND radius: total BMD = 8.55 ± 2.26% versus 1.50 ± 2.04%, p = 0.040 and trabecular BMD = 1.86 ± 0.90% versus -1.30 ± 0.81%, p = 0.029) and lower limb (ND tibia trabecular BMD = 1.22 ± 0.55% versus -0.82 ± 0.50%, p = 0.017), more than RT. IT also improved upper limb bone strength index (BSI) (ND radius total BSI = 15.35 ± 2.83% versus 2.67 ± 2.55, p = 0.005) and lower limb BSI (D tibia total BSI = 5.16 ± 1.13% versus 0.37 ± 1.02%, p = 0.008; D tibia trabecular BSI = 3.93 ± 1.76% versus -2.84 ± 1.59, p = 0.014, ND tibia trabecular BSI = 3.57 ± 1.63% versus -3.15 ± 1.48%, p = 0.009) more than RT. Conversely, RT improved DXA-derived cortical

volumetric BMD at the femoral neck more than IT ($3.68 \pm 1.99\%$ versus $-4.14 \pm 2.20\%$, $p = 0.021$). Results suggest that IT and RT provide differing site-specific effects in both the upper and lower limbs, with superior bone responses observed at the distal segment from IT, while RT appeared to have greater effect on the shaft of the bone, on indices of bone-strength in young adult women.

Keywords:

bone mass, bone geometry, boxing, impact exercise, jumping, resistance training, young women

1. Introduction

Physical activity is recognised as one of the most important lifestyle strategies to maximise peak bone mass during growth [1]. Yet the bone response to different types of physical activity is highly dependent on the nature of loads imposed, most importantly but not limited to, the magnitude and rate of strain [2]. As the skeletal physiological response to mechanical stimuli has been proposed to be threshold driven [3, 4], the training variable of intensity, specifically load intensity, is of utmost importance. Both gravity-derived loads (impact training) [5-7] and muscle-derived loads (resistance training) [8-10] have produced positive effects on bone in young adult and premenopausal women. While high-impact exercise at accelerations greater than 4 g have led to bone benefits in premenopausal women [11], low-or moderate-intensity impact training below 4 g has not been as effective. Similarly, studies of resistance training applying low to moderate loads (i.e. 60% or less of 1 repetition maximum (RM)) appear to provide insufficient load intensity to have an effect on bone mineral density (BMD) beyond merely maintenance [8, 12], further highlighting the important relationship between load intensity and bone response.

Previously, debate has occurred as to what source of loading provides the most effective stimulus – gravity-derived impact loads or muscle forces [13]. Nevertheless, few direct comparisons of the effect of impact-style loading and resistance training are available, with only two studies in younger women [14, 15] and one in older women [16]. However, the loading intensity of the exercises used in the interventions were not always comparable, nor always high-intensity, and none specifically targeted the bones of the upper limb. Despite upper extremity fractures being relatively common in osteoporosis, the upper limb has been largely overlooked as a target for bone health interventions. Only a few studies have reported upper limb bone outcomes following impact loading [17-19], or resistance training [20, 21]. Typical impact loading protocols include deliberate falls onto an outstretched arm [17, 18].

Observational data of those who participate in fight sports (such as boxing) shows greater arm BMD of fighters than controls and other active populations [22-25]. Therefore, the efficacy of punch-based upper limb impact exercises on upper limb bone health warrants investigation.

The effect of bone-targeted exercise interventions are commonly evaluated by DXA, through the examination of areal BMD, however, the interpretation of areal BMD does not account for other structural features of bone such as area, geometry and thickness [26]. Other devices such as pQCT provide a more comprehensive account of bone density and structure, including measures of volumetric BMD, indices of bone strength (area, geometry and thickness), and the independent quantification of trabecular and cortical bone. Few studies have looked at the effect of exercise, in this case impact loading, on bone strength parameters in young adult women [27, 28]. Thus, further examinations of the site-specific responses to different exercise modalities on bone strength parameters in this demographic are required.

To date, the comparative efficacy of true high impact loading and heavy resistance training on bone mass and bone strength parameters of the upper and lower limbs has not been established. Thus, the aim of the current study was to directly compare the effects of a 10-month high-intensity predominantly gravity-derived loading intervention (impact training) and a 10-month high-intensity predominantly muscle-derived loading intervention (resistance training) on indices of bone strength of the upper and lower limbs of young adult women.

2. Methods

2.1 Study design

The current work represents a re-analysis of data from the OPTIMA-Ex trial, to determine the relative site-specific effects of targeted impact training (IT) and resistance training (RT) in young physically inactive women with lower than average bone mass. The OPTIMA-Ex trial was a single-blinded, single centre randomised controlled exercise intervention trial. The trial was registered on the Australian and New Zealand Clinical Trials Registry (Trial number ACTRN12616001444471) and ethical approval was granted by the Griffith University Human Research Ethics Committee (GU Ref: 2015/775).

2.2 Participants

Physically inactive, otherwise healthy, young adult women (18-30 years) with below average bone mass (BMD T-score less than or equal to 0 at the lumbar spine and hip) were recruited. Exclusion criteria included musculoskeletal or medical conditions affecting the ability to participate in high-intensity physical activity, medications and medical conditions known to affect bone health, change of contraceptive medication in the past twelve months, cancer, uncontrolled cardiovascular disease, excessive radiation exposure and current regular participation in exercise programs known to influence bone, as previously published [29]. Participants were withdrawn from the trial if consent was withdrawn, a change in medication of relevance to bone occurred, injury or illness prevented further participation, they were advised to cease training by a medical professional, or the investigators became aware that additional exercise was commenced during the trial.

2.3 Exercise interventions

2.3.1 High-intensity progressive impact training program

Participants in the IT group attended two, 40 - 45 minute instructor-led exercise sessions per week on non-sequential days over a 10 month intervention period. Each session was comprised of three fundamental upper limb punching exercises (jab, cross, hook) and three fundamental lower limb landing exercises (jump, hop, drop jump). The program consisted of a one-month familiarisation period with lower load variants to ensure correct technique and safe movement patterns were established for the upper and lower limb impact exercises. Punching exercises were performed in both orthodox and southpaw stance, to ensure that both limbs were receiving comparable loading opportunities, participants changed from gloves to hand wraps after the familiarisation phase (week 4), with the punching combinations progressed every seven weeks. Furthermore, punch kinematics were measured at week 2, 4, 12, 24 and 36 using a GymAware device (Kinetic Performance, Canberra, Australia), utilising a previously validated method [30]. Lower limb loading impact exercises were also progressed every seven weeks and participants progressed from shod to barefoot after week 4. The complexity of jumps and hops was achieved with increases in hurdle height, changes in direction, and progressively increased drop jump heights from 15 cm to 80 cm. Jump and hop exercises could be classified under two sub categories – unidirectional and multidirectional movements. The high-intensity and progressive nature of the lower limb impact program has been quantified previously [31].

2.3.2 High-intensity progressive resistance training program

Participants in the RT group attended two, 40 - 45 minute instructor-led exercise sessions per week, on non-consecutive days over a 10 month intervention period. The sessions were comprised of progressive high-intensity RT exercises for the upper and lower limb. Six fundamental exercises were undertaken throughout the duration of the program, with three upper limb exercises (bench press, over-head press and bent over row) and three lower limb exercises (deadlift, squat and calf raise) using Olympic weights. The program consisted of a one-month familiarisation period utilising low-load exercise variants with a focus on controlled movement to ensure that participants could demonstrate safe lifting technique. The weight of the six fundamental exercises was progressively increased to maintain a minimum of 85% 1 RM for 5 sets of 3-5 repetitions, with calf raises performed for 5 sets of 10 repetitions. Strength was measured for the upper limb and lower limb every 12 weeks through 1RM tests of bench press and deadlift.

2.4 Data collection

Participants attended two testing sessions at the Bone Densitometry Research Laboratory at Griffith University Gold Coast campus; one at baseline (T0) and one at 10 months (T10). All measures were performed by a single unblinded investigator.

2.4.1 Anthropometrics and lifestyle characteristics

Measurements of height (cm) and weight (kg) were determined using a wall-mounted stadiometer (Seca, Hamburg, Germany) and mechanical beam scale (Seca, Hamburg, Germany). Subsequently, body mass index (BMI) was calculated as per the accepted formula

(BMI = weight/height^2, kg/m^2). The Bone-Specific Physical Activity Questionnaire (BPAQ) was used to derive bone-relevant lifetime (tBPAQ) physical activity participation [32]. The BPAQ was scored using a custom-designed program (http://www.fithdysign.com/BPAQ/) to derive a bone-specific score based on algorithms that rank and weight activities based on rates and magnitudes of loading. The AusCal, a calcium-focused diet questionnaire specific to the Australian diet [33], was used to estimate calcium intake, including supplementation, to establish daily calcium intake (mg/day) and was scored using a custom-written FoodWorks software (Version 7, Xyris Software, Brisbane, Australia).

2.4.2 Bone strength indices

DXA (Medix DR, Medilink, Perols, France) was utilised to scan both the skeletally dominant and non-dominant proximal femur (femoral neck, FN), and forearm (distal radius, 1/3 RAD) to obtain areal bone mineral density (aBMD; g/cm^2). Bone mineral content (BMC; g), volume (Vol; cm^3), and volumetric bone mineral density (vBMD; g/cm^3) of the FN were estimated using 3D hip analysis software (Version1.0, DMS Group, Mauguio, France). The coefficient of variation (CV) for 3D hip outcomes at the FN for young adult women aged 18-30 in our laboratory range from 1.84% to 6.66%. Both dominant and non-dominant tibiae and radii were scanned using peripheral quantitative computed tomography (pQCT, XCT-3000, Stratec Medizintechnik GmbH, Pforzheim, Germany) to determine total and trabecular content (mg), density (mg/cm^3), area (mm^2) and bone strength index (BSI; g^2/cm^4) at the distal (4%) site. Cortical content (mg), density (mg/cm^3) and area (mm^2), cortical thickness (mm), periosteal and endosteal circumference (mm), polar section modulus (mm^2) and weighted polar section modulus (mm^3) were measured at the tibial (38%) and radial shafts (66%). In our laboratory, pQCT scans at the manufacturer standard of 4 %, 14 %, 38 % and

66 % of tibial length from the distal endplate, and 4% and 66 % of radial length from the distal endplate are routine. The 4% site for both the tibia and radius is examined for trabecular outcomes, while for cortical outcomes the 38% site of the tibia and the 66% site of the radius are investigated. The 38% site of the tibia is used for cortical outcomes as the junction of the middle to distal one third is the site at which the most profound tibial bending occurs [34]. The 66% site of the tibia and the radius are used to determine leg muscle CSA and density outcomes (not reported in the current work). Such standard scanning procedures afford comparison between study groups and interventions at multiple sites from our own laboratory [35-38] and other laboratories [39-43]. For pQCT-derived bone outcomes the CV ranges from 0.74% to 2.71% at the 4% tibial site; 0.21% to 1.40% at the 38% tibial site; 0.96% to 5.05% at the 4% radius site; and 0.62% to 3.27% at the 66% radius site. Finally, quantitative ultrasound (QUS) (Lunar Achilles InSight™, GE Healthcare, Wisconsin, USA) was used to obtain calcaneal broadband ultrasound attenuation (BUA) (db/MHz), speed of sound (SOS) (m/s), and stiffness index (SI) (unitless). The CV for QUS-derived outcomes at the calcaneus range from 0.30% to 2.44%. Skeletal dominance was determined from functional dominance, where the functionally dominant leg was deemed the skeletally non-dominant side [44].

2.4.3 Compliance

Exercise compliance was recorded in attendance logs where 100% compliance was defined as completion of 88 sessions over 44 weeks or 10 calendar months.

2.5 Statistical analysis

Statistical analysis was undertaken using SPSS statistical software (Version 24.0; IBM Inc., Chicago, IL, USA). Descriptive statistics were generated for participant characteristics, biometrics, and all dependent variables. Per protocol analyses were conducted. One-way ANOVA was used to examine differences between IT and RT at baseline. Repeated measures ANCOVA was used to determine main effects for dependent variables and univariate ANCOVA was conducted to analyse percent change. Age and values that differed between groups at baseline were applied as covariates. Bonferroni-adjusted pairwise comparisons were applied to the repeated measures ANCOVA results. Group percent change was calculated as the mean of the individual percent changes. Participant characteristics are presented as mean ± SD with all other results displayed as adjusted change ± SE unless otherwise stated. Statistical significance was accepted at $p \leq 0.05$.

3. Results

3.1 Participant characteristics

A total of 34 participants were randomised to the supervised training groups (IT = 17, RT = 17), and 22 (IT = 10, RT = 12) completed the supervised training arms of the OPTIMA-Ex trial (age = 21.7 ± 3.2 years; height 164.5 ± 6.4 cm; weight 55.9 ± 7.1 kg). Compliance to the training programs did not differ between groups (IT = 61.4 ± 15.1%; RT = 66.4 ± 11.2%; p = 0.381). At baseline, the IT group were older than the RT group (23.2 ± 3.8 years versus 20.5 ± 1.8 years; p = 0.042), however, there were no other differences between groups in anthropometric characteristics, daily calcium, or bone relevant physical activity at baseline (Table 1). No difference was seen for Z-score for either dominant FN (IT = -0.61 ± 0.57; RT = -0.72 ± 0.62; p = 0.660) or non-dominant FN (-0.42 ± 0.69, RT = -0.52 ± 0.56; p = 0.721) and contraception use was similar for IT (Non HC = 5, HC = 5) compared to RT (Non HC = 5, HC = 7). However, differences were observed between IT and RT at baseline for dominant

FN cortical BMC (1.21 ± 0.37 g versus 0.93 ± 0.16 g; p = 0.032) and volume (1.89 ± 0.39 cm^3 versus 1.56 ± 0.27 cm^3; p = 0.031), non-dominant heel BUA (109.10 ± 9.19 db/MHz versus 121.07 ± 10.64 db/MHz; p = 0.018) (Supplementary Table 1), non-dominant radius trabecular density (182.33 ± 20.78 mg/cm^3 versus 205.39 ± 17.78 mg/cm^3; p = 0.011) and BSI (0.06 ± 0.01 g^2/cm^4 versus 0.07 ± 0.01 g^2/cm^4; p = 0.004) (Supplementary Table 2).

[Table 1]

3.2 Ten‑month change in indices of bone strength

3.2.1 Upper limb

For DXA-derived radius aBMD, no percent change differences between IT or RT were observed for either the dominant ($5.24 \pm 2.32\%$ versus $5.13 \pm 2.10\%$, p = 0.975) or non-dominant ($4.75 \pm 2.40\%$ versus $2.74 \pm 2.17\%$, p = 0.562) limb, however, for the dominant radius both IT (0.033 ± 0.015 g/cm^2, p = 0.046) and RT (0.037 ± 0.014 g/cm^2, p = 0.015) stimulated bone improvements (Supplementary Table 3).

For pQCT-derived measures of the distal radius, no between-group differences were observed at the skeletally dominant limb, however, the IT group showed superior improvements to RT for distal radius total density ($8.55 \pm 2.26\%$ versus $1.50 \pm 2.04\%$, p = 0.040), trabecular density (1.86 ± 0.90 % versus $-1.30 \pm 0.81\%$, p = 0.029) (Figure 1A), and total BSI ($15.35 \pm 2.83\%$ versus $2.67 \pm 2.55\%$, p = 0.005) (Figure 1B) in the non-dominant limb. Although no between-group differences were evident for the dominant limb, an improvement was seen in total content after both IT (3.65 ± 1.45 mg, p = 0.021) and RT (3.29 ± 1.31 mg, p = 0.021) (Table 2).

[Table 2]

For the proximal radius site (66%), no between-group differences were seen in the dominant limb or non-dominant limb (Table 3), with no within-group differences observed for the dominant limb. Conversely, in the non-dominant limb, RT improved cortical content (2.63 ± 1.08 mg, p = 0.025), density (29.53 ± 7.70 mg/cm^3, p = 0.001) (Figure 1C), cortical thickness (0.06 ± 0.02 mm, p = 0.019), and weighted polar section modulus (10.01 ± 4.79 mm^3, p = 0.05) (Figure 1D).

[Table 3]

3.2.2 Lower limb

No between-group differences were evident for DXA-derived FN aBMD for either the dominant (2.80 ± 1.78% versus 4.30 ± 1.61%, p = 0.559) or non-dominant lower limb (1.89 ± 1.86% versus 2.23 ± 1.68%, p = 0.901), although a within-group aBMD improvement was seen in the non-dominant FN following RT (0.035 ± 0.013 g/cm^2, p = 0.017). The RT group increased compared to the loss seen for IT for dominant FN trabecular BMC (9.64 ± 5.29% versus -10.74 ± 5.86%, p = 0.024), total BMC (8.06 ± 5.22% versus -11.15 ± 5.77%, p = 0.030), and cortical vBMD (3.68 ± 1.99% versus -4.14 ± 2.20%, p = 0.021), however, this difference was not seen in the non-dominant FN. Significant decreases were observed in the IT group for dominant FN trabecular BMC (-0.78 ± 0.37 g, p = 0.047), total BMC (-1.03 ± 0.48 g, p= 0.046) and cortical vBMD (-0.03 ± 0.02 g/cm^3, p = 0.050). Conversely, no within-group differences were found for the non-dominant FN (Table 4).

[Table 4]

IT improved pQCT-derived measures of the dominant distal tibia (4%) (Table 5) more than RT in total content (3.00 ± 0.85% versus -0.18 ± 0.77%, p = 0.016), total BSI (5.16 ± 1.13% versus 0.37 ± 1.02%, p= 0.008) (Figure 1B) and trabecular BSI (3.93 ± 1.76% versus -2.84 ± 1.59%, p = 0.014). IT also improved non-dominant tibial trabecular content (2.52 ± 1.22% versus -1.94 ± 1.10%, p = 0.018), trabecular density (1.22 ± 0.55% versus -0.82 ± 0.50%, p = 0.017) (Figure 1A) and trabecular BSI (3.57 ± 1.63% versus -3.15 ± 1.48%, p= 0.009) more than RT.

[Table 5]

There were no differences in effect of IT and RT at the tibial shaft (38%) for either the dominant or non-dominant limb (Table 6). However, RT improved dominant limb cortical area (3.41± 1.31 mm^2, p = 0.017), periosteal circumference (0.38 ± 0.15 mm, p = 0.018), polar section modulus (26.96 ± 11.62 mm^2, p = 0.032) and weighted polar section modulus (30.36 ± 9.72 mm^3, p = 0.006) (Figure 1D), while cortical thickness improved for both RT (0.05 ± 0.02 mm, p = 0.021) and IT (0.05 ± 0.02 mm, p = 0.047). In the non-dominant tibial shaft, IT increased cortical content (2.99 ± 1.42 mg, p = 0.049) and RT improved cortical density (8.75 ± 2.51 mg/cm^3, p = 0.002) (Figure 1C).

[Table 6]

No between-group differences were observed in percent change for QUS determinants of calcaneal bone quality. Despite no significant within-group improvements, IT exhibited higher SOS scores than RT at follow-up with between-group differences of 22.04 ± 9.66 m/s, $p = 0.042$ for the dominant heel and 21.20 ± 8.96 m/s, $p = 0.036$ for the non-dominant heel (Supplementary Table 4).

[Figure 1 A,B,C,D]

3.3 Training program progression

3.3.1 High-intensity progressive impact training progression

For the IT group a significant time effect was observed for punch acceleration for those who completed the three testing points. The jab acceleration increased for both limbs over the duration of the intervention (Left: Week 4 = 41.45 ± 6.50 m/s^2, Week 12 = 50.18 ± 9.29 m/s^2, Week 24 = 53.58 ± 4.05 m/s^2, $p = 0.016$; Right: Week 4 = 44.67 ± 8.53 m/s^2, Week 12 = 53.87 ± 7.74 m/s^2, Week 24 = 54.15 ± 6.82 m/s^2, $p = 0.024$). For the cross, a significant time effect was also observed (Left: Week 4 = 41.68 ± 7.22 m/s^2, Week 12 = 52.26 ± 12.37 m/s^2, Week 24 = 57.02 ± 4.63 m/s^2, $p = 0.005$; Right: Week 4 = 43.15 ± 9.61 m/s^2, Week 12 = 58.64 ± 9.35 m/s^2, Week 24 = 57.71 ± 8.87 m/s^2, $p = 0.042$). For the hook, only the left limb demonstrated a significant increase in acceleration over time (Week 4 = 69.08 ± 14.44 m/s^2, Week 12 = 70.32 ± 13.05 m/s^2, Week 24 = 85.27 ± 9.25 m/s^2, $p = 0.017$).

3.3.2 High-intensity progressive resistance training progression

For the RT group, 1RM results demonstrated a significant time effect for both the deadlift

and bench press over the three measured time points for those who completed the trial. For the deadlift 1RM improvements were seen between week 12 (66.6 ± 6.3 kg) and week 24 (75.0 ± 7.3 kg, p = 0.012) and week 24 (75.0 ± 7.3 kg) and week 36 (80.3 ± 7.7 kg, p = 0.002). The same results were evident for the bench press with 1RM weight increasing between week 12 (35.3 ± 5.9 kg) and week 24 (41.8± 4.7 kg, p < 0.001) and week 24 (41.8± 4.7 kg) and week 36 (44.3 ± 4.1 kg, p = 0.007).

4. Discussion

The aim of the current study was to compare the effects of high-intensity impact training (predominantly gravity-derived loading) and high-intensity resistance training (predominantly muscle-derived loading) on indices of bone strength in both the upper and lower limbs of young adult women. The effects of IT and RT differed in both outcome- and site-specific ways. RT appeared to exert greater effects on cortical measures in the proximal femur and the shafts of long bones of the upper and lower limbs, while IT improved indices of bone strength in the distal ends of long bones, irrespective of upper or lower extremity. To our knowledge, these findings represent the first direct comparisons of targeted upper and lower limb high-intensity impact and resistance exercises on indices of bone strength in young adult women.

The upper limb has exhibited a variety of bone responses to impact training in young adult and premenopausal women [17-19, 45]. The most recent upper limb IT intervention found falling onto an outstretched arm onto the heel of the hand improved ultra-distal radius aBMD 3.9% in premenopausal women [18], while another using a similar loading strategy reported no improvement in aBMD at the one-third shaft site of the radius [17]. The only other upper

limb intervention in young adult women evaluated QCT changes and demonstrated a protective effect on ultra-distal trabecular vBMD and a reduction in total cortical bone vBMD of the distal radius compared to control, from a non-impact but gravitationally-derived mechanical loading strategy, suggesting a potential site and structure specific effect [19]. While we observed an improvement in DXA-derived aBMD of the radial shaft in the dominant forearm, our pQCT-derived results follow a similar pattern to others who have shown upper limb impact loading interventions preferentially benefit distal sites. Specifically, the upper limb impact loading (punching) intervention in the current study evoked bilateral improvements at the 4% site of the radius in total content along with improvements in total density, total BSI and trabecular density for the non-dominant radius. The increase in non-dominant trabecular density was associated with non-significant decreases in content and area, with the reduction in content within the error of the machine for that outcome. Despite this the reported increase in trabecular density for the non-dominant radius may be a result of these non-significant reductions as trabecular area reduced greater than content. Indeed, in vivo compressive strain at the distal radius site in females, for falling onto an outstretched arm (impact-loading) was significantly greater than the compressive strain from a chin-up, bicep curl and wrist curl exercise all of which are considered muscle-loading based exercises [46]. It is likely that these site-specific distal bone adaptations in the upper limb correspond to the location of the greatest mechanical load, being closest to the site of impact, while loads are attenuated more proximally thereby applying insufficient mechanical stimulus to those bony sites.

For the lower limb, in the IT group we observed a decrease in FN cortical vBMD at the dominant hip, despite a non-significant increase in aBMD at the same site. Although seemingly unusual, disparity between aBMD and vBMD at the femoral neck, specifically

cortical vBMD, has been previously been reported [47]. IT has previously evoked positive bone responses at the hip in young women [48]; however, most previous investigations in young adult women only report aBMD, with one looking at DXA-based hip structural analysis [49]. This intervention showed improvements in section modulus and cross-sectional area at the FN in response to a 12-month jumping and stepping program, however comparisons are somewhat difficult due to difference in outcomes reported. Limited investigations of the effect of impact training on indices of bone strength in young adult and premenopausal women have been reported [28]. No improvements in QCT-derived measures of bone strength or geometry were observed at the either the distal (5%) or proximal (67%) tibia following a 12 month impact-style intervention utilising stepping, stamping, jumping and running [28]. Differences in results to the present study may be owing to the differing training parameters applied, scan sites used and outcomes reported (trabecular attenuation alone at the 5% site). On balance, our findings suggest the distal tibia experiences a greater bone response to IT than the shaft, notwithstanding an improvement in cortical thickness at the 38% site of the dominant tibia. As the distal regions of the tibia undergo predominantly compressive forces during gait [50], which is an example of a relatively low-intensity activity from an osteogenic loading perspective [32], it is likely that the site-specific bone adaptations to IT we observed corresponds to the area subjected to the greatest mechanical strains. Again, such loads are likely compressive due to proximity to site of impact. Furthermore, previous cross-sectional relationships have been established for higher trabecular density of the distal tibia in hurdlers, racket sport players and soccer players [51], all of which experience significant gravitationally-derived loads as a feature of their sport, further highlighting the likely site-specific loading response to impact-style exercise.

The findings from previous investigations of young adult women suggest that RT provides

minimal adaptive stimulation for bone mass, bone geometry or bone strength parameters of upper limb bones [21]. By contrast, our results indicate that high-intensity RT improves indices of bone strength in this population, owing to improvements seen predominantly in the shaft of the radius measured by both DXA (dominant 1/3 radius aBMD) and pQCT (non-dominant cortical content, density and thickness and weighted polar section modulus). The greater effect observed in our trial is likely to reflect both the higher intensity of loading applied, and the use of multi-joint compound style lifts compared to isolated elbow flexion and extension exercises used in previous work. While there are no other trials in young adult women to compare our findings with, our positive observations, specifically in cortical bone, correspond to those from upper limb resistance training interventions in postmenopausal women [20, 52]. Indeed, cross-sectional work in young adult women suggest that estimated joint moments based on muscle force production are the strongest determinant of bone strength indices for the radial shaft [51], highlighting the important relationship that exists between muscle-loading and a site-specific bone response.

In the lower limb, RT stimulated an increase in aBMD of the dominant FN and a superior effect on cortical vBMD than IT. The lack of improvement seen for trabecular and total vBMD at the same site is likely a result of the interdependency of bone parameters, as the large between-group improvements reported in trabecular and total BMC for RT appear to be washed out by the large yet statistically non-significant increases in trabecular and total volume. Despite statistical non-significance, the improvements in trabecular and total volume were greater than the CV for the given outcome. While previous evidence suggests that RT, has minimal effect on the hip in young adult and premenopausal women [53], non-significant responses at the FN are likely a result of insufficient loading stimulus (60% or less of 1 RM) [8, 12]. As the bone response to loading is site specific [54, 55], our results may be a product

of sufficient loading intensity (high-intensity 85% 1RM) delivered through exercise that targeted the measured site (i.e. squat). Furthermore, RT improved bone in the shaft of the tibia. Such cortical bone adaptations correspond to those of a previous investigation that found increases in cortical vBMD, cortical thickness and polar stress strain index at the 20% site of the tibia in response to RT in young adults [10]. While those results were a part of a combined study of men and women, on and off protein supplementation, the authors reported that neither gender nor supplementation condition influenced the bone-based outcomes [10]. For comparison, larger cortical wall thickness is reportedly observed in competitive weight-lifters who also lift at high-intensity [56]. External forces from muscle contraction can subject the tibia to bending forces, in fact, it has been reported that two thirds of the variation in antero-posterior tibial moment of resistance at the one third shaft site can be explained by muscle bending moment alone [57]. Although bending moments were not measured in the current work, it may help explain the changes we observed at the shaft of long bones from our high-intensity RT regime.

Several limitations of the current work warrant acknowledgement. Firstly, there is no control comparison in the present study. This was an omission by design as the aim of this study was to compare the regional bone responses of two osteogenic training interventions, IT and RT. Furthermore, the control group used in the OPTIMA-Ex trial was that of an 'active sham' or 'positive control' in an attempt to improve recruitment, compliance, retention and blinding of the intervention groups. However, during the OPTIMA-Ex trial (results published elsewhere), a significant increase in osteogenic physical activity independent of the study was captured through the bone-specific physical activity questionnaire in the control group between baseline and follow-up, which is likely to have confounded our analyses. Secondly, data in the present study represents a composite of participants both on and off hormonal

contraceptives. Many forms of hormonal contraception are available, with varying possible interactions with bone. Due to our limited numbers we were unable to sub-divide the sample further based on type of contraception use, however, a relatively even split of participants both on and off hormonal contraception was achieved organically through the process of randomisation. Additionally, the effect of skeletal dominance on our outcomes was not examined as it was not a primary aim of the study nor was the study powered to examine its influence. While no clear pattern emerged for either limb in response to either form of training, it could be speculated that this lack of pattern observed was a result of the principles of initial values and/or preferential loading. The interpretation of such interlimb responses is further complicated by discordance between functional dominance and skeletal dominance of the lower limbs [44]. Finally, we acknowledge that the sample size for this study is relatively low, thus, the conclusions that can be drawn are somewhat limited. However, significant changes were greater than the coefficient of variation for the corresponding measure. Furthermore, young adult women are known to be difficult to recruit and retain for bone-targeted exercise interventions [5-7, 14, 15, 58-60]. While a broad range of factors influence physical activity participation, it is possible that barriers exist to participation in bone health related physical activity in this population. Nevertheless, we feel this data represents a novel investigation into the differential effects of high-intensity IT and RT on site-specific indices of bone strength in young adult women.

In conclusion, IT and RT showed differential site-specific effects in both the upper and lower limbs on indices of bone-strength. IT showed greater improvements at distal sites of both the radius and tibia, while RT appeared to have a greater effect on the shafts of the radius and tibia and at the femoral neck. The differing bone responses stimulated by the two training modalities are likely due to localised adaptation in bone structure and distribution at the sites

subjected to the greatest strain. Further investigations will help to clarify the mechanisms

responsible for bone adaptations to the differing mechanical loads in this novel investigation

into the comparative effect of high-intensity IT and RT in young adult women.

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Acknowledgements

Figure Legend

Figure 1. Adjusted percent change (± SE) for pQCT-derived (A) trabecular volumetric bone mineral density (4% site for upper and lower limb), (B) total bone strength index (4% site for upper and lower limb), (C) cortical volumetric bone mineral density (66% site for upper limb and 38% site for lower limb) and (D) weighted polar section modulus (66% site for upper limb and 38% site for lower limb)of the skeletally dominant and non-dominant limbs of the upper and lower extremity for IT and RT after a 10-month exercise intervention in healthy young adult women with lower than average bone mass (n = 22). + Indicates within-group difference (p<0.05); * Indicates between-group difference (p<0.05).

Table 1. Baseline participant characteristics, mean ± SD (n = 22)

Parameter	IT (n = 10)	RT (n = 12)	*p*
Age (years)	23.2 ± 3.8	20.5 ± 1.8	0.042*
Height (cm)	165.7 ± 6.5	163.5 ± 6.5	0.427
Weight (kg)	55.6 ± 9.0	56.9 ± 5.5	0.872
BMI (kg/m^2)	20.1 ± 2.4	21.0 ± 1.8	0.370
Right forearm length (mm)	263.5 ± 12.8	257.5 ± 13.4	0.300
Left forearm length(mm)	262.2 ± 12.4	257.4 ± 12.7	0.408
Right shank length (mm)	374.4 ± 24.8	368.5 ± 21.7	0.565
Left shank length (mm)	374.6 ± 24.4	369.2 ± 21.7	0.588
Age of menarche (years)	13.7 ± 2.1	12.9 ± 1.4	0.309
tBPAQ	18.6 ± 18.5	18.7 ± 23.0	0.995
Dietary calcium (mg/day)	381.5 ± 235.4	390.3 ± 133.2	0.914
Hormonal Contraception	-	-	-
None	5	5	-
OC	5	4	-
Implanon	0	1	-
Merina	0	2	-

BMI = body mass index; tBPAQ = total bone-specific physical activity questionnaire score; OC = oral contraceptive * Between-group difference ($p < 0.05$)

Table 2. Adjusted baseline and follow-up indices of bone strength and percent change ($\pm$ SE) in pQCT-derived measures of the distal (4%) radius after a 10-month exercise intervention in healthy young adult women with lower than average bone mass (per protocol data, $n = 22$) $p =$ between-group difference for percentage change univariate ANCOVA (Age and values that differed between-groups at baseline were applied as covariates)

Parameter	IT (n = 10)			RT (n = 12)			
	Baseline	Follow-up	% Change	Baseline	Follow-up	% Change	p
Dominant							
Total content (mg)	74.94 ± 2.52	78.59 ± 2.85[a]	4.95 ± 1.88 [×]	80.83 ± 2.28	84.12 ± 2.57[a]	4.14 ± 1.70 [×]	0.763
Total density (mg/cm^3)	301.83 ± 15.63	316.11 ± 12.94	5.26 ± 3.19 [×]	307.35 ± 14.13	310.91 ± 11.70	2.04 ± 2.89	0.484
Total area (mm^2)	252.07 ± 13.05	250.90 ± 9.52	0.15 ± 2.75	267.23 ± 11.80	271.69 ± 8.61	2.74 ± 2.48	0.513
Trabecular content (mg)	33.59 ± 2.21	33.57 ± 1.84	0.66 ± 3.98	37.03 ± 1.99	38.17 ± 1.67	4.36 ± 3.60	0.520
Trabecular density (mg/cm^3)	188.69 ± 7.17	191.65 ± 7.36	1.80 ± 1.23 [×]	194.17 ± 6.48	196.71 ± 6.65	1.28 ± 1.11 [×]	0.769
Trabecular area (mm^2)	180.61 ± 11.82	177.04 ± 8.61	-1.11 ± 3.70	191.68 ± 10.68	194.11 ± 7.78	3.04 ± 3.35	0.439
Total BSI (g^2/cm^4)	0.23 ± 0.02	0.25 ± 0.02	10.16 ± 4.94 [×]	0.25 ± 0.01	0.02 ± 0.18	6.69 ± 4.47 [×]	0.626
Trabecular BSI (g^2/cm^4)	0.06 ± 0.01	0.06± 0.01	2.17 ± 5.72	0.07 ± 0.01	0.08 ± 0.01	4.68 ±5.17	0.760
Non-Dominant							
Total content (mg)	72.68 ± 2.34[b]	76.57 ± 2.86[a,b]	5.11 ± 1.50 [×]	82.84 ± 2.12[b]	84.82 ± 2.58[b]	2.50 ± 1.35 [×]	0.227
Total density (mg/cm^3)	287.15 ± 15.34	310.69 ± 15.07[a]	8.55 ± 2.26 [c×]	315.10 ± 13.87	319.11 ± 13.63	1.50 ± 2.04[c]	0.040
Total area (mm^2)	257.28 ± 12.65	249.25 ± 12.33	-2.96 ± 3.09 [×]	266.71 ± 11.43	269.54 ± 11.15	1.53 ± 2.79	0.319
Trabecular content (mg)	34.13 ± 1.72	32.98 ± 1.90	-3.05 ± 4.17	38.46 ± 1.56	38.47 ± 1.72	0.51 ± 3.77	0.555
Trabecular density (mg/cm^3)‡	194.91 ± 0.00	198.67 ± 1.76[a,b]	1.86 ± 0.90 [c×]	194.91 ± 0.00	192.36 ± 1.57[b]	-1.30 ± 0.81[c×]	0.029
Trabecular area (mm^2)	186.78 ± 11.42	177.56 ± 10.84	-4.53 ± 3.83 [×]	191.40 ± 10.33	192.84 ± 9.80	1.42 ± 3.47	0.287
Total BSI (g^2/cm^4)	0.21 ± 0.02[b]	0.24 ± 0.02[a]	15.35 ± 2.83 [c×]	0.26 ± 0.01[b]	0.27 ± 0.02	2.67 ± 2.55[c]	0.005
Trabecular BSI (g^2/cm^4)‡	0.07 ± 0.00	0.07 ± 0.00	0.47 ± 5.96	0.07 ± 0.00	0.07 ± 0.00	-0.09 ± 5.31	0.951

[a] Within-group based on adjusted mean difference ($p < 0.05$)

[b] Between-group difference based on adjusted values ($p < 0.05$)

[c] Between-group differences based on adjusted percent change ($p < 0.05$)

‡ Baseline value used as covariate in analysis

[×] Change observed greater than %CV for given variable

Table 3. Adjusted baseline and follow-up indices of bone strength and percent change ($\pm$ SE) in pQCT-derived measures of the proximal (66%) radius after a 10-month exercise intervention in healthy young adult women with lower than average bone mass (per protocol data, $n = 22$) $p =$ between-group difference for percentage change univariate ANCOVA (Age and values that differed between-groups at baseline were applied as covariates)

Parameter	IT (n = 10)			RT (n = 12)			
	Baseline	Follow-up	% Change	Baseline	Follow-up	% Change	p
Dominant							
Cortical content (mg)	78.38 ± 2.47	78.55 ± 2.63	0.26 ± 1.26	79.38 ± 2.24	80.46 ± 2.38	1.54 ± 1.14	0.483
Cortical density (mg/cm^3)	1127.95 ± 14.34	1127.75 ± 13.26	-0.01 ± 0.60	1107.74 ± 12.97	1116.36 ± 11.99	0.83 ± 0.54 ˣ	0.334
Cortical area (mm^2)	69.38 ± 1.87	69.57 ± 1.88	0.28 ± 1.18	71.47 ± 1.69	71.90 ± 1.70	0.71 ± 1.07	0.797
Cortical thickness (mm)	2.37 ± 0.11	2.37 ± 0.12	-0.08 ± 1.22	2.35 ± 0.10	2.35 ± 0.11	-0.31 ± 1.10	0.895
Periosteal circumference (mm)	36.86 ± 1.05	36.97 ± 1.03	0.32 ± 1.05	38.27 ± 0.95	38.60 ± 0.93	0.94 ± 0.95 ˣ	0.680
Endocortical circumference (mm)	21.96 ± 1.60	22.07 ± 1.67	0.54 ± 1.99	23.51 ± 1.44	23.85 ± 1.51	1.36 ± 1.80	0.775
Polar section modulus (mm^2)	253.21 ± 13.37	256.77 ± 12.93	1.35 ± 1.75	269.97 ± 12.09	266.83 ± 11.69	-0.96 ± 1.58	0.363
Weighted polar section modulus (mm^3)	236.14 ± 11.47	237.86 ± 11.67	0.87 ± 2.02	243.45 ± 10.37	244.22 ± 10.55	0.47 ± 1.83	0.892
Non-Dominant							
Cortical content (mg)	78.26 ± 2.80	79.49 ± 2.15	1.75 ± 2.51	80.98 ± 2.53	83.61 ± 1.94[a]	4.27 ± 2.27 ˣ	0.486
Cortical density (mg/cm^3)	1126.96 ± 16.61	1130.98 ± 12.08	0.40 ± 0.84	1101.05 ± 15.02	1130.58 ± 10.92[a]	2.78 ± 0.76 ˣ	0.059
Cortical area (mm^2)	69.40 ± 2.00	70.25 ± 1.62	1.36 ± 1.91	73.34 ± 1.81	73.94 ± 1.47	1.35 ± 1.73	0.995
Cortical thickness (mm)	2.39 ± 0.12	2.42 ± 1.11	1.38 ± 1.27	2.41 ± 0.11	2.47 ± 0.10[a]	2.84 ± 1.15 ˣ	0.427
Periosteal circumference (mm)	36.83 ± 1.05	36.96 ± 0.95	0.32 ± 1.04	38.41 ± 0.95	38.07 ± 0.86	-0.72 ± 0.94 ˣ	0.491
Endocortical circumference (mm)	21.85 ± 1.62	21.76 ± 1.56	-0.68 ± 1.61	23.25 ± 1.47	22.54 ± 1.41	-2.59 ± 1.46 ˣ	0.413
Polar section modulus (mm^2)	250.58 ± 15.50	252.19 ± 14.78	0.74 ± 2.59	270.50 ± 14.01	268.12 ± 13.36	-0.15 ± 2.35	0.809
Weighted polar section modulus (mm^3)	231.07 ± 12.60	235.05 ± 12.65	1.73 ± 3.25	237.28 ± 11.39	247.30 ± 11.43[a]	5.47 ± 2.94 ˣ	0.427

[a] Within-group based on adjusted mean difference ($p < 0.05$)

ˣ Change observed greater than %CV for given variable

Table 4. Adjusted baseline and follow-up femoral neck morphology and percent change ($\pm$ SE) in DXA-derived 3D hip outcomes after a 10-month exercise intervention in healthy young adult women with lower than average bone mass (per protocol data, $n = 22$) $p =$ between-group difference for percentage change univariate ANCOVA (Age and values that differed between-groups at baseline were applied as covariates)

Parameter	IT (n = 10)			RT (n = 12)			
	Baseline	Follow-up	% Change	Baseline	Follow-up	% Change	p
Dominant							
FN aBMD (g/cm^2)	0.857 ± 0.025	0.878 ± 0.019	2.80 ± 1.78	0.847 ± 0.023	0.882 ± 0.017[a]	4.30 ± 1.61	0.559
FN trabecular BMC (g)	2.83 ± 0.36	2.05 ± 0.10	-10.74 ± 5.86[b] ×	1.84 ± 0.32	2.15 ± 0.09	9.64 ± 5.29[b] ×	0.024
FN cortical BMC (g)‡	1.06 ± 0.00	0.99 ± 0.08	-1.88 ± 5.27	1.06 ± 0.00	0.99 ± 0.07	-1.96 ± 4.72	0.992
FN total BMC (g)	4.06 ± 0.44	3.03 ± 0.14	-11.15 ± 5.77[b] ×	2.76 ± 0.40	3.14 ± 0.13	8.06 ± 5.22[b] ×	0.030
FN trabecular volume (cm^3)	10.83 ± 1.37	7.92 ± 0.54	-7.90 ± 6.33 ×	7.36 ± 1.24	8.67 ± 0.49	9.26 ± 5.73 ×	0.071
FN cortical volume (cm^3)‡	1.72 ± 0.00	1.58 ± 0.12	-3.64 ± 5.96	1.72 ± 0.00	1.66 ± 0.11	-1.91 ± 5.36	0.845
FN total volume (cm^3)	12.70 ± 1.46	9.53 ± 0.62	-8.44 ± 6.12 ×	8.95 ± 1.32	10.30 ± 0.56	7.91 ± 5.53 ×	0.075
FN trabecular vBMD (g/cm^3)	0.26 ± 0.01	0.27 ± 0.01	1.18 ± 4.17	0.25 ± 0.01	0.25 ± 0.01	-0.44 ± 3.77	0.787
FN cortical vBMD (g/cm^3)	0.65 ± 0.02	0.61 ± 0.01[a]	-4.14 ± 2.20[b] ×	0.59 ± 0.02	0.61 ± 0.01	3.68 ± 1.99[b] ×	0.021
FN total vBMD (g/cm^3)	0.33 ± 0.01	0.33 ± 0.01	0.40 ± 3.38	0.31 ± 0.01	0.31 ± 0.01	-0.49 ± 3.05	0.855
FN cortical thickness (mm)	1.14 ± 0.05	1.10 ± 0.05	-3.10 ± 5.51	1.08 ± 0.05	1.07 ± 1.05	-1.07 ± 4.98	0.599
Non-Dominant							
FN aBMD (g/cm^2)	0.874 ± 0.026	0.886 ± 0.017	1.89 ± 1.86	0.875 ± 0.024	0.893 ± 0.016	2.23 ± 1.68	0.901
FN trabecular BMC (g)	2.02 ± 0.14	2.01 ± 0.12	-1.46 ± 3.52	1.98 ± 0.12	2.05 ± 0.11	3.92 ± 3.18	0.627
FN cortical BMC (g)	0.85 ± 0.07	0.87 ± 0.07	2.34 ± 6.83	1.00 ± 0.06	1.00 ± 0.06	0.59 ± 6.18	0.859
FN total BMC (g)	2.87 ± 0.18	2.88 ± 0.18	0.39 ± 2.55	2.98 ± 0.16	3.05 ± 0.16	2.50 ± 2.31	0.567
FN trabecular volume (cm^3)	7.72 ± 0.59	7.90 ± 0.61	4.55 ± 4.73 ×	8.53 ± 0.53	8.50 ± 0.55	-0.76 ± 4.28	0.439
FN cortical volume (cm^3)	1.39 ± 0.12	1.41 ± 0.12	2.19 ± 6.15	1.64 ± 0.11	1.59 ± 0.11	-2.31 ± 5.56	0.612
FN total volume (cm^3)	9.11 ± 0.68	9.31 ± 0.71	3.73 ± 4.41 ×	10.17 ± 0.61	10.08 ± 0.64	-1.04 ± 3.99	0.454
FN trabecular vBMD (g/cm^3)	0.27 ± 0.01	0.26 ± 0.01	-1.13 ± 4.27	0.23 ± 0.01	0.24 ± 0.01	4.96 ± 3.87 ×	0.327
FN cortical vBMD (g/cm^3)	0.62 ± 0.02	0.62 ± 0.02	0.05 ± 2.38	0.61 ± 0.02	0.63 ± 0.01	3.10 ± 2.15 ×	0.375
FN total vBMD (g/cm^3)	0.32 ± 0.01	0.31 ± 0.01	-1.57 ± 3.33	0.29 ± 0.01	0.31 ± 0.01	3.86 ± 3.01 ×	0.264
FN cortical thickness (mm)	0.97 ± 0.05	0.95 ± 0.05	-1.05 ± 5.20	1.08 ± 0.05	1.05 ± 0.05	-1.94 ± 4.70	0.905

[a] Within-group based on adjusted mean difference ($p < 0.05$)

[b] Between-group differences based on adjusted percent change ($p < 0.05$)

‡ Baseline value used as covariate in analysis

× Change observed greater than %CV for given variable

Table 5. Adjusted baseline and follow-up indices of bone strength and percent change (± SE) in pQCT-derived measures of the distal (4%) tibia after a 10-month exercise intervention in healthy young adult women with lower than average bone mass (per protocol data, $n = 22$) $p =$ between-group difference for percentage change univariate ANCOVA (Age and values that differed between-groups at baseline were applied as covariates)

Parameter	IT (n = 10)			RT (n = 12)			
	Baseline	Follow-up	% Change	Baseline	Follow-up	% Change	p
Dominant							
Total content (mg)	240.10 ± 9.19	247.01 ± 9.35[a]	3.00 ± 0.85[b] ×	234.95 ± 8.31	234.58 ± 8.45	-0.18 ± 0.77[b]	0.016
Total density (mg/cm^3)	280.67 ± 10.36	286.02 ± 10.98[a]	1.93 ± 0.83 ×	280.07 ± 9.37	282.13 ± 9.92	0.72 ± 0.75	0.317
Total area (mm^2)	857.19 ± 34.26	863.73 ± 32.69	1.19 ± 1.26	846.93 ± 30.98	840.02 ± 29.55	-0.87 ± 1.14	0.263
Trabecular content (mg)	164.48 ± 7.79	167.44 ± 7.86	2.08 ± 1.44	157.10 ± 7.04	154.15 ± 7.10	-1.88 ± 1.30	0.067
Trabecular density (mg/cm^3)	236.21 ± 8.93	238.65 ± 9.39	1.04 ± 0.61 ×	230.42 ± 8.07	228.71 ± 8.49	-0.75 ± 0.55 ×	0.052
Trabecular area (mm^2)	697.49 ± 29.86	701.78 ± 29.03	1.09 ±1.38	686.74 ± 27.00	679.50 ± 26.25	-1.14 ± 1.25	0.270
Total BSI (g^2/cm^4)	0.68 ± 0.04	0.71 ± 0.04[a]	5.16 ± 1.13[b] ×	0.66 ± 0.04	0.66 ± 0.04	0.37 ± 1.02[b]	0.008
Trabecular BSI (g^2/cm^4)	0.39 ± 0.03	0.41 ± 0.03	3.93 ± 1.76[b] ×	0.36 ± 0.03	0.35 ± 0.03	-2.84 ± 1.59[b] ×	0.014
Non-Dominant							
Total content (mg)	243.54 ± 8.71	247.51 ± 9.14[a]	1.59 ± 0.75	238.61 ± 7.88	238.48 ± 8.26	-0.09 ± 0.68	0.131
Total density (mg/cm^3)	289.72 ± 10.92	290.57 ± 11.55	0.32 ± 0.45	278.92 ± 9.87	281.08 ± 10.44	0.71 ± 0.41	0.549
Total area (mm^2)	844.85 ± 33.91	854.45 ± 35.90	1.29 ± 0.80	864.40 ± 30.66	859.29 ± 32.46	-0.77 ± 0.72	0.084
Trabecular content (mg)	163.68 ± 7.70	167.50 ± 7.97	2.52 ± 1.22[b] ×	160.73 ± 6.96	157.84 ± 7.20	-1.94 ± 1.10[b]	0.018
Trabecular density (mg/cm^3)	239.76 ± 8.82	242.42 ± 8.91[a]	1.22 ± 0.55[b] ×	231.05 ± 7.98	229.11 ± 8.06	-0.82 ± 0.50[b] ×	0.017
Trabecular area (mm^2)	685.12 ± 30.27	692.42 ± 31.81	1.28 ± 0.92	701.55 ± 27.37	695.17 ± 28.76	-1.14 ± 0.83	0.079
Total BSI (g^2/cm^4)	0.71 ± 0.04	0.72 ± 0.04	1.95 ± 0.97	0.67 ± 0.04	0.67 ± 0.04	0.79 ± 0.87	0.408
Trabecular BSI (g^2/cm^4)	0.40 ± 0.03	0.41 ± 0.03	3.57 ± 1.63[b]	0.37 ± 0.02	0.36 ± 0.03	-3.15 ± 1.48[b]	0.009

[a] Within-group based on adjusted mean difference ($p < 0.05$)

[b] Between-group differences based on adjusted percent change ($p < 0.05$)

× Change observed greater than %CV for given variable

Table 6. Adjusted baseline and follow-up indices of bone strength and percent change (± SE) in pQCT-derived measures of the tibial shaft (38%) after a 10-month exercise intervention in healthy young adult women with lower than average bone mass (per protocol data, $n = 22$) p = between-group difference for percentage change univariate ANCOVA (Age and values that differed between-groups at baseline were applied as covariates)

Parameter	IT (n = 10)			RT (n = 12)			p
	Baseline	Follow-up	% Change	Baseline	Follow-up	% Change	
Dominant							
Cortical content (mg)	280.80 ± 10.21	283.11 ± 10.43	0.82 ± 0.42 ×	271.30 ± 9.23	276.30 ± 9.43	1.83 ± 0.38 ×	0.103
Cortical density (mg/cm^3)	1169.66 ± 6.15	1168.48 ± 6.02	-0.09 ± 0.30	1169.78 ± 5.56	1174.37 ± 5.44	0.39 ± 0.27 ×	0.259
Cortical area (mm^2)	240.37 ± 9.20	242.48 ± 9.30	0.93 ± 0.59 ×	231.94 ± 8.32	235.35 ± 8.41[a]	1.44 ± 0.53 ×	0.546
Cortical thickness (mm)	5.04 ± 0.16	5.08 ± 0.15[a]	0.94 ± 0.41 ×	4.87 ± 0.14	4.92 ± 0.14[a]	0.96 ± 0.37 ×	0.971
Periosteal circumference (mm)	63.40 ± 1.25	63.55 ± 1.28	0.23 ± 0.25 ×	63.06 ± 1.13	63.43 ± 1.16[a]	0.59 ± 0.23 ×	0.313
Endocortical circumference (mm)	31.75 ± 1.26	32.46 ± 1.14	-0.48 ± 0.28	32.46 ± 1.14	32.54 ± 1.18	0.24 ± 0.25	0.084
Polar section modulus (mm^2)	1285.41 ± 71.54	1291.81 ± 73.48	-0.60 ± 0.97	1248.27 ± 64.68	1275.23 ± 66.44[a]	2.08 ± 0.87 ×	0.293
Weighted polar section modulus (mm^3)	1246.67 ± 66.53	1255.10 ± 69.42	0.69 ± 0.81	1215.98 ± 60.15	1246.33 ± 62.77[a]	2.43 ± 0.73 ×	0.146
Non-Dominant							
Cortical content (mg)	279.76 ± 10.92	282.76 ± 10.60[a]	1.15 ± 0.49 ×	281.89 ± 9.88	281.97 ± 9.88	0.08 ± 0.45	0.141
Cortical density (mg/cm^3)	1165.42 ± 5.70	1169.02 ± 6.22	0.31 ± 0.24 ×	1163.86 ± 5.15	1172.61 ± 5.62[a]	0.75 ± 0.22 ×	0.206
Cortical area (mm^2)	240.34 ± 9.92	242.16 ± 9.67	0.84 ± 0.66 ×	242.30 ± 8.97	240.60 ± 8.74	-0.66 ± 0.59 ×	0.121
Cortical thickness (mm)	5.05 ± 0.16	5.08 ± 0.15	0.68 ± 0.55 ×	5.02 ± 0.14	4.99 ± 0.13	-0.51 ± 0.50	0.144
Periosteal circumference (mm)	63.27 ± 1.33	63.44 ± 1.32	0.28 ± 0.24 ×	64.17 ± 1.20	64.01 ± 1.20	-0.25 ± 0.22 ×	0.137
Endocortical circumference (mm)	31.56 ± 1.24	31.54 ± 1.23	-0.08 ± 0.31	32.66 ± 1.12	32.67 ± 1.12	0.06 ± 0.28	0.753
Polar section modulus (mm^2)	1262.29 ± 75.23	1274.45 ± 74.15	1.18 ± 0.99 ×	1307.26 ± 68.20	1286.63 ± 67.04	-1.50 ± 0.89 ×	0.070
Weighted polar section modulus (mm^3)	1217.30 ± 69.31	1236.85 ± 71.66	1.70 ± 0.80 ×	1254.24 ± 62.67	1249.07 ± 64.79	-0.47 ± 0.73	0.072

[a] Within-group based on adjusted mean difference ($p < 0.05$)
× Change observed greater than %CV for given variable

Highlights

- Impact training and resistance training resulted in differing site-specific effects

- Impact training provided a superior bone response at the distal segment of the radius and tibia

- Resistance training had a greater effect on the hip and the shaft of the radius and tibia

- Impact training produced a greater response in trabecular bone, while resistance training preferentially improved cortical bone
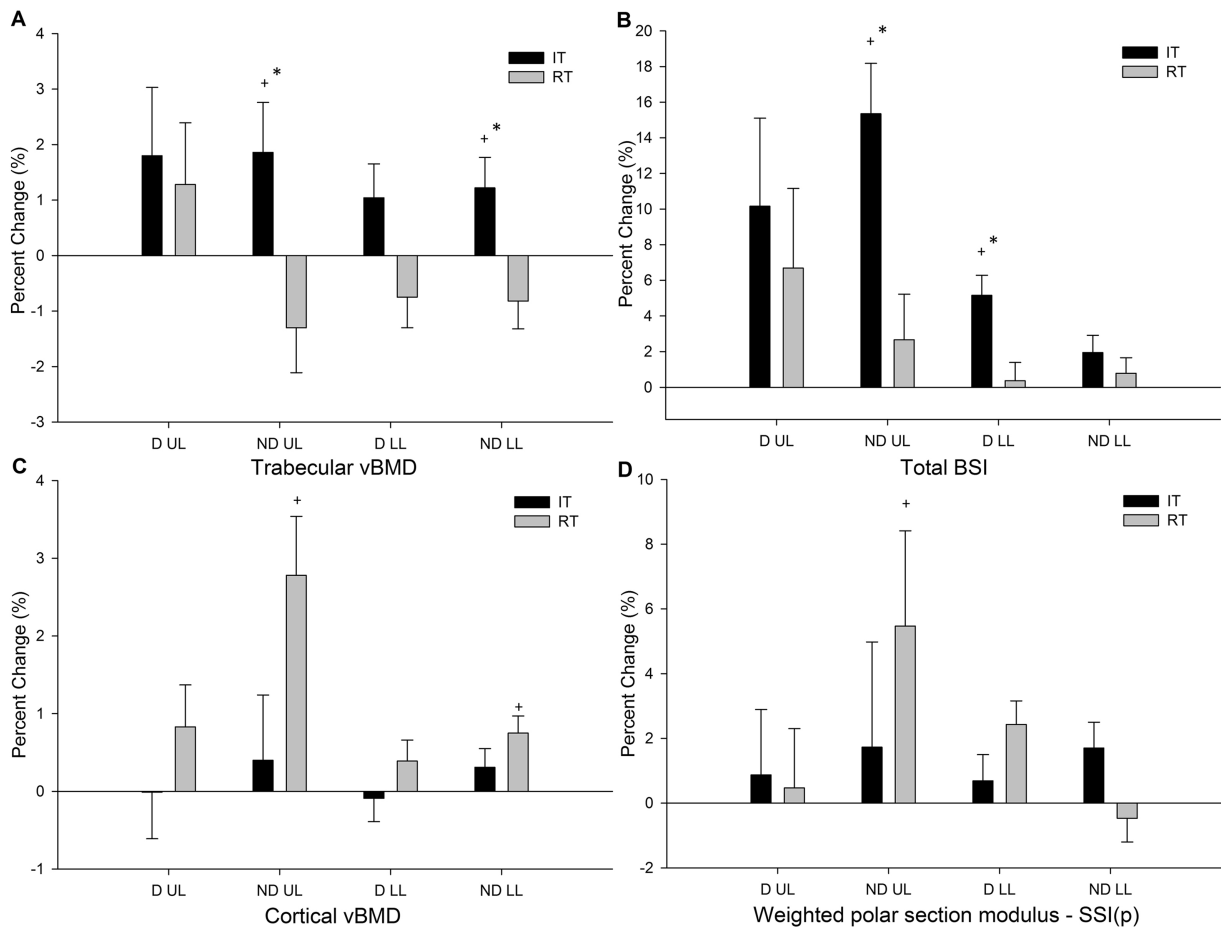
Figure 1