COMPARISON OF TIBIAL GEOMETRY, DENSITY AND STRENGTH BETWEEN ADULT FEMALE DANCERS, GYMNASTS AND RUNNERS

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Dedication

This dissertation is dedicated to my daughter Isabel and my husband Leandro Ribeiro for their love, support, and patience during the completion of my Doctorate studies and to my parents, who taught me the value of education.

Abstract

Physical activity has a site-specific osteogenic effect that is known to positively improve bone health (Schoenau, 2006, Greene, 2006, Uusi-Rasi, 2006). The effect of dancing on bone health has received sparse attention and the extent of the osteogenic effect of dancing is not known. Given that dancing may be considered a medium impact activity, one would expect that the magnitude of its osteogenic effect might be between those of high impact activities such as gymnastics and cyclic low impact activities like running with the most pronounced effects in the weight bearing bones such as the tibia and femur. Thus, the purpose of this study is to compare the osteogenic effects of dance, gymnastics and middle/long-distance running in adult females, as measured by tibial geometry, density, and strength.

Methods: Eleven dance majors and eleven collegiate gymnasts (ages 18-22) were recruited for the study. Runner (n=22) and control (n=19) data were obtained from the UM Laboratory of Musculoskeletal Health database (Smock et al., 2009 and Bruininks, 2009). The control subjects were young adult, sedentary females. Total cross-sectional area (ToA) was measured by peripheral quantitative computed tomography (pQCT) at the tibia (4% and 66% from its distal end); total volumetric bone mineral density (vBMD) and bone strength index (BSI) were measured at the 4% site. Polar strength-strain index (SSIp) was measured at the 66% site.

Results: After controlling for height and body mass, the distal and proximal cross-sectional areas of the tibia (ToA 4%, ToA 66%) and SSIp did not differ significantly between groups. However, total vBMD was significantly higher for dancers and gymnasts when compared to controls (p=0.01 and p=0.02, respectively). In addition, BSI was significantly higher for dancers, gymnasts, and runners when compared to controls (p=0.001, p<0.001, and p=0.03, respectively). Participants did not differ in age, weight or tibial length, assuring that the samples were not biased with respect to age and anthropometrics.

Conclusion: The current results suggest that dance and gymnastics have the greatest osteogenic effects at the tibia in eumenorrheic adult females, followed by middle-long distance running, when compared to sedentary healthy controls.

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Introduction

Osteoporosis is defined as reduced bone density leading to reduced bone strength and greater fracture risk (Glaser and Kaplan, 1997). There is growing consensus that osteoporosis is best assessed with measures of bone strength and quality of bone (structural and material properties) rather than bone mass alone (Felsenberg and Boonen, 2005). Bones adapt to mechanical loads by optimizing their structural stiffness via architectural and densitometric changes rather than by just adding mass; therefore increased dynamic strains[1] increase bone strength primarily by changes in bone geometry (Schoenau, 2006), architecture, and density at weight-bearing sites (To et al., 2005, Nichols et al., 2007, Hinrichs et al., 2010, Kemper et al., 2000, Bemben et al., 2004, Mudd et al., 2007, Smock et al., 2009, Nikander et al., 2010). These changes are primarily reflected in differences in spatial distribution of material (Cointry et al., 2004), size, cortical thickness and porosity (Seeman, 2003).

Osteoporosis prevention starts with participation in weight-bearing exercise during the pre and early pubertal years, which provides the greatest gains in bone strength. Physically active adolescents in the Saskatchewan Pediatric Bone Mineral Accrual Study (PBMAS) had greater bone mineral accrual than their less active peers by up to 17%, which indicates that the pre and early pubertal periods represent a critical window to enhance bone accrual and peak bone mass (Bailey, 1999). These changes have been shown to perpetuate into

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[1] Strain or deformation is equal to the change in length divided by the original length.

early adulthood and beyond (Baxter-Jones et al., 2008, Kemper et al., 2000, Ducher et al., 2009). As an example, eumenorrheic retired gymnasts (Ducher et al., 2009) exhibited tibial and lumbar spine bone mineral content (BMC) and areal density (aBMD), along with increased tibial strength than inactive controls. Also, retired pre-menopausal professional adult female dancers (mean age 36 years old) had greater femoral neck aBMD *z*-scores when compared to amenorrheic dancers and the normal population (Keay, et al, 1997). In addition, since periosteal expansion continues to occur after cessation of linear growth (Petit et al., 2004); determining which types of physical activities promote the greatest gains in bone health (bone strength and its densitometric and geometric underpinnings) has also practical importance in the prevention of osteoporosis.

Since changes in bone geometry, density and strength depend on the type of loading, loading magnitude and loading frequency provided by different types of physical activity, it is important to understand how their osteogenic effects differ in order to potentially prevent osteoporosis (NIH, 2001, Felsenberg and Boone, 2005, Friedman 2006). The osteogenic effects of repetitive low impact and high impact sports are well described in the literature and are more pronounced in the weight bearing bones such as the tibia and femur. As an example, dual x-ray absorptiometry (DXA) studies demonstrated that adolescent and young adult females that participate in high impact sports (squash, rope skipping, soccer, gymnastics, among others) have greater lower limb (femur and tibia) bone mineral areal density (aBMD) than athletes that participate in low repetitive impact sports (middle/ long distance running, cross-country), non-impact sports (swimming and diving), and controls (Heinonen et al., 1995, Petterson et al., 2000, Mudd et al., 2007, Nichols et al., 2007) and that runners have greater total body, spinal, femoral and tibial aBMD than sedentary controls (Duncan et al., 2002). Furthermore, Nikander et al. (2010), used peripheral quantitative computed tomography (pQCT) and demonstrated that adult female athletes who participate in impact sports (volleyball, soccer, tennis, endurance running, among others) have greater tibial compressive strength (bone strength index - BSI), total area (proximal tibia), and cortical area (both proximal and distal sites) than active non-athlete controls. In addition, athletes who participated in high impact sports (volleyball, hurdling, triple jump and high jump) had significantly higher total area at the distal tibia than controls.

The effect of dance on bone health has received sparse attention. Previous DXA studies of bone density in female ballet dancers of different ages indicated increased hip and femoral aBMD, adjusted femoral neck BMD (BMAD), and BMC when compared to controls (Bennell et al., 2000, Matthews et al., 2006, Buckhardt et al., 2011), but lower femoral aBMD than combat/power athletes and team athletes (Hinrichs et al. 2010). A pQCT study of adolescent dancers (To et al, 2005) indicated that bone strength index (BSI) and mean core tibia volumetric bone density (vBMD) at the distal tibia were significantly higher in dancers than in sedentary controls, but geometric benefits were not found. A summary of bone studies in dancers of different styles and ages is presented in Table 1.

Table 1. Summary of DXA and pQCT Bone Studies in Dancers

Author(s)	**Study Design**	**Outcomes**	**Conclusions**
Lichtenbelt et al. (1995)	Cross-sectional. Female ballet dancers (n=24) vs. controls (n=29) and German reference data. Mean age 22.6 years.	Total (TB), lumbar spine (LS), pelvis, leg, trunk, and arms aBMD (g/cm^2)(DXA)	Dancers↓body fat percentage No differences in fat free mass. Dancers↑TB (+ 6%) due to higher leg and pelvis BMD. TB aBMD was positively associated with BMI and negatively associated with age of menarche. Leg aBMD was significantly associated with training load (hours/day) indicating the site specific osteogenic effect of weight bearing exercise.
Heinonen et al. (1995)	Cross-sectional. Competitive female aerobic dancers (n=27), squash players (n=18) and speed skaters (n=14) vs. sedentary and active controls. Mean age of approximately 25 years.	Lumbar spine(LS), femoral neck (FN), distal femur, patella, proximal tibia, calcaneus, and distal radius of the dominant extremity aBMD (DXA)	After adjusting for weight: Dancers↑ FN aBMD (+8.5%), proximal tibia (+5.5%), and calcaneus (+13.6%). Dancers↓ radius aBMD (-7.8%) Squash players↑aBMD at all sites. Results suggest that the impacts from aerobic dance provided osteogenic benefits at weight-bearing sites when compared to sedentary controls, but the higher magnitude strains from squash playing provided the greatest benefits overall.
Khan et al. (1996)	Cross-sectional Retired female ballet dancers (n=106) to age, menstrual status, height, and weight-matched non-athletic controls and the normal population reference data. Average age 51 years.	LS, hip aBMD, and radius aBMD (DXA)	No differences in at hip or spine. History of menstrual disturbance was associated with lower BMD except at weight-bearing sites (femur). Dancers↓ radius aBMD, but that could be attributed to the selection of slender individuals in ballet. No differences in occurrence of osteopenia and osteoporosis, despite the greater prevalence of risk factors for osteoporosis in the dancers.
Keay et al. (1997)	Cross-sectional. Mostly retired premenopausal classical and contemporary dancers (n=57) vs. normal population reference data. Mean age of 36 years old and average career length of 11 years.	LS and FN aBMD (DXA)	Amenorrheic dancers ↓LS aBMD, but not FN aBMD, suggesting a site-specific protective effect of weight bearing exercise. Eumenorrheic dancers ↑ FN aBMD Age at menarche, duration of amenorrheia and difference between ideal and lowest weight were negatively associated with aBMD.

Bennell et al. (2000)	Cross-sectional. Novice female ballet dancers (n=78) vs. sedentary age and postal code-matched controls. Ages 8-11.	Bone area (cm^2), BMC (g), aBMD (g/cm^2) for TB, LS, and proximal femur. In addition, LS and FN BMAD (g/cm^3) and index of bone strength (IBS) (DXA)	After accounting for maturity, size, body composition and dietary calcium: Dancers↓upper limb area and BMC ↑ total hip aBMD (+4.5%) FN aBMD (+4.9%) FN BMAD (+6.7%) No differences in any of the LS parameters. No differences in BMD at upper limb, lower limb or TB. The mechanical loading provided by dance explained the site-specific differences.
Matthews et al. (2006)	Longitudinal. Female ballet dancers (n=82) to active controls (n=61). Ages 8-11 for three years.	Bone mineral content (BMC) and TB aBMD (DXA)	After adjusting for growth and maturation: Dancers↑TB, LS, FN and lower limbs BMC Since prepuberty, dancers↑ BMC (+4%) and maintained this advantage over time. The results suggest site and maturity-specific effects of mechanical loading on bones.
Hinrichs et al. (2010)	Cross-sectional Collegiate aged female ballet dancers (n=13) vs. middle-long distance runners (n=16), cyclists (n=4), triathletes (n=4), power/combat athletes (n=17), team sport athletes (n=37), sports students (n=82) and untrained controls (n=36). Ages 17-30 years.	Mean LS, mean femur aBMD (DXA)	Ballet dancers ↓ LS aBMD Non-athletes, dancers and endurance athletes ↓ BMD Power/combat and team athletes ↑ BMD Their results suggest that high impact activities provide greater osteogenic benefits than medium, low, repetitive, and non-impact ones.
Buckhardt et al. (2011)	Cross-sectional. Pre-professional female ballet dancers (n=127) vs. UK reference data. Ages 15-18.	LS and FN BMAD (adjusted BMD) (DXA)	Dancers↓mean LS BMAD ↑ mean FN BMAD, despite their low BMI. There was a positive correlation between BMAD and years since menarche, indicating the importance of exposure to estrogens.
To et al. (2005)	Cross-sectional. Chinese dancers (n=35) of different modalities (Chinese dance, classical ballet, modern dance, or musical theater) vs. sedentary controls (n=35) Ages 17-19.	LS and hip aBMD (DXA) Tibial vBMD (total and core – 50% of bone area), cortical thickness (CoTh), and BSI (pQCT).	Dancers ↑ LS and FN aBMD ↑distal tibia core vBMD ↑distal tibia BSI No differences in total vBMD and CoTh. The osteogenic advantage of dance training was lost on oligo/amenorrheic dancers.

The extent of the osteogenic effect of dance on tibial geometry, density and strength in young adult female dancers in comparison to other sports is also not known. Based on reported peak ground reaction forces (GRF) of commonly performed dance jumps - 6 body weights (BW) - dancing may be considered a medium impact activity (Chockley, 2008, Kulig et al., 2011, Walter et al., 2011). Therefore, one would expect that the magnitude of its osteogenic effect might be between those of high impact activities such as gymnastics - peak GRF up to 9 times BW (Burt et al., 2010) - and cyclic/ repetitive low impact activities like middle/long-distance running (peak GRF of less than 3 BW - Janz, et al., 2003).

Assessing Bone Geometry, Density and Strength

Bones are subjected to axial compressive forces, shear forces, and bending forces. In long bones, the spatial distribution of bone mass along the neutral bending axis is critical for its bending strength/ cross-sectional moment of inertia [2](CSMI) (Greene at al., 2005). In order to increase CSMI, it is best to increase the distance from the bone mass from the neutral axis; thus increased periosteal and endosteal apposition (changes in geometry) will result in greater contributions to bone bending strength (Greene et al., 2005). In order to assess bone strength, it is necessary to observe material and structural (geometry) parameters (Petit et al., 2004), as well as bone mineral density, which provides a surrogate of bone material properties and is an important component of bone compressive strength (Petit et al., 2005).

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[2] CSMI = $\pi/2*$ (outer radius^4 – inner radius^4)

Dual x-ray absorptiometry (DXA) provides bone mineral content (BMC, g) and bone mineral areal density [3]outcomes (aBMD, g/cm^2) without differentiating between cortical and trabecular bone (Rauch and Schoenau, 2001). Its outcomes are influenced by bone size; therefore small changes in mass distribution such as increased periosteal diameters may reduce BMD results by dividing the existing bone mass by an increased area (Petit et al., 2005). Clinically, DXA *t*-scores are used as criteria to define osteoporosis[4] (Glaser and Kaplan, 1997), but are not sufficient to assess bone strength and geometry. Newer technology provided by peripheral quantitative computed tomography (pQCT) can assess bone size and geometry in three dimensions and allows one to analyze cortical and trabecular bone separately (Schoenau, 2006), while providing estimates of bone strength and reflecting the effects of mechanical loading on weight-bearing bones.

Bone geometric outcomes provided by pQCT include total cross-sectional area (mm^2), cortical area (mm^2), and cortical thickness (mm) and they are important in explaining how bone adapts to mechanical stimuli, since the distribution of bone mass greatly affects strength outcomes. Bone densitometric outcomes provided by pQCT include total volumetric bone density (vBMD) and trabecular vBMD. Volumetric bone density is measured in fixed width slices but provides a three-dimensional picture of bone density instead of a two-dimensional picture as provided by DXA.

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[3] Mineral mass divided by the area (Rauch and Schoenau, 2001)

[4] Bone density values of 2.5 standard deviations or more below the healthy population reference mean.

Bone strength estimates provided by pQCT include a Bone Strength Index (BSI) and Strength Strain Index (SSIp). BSI is calculated as the product between total cross-sectional area (ToA, mm^2) and total density squared ([ToD, $mg/cm^3]^2$). In human tibias (Kontulainen et al., 2008), BSI at the 4% metaphyseal site predicted 85% of the variance in failure load and 57% of the variance in stiffness. Also, when compared to other variables (trabecular and cortical area, and mineral content in each compartment), BSI was the best predictor of tibial failure load and stiffness. Since it does not take into consideration the effect of strain rate, it is only an estimate of bone compressive strength that captures the contribution of bone mineral mass to bone strength (Kontulainen et al., 2008). The Strength Strain Index (SSIp) is a density-weighted measure of bone strength at the midshaft or proximal end of bones. It is the polar moment of inertia[5] of the cortical bone area divided by the maximum distance to the bending axis (Petit et al., 2005).

Physical Activity and Bone Adaptations

Bones will adapt to optimize their structures and material properties to withstand loading (Wolff, 1986). Frost's *mechanostat theory* described a negative feedback mechanism that increases bone strength when a modeling threshold is achieved and that removes bone when levels below the remodeling threshold are achieved (Frost, 2001); therefore bone adaptations would be primarily driven by mechanical strain magnitude. In addition, Skerry (2006) suggested that the skeleton responds to "strain magnitude, rate, frequency, rest periods, subsequent

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[5] Sum of the moment of inertia in the x and y axes – in mm^4.

loading events, and to some extent duration or number of cycles of loading, and their timing of application as one or more events per day" (Skerry, 2006, p. 125). This has been demonstrated in animal models where dynamic compressive loads, but not static loads, increased avian ulnar cross sectional area (primarily by periosteal apposition) (Lanyon and Rubin, 1984). A small number of jumps per day (strain events) increased bone mass, cortical area, and strength at the femur and tibia in immature female rats, but more jumps did not produce significant additional benefits (Umemura et al., 1997).

Recent research has shown that physical activity has a site-specific osteogenic effect on bone (Schoenau, 2006, Greene, 2006, Uusi-Rasi, 2006). The magnitude, frequency, and patterns of mechanical loading are important factors in how the bone changes its biomechanical properties, with weight bearing, high-impact activities, promoting the greatest benefits in site-specific bone mineral areal density (aBMD) (Petterson et al., 2000, Greene et al., 2005, Deriaz et al., 2010, Nichols, 2007, Duncan et al., 2002, To et al., 2005), vBMD (Greene et al., 2005, Ward et al., 2005), cortical area (Ducher, 2009), and bone strength index (BSI) (Smock et al., 2009, Greene et al., 2005, To et al, 2005, Ward et al., 2005, Uusi-Rasi et al., 2006) in females of different ages. Overall, for adolescent and adult female athletes, high impact physical activity is known to promote greater gains in bone strength than repetitive low impact activity (Nichols et al., 2007, Uusi-Rasi et al., 2006, Nikander et al. 2010).

The importance of the type of mechanical loading has been demonstrated by many authors. Nichols et al. (2007) found that eumenorrheic high school athletes in high/odd impact sports (soccer, softball, volleyball, tennis, lacrosse, and track sprinters) had significantly greater hip and trochanter aBMD than athletes in repetitive/non-impact sports (swimming, cross-country, and track distance running), after adjusting for age, BMI, and gynecological age. As a recent example, Nikander et al. (2010) divided sports and their associated mechanical loading types into five categories[6] and assessed tibial geometry and strength using pQCT. They found that the adult females in the high impact exercise group had greater tibial total cross-sectional area (ToA) at the 5% and 50% sites, cortical area (CoA) at the 5% site, BMC at the 5 and 50% sites, and density-weighed polar section modulus (BSI) at the 5% and 50% sites than controls. Females in the repetitive low impact group had greater ToA at the 50% sites, CoA at the 5% site, and BSI at the 5% and 50% sites than controls.

Participation in gymnastics has been associated with geometric, densitometric and strength benefits at the tibia. This is demonstrated by greater total bone volumetric density at the distal tibia (10mm proximal to the distal surface of the distal metaphysis) in pre-pubertal competitive gymnasts of both sexes versus school children (Ward et al., 2005); cortical thickness and SSIp at

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[6] High-impact (maximal vertical jumps), odd-impact (rapid turns and stops), high-magnitude (maximally applied muscle forces in slow coordinated movements), repetitive low-impact (long-lasting running performances), and repetitive non-impact (long lasting performances with applied muscle forces but without ground impacts). High-impact was represented by volleyball, hurdling, triple jump and high jump, odd-impact by soccer and racket games, high-magnitude by powerlifting, repetitive low-impact by endurance running, and repetitive non-impact by swimming.

the tibia (38% site) in premenarcheal rhythmic gymnasts versus controls (Tournis et al., 2010), and increased total body, lumbar spine, pelvis and leg aBMD in adult female collegiate athletes when compared to athletes in low/ no-impact sports (Mudd et al., 2007). The osteogenic benefits at the tibia in adult female middle/ long-distance runners were described by Smock et al. (2009). At the 4% site, runners had greater BSI and total area than inactive healthy controls, but did not differ in total vBMD from them. At the 66% site, runners had greater SSIp, total area, cortical area and cortical thickness than controls. When compared to female gymnasts, division I collegiate middle/ long-distance runners had lower aBMD at the lumbar spine, pelvis and leg (Mudd et al. 2007) and female adult cross-country runners had significantly lower aBMD at the hip and femur (Bemben et al., 2004). Previous studies of bone density in female ballet dancers using DXA indicated that novice pre and early pubertal ballet dancers had greater hip and femoral aBMD and BMC than controls (Bennell et al., 2000 and Matthews et al., 2006), that adolescent dancers ages (15-18) had significantly higher femoral neck BMAD than the reference data (Buckhardt et al., 2011) and that female adult ballet dancers and endurance runners had lower aBMD at the proximal femur than combat/power athletes and team athletes (Hinrichs et al. 2010).

In a pQCT study of bone mineral differences of 35 full-time 17-18 year old dancers (To et al, 2005), bone strength index (BSI) at the distal tibia were significantly higher in dancers than in eumenorrheic sedentary controls[7], as well as mean tibia core vBMD (average trabecular vBMD in a core volume), but the cortical thickness did not differ between the groups at either site. Dancers had significantly higher aBMD at the lumbar spine, femoral neck, mean trochanter, and Ward's triangle (measured by DXA). The dancers in their study participated in a minimum of eighteen hours a week of dance training, which included classical ballet, Chinese dance, modern dance, or musical theater dance. These limited studies seem to indicate that dance has an osteogenic effect compared to relatively inactive controls, yet it is unclear how the osteogenic effects of dance compare to other sports in eumenorrheic adult females.

It is well established in the literature that gymnastics is a high impact sport with peak impacts up to 9 times BW (Burt et al., 2010) and that middle-long distance running is a low repetitive impact sport with peak GRF around 3 times BW (Logan et al., 2010). Based on common jumps performed in multiple styles of dance (vertical jumps, split leaps/ saut de chat and assembles) peak GRF in dance does not seem to exceed 6 times BW (Burt et al., 2010, Kulig et al., 2011, Walter et al., 2011, and Chockley, 2008). Unfortunately, comparison studies of different sports/ physical activities did not separate them according to peak GRF as a classification of loading. Furthermore, it is not clear if the osteogenic effects at the tibia of intermediate impact activities such as dance fall between high impact (gymnastics) and low impact activities (running). This study compared

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[7] Not engaged in sports and engaged in less than 3 hours of weight-bearing physical activity per week.

bone geometry, density and strength between dancers, gymnasts and middle/long distance runners; three activities that differ in peak impact forces.

Statement of Purpose and Specific Aims

The purpose of this study is to compare tibial geometry, density, and strength between dancers, gymnasts and runners to elucidate the osteogenic effects of dancing at the tibia in eumenorrheic adult females. There are no known studies comparing the effect of dance, gymnastics, and middle/long-distance running in eumenorrheic adult females on tibial geometry, density and strength. Furthermore, no studies have compared tibial geometry, density and strength in eumenorrheic adult females that participate in high, medium, and low-repetitive impact activities. From a clinical perspective, it is important to know how these activities compare in their osteogenic abilities to potentially prevent bone fragility later in life. To help fill this knowledge gap, the current study will attempt <u>to compare the effects of three different physical activities (dance, gymnastics, and running) and their respective loading types</u> on tibial health (bone strength and its densitometric and geometric underpinnings) in eumenorrheic adult female dancers, gymnasts, and runners. The following hypotheses are put forward, based on pilot study results and supporting literature:

<u>First</u>, tibial geometry, as measured by total cross-sectional area (ToA), will be significantly greater in gymnasts and runners than in dancers and controls at both 4% and 66% sites and that gymnasts and runners will not differ in ToA at the 66% site, based on the results of Nikander et al. (2010) and Smock et al.

(2009). Based on the findings of To et al. (2005), we do not expect dancers to differ in geometry from controls.

Second, distal tibia density, as measured by total volumetric bone mineral density (vBMD) at the 4% site, will be significantly greater for dancers and gymnasts than runners and controls. Gymnasts and dancers will not differ in total volumetric density, according to our pilot study results. Based on the findings of Hinrichs et al. (2010), Mudd et al. (2007), and Smock et al. (2009), Nichols et al. (2007) and Bemben et al. (2004), middle/long-distance runners are expected to have lower total vBMD than gymnasts and to not differ from healthy controls. Based on the findings of To et al. (2005), we expect dancers to have greater tibial vBMD than controls.

Third, distal tibial compressive strength, as measured by BSI (4% site), will be greater in the medium and high impact groups than in the control group and low repetitive impact group, but will not differ between gymnasts and dancers, based on our pilot study findings and the findings of To et al. (2005) and Nikander et al. (2010). According to the findings of Nikander et al. (2010), we expect that runners to have greater BSI than controls.

Fourth, proximal tibial torsional/ bending strength, as measured by SSIp (66% site), will be greater in the exercise groups than in the control group according to the findings of Nikander et al. (2010) and Smock et al. (2009); and gymnasts will have greater SSIp than dancers, based on our pilot study results.

Methods

Subjects

Twenty two adult females (11 collegiate dancers and 11 collegiate gymnasts), with ages ranging from 18 to 22 years old, were recruited for this study. The dancers were mostly Caucasian (9 dancers), with one Asian American, and one Middle-Eastern. All gymnasts were Caucasian. The study was advertised in local colleges. Existing tibial data from the Laboratory of Musculoskeletal Health's pQCT database on adult female runners (n=22) and healthy controls (n=19) (Smock et al., 2009 and Bruininks, 2009) were used; therefore only dancers and gymnasts were recruited for this study. The study was approved by the University of Minnesota Institutional Review Board and written informed consent was obtained from participants.

The dancers were enrolled in dance classes for at least the three preceding years for a minimum of 3 hours of practice/week and were eumenorrheic (inclusion criteria). They participated in a combination of styles, which included: classical ballet (n=7), modern dance (n=7), Irish dance (n=1), jazz (n=9), contemporary (n=5) tap dance (n=3), hip-hop (n=2), high-kick (n=2), African dance (n=2), belly dancing (n=2), and musical theater (n=2). All dancers participated in at least one style that involved jumping. The gymnasts had been training and competing for at least the three preceding years for a minimum of 3 hours of practice/ week as part of a collegiate team or club and were eumenorrheic (inclusion criteria).

The runners and controls were 18-25 years old. The runners included post-collegiate running club members, road race participants, and intercollegiate cross-country team members that were involved in running for at least 3 years leading up to the study and were running an average of 35 miles/ week. The control group was comprised of apparently healthy females that were involved in less than 3 hours of physical activity/ week.

The exclusion criteria were pregnancy, menstrual disorders (less than 10 periods in the last 12 months), or lower limb fractures in the previous 12 months. In addition, for the dancer group, participation in other high-impact activities (such as gymnastics, volleyball, among others) during the previous 24 months was also an exclusion criterion.

Procedures: Obtaining Bone and Other Relevant Measures in the Laboratory

During the visit to the Clinical and Translational Science Institute, consent was obtained from participants. The form in Appendix A was used to obtain subjects' health and physical activity histories. The health history included questions on smoking, birth control use, history of menstrual dysfunctions, and previous fractures. Physical activity participation items included age at onset of training, duration of training, intensity, and participation in other physical activities. Dancers were asked to complete an additional dance history questionnaire (Appendix B). In order to confirm whether potential differences between dancers and gymnasts were due to length of training, weekly training load or to impact type, training histories of the two groups were compared using pairwise t-tests.

Following the consent process, a pregnancy test was administered to all participants. Since exposure to x-ray is a risk for pregnancy, participants with positive results were excluded from the study. After the results were obtained, tibial length (mm) was measured from the distal end of the lateral malleolus to the proximal end of the tibial plateau (both landmarks found via palpation) using an anthropometric tape. The average of three measurements was used and limb length was used as a reference for the pQCT machine (XCT 3000, Orthometrix, White Plains, NY) scan distance calculations.

After completing the required health forms and anthropometric measurements, participants' non-dominant lower legs, opposite of dominant hand, were positioned using leg holds and Velcro straps and were scanned. A scan speed of 25 mm/s and a sample resolution of 0.4mm (voxel size) were used. A Scout view and two slices (2.3±0.2 mm) were obtained at the 4% (distal) and 66% (proximal) sites of the non-dominant tibia. Slices were taken as a percentage of limb length from the distal end of the tibia, based on the anatomical landmarks used to measure tibial length.

At a separate visit to the Recreational Center at the University of Minnesota, participants were weighed on an electronic scale calibrated to the nearest 0.1kg. Their heights were measured to the nearest millimeter using a wall-mounted stadiometer. In order to verify if anthropometric differences existed between the groups, participants' age, height, weight, tibial length, BMI and muscle cross-sectional area (CSA) were compared using pairwise *t*-tests. Muscle CSA was measured via pQCT at the 66% site.

Measurements

PQCT Measurements

Data were collected on the following parameters: total bone cross-sectional area[8] (ToA, mm^2) at the distal (4%) and proximal (66%) sites; total density ($mg.mm^{-3}$) at the 66% site; bone strength index[9] (BSI – $mg.mm^{-4}/10,000$) at the 66% site and polar strength-strain index [10](SSIp, mm^3) at the 4% site. Additional bone geometric and densitometric parameters were collected and included: trabecular density (4%), trabecular area (4%), cortical thickness (66%), cortical area (66%), cortical density (66%), and total density (66%).

Statistical Analysis

The dependent variables analyzed in the current study were ToA (4% and 66% sites), total vBMD (4% site), BSI (4% site) and SSIp (66% site). To determine whether age, tibial length, height, body mass, BMI or muscle cross-sectional area needed to be controlled in the models, the correlations between these predictor variables and the dependent variables were computed. The correlation coefficients and *p*-values are shown in Table 2.

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[8] Result of subcortical, trabecular (TrA) and cortical (CoA) bone areas (all in mm^2). (Petit et al., 2005)

[9] BSI is the product of ToA by $ToD^2/100.000$, and is an estimate of bone compressive strength (Smock et. al. 2009) at metaphyseal sites (Farr et al. 2010).

[10] SSI is an estimate of bone's ability to resist torsion at diaphyseal sites (Farr et al. 2010) and is the density weighted polar moment of inertial (Zemel et al., 2008). This measurement accounts for bone geometry (cross-sectional moment of inertia) and for reasonable surrogates of material properties of cortical and trabecular bone (Petit et. al, 2005).

Table 2. Correlations between predictor variables (age, tibial length, height, BMI, and muscle cross-sectional area) and tibial geometry, density, and strength. Upper diagonal contains the correlation coefficients and lower diagonal contains the corresponding p-values.

	Age	Tibial Length	Mass	Height	BMI	MUSC_A	TOT_DEN	TOT_A 4%	BSI	TOT_A 66%	SSIp
Age	*****	0.117	0.112	0.203	-0.01	-0.082	-0.162	0.112	-0.116	0	0.016
Tibial Length	0.36	*****	0.45	0.765	0.027	-0.058	-0.111	0.073	-0.092	0.461	0.489
Mass	0.384	**<0.001**	*****	0.517	0.826	-0.048	0.219	0.192	0.315	0.531	0.559
Height	0.111	**<0.001**	**<0.001**	*****	-0.051	-0.132	-0.097	0.272	0.024	0.448	0.538
BMI	0.936	0.832	**<0.001**	0.691	*****	0.026	0.32	0.054	0.357	0.344	0.311
MUSC_A	0.525	0.653	0.709	0.303	0.84	*****	0.273	0.077	0.328	0.1	0.101
TOT_DEN	0.205	0.388	0.085	0.447	**0.011**	0.031	*****	-0.384	0.861	0.189	0.278
TOT_A 4%	0.384	0.567	0.132	**0.031**	0.673	0.55	0.002	*****	0.126	0.344	0.339
BSI	0.366	0.472	**0.012**	0.855	**0.004**	0.009	<0.001	0.324	*****	0.381	0.477
TOT_A 66%	0.998	**<0.001**	**<0.001**	**<0.001**	**0.006**	0.437	0.138	0.006	0.002	*****	0.892
SSIp	0.903	**<0.001**	**<0.001**	**<0.001**	**0.013**	0.429	0.027	0.007	<0.001	<0.001	*****

Note: MUSC_A= muscle cross-sectional area at 66% tibia,TOT_DEN = total volumetric bone density, TOT_A4% = total cross-sectional area at 4% tibia, BSI = bone strength index, TOT_A66% = total cross-sectional area at 66% tibia,SSIp = polar stress strain index. Statistically significant p-values (p<0.05) are bolded

Across all predictor variables, the addition of height and mass consistently explained large amounts of the variance in tibial outcomes in the regression models; therefore an ANCOVA was performed with height and mass as covariates to analyze the distal and proximal tibia data. The mean height and mass were used to obtain adjusted results.

Although body mass index (BMI) was moderately significantly correlated with Total vBMD (4%), BSI (4%), ToA (66%) and SSIp (66%), it was not used as a covariate for the distal tibia outcomes to avoid collinearity issues with mass (BMI was highly correlated to mass r=0.83).

Although, muscle CSA was moderately significantly correlated to total vBMD (4%) and BSI (r=0.27 and r=0.32, respectively), it did not explain the variability in tibial strength and geometry above and beyond the group predictors – its addition to the models only explained an additional 1% in the variability in the outcomes; therefore it was not used as a factor.

When the F ratio was significant ($p<0.05$), pairwise comparisons between groups were performed using Tukey *post hoc* adjustment. Assumptions of normality of distribution and homogeneity of variance were tested for all variables prior to all ANCOVA. There were no extreme violations of either assumption[11] for any of the variables. Statistical analyses were performed using R-Software (R Development Core Team, 2010).

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[11] Skew and kurtosis of approximately ±1 and ratio between highest to lowest variance of less than four.

Results

Subjects

Training History

Dancers had been practicing for an average of 11.6 years (SD=4.1) and were currently taking classes and performing for an average of 17.2 hours/week (SD=10.3). Gymnasts had been practicing for an average of 13.8 years (SD=1.8) and were currently taking classes and performing for an average of 13 hours/week (SD=3.5). The dancers and gymnasts did not differ in terms of length of practice (p=0.18) and weekly hours of practice (p=0.25).

Anthropometry

Dancers had a mean age of 19.8 years (SD=1.2), mean height of 165.8 cm (SD=7.3), mean mass of 59.9 kg (SD=8.4), mean tibial length of 365 mm (SD=43), mean BMI of 22.0 kg/ m^2 (SD=1.84), and mean muscle CSA of 6768.7 mm^2 (SD=1190.3). Gymnasts had a mean age of 19.8 years (SD=1.3), mean height of 160 cm (SD=3.1), mean mass of 59.5 kg (SD=3.3), mean tibial length of 361 mm (SD=14), mean BMI of 23.6 kg/ m^2 (SD=1.49), and mean muscle CSA of 6664.7 mm^2 (SD=590.3). Runners had a mean age of 20.3 years (SD=1.9), mean height of 167.6 cm (SD=6.3), mean mass of 58.1 kg (SD=7), mean tibial length of 378 mm (SD=16), mean BMI of 20.75 kg/ m^2 (SD=1.63), and mean muscle CSA of 7057.1 mm^2 (SD= 609.2). Controls had a mean age of 20.7 years (SD=2), mean height of 168.4 cm (SD=6.4), mean mass of 63.9 kg (SD=11.6), mean tibial length of 378 mm (SD=21), mean BMI of 22.4 kg/ m^2 (SD=3.84), and mean muscle CSA of 3231 mm^2 (SD=2867.6). The groups did not significantly differ in age, weight, or tibial length (p>0.05). Gymnasts had significantly lower height than controls (p=0.003) and runners (p=0.007), runners had significantly lower BMI than gymnasts (p=0.03), and controls had significantly lower muscle CSA than the exercise groups (p<0.001) after Tukey adjustment. Table 3 summarizes their characteristics.

Table 3. Descriptive characteristics in dancers, gymnasts, runners and controls. Values represent means and SD values in parentheses.

	Age (years)	**Height (cm)**	**Mass (kg)**	**Tibial Length (mm)**	**BMI (kg/m^2)**	**Muscle CSA (mm^2)**
Dancers	19.8	165.8	59.9	365	22.0	6768.7^a
(n=11)	(1.2)	(7.3)	(8.4)	(43)	(1.84)	(1190.3)
Gymnasts	19.8	160.0^{a,b}	59.5	361	23.6^b	6664.7^a
(n=11)	(1.3)	(3.1)	(3.3)	(14)	(1.49)	(590.3)
Runners	20.3	167.6	58.1	378	20.75	7057.1^a
(n=22)	(1.9)	(6.3)	(7.0)	(16)	(1.63)	(609.2)
Controls	20.7	168.4	63.9	378	22.4	3231
(n=19)	(2.0)	(6.4)	(11.6)	(21)	(3.84)	(2867.6)

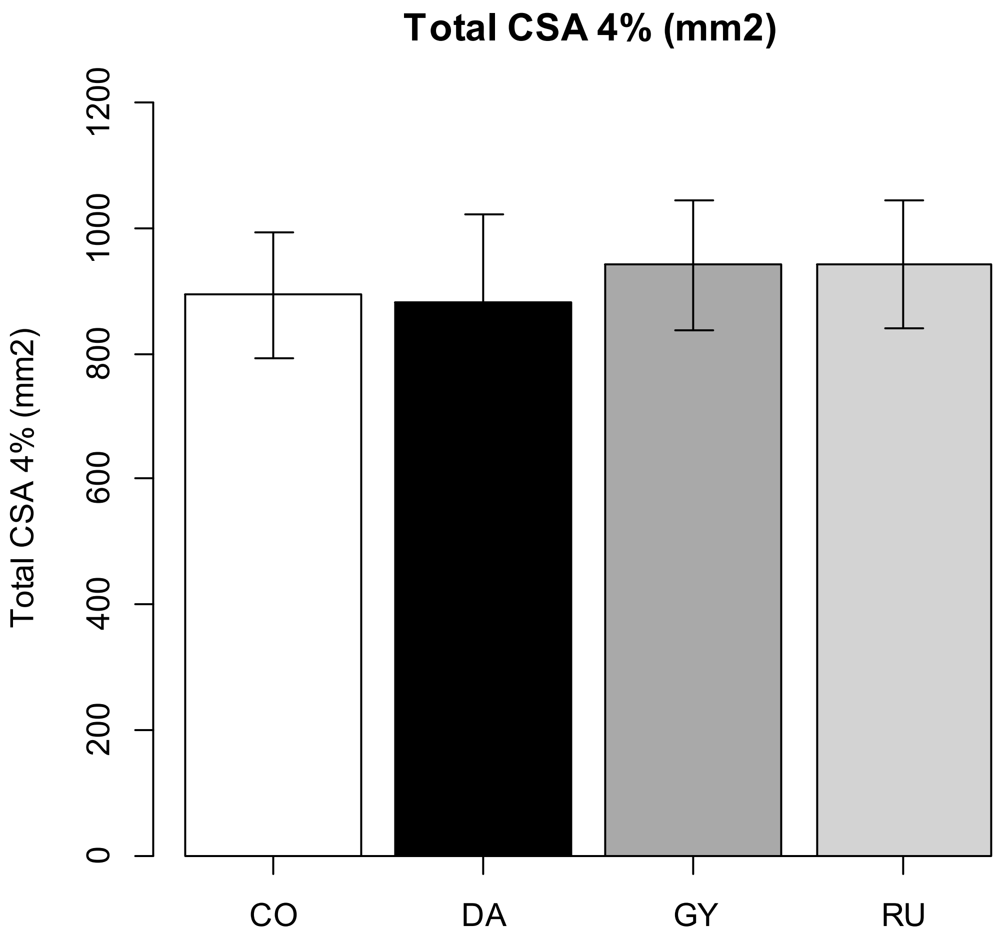
Note: a= different from controls, b= different from runners (p<0.05) after Tukey adjustment

First Hypothesis – Tibial Geometry Group Differences

The first hypothesis stated that tibial geometry, as measured by total cross-sectional area (ToA), would be significantly greater in gymnasts and runners than in dancers and controls at both sites, that dancers would not differ from controls, and that gymnasts and runners would not differ in total area at the 66% site.

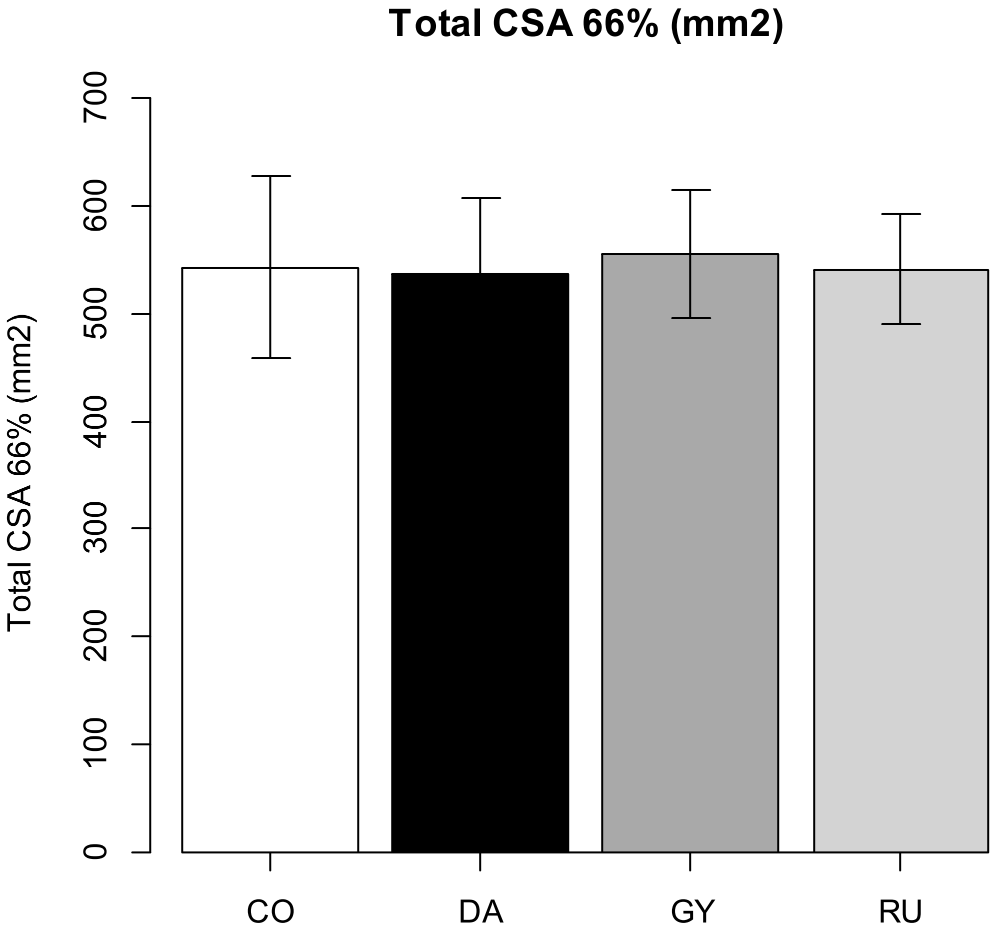
At the 4% site, dancers had adjusted mean ToA of 1134.1 mm^2 (SE=39.8), gymnasts had adjusted mean area of 1228.6 mm^2 (SE=43.6), runners had adjusted mean ToA of 1187.3 mm^2 (SE=33.9), and controls had adjusted mean ToA of 1128 mm^2 (SE=394.1). At the 66% site, dancers had an adjusted mean ToA of 540.3 mm^2 (SE=20.8), gymnasts had an adjusted mean ToA of 581.3 mm^2 (SE=22.8), runners had an adjusted mean ToA of 542.2 mm^2 (SE=17.7), and controls had an adjusted mean ToA of 524.2 mm^2 (SE=205.5). Unadjusted ToA results for the 4% site are demonstrated in Figure 1 as group mean (bars) and plus or minus one standard deviation (vertical lines). Unadjusted ToA means for the 66% site are shown in Figure 2. Group means and standard deviations are summarized in Table 4 (4%site) and Table 5 (66% site).

Figure 1. Comparison of Total Cross-sectional Area at the 4% site among groups. Bars represent unadjusted means and vertical lines represent plus or minus one standard deviation.



Note: CSA= Cross-sectional area, CO = controls, DA = dancers, GY = gymnasts, and RU = runners

Figure 2. Comparison of Total Cross-sectional Area at the 66% site among groups. Bars represent means and vertical lines represent plus or minus one standard deviation.



Note: CSA = Cross-sectional area, CO = controls, DA = dancers, GY = gymnasts, and RU = runners

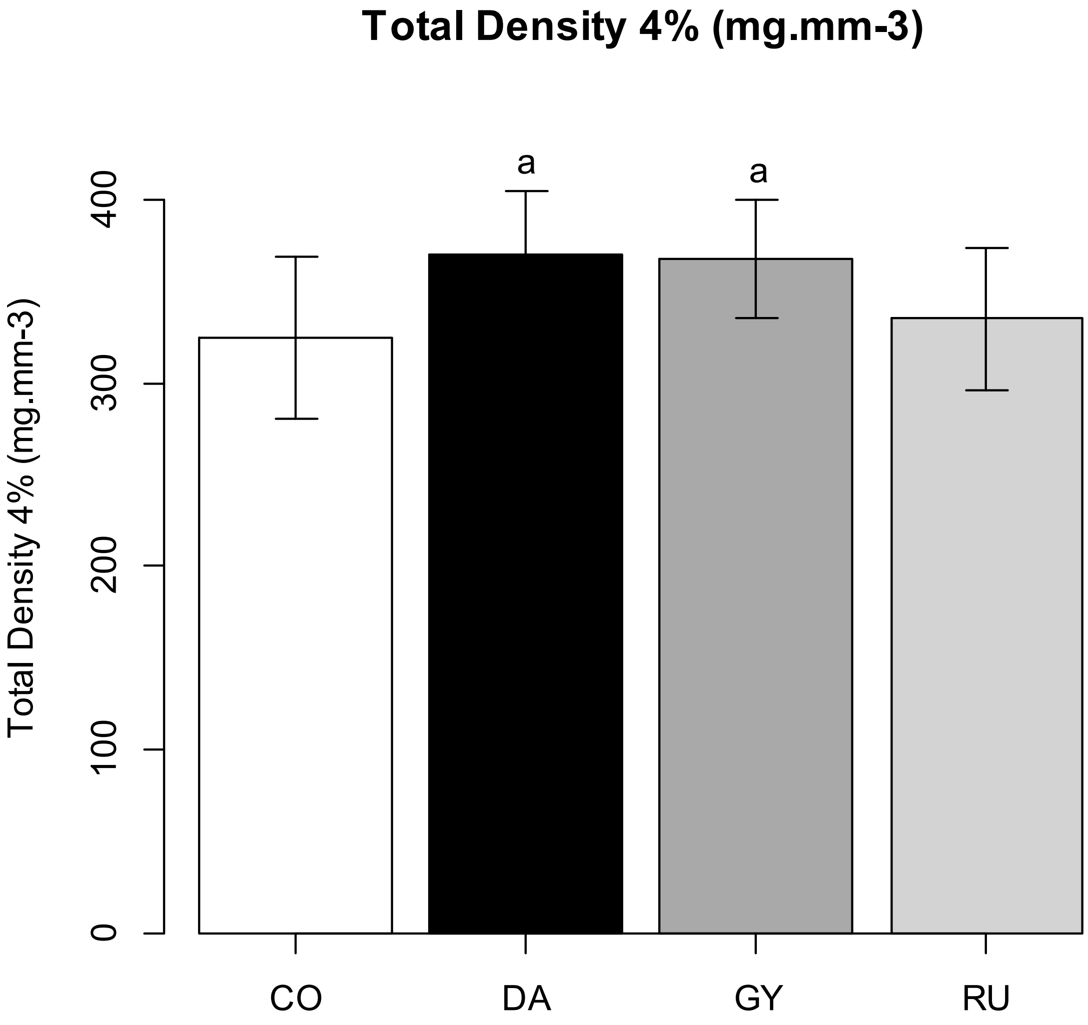
Single and multiple regression models were fitted to test the first hypothesis, as shown in Table 6 (Appendix C). Total area at the 4% site was not significantly different between the groups (model “Total Area 2”), F(5,57)=2.618, *p*=0.03. This model explained approximately 18.7% of the variability in ToA at the distal tibia. At the proximal tibia (66% site), even though the model (“Total Area 5”) was significant (F(5,57)=7.314, *p*<0.001) and explained approximately 39% of the variability in ToA, there was not a significant difference between groups. The adjusted group means are shown in Table 4 (4% site) and Table 5 (66%site). The tibial geometry results did not confirm the first hypothesis.

Second Hypothesis – Total Density Group Differences at the 4% Site

We tested the second hypothesis that distal tibia density, as measured by total vBMD at the 4% site, would be significantly greater for dancers and gymnasts than runners and controls, that gymnasts and dancers would not differ in total vBMD, that dancers would have greater total vBMD than controls, and that runners and controls would not differ in total vBMD.

At the 4% site, dancers had adjusted mean total vBMD of 370.8 mg.mm^{-3} (SE=14.3), gymnasts had adjusted mean total vBMD of 364.2 mg.mm^{-3} (SE=15.7), runners had adjusted mean total vBMD of 340.7 mg.mm^{-3} (SE=12.2), and controls had adjusted mean total vBMD of 320 mg.mm^{-3} (SE= 141.5). Unadjusted total vBMD means for the 4% site are demonstrated in Figure 3 as group means (bars) and plus or minus one standard deviation (vertical lines). Group means and standard deviations are summarized in Table 4.

Figure 3. Comparison of Total Volumetric Bone Mineral Density at the 4% site among groups. Bars represent means and vertical lines represent plus or minus one standard deviation.



Note: CO = controls, DA = dancers, GY = gymnasts, and RU = runners, a=different from controls after Tukey adjustment (p<0.05)

There was a significant difference between groups on total vBMD at the 4% site F(5,57) = 4.799, *p*<0.001. Our model (Table 7 Appendix D) explained 29.6% of the variability in total vBMD. Table 8 below demonstrates the individual contrasts and adjusted *p*-values (using Tukey adjustment).

Table 8. Total Volumetric Bone Mineral Density pairwise comparisons between groups after Tukey adjustment

	Estimate	**Std. Error**	**t value**	**p value**
DA - CO	47.1072	14.96	3.148	0.01*
GY - CO	47.974	16.40	2.925	0.02*
RU - CO	11.3423	12.26	0.925	0.79
GY - DA	0.8668	17.36	0.05	1.00
RU - DA	-35.7649	14.50	-2.466	0.07
RU - GY	-36.6317	15.75	-2.325	0.10

*Note: DA = dancers, GY = gymnasts, RU= runners, and CO = controls. * p<0.05*

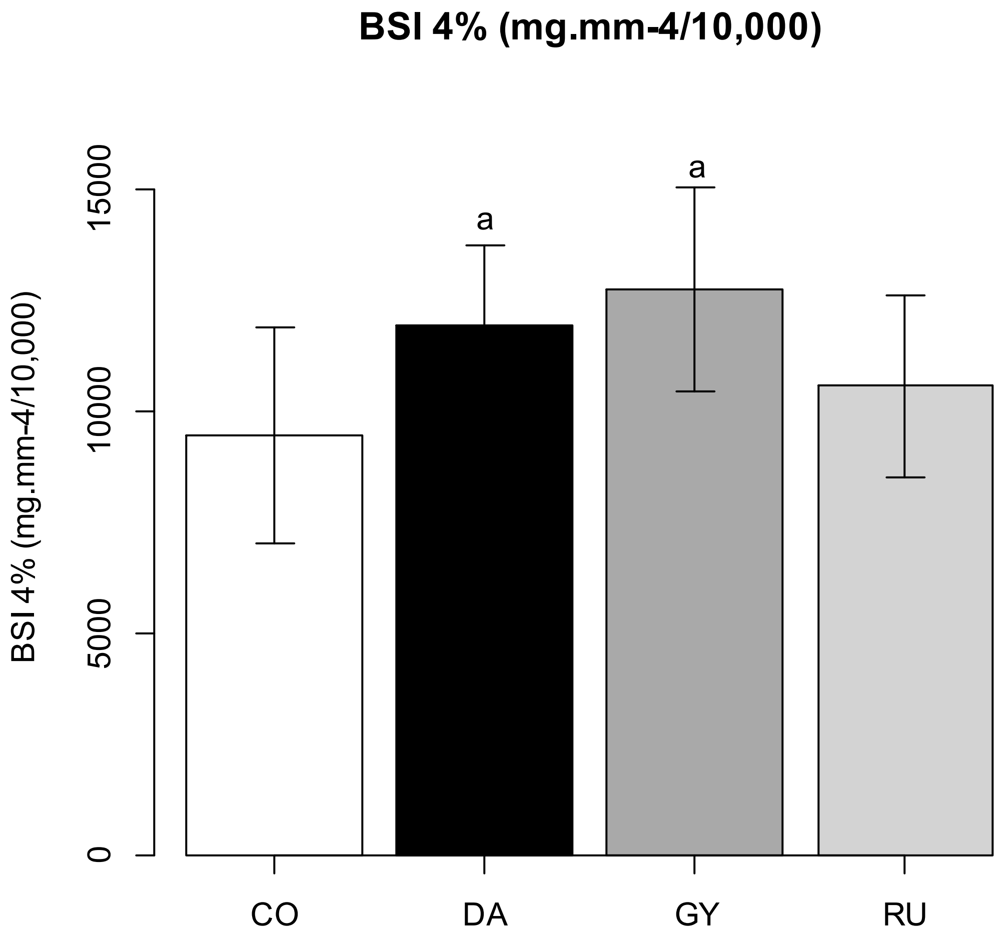
As hypothesized, dancers and gymnasts did not differ in total vBMD, total vBMD was significantly higher for dancers and gymnasts when compared to controls, and runners were not different from the controls, after controlling for height and mass. Contrary to our hypothesis, there were no significant differences between dancers and gymnasts versus runners.

Third Hypothesis – Tibial Compressive Strength as Measured by BSI

We tested our third hypothesis that distal tibial compressive strength, as measured by BSI (4% site), would be greater in the middle and high impact exercise groups than in the low repetitive impact and control groups; gymnasts would not differ from dancers; and runners would be greater than controls.

At the 4% site, dancers had adjusted mean BSI of 12023.9 mg.mm^{-4}/10,000 (SE=752.2), gymnasts had adjusted mean BSI of 12972.5 mg.mm^{-4}/10,000 (SE=824.1), runners had adjusted mean BSI of 10830.7 mg.mm^{-4}/10,000 (SE=640.3), and controls had adjusted mean BSI of 9026 mg.mm^{-4}/10,000 (SE= 7441.3). Unadjusted BSI means for the 4% site are demonstrated in Figure 4 as group means (bars) and plus or minus one standard deviation (vertical lines). Group means and standard deviations are summarized in Table 4.

Figure 4. Comparison of BSI at the 4% site among groups. Bars represent means and vertical lines represent plus or minus one standard deviation.



Note: CO = controls, DA = dancers, GY = gymnasts, and RU = runners, a= different from controls after Tukey adjustment (p<0.05)

There was a significant difference between groups on bone compressive strength (model "BSI 2", F(4,58) = 8.191, *p*<0.001), as shown in Table 9 (Appendix E). Participation in exercise, height and mass explained 41.74% of the variability in compressive strength at the distal tibia. Individual contrasts and adjusted *p*-values are shown in Table 9 below.

Table 10. BSI pairwise comparisons between groups after Tukey adjustment

	Estimate	**Std.Error**	**t value**	**p value**
DA - CO	2997.9	752.2	3.986	0.001*
GY - CO	3946.5	824.1	4.789	< 0.001*
RU - CO	1804.6	640.3	2.818	0.03*
GY - DA	948.6	881	1.077	0.702
RU - DA	-1193.2	734.2	-1.625	0.370
RU - GY	-2141.9	829.9	-2.581	0.058

*Note: DA = dancers, GY = gymnasts, RU= runners, and CO = controls. * p<0.05*

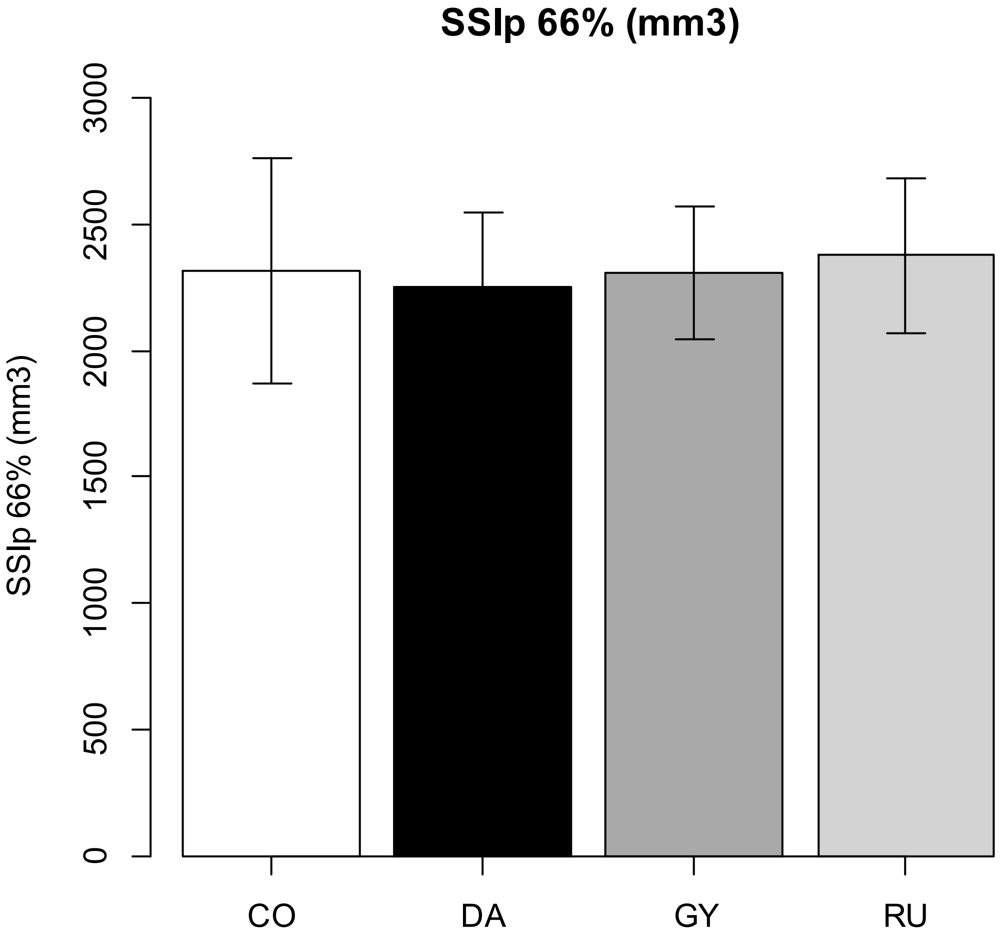
Confirming the third hypothesis, gymnasts did not differ from dancers in BSI, gymnasts, dancers, and runners had significantly greater BSI than controls, after controlling for height and mass. Contrary to the stated hypothesis, dancers and gymnasts did not differ in BSI from runners.

Fourth Hypothesis – Tibial Torsional Strength as Measured by SSIp

We tested our fourth hypothesis that proximal tibial torsional/ bending strength, as measured by SSIp (66% site), would be greater in the impact groups than in the control group; and gymnasts would have greater strength than dancers.

At the 66% site, dancers had an adjusted mean SSIp of 2268.2 mm^3 (SE=100.7), gymnasts had an adjusted mean SSIp of 2451.8 mm^3 (SE=110.4), runners had an adjusted mean area of mean SSIp of 2386 mm^3 (SE=85.8), and controls had an adjusted mean area of mean SSIp of 2213.2 mm^3 (SE=996.55). Unadjusted SSIp results for the 66% site are demonstrated in Figure 5 as group means (bars) and plus or minus one standard deviation (vertical lines). SSIp results are summarized in Table 5.

Figure 5. Comparison of SSIp at the 66% site among groups. Bars represent means and vertical lines represent plus or minus one standard deviation.



Note: CO = controls, DA = dancers, GY = gymnasts, and RU = runners

Our model ("SSIp 3", Table 8 Appendix D) explained approximately 46% of the variability in tibial torsional strength (F(5,57)=0.34, *p*<0.001), but there were no significant differences between groups, contradicting the stated hypothesis.

Summary of Descriptive Bone Parameters

Descriptive bone geometric, densitometric, and strength parameters are summarized in Table 4 (4% site) and Table 5 (66% site).

Table 4. Summary of distal tibia (4%) density, geometry, and strength outcomes for groups. Values are presented as unadjusted mean (SD) and height and mass adjusted mean (SE).

	Dancers (n=11)	**Gymnasts (n=11)**	**Runners (n=22)**	**Controls (n=19)**
Total Area	880.3	941.5	941.4	893.4
(mm^2)	(141.6)	(104.0)	(102.4)	(99.3)
Adjusted	*1134.1*	*1128.6*	*1187.3*	*1128.0*
	(39.8)	*(43.6)*	*(33.9)*	*(394.1)*
% diff	0.5	8.9	5.2	
Total vBMD	370.1^a	368.0^a	335.3	324.4
(mg.mm^{-3})	(34.5)	(32.4)	(38.9)	(44.1)
Adjusted	*370.8*	*364.2*	*340.7*	*320.0*
	(14.3)	*(15.7)*	*(12.2)*	*(145.5)*
% diff	15.9	13.8	6.4	
BSI	11955.9^a	12777.3^a	10581.3^a	9462.8
(mg.mm^{-4}/10,000)	(1782.4)	(2310.6)	(2068.8)	(2431.6)
Adjusted	*12007.5*	*12304.2*	*10986.8*	*9243.2*
	(773.6)	*(773.0)*	*(664.8)*	*(2398.3)*
% diff	29.9	33.1	18.9	
Trabecular Density	284.31	291.93^a	279.04	262.17
(mg.mm^{-3})	(33.8)	(28.4)	(31.9)	(30.7)
Adjusted	*280.6*	*294.8*	*281.6*	*259.7*
	(11.8)	*(13.0)*	*(10.1)*	*(117.2)*
% diff	8.0	13.5	8.4	
Trabecular	664.67	746.7	751.8	721.08
Area (mm^2)	(120.2)	(107.9)	(91.9)	(93.1)
Adjusted	*676.1*	*771.4*	*744.0*	*709.1*
	(37.6)	*(41.2)*	*(32.0)*	*(372.2)*
% diff	-5.3	8.8	4.9	

Note: %diff = percent difference from controls, a= different than controls ($p<0.05$) after Tukey adjustment

Table 5. Summary of proximal tibia (66%) density, geometry, and strength outcomes for groups. Values are presented as unadjusted mean (SD) and height and mass adjusted mean (SE).

	Dancers (n=11)	**Gymnasts (n=11)**	**Runners (n=22)**	**Controls (n=19)**
Total Area (mm^2)	525.7	567.7	564.6	522.2
	(45.8)	(61.6)	(51.1)	(77.1)
Adjusted	*540.3*	*581.3*	*542.2*	*524.2*
	(20.8)	*(22.8)*	*(17.7)*	*(205.5)*
% diff	3.1	10.9	3.4	
SSIp (mm^3)	2205.13	2414.75	2503	2168.09
	(110.64)	(383.73)	(308.07)	(436.6)
Adjusted	*2268.2*	*2451.8*	*2386.0*	*2213.2*
	(100.7)	*(110.4)*	*(85.8)*	*(996.6)*
% diff	2.5	10.8	7.8	
Cortical Thickness (mm)	4.51	4.32	4.51	4.1
	(0.7)	(0.4)	(0.4)	(0.5)
Adjusted	*4.5*	*4.3*	*4.5*	*4.1*
	(0.2)	*(0.2)*	*(0.2)*	*(1.9)*
% diff	10.5	6.5	10.3	
Cortical Area (mm^2)	298.87	303.99[a]	306.81[a]	284.03
	(22.59)	(26.93)	(31.34)	(34.05)
Adjusted	*300.0*	*313.1*	*307.7*	*277.1*
	(10.1)	*(11.1)*	*(8.6)*	*(100.2)*
% diff	8.3	13	11	
Cortical Density (mg.mm^{-3})	1141.77	1141.23	1131.01	1142.16
	(30.5)	(21.8)	(19.2)	(22.3)
Adjusted	*1141.2*	*1139.0*	*1224.6*	*1146.1*
	(8.2)	*(9.0)*	*(7.0)*	*(81.1)*
%diff	-0.4	-0.6	6.8	
Total Density (mg.mm^{-3})	723.05	700.37	713.66	675.43
	(103.2)	(59.6)	(50.3)	(59.9)
Adjusted	*722.6*	*693.5*	*712.2*	*681.3*
	(25.4)	*(27.9)*	*(21.7)*	*(251.6)*
%diff	6.1	1.8	4.5	

Note: %diff = percent difference from controls, a= different than controls ($p<0.05$) after Tukey adjustment

Discussion

The literature has provided a few comparisons between the osteogenic effects of high impact and repetitive low impact sports on tibial geometry, density and strength. In adult females, at the tibia, middle/long-distance runners had 19% greater BSI and 11% greater total area (at 4% site) than inactive healthy controls (Smock et al. 2009). Positive geometric adaptations were present for adult female athletes in any kind of impact sport (including volleyball, soccer, racket games, and endurance running) in comparison to controls, after controlling for age, height and weight (Nikander et al. 2010): up to 50% greater distal tibia cortical area (5% site) and 8% greater total distal tibia area only for athletes in high impact sports (volleyball, hurdling, triple jump and high jump, among others). At the mid-shaft (50% site) all impact groups had 13% to 21% greater total area (50% site), and 18% to 28% greater cortical area. Benefits in distal tibia volumetric density, along with greater aBMD at the hip and spine were found in female adolescent dancers in comparison with non-exercising controls, but not in geometry (cortical thickness) (To et al, 2005).

This study is the first to compare the osteogenic effects in terms of geometry, volumetric density and strength between a medium impact activity (dance) and high impact (gymnastics) and repetitive low-impact (middle-long distance running) activities in adult females at a heavily loaded site - tibia.

Tibial Geometry Group Differences

We hypothesized that tibial geometry, as measured by total cross-sectional area (ToA), would be significantly greater in gymnasts and runners than in dancers and controls at both sites, that gymnasts and runners would not differ at the 66% site, and that dancers would not differ in ToA from controls. At the 4% and 66% sites, the tibia total cross sectional area was not significantly different between groups. With respect to the 4 % site statistical power was sufficient to detect group differences, but at the proximal (66%) site 0.8 power was not achieved, based on a priori sample size calculations. Thus we cannot exclude the possibility that these null results were influenced by small sample size.

Our dancer tibial geometry results were in accordance with findings in the literature (To et al., 2005).The distal tibial geometries (cortical thickness) of their dancers (ages 17-19) and controls were the same. Ward et al. (2005) also reported similar proximal tibia total area (65% site), cortical area, cortical thickness and medullary area in a comparison between pre-pubertal gymnasts and school children. Contrary to our distal tibia findings, a comparison of impact types from different sports indicated that, after controlling for age, height and weight, adult females that participated in impact sports in general had up to 50% greater distal tibia cortical area (5% site) than controls, but only the athletes in high impact sports had greater distal tibia total area (by 8%) than controls (Nikander et al., 2010). At the proximal site (50% site), they found that females that participated in impact sports in general had greater total area (ranging from

13% to 21%) than controls and greater cortical area (ranging from 18% to 28%) than controls.

Smock et al. (2009) found geometric benefits when comparing female adult middle/ long-distance runners to inactive controls at both tibial sites (4% and 66%): runners had greater total area by 11% at the 4% site and by 10% at the 66% site, along with 15% greater cortical area and 14% thicker cortices at the 66% site. These studies suggest that both high impact (volleyball, triple jump, hurdling, among others) and repetitive low impact activities such as middle/long-distance running would have the greatest effects on bone geometry, rather than medium-impact activities, such as dance. Tibial cross-sectional area is a relevant geometry parameter to be observed, as adult bones continue to expand in periosteal diameter.

The use of healthy inactive controls and the inability to control for participation in physical activity during the peri-pubertal period may explain the similar cross-sectional area in our groups. Since tibial shaft (60% site) ToA growth velocity peaks 20 months before menarche and cortical area peaks 13 months before menarche (Wang et al., 2005), participation in sports at younger ages could have positively affected the tibial geometry of our subjects and these improvements could have been sustained into adulthood, as indicated by the literature (Baxter-Jones et al., 2008, Kemper et al., 2009, Ducher et al., 2009). In addition, the activities selected for this study emphasize slender body types, which could also explain the lack of differences in geometry between groups.

Volumetric Bone Mineral Density Group Differences

As hypothesized, distal tibia density measured by total vBMD at the 4% site was significantly greater for dancers and gymnasts than controls, runners did not differ from controls, and dancers did not differ from gymnasts. Contrary to our hypothesis, there were no significant differences between dancers and gymnasts versus runners.

Dancers had approximately 15.9% greater total vBMD than controls, while gymnasts had 13.8% greater total vBMD than controls, after adjusting for height and mass. When comparing dancers to non-exercising controls, To et al. (2005), found that mean distal tibia vBMD in dancers was 12.2% higher than controls, which is very similar to our findings. Their aBMD at the hip and spine were also significantly higher than controls (13 to 17% higher at the hip and 7% higher at lumbar spine). Contradicting our findings, studies have shown that for female athletes, repetitive loading from middle/ long-distance running is associated with decreased aBMD at the leg (Mudd et al, 2007), spine and femur (Hinrichs et al. 2010), decreased vBMD at the 4% tibia (Smock et al, 2009), when compared to controls. Also contradicting our findings, runners also had significantly lower aBMD at the lumbar spine, pelvis and leg (Mudd et al. 2007) and lower aBMD at the hip and femur (Bemben et al., 2004) when compared to gymnasts.

In our study, dancers and gymnasts did not differ in terms of total volumetric density at the distal (4%) tibia, suggesting that the magnitude of the stimulus provided by dance was sufficient to produce similar increases in density as gymnastics, despite the greater magnitude of ground reaction forces associated with gymnastics. According to Frost (2003), load bearing bones achieve mechanical competence by adapting to typical peak voluntary loads (TPVL) experienced during physical activity, excluding rare strenuous activities. It is possible that the gymnasts' TPVLs are of lesser magnitude than the peak GRF forces of 9 times BW (Burt et al., 2010), thus explaining their similar total volumetric density to dancers. Another possible explanation is that their peak loads exceeded the modeling thresholds and caused microdamage accumulation, resulting in similar total volumetric density to dancers.

Distal Tibia Strength Group Differences

We confirmed our third hypothesis that distal tibial compressive strength, as measured by BSI (4% site), would be greater in the medium and high impact groups than in the control group. We also confirmed that gymnasts would not differ from dancers and that runners would have greater BSI than controls. Contrary to our hypothesis, dancers and gymnasts did not differ in BSI from runners.

Dancers had 33.2% greater BSI than controls, gymnasts had 43.7% greater BSI than controls, and runners had 20% greater BSI than controls, after controlling for height and mass. These findings are consistent with reports of approximately 15% higher BSI in adolescent female dancers versus controls (To et al., 2005). Also in accordance to our findings, female adolescent elite middle distance runners had 25% greater cross-sectional moment of inertia [12](CSMI) and 43% higher BSI at the distal tibia (20-30% of the tibial length) than controls (Greene et al. 2005) and adult female runners had significantly higher values (19%) of estimated bone strength (BSI) at the 4% tibia than healthy inactive controls (Smock et al., 2009).

Similar to the findings of greater BSI by 20 to 46% in all impact groups than non-athletic referents by Nikander et al. (2010), in our study, all impact activities were associated with significantly greater bone strength (BSI) at the tibia when compared to inactive controls. Gymnasts had higher compressive strength than dancers due to their greater cross sectional area (although not significant) as a result of the high impacts experienced during training. Since density contributes more to BSI calculation than area, dancers had the second highest compressive strength due to increased total volumetric density, when compared to runners.

Proximal Tibia Strength Group Differences

We did not confirm our hypothesis that proximal tibial torsional/ bending strength, as measured by SSIp (66% site), would be greater in the exercise groups than in the control group. Our findings are not in accordance with the literature. Smock (2009) found that runners had 19% greater tibial SSIp at the 66% site than controls and Nikander et al. (2010) found that the athletes in the high impact group had 38% higher SSIp than controls and that athletes in the repetitive

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[12] Measured with MRI and calculated using customized algorithms. BSI was calculated as the product between CSMI and volumetric cortical BMD

impact group had 25% higher SSIp than controls. Since tibial bending strength is determined by the distribution of material with respect to its bending axis and there were no differences in total area between the groups, this explains why no significant differences in SSIp were found between groups, despite the greater cortical area in gymnasts and runners than controls. In addition, based on *a prori* sample size calculations, our sample sizes were not sufficiently large to detect group differences in SSIp at the 66% site.

Study Limitations

It is important to consider whether additional factors could have explained this study's results such as extraneous factors and experimental factors; therefore some potential limitations will be addressed below.

Possible Anthropometric Effects on Bone Parameters

All activities selected for this proposed study emphasize leanness- low body mass index and low body fat, which have known detrimental effects on bone geometry, density and strength (Madsen et al., 1998, Markou et al 2004). Since all three activities; dance, gymnastics and middle/ long-distance running, emphasize a lean constitution, any detrimental effects it might have on bone geometry, density and strength should be similar across the groups. In addition, despite the lower mean BMI in runners in comparison with the gymnasts in our study, the mean body mass indices of all our groups were within the normal range of 18.5 to 24.9 kg/m^2.

In addition, since age and weight were not significantly different between the exercise groups and controls, this could potentially explain why we did not find additional osteogenic benefits at the proximal tibia when comparing to inactive healthy controls. Although muscle cross-sectional area – commonly used as a surrogate for muscle force (Schoenau et al., 2002) - was significantly higher for the exercise groups when compared to controls, it did not translate into a significant predictor of bone geometry, density, or strength. When added to the multiple regression models, it only explained approximately an additional 1% of the variance in the outcome variables. This suggests that other factors, such as external forces, were responsible for the differences found in tibial compressive strength and density.

Limitations of the Experimental Design

The cross-sectional design of this study is a limitation, as the physical activity levels of participants before menarche cannot be directly measured and could potentially influence the outcomes - especially due to increased periosteal apposition in participants involved in organized physical activity in the peri-pubertal period, for example (Tournis et al., 2010). Also, we cannot exclude some selection bias, because participants were not randomly assigned to groups.

In order to be admitted to a dance major program, dancers undergo an audition process. The program has an acceptance rate of 1 in 4 and most dancers have participated in dance since their childhood. Competitive collegiate gymnasts also have participated in gymnastics clubs and progressed through different levels of competition since their childhood. By recruiting from these highly specialized groups, every effort was made to obtain two samples whose bone geometries, densities and strengths will largely be influenced by a few decades dominated by dance or gymnastics training. Regarding our dance group results, we cannot identify the specific effects of individual styles of dance because the participants were engaged in multiple styles.

Measurement Resolution Limitations

There are also limitations in the measurement procedures, as pQCT cannot measure bone material properties. According to Petit et al. (2005), changes in mineralization and orientation of collagen fibers constituting the organic bone matrix (material level) and changes in osteon arrangement and orientation (macroscopic level) that would account for changes in bone strength cannot be measured via pQCT. It is possible that our sample of athletes adapted to their activity-specific loads by changes in the arrangement of osteons at the proximal tibia. In that case, pQCT measurements would not be able to detect differences that would make their tibias stronger than controls.

Sample Size

A priori sample size calculations based on our pilot study indicated that larger sample sizes would be necessary to detect differences at the proximal tibia. However, based on the large observed effect sizes of 0.79 and 0.92 for ToA and SSIp at the 66% site, respectively, a 0.8 statistical power was achieved to detect differences between groups. Thus, our null results for ToA and SSIp at the 66% site were not influenced by the size of our samples. *Post-hoc* power calculations were conducted using G Power software (version 3.1.5). Even though enough statistical power was achieved, there are limitations in estimating population effect size based on sample effect sizes.

In order to further investigate our results, p*ost-hoc* pairwise contrasts were conducted and indicated that groups of approximately 1032 subjects were needed in order to detect differences in ToA (66%) between runners and controls. One would need groups of 1293 subjects to detect differences between dancers and controls and groups of 1623 subjects to detect differences between dancers and runners. While the contrasts indicate that while it is possible that runners and dancers would statistically differ from healthy controls and that runners would statistically differ from dancers in ToA at the 66% site, these differences would be small and their significance with respect to bone health would be likely be very minor. Regarding proximal tibia bending strength, groups of approximately 2605 subjects would be needed in order to detect differences in SSIp between dancers and controls; and groups of 264 subjects would be required to detect differences between runners and controls; and groups of 140 subjects to detect differences between gymnasts and controls. Again, from this contrast it becomes clear that very large samples would be needed to reveal statistically significant group differences and their functional significance would be difficult to ascertain. In addition, given that bones adapt according to the direction of the greatest loads experienced, it is possible that the tibias of our sample of athletes adapted to their peak vertical loads by changes in distal tibial density and strength to reduce compressive stress[13] rather than by changes in proximal tibia geometry, density and strength.

Significance of Findings

This study aimed to fill a knowledge gap on how load supporting bones of adult dancers adapt to training and how dance compares to other sports in osteogenic ability. The clinical relevance of this study's findings is that dance may be equally effective as gymnastics at increasing bone total volumetric density and compressive strength (BSI) at the distal tibia, which are known to delay or prevent bone fragility later in life. In terms of sports comparisons, dance and gymnastics (medium and high impacts, respectively) provided greater total volumetric density and BSI at the distal tibia, while running (repetitive low impact) only provided greater BSI, when compared to healthy inactive controls. We did not find significant differences between groups in proximal tibia total area or bending strength.

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[13] Stress = Force / area

Conclusions

Even though the magnitudes of the peak mechanical loads experienced during dance training are smaller than in gymnastics, they may be sufficient to elicit similar changes in compressive bone strength and density between the two groups at the distal tibia. Medium and high impact activities provided the greatest benefits in total volumetric density and strength at the distal tibia (4% site), while repetitive low-impact only provided benefits in compressive strength - when compared to healthy inactive controls. There were no significant differences in total area or bending strength between the groups at the proximal tibia (66% site).

The present study addressed differences in bone geometry, density and strength between dancers, gymnasts and runners, but did not investigate the potential effects of nutrition, hormonal status, and other lifestyle factors on bone health. Future studies of bone adaptations in dancers should compare individual styles of dance separately and longitudinally, ideally from the peri-pubertal years into young adulthood. In addition, comparisons of different sports should include measurements of magnitude and frequency/ pattern of loadings to further identify which activities provide the greatest osteogenic benefits in adult females.

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APPENDIX A

Health History Questionnaire

Health History Questionnaire

The questions in this survey are directed towards those events in childhood, adolescence and your adult life that may have some influence on your bone mineral density. Read the questions carefully and answer honestly. Mark those questions which are not relevant or to which you are unable to respond with N/A. All information received remains strictly confidential.

1. IDENTIFICATION

Last initial ______________________________ First initial _________________________
Street Address ____
City or Town ____________________________ Zip Code ___________________________
Telephone (Home) _______________________ (Other) _____________________________
Date of Birth: Month ______ Day ___________ Year _____________
Sex: (circle one): Female Male

2. SOCIODEMOGRAPHIC DATA (CHECK ALL THAT APPLY)

2.1 Do you consider yourself…
_____White
_____Black or African American
_____Hispanic or Latino
_____Asian American
_____Hawaiian or Pacific Islander
_____American Indian or Native American
_____ Other ________________________________

3. LIFESTYLE DATA

3.1 Have you ever smoked (circle one)? Yes No (if no, go to question 3.4)

3.2 Do you still smoke (check one)? _____ Yes, daily

_____ Yes, occasionally

_____ No, not at all

3.3 When you are/were smoking, how many cigarettes do/did you usually smoke per day?

About __________ cigarettes/day for _________ years.

3.4 How often do you drink some kind of alcoholic beverage (check one)?

_____Daily or almost every day

_____3 or 4 times a week

_____Once or twice a week

_____Once or twice a month

_____Less than once a month

_____Never

_____Don’t know

3.5 How many cups of coffee do you/did you usually have during the time periods indicated?

Adolescence Adulthood

(12-17) (>18)

Never ________ ________

Sometimes ________ ________

1 to 2 cups per day ________ ________

3 or more cups per day ________ ________

3.6 How many cups of tea do you/did you usually have during the time periods indicated?

Adolescence Adulthood

(12-17) (>18)

Never ________ ________

Sometimes ________ ________

1 to 2 cups per day ________ ________

3 or more cups per day ________ ________

3.7 How many cans/bottles of pop/soda do you/did you usually have during the time periods indicated?

Adolescence	Adulthood
(12-17)	(>18)

Never ________ ________

Sometimes ________ ________

1 to 2 cups per day ________ ________

3 or more cups per day ________ ________

3.8 Do you eat a special diet? ________Yes ________No

If yes, please circle any and all that apply

Vegetarian

Vegan

No dairy (lactose intolerant)

No gluten

Low sodium

Low cholesterol

Other (please specify): ____________________

3.9 Do you take a calcium supplement? ________Yes ________No

If yes, how many times a day do you take it? ___________times/day

What is the name of the supplement? ________________________________

3.10 Do you take a multi-vitamin supplement? ________Yes ________No

If yes, how many times a day do you take it? ___________times/day

What is the name of the supplement? ________________________________

4. LIFESTYLE DATA – PHYSICAL ACTIVITY

4.1 Rate your overall level of physical activity as a child and youth? (circle one)

1	2	3	4	5
seldom active	sometimes active	active	moderately active	very active

4.2 How would you describe the games you played most often as a child? (circle one)

1	2	3
games such as board games, drawing, puzzles, etc.	games requiring some running, jumping, climbing, throwing, etc.	mostly running, jumping, climbing, throwing games

4.3 During which years were you physically active? (circle all that apply)

1	2	3
Age: 5-10	10-15	15-20

4.4 During which years were you the MOST physically active? (circle one)

1	2	3
Age: 5-10	10-15	15-20

4.5 Did you participate in organized sport as a child or youth (to 18 years)? _____Yes _____No

If Yes, list the sports you participated in and the approximate years of your participation:

Example: soccer 5 years , gymnastics 1 year

ACTIVITY	NUMBER OF YEARS

4.6 Approximately how many hours of television do you watch each day?

________less than 2h/ day on weekdays

________2h-5h/ day on weekdays

________ more than 5h/ day on weekdays

________ Hours on Saturday and Sunday

5. REPRODUCTIVE HISTORY (FEMALES ONLY)

5.1 Have you ever used birth control pills or oral contraceptives? ______Yes _______No

If yes,

5.1a At what age did you start (approximately)? _____ years of age

5.1b For approximately how long have you used birth control pills? _____ years _____ months

5.2 How old were you when you had your first menstrual period? ________ years old

5.3 Did you have regular periods once they began? _____ Yes _____ No

(one period every 35 days or less)

5.4 Are you currently having menstrual cycles? _____ Yes _____ No

If no,

5.4a How many years have you had irregular and/or absence of menstrual cycles? ______

5.5 How many menstrual cycles have you had in the past year?

_____3 or less

_____4 – 10

_____10 or more

5.6 On average, how often do you have menstrual periods? (check one)

_____20 days or less

_____21-25 days

_____26-30 days

_____31-36 days

_____37 days or more

_____Do not know

6. PERSONAL AND FAMILY HEALTH HISTORY

6.1 Have you ever been treated for any of the following conditions?

	YES	NO
Allergies		
Scoliosis		
High Blood Pressure		
Diabetes		
Asthma		
Anemia		
Polycystic Ovarian Syndrome		
Sleep Apnea		
Depression		
Other conditions:		

(Please list):

6.2 Have you ever had any problems with your bones such as a fracture? _____Yes _____No

If Yes, how many fractures have you had? ___________

Please list the type/location of fracture and year of occurrence:

Type/location of fracture ~Year or age

_________________________ __________________________

_________________________ __________________________

_________________________ __________________________

6.3 Is there a history of wrist, hip, or spine fracture in your family? _____Yes _____No

If Yes, indicate who was affected

_____Mother

_____Maternal grandmother

_____Maternal grandfather

_____Father

_____Paternal grandmother

_____Paternal grandfather

6.4 Is there a history of osteoporosis in your family? _____Yes _____No

7. MEDICATIONS

7.1 Are you currently taking any medications? Yes No

If Yes,

What medication(s) are you taking? What are these medication(s) for?

____

7.2 Have you ever taken any medication for more than 3 months? Yes No

If Yes,

What medication(s) are you taking? What are these medication(s) for?

____

8. ADDITIONAL QUESTIONS

8.1 Are you satisfied with your current weight? _____ Yes _____ No

8.1a. If not, what weight would you prefer to be? __________ Pounds.

8.2 Did you ever have a fracture on your legs in the last 12 months? ________ Yes ______ No

If yes, which one and when?

____

8.3. If you are a gymnast, at what age did you start training?

____

8.4 At what age did you start competing?

____

8.5 How many hours/ week have you trained the last year?

____

8.6 How many hours/ week on average have you trained the last 3 years?

____

8.7 What level/ division are you in currently?

____

Appendix B

Dance History Questionnaire

DANCE HISTORY QUESTIONNAIRE:
PERSONAL HISTORY (Please print):

First Name Initial_____ Middle Initial _____ Last Name Initial _______ Date of Birth: ____/____/_____

1) School/ Company where you primarily study/ perform:

____

2) Type of dance you primarily study (check all that apply)

___ Classical Ballet (if yes, which level/ years ____)
___ Classical Ballet (pointe)
___ Jazz
___ Modern (if yes, which technique ____)
___ Contemporary
___ Dance team (high kick)
___ Dance team (jazz)
___ Gymnastics / Tumbling
___ Tap
___ Other (please name ____)

3) How many hours in a typical week do you take the following **dance classes**:

Classical Ballet _________ hours/ week
Classical Ballet (pointe) _________ hours/ week
Jazz _________ hours/ week
Modern _________ hours/ week
Contemporary _________ hours/ week
Dance team (high kick) _________ hours/ week
Dance team (jazz) _________ hours/ week
Gymnastics / Tumbling _________ hours/ week
Tap _________ hours/ week
Other _________ hours/ week

4) How many hours in a typical week do you rehearse the following: **(only answer if it is in ADDITION to your regular class load)**

Classical Ballet _________ hours/ week
Classical Ballet (pointe) _________ hours/ week
Jazz _________ hours/ week
Modern _________ hours/ week
Contemporary _________ hours/ week
Dance team (high kick) _________ hours/ week
Dance team (jazz) _________ hours/ week

Gymnastics / Tumbling _________ hours/ week
Tap _________ hours/ week
Other _________ hours/ week

5) At what age did you start serious dance training (competing or performing at pre-professional level)? _______________ years old
6) If applicable, at what age did you start training on pointe? ____________ years old.
7) What type of dance shoes do you wear more often? ____
8) Do you dance on sprung wood floors? ____ Yes ______No
9) If not, what kind of floor do you dance most of the time? ____
10) Do you wear orthotics? _______ Yes _______ No
11) If yes, what type, when, and for how long? ____
12) Do you do any other form of exercise on a regular basis? _____ YES ______ NO

13) If yes, what **type** and how many **hours/ week** at **what intensity** on a scale from 1-10 (1 =very easy, 10 = as hard as possible).

i.e. Yoga, 1h/week, 5

____
____
____
____

14) For the past 3 years, what was your average training load per week (including rehearsal, performances, and classes): _____________________ hours/ week.

Appendix C

Table 6

Table 6. Multiple Regression Models Predicting Average Total Bone Cross Sectional Area at the Tibia (4% and 66% sites)

	Total Area 1 (4%)	Total Area 2 (4%)	Total Area 3 (4%)	Total Area 4 (66%)	Total Area 5 (66%)	Total Area 6(66%)
	B	B	B	B	B	B
Predictor	SE	SE	SE	SE	SE	SE
Controls	893.41***	-196.912	-125.5	542.84***	260.1469***	-275.014
	25.1	370.996	394.1	15.54	57.2083	205.491
Dancers	-13.08	3.913	6.1	-5.5	12.2934	16.117
	41.45	39.421	39.8	25.66	21.8184	20.772
Gymnasts	48.08	102.862*	100.6*	12.38	31.9866	57.049*
	41.45	43.206	43.6	25.66	21.8788	22.759
Runners	48.01	53.734	59.2	-2.3	23.2715	17.953
	34.27	32.294	33.9	21.21	18.5009	22.759
Height		6.474**	5.6*			3.744**
		2.198	2.7			1.386
Mass			1.1		4.4217***	2.93**
			1.9		0.8713	0.995
R^2	0.6	0.18	0.19	0.007788	0.3129	0.3908

*Note: * $p<0.05$, **$p<0.01$, ***$p<0.001$*

APPENDIX D

Table 7

Table 7. Multiple Regression Models Predicting Average Bone Density at the Tibia (4% site)

Predictor	B SE	B SE
Controls	237.2	358.0*
	140.8	141.5
Dancers	47.1**	50.7***
	15.0	14.3
Gymnasts	48.0**	44.1**
	16.4	15.7
Runners	11.3	20.6
	12.3	12.2
Height	0.5	-0.9
	0.8	1.0
Mass		1.8*
		0.7
R^2	0.21	0.30

*Note: * $p<0.05$, **$p<0.01$, ***$p<0.001$*

APPENDIX E

Table 9

Table 9. Multiple Regression Models Predicting Average Bone Strength at the Tibia

	BSI 1 (4%)	BSI 2 (4%)	SSIp 1 (66%)	SSIp 2 (66%)	SSIp 3 (66%)
Predictor	B	B	B	B	B
	SE	SE	SE	SE	SE
Controls	-8015.8	-279.4	2317.09^{***}	-3318.11^{**}	-2232.35^{*}
	7599.8	7441.3	79.86	1025.514	996.551
Dancers	2765.5^{**}	2997.9^{***}	-65.43	22.403	55.011
	807.5	752.2	131.88	108.968	100.734
Gymnasts	4192.6^{***}	3946.5^{***}	-10.01	273.105^{*}	238.563^{*}
	885.1	824.1	131.88	119.429	110.371
Runners	1210.2	1804.6^{**}	59.77	89.351	172.772^{*}
	661.6	640.3	109.02	89.269	85.752
Height	103.8^{*}	13.6		33.46^{***}	20.803^{**}
	45	50.2		6.077	6.724
Mass		116.6^{**}			16.359^{**}
		36			4.825
R^2	0.31	0.41	0.017	0.35	0.46

Note:* $p<0.05$, **$p<0.01$, ***$p<0.001$