Spring 2018

Contribution of high school sport participation to young adult bone strength

Ryan C. Ward
University of Iowa

Follow this and additional works at: https://ir.uiowa.edu/etd
Part of the Physiology Commons

CONTRIBUTION OF HIGH SCHOOL SPORT PARTICIPATION TO YOUNG ADULT BONE STRENGTH

by

Ryan C. Ward

A thesis submitted in partial fulfillment
of the requirements for the Master of Science
degree in Health and Human Physiology in the
Graduate College of
The University of Iowa

May 2018

Thesis Supervisor: Professor Kathleen F. Janz

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Ryan C. Ward

has been approved by the Examining Committee for
the thesis requirement for the Master of Science degree
in Health and Human Physiology at the May 2018 graduation.

Thesis Committee: ____________________________________
Kathleen F. Janz, Thesis Supervisor

____
Clayton Peterson

____
Steven M. Levy

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Janz, for her thoughts, ideas, guidance, mentorship, and kindness during my graduate education and for the opportunity to be part of an outstanding lab. I would also like to thank my other thesis committee members, Dr. Peterson and Dr. Levy, for their time, critiques, and suggestions as this thesis evolved. Thank you also to Piroska Boros and Minsuk Oh for their comments on this thesis and for their friendship.

I would be remiss if I did not express my gratitude towards all those involved in the Iowa Bone Development Study. Their hard work in data collection over the years has made this project possible. Furthermore, a special thank you to Elena Letuchy for her thoughts and statistical assistance. The Physical Activity and Health Outcomes Lab is lucky to have you.

Finally, I would like to thank my wife, Elyse, and the rest of my family and friends for all their support and good wishes during my graduate career.

ABSTRACT

Introduction: Nearly 8 million American adolescents participate in sports. Normally, participation declines in young adulthood. The purpose of this study was to assess longitudinal effects of interscholastic high school sport participation and muscle power on young adult bone strength. **Methods:** 295 young adults from the Iowa Bone Development Study were classified into sport participation groups based on an interscholastic sport participation history questionnaire. Groups included Power Sport Participant (PSP), Other Sport Participant (OSP), and Nonparticipant (NP). Current physical activity (PA) behaviors were assessed via questionnaire. Dual x-ray absorptiometry (DXA) assessed hip areal bone mineral density (aBMD) and was used with Hip Structure Analysis (HSA) to estimate femoral neck section modulus (FN Z) and hip cross-sectional area (CSA). Peripheral quantitative computed tomography (pQCT) provided stress-strain index (SSI) and bone strength index (BSI) at 38% and 4% midshaft tibial sites respectively. Vertical jump estimated muscle power at age 19. Gender-specific multiple linear regression predicted young adult bone outcomes based on sport participation groups. Mediation analysis analyzed effects of muscle power on relationships between sport participation and bone strength. All analyses were adjusted for current PA. **Results:** For both males and females, bone outcomes for PSPs were greater than bone outcomes for NPs ($P < 0.025$). Bone outcomes for PSPSs were also greater than OSPs in females ($P < 0.025$). Mean differences for PSPs and NPs differed between 6.5% to 15.7%. Muscle power mediated 14% to 27.5% of the effect of sport participation on bone outcomes. **Conclusion:** Former male interscholastic sport participants and female interscholastic power sport participants have stronger bones than peers even when adjusting for current PA. Muscle power did not fully

explain differences in all bone outcomes suggesting that sport participation has additional bone health benefits.

PUBLIC ABSTRACT

Many sports, such as basketball and volleyball, require powerful muscle movements in addition to ground impacts. Both muscle forces and ground impacts are signals for increasing bone strength. Therefore, sport participation is associated with strong bones. In the United States, there were nearly 8 million participants in interscholastic high school sports for the 2016-2017 school year. Unfortunately, sport participation declines as adolescents reach young adulthood. For this reason, we wanted to assess the longitudinal effects of interscholastic high school sport participation on young adult bone strength. Additionally, we wanted to see if muscle power was responsible for the increases in bone strength.

Two hundred ninety-five young adults (18-21 years old; 163 females, 132 males) had clinical scans performed for bone strength and structure. Additionally, the participants were classified into sport participation groups based on an interscholastic sport participation history questionnaire (Power Sport Participant, Other Sport Participant, Nonparticipant). Participants also completed questionnaires to assess current physical activity and performed vertical jumps as a measure of muscle power. Relationships between sport groups and bone strength were examined. Furthermore, differences between the average bone strength values in the three different sport groups were calculated. Finally, we assessed if muscle power could explain the differences in bone outcomes from the sport groups. The results indicate that male sport participants and female Power Sport Participants have stronger bones than peers even when accounting for current physical activity. Muscle power did not fully explain differences in all bone outcomes suggesting that sport participation has additional bone health benefits.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Bone strength is defined as resistance to fracture and is a key indicator of bone health throughout the lifespan (1). In clinical and epidemiological studies, bone strength is approximated using measures of bone mass and bone structure (2). Common methods of assessing mass and structure include dual-energy x-ray absorptiometry (DXA) and peripheral quantitative computed tomography (pQCT). DXA uses two-dimensional imaging to measure areal bone mineral density (aBMD) and bone mineral content. When paired with bioengineering software, DXA can provide further information on the quality of bone. One example of this pairing is hip structure analysis (HSA). HSA uses the distribution of mineral mass that lies in a transverse plane to the bone to measure geometric characteristics at that location (3). From there, further indices of bone strength can be derived such as section modulus, which is an indicator of bending resistance in cross section. pQCT, on the other hand, uses three dimensional images of the bone to measure volumetric bone mineral density (vBMD) and to derive indices of structure including bone strength index (BSI), a measure of bone compressive strength. Stress strain index (SSI), an estimate of bone resistance to torsion, can also be derived using pQCT (2). Together, these bone outcomes provide important in vivo information on fracture risk.

In addition to other determinants, such as dietary patterns and genetics, physical activity is causally related to bone strength (4,5). Experimental animal studies and randomized control trials indicate that the most beneficial physical activities for bone are dynamic, short in duration, applied quickly, and are high in load magnitude (6,7). For example, Robling et al. have demonstrated in rat models that bone is more responsive short, intermittent activity bouts compared to a single longer bout, emphasizing the importance of activities that are brief in nature (8). Another rat study displayed the importance of the aspects of quick application and high load magnitudes. Järvinen et al. found that rats exposed to mill walking and sudden impacts had higher cross-sectional moment of inertia values, a measure used to calculate bending stress, compared to sedentary animals or animals that only walked (9). In humans, high load magnitudes are delivered to bone during forceful contacts with the ground or other objects (i.e. impact loading) (10). These loads serve as a signal to induce bone adaptations, and commonly occur during jumping, sprinting, or racquet sports (11,12,13). Importantly, high load magnitudes are also applied when muscle rapidly pulls on bone, such as during power lifting (14) or the up-phase of jumping (15). On the other hand, activities without loads, such as cycling, are not effective at strengthening bone (16).

Sport is widely accessible to children and adolescents through educational institutions. The National Federation of State High School Associations reports 7.9 million interscholastic high school sport participants for the 2016-2017 school year (17). Many types of sport expose participants' bones to both impact and muscle forces (18) making it a valuable method of developing bone strength. Both adolescent and young adult athletes that participate in sports such as basketball, soccer, or gymnastics have stronger bones compared to those that participate in non-impact sports or sedentary peers (16,19,20,21). In addition to sport participation, physical fitness, specifically muscle power, has been shown to be predictive of markers of bone strength (22,23).

Although it is common to classify osteogenic activities and sports into weight bearing (18) or impact (20,21) categories, focusing on sports that primarily emphasize muscle power, for example basketball or volleyball, may be more advantageous. Athletes in these sports may train for muscle power by jump training or explosive weight-lifting. By doing so, they expose their bones to both rapidly applied muscle forces and ground impacts while bettering their performance. On the other hand, impact training, such as repeated box step offs, has no power benefits. In addition, muscle power can be tested in a field setting with a vertical jump (22), whereas impact testing requires laboratory equipment. Therefore, by getting coaches, instructors, parents, and athletes to support the notion of muscle power, participants increase sport performance with the bonus of improved bone strength.

Late adolescence and young adulthood are important osteogenic time periods because clinically-relevant bone sites achieve peak mass accrual and ultimately peak bone strength, during this time (24). Regrettably PA, including participation in sport, decreases from adolescence to young adulthood (25). Consequently, exposure to bone strengthening PA is reduced for many young adults. Therefore, there is value in understanding if bone health benefits associated with sport participation during high school are sustained during young adulthood. To this end, using a longitudinal design and a two-year follow up, we examined the amount of explained variability in young adult bone strength attributed to high school interscholastic sport participation. To better understand how sport contributes to bone health, we tested the potential mediating effect of muscle power on the relationship between high school interscholastic sport participation and young adult bone strength. We hypothesized that interscholastic sport participation during high school would positively predict bone strength in the young adults and that much of the association could be explained by muscle power.

CHAPTER 2: LITERATURE REVIEW

Bone Strength and Its Measurements

Healthy bone are strong bones. Bone strength is defined as increased resistance to fracture and decreased fragility. These characteristics can be determined by mineral content, mass, bone structure, and bone morphology (1). According to Weaver et al. (2), maximizing these qualities during growth may be the most efficacious method of decreasing fracture risk in future life.

The most common method of measuring mass and structure is by using dual x-ray absorptiometry (DXA). DXA is a low radiation dose, two-dimensional x-ray technique. The two-dimensional aspect of DXA yields a planar image of bone that can be used to estimate bone area. The attenuation of the x-rays through the bone provides information on the amount of mineral content contained within. Combining the bone area and mineral content provides areal bone mineral density (aBMD) (2). However, structural bone strength is not fully characterized solely by bone mineral content. For that reason, Beck et al. (3) developed a computer program called Hip Structural Analysis (HSA). HSA combines hip bone scan data from DXA with mechanical engineering principles to obtain structural strength properties of bone. For example, HSA can calculate strength estimates of stress, shear, and tension. One index calculated is cross sectional moment of inertia, which is an integration of the products of incremental areas along the femoral neck and the square of their distances from the neutral axis. Cross sectional area is also computed by estimating the amount of bone surface area in cross section without including trabecular bone and soft tissue. Dividing cross sectional moment of inertia by cross sectional area yields section modulus of the femoral neck (FN Z) (3). FN Z is an index of bending resistance in cross section (2).

Peripheral quantitative computed tomography (pQCT) is another imaging technique used to assess bone strength in the extremities, such as the radius and tibia. pQCT, however, is not as widely used as DXA (2). pQCT uses three-dimensional x-ray technology and therefore can provide more information than DXA. The three-dimensional aspect of pQCT can assess bone depth, something DXA cannot do, and therefore, volume of bone can be obtained. pQCT also measures the attenuation of x-ray beams through bone to calculate bone density. Combining the volumetric measure and bone density data yields volumetric bone mineral density, which is grams of bone mineral content per cm^3 of bone. However, pQCT can also provide structural information about bone. One structural index provided by pQCT is bone strength index (BSI), which has units of mg^2/mm^4 and is a measure of bone compressive strength (2). Another structural index of bone that pQCT can obtain is stress strain index (SSI). SSI is measured in mm^3 and is an index of bone torsional strength (22).

Activity Modalities Increasing Bone Strength

Bone strength is influenced by numerous things. Genetics and dietary calcium intake positively impact bone strength (2). Physical activity is another modality that increases bone strength. In observational studies, physical activity is causally related to bone strength. For example, Welten et al. (4) performed a 15-year longitudinal study analyzing the relationship between lumbar bone mineral density and questionnaire measured activity and calcium intake in 84 males and 98 females. The study began when subjects were 13 years. The researchers used multiple linear regression to create bone strength prediction equations using body weight, calcium intake and weight bearing activity. Weight bearing activity was found to be a significant predictor of bone mineral density whereas calcium was not. The researchers concluded that regular weight bearing activity was of key importance in developing lumbar bone strength (4).

A more recent longitudinal study by Janz et al. (5) had a similar conclusion. The researchers followed 530 children from age 5 to age 17. At ages 5, 8, 11, 13, 15, and 17, participants wore an accelerometer to objectively measure physical activity. At age 17, study subjects had both DXA and pQCT scans taken. Study subjects were separated into three groups based on amount of activity achieved. Generalized linear models were used to examine the groups as predictors of age 17 bone strength. In both males and females, those who achieved more moderate-and-vigorous physical activity (MVPA) had greater bone mass and better indices of bone geometry (5).

As informative as these observational studies are, they do not fully explain what types of activity are most beneficial for strengthening bone. A review by Turner & Robling (6) stated that the fluid with bone's lacuna-canalicular system was key in bone formation. Dynamic loading of the bones causes pressure to increase within the lacuna-canalicular system, driving fluid to other parts of the bone which creates shear stress on the osteocytes lining the system. This shear stress is the signal that begins a cascade of bone formation events (6). Therefore, dynamic activities, as opposed to static, are more efficacious at strengthening bone.

Animal studies have also been used to inform the scientific community about bone strengthening activities. For example, Robling et al. (8) performed a study with lab rats to study the effect of the number of osteogenic bouts on bone formation. In the study, rat ulnas were mechanically loaded using a device that compressed the ulna along the axial axis. Rats were randomized to receiving 360 load cycles of compression in one bout or receiving 4 bouts of 90 load cycles with 3 hours between bouts. These bouts occurred 3 times per week for 16 weeks. After the 16 weeks, rats that had 4 bouts of 90 cycles had greater resistance to fracture and bone mineral density. The conclusion reached was that mechanical loading is better for bone strength if the loads are not applied in one single bout. To the contrary, loadings should be separated by a rest period to realize stronger bones (8). Another lab rat study was performed by Järvinen et al. (9) in which rats were randomized to two exercise groups or a control group. One exercising group simply ran on an exercising mill. The second exercising group ran on a modified mill in which the mill would randomly and suddenly tilt to the side or rise and drop to create a sudden up-down movement. These random, sudden movements created impact stimuli on the rats' bones. The study lasted 9 weeks before animals were sacrificed. Both exercise groups had greater bone strength indices after the intervention compared to the sedentary rats. However, the rats that ran on the modified mill and experienced impacts had significantly greater cross-sectional moment of inertia values compared to the rats that ran on a traditional mill (9). Therefore, this study provides evidence that activities that impose quick applications of high loads are important for bone strength.

Research has also been performed in human trials on the types of activity that are beneficial for developing bone strength. A systematic review by Gaudalupe-Grau et al. (10) that assessed the effects of exercise and physical activity on bone mass and geometry concluded that events that require high forces or generate high impacts have the greatest osteogenic potential in humans. High forces and high impacts are generated when muscle pulls on bone or when impact with the ground or another object is made. Research by Fuchs et al. (7) examined jumping, a quick action with high load impacts, and its osteogenic potential in children. Eighty-nine children between the ages of 5.9 and 9.8 were randomized to a control group or a group that performed 100 jumps off of a 61-cm box three times a week. At the end of the study, which lasted 7 months, the jumping group had significantly greatly bone mass at the lumbar spine and femoral neck than controls. Therefore, these animal and randomized control studies indicate that the most beneficial activities for bone are dynamic, short in duration, applied quickly, and are high in load magnitude.

Sport Participation and Bone

The dynamic nature and load impacts experienced during sport participation have made sport an active area of research for its influence on bone strength. For example, a cross-sectional study by Rantalainen et al. (12) researched sprint athletes' bones compared to age matched controls. Sprint athletes, such as those who participate in the 100 or 400-meter dash, were chosen because sprinting requires great muscle forces and exposes participants to high ground reaction forces. These are very osteogenic stimuli and the results support what would be expected for bones exposed to these loads. The sprint athletes had 21% greater midshaft stress-strain index compared to the controls. Therefore, there is evidence to say that sports that involve sprinting expose participants to beneficial bone strengthening phenomena (12).

A longitudinal study of sport participation and bone mineral content in young adolescent males was performed by Vlachopoulos et al. (16). In the study, 116 13 to 14-year-old soccer players, swimmers, cyclists, and active controls, subjects who did not participate in any of the previous groups, were followed for one year. At follow-up, the soccer players had greater total body and total hip bone mineral content compared to all other groups. Cyclists and swimmers did not have significantly different outcomes compared to the active controls. This study indicates that not all sport participation is equal in terms of osteogenic potential. (16). These findings support the results from the research by Lima et al. (20). The study was a cross-sectional study of male impact sport participants (gymnastics, athletics, basketball, and tennis), non-impact sports participants (swimming and water polo), and non-sport participant controls. Impact sport participants were found to have greater BMD at the lumbar spine, femoral neck, and total body compared to all other groups. There was not a significant difference in lumbar spine or femoral neck BMD between the non-impact group and control group (20).

Lynch et al. (21) provided more evidence for the benefits of sports that involve impacts and muscle power. In addition to analyzing BMD, Lynch also investigated the occurrence of stress fractures during a nine-month follow-up period. 184 young adolescents (mean age 12.3 years old) were categorized based on sport participation. Soccer, basketball, volleyball, karate, judo, and kung-fu were classified as impact sports. The impact sports group was compared to a swimming group and a non-sport participation group. The impact sports group was found to have higher values for BMD compared to other groups. More importantly, the impact sports group had a reduced fracture risk compared with controls while swimming did not have a reduced fracture risk. Therefore, there is evidence to say that sport participation, particularly in sports that emphasize impacts and muscle power, has physiologically and clinically significant implications (21).

Impact does not need to be made with the ground, such as what occurs during jumping, to be osteogenic. Impacts with other objects, racquet sports for example, also provide stimuli for bone development. This is shown in the research by Haapsalo et al. (13). BMD was assessed in the dominant arm and non-dominant arm of female youth tennis players. These outcomes were then compared to non-tennis playing controls. BMD in the dominant arm of the tennis players was greater than the nondominant arm. Tennis playing girls aged 12 and above also had greater arm BMD values compared to controls. These results signify that racquet sports can influence bone health and that bone development due to impact is site-specific (13).

There is speculation that since distance running is weight-bearing that it is osteogenic and should be included with other impact sports. However, results from Taffe et al. (19) would dispute this. Changes in BMD over 8 months were analyzed in young adult females. The subjects included 34 college gymnasts, 36 distance runners, and 25 nonathletic controls. The gymnasts had great lumbar spine and femoral neck BMD compared to runners and had greater lumbar spine BMD compared to controls. Runners did not have any outcomes significantly different compared to controls (19).

The literature reviewed suggests that all sport participation is not equal in terms of developing bone. The best sports therefore are those that involve impacts and powerful muscle movements, such as sprinting and jumping.

Muscle Power and Bone

Many of the sports previously discussed, such as soccer, sprinting, and gymnastics, require powerful movements. For this reason, muscle power and its relation to bone strength has been researched. For example, Janz et al. (22) investigated the association between lower body muscle power and tibial BSI and SSI in adolescents. 141 males and 162 females, mean age 17 years old, had pQCT scans taken. The study subjects also performed a vertical jump. Muscle power was estimated using the Sayer's et al. (30) equation by using jump height and body mass as variables. Pearson correlation coefficients for muscle power and bone outcomes were significant. The correlation coefficients for SSI were 0.74 for males and 0.78 for females while the coefficients for BSI were 0.58 and 0.54 for males and females respectively. These results indicate that muscle power can predict bone strength (22). Further evidence for the predictive capability of muscle power was shown in another cross-sectional study performed in college athletes. Yingling et al. (23) analyzed the relationship between vertical jump and tibial SSI. There were 86 student-athletes, of which 56 were female, that participated in the study. The sports represented were track and field, cross country, volleyball, soccer, swimming, and basketball. The Sayer's et al. (30) equation was also used to estimate lower body muscle power. A multiple linear regression model was created to predict SSI from muscle power and sex. These two variables explained 54.1% of the variance in SSI. The model also indicated that muscle power explained more of the variance than sex did (23).

Muscle power is generally thought of as necessary for performance or fitness. However, these studies together indicate that muscle power has bone health benefits. Therefore, muscle power should not be thought of solely in terms of athletic ability, but also as a mechanism that boosts health. As such, all people, not just athletes, should participate in activities requiring muscle power for its osteogenic benefits.

Summary and Need for Further Study

The review of literature above describes how activity and sport influences bone strength indices. What has been shown is that activities that are dynamic, short in duration, high in load magnitude, and applied quickly are osteogenic. Also, not all sports are equal in their ability to develop bone strength. In addition, muscle power is related to bone strength. However, much of the research investigating sport participation and bone outcomes is cross-sectional (12,13,18,20,39). Cause and effect conclusions cannot be made in this study design. Additionally, PA, including sport participation, tends to decline from adolescence to young adulthood (25), a time when peak bone mass, and presumably peak bone strength, tends to be achieved (24). This raises the question whether previous history of sport participation influences bone strength during young adulthood, a time after participation ends and PA levels decline. Furthermore, the effect of muscle power on bone should further be investigated to assess its nature in the role of bone development.

Research Questions

Research Question 1: Does interscholastic high school sport participation predict young adult bone strength when adjusting for current PA behavior?

Research Question 2: Does muscle power mediate the relationship between interscholastic sport participation and bone strength?

CHAPTER 3: RESEARCH PAPER

Abstract

Introduction: Nearly 8 million American adolescents participate in sports. Normally, participation declines in young adulthood. The purpose of this study was to assess longitudinal effects of interscholastic high school sport participation and muscle power on young adult bone strength. **Methods:** 295 young adults from the Iowa Bone Development Study were classified into sport participation groups based on an interscholastic sport participation history questionnaire. Groups included Power Sport Participant (PSP), Other Sport Participant (OSP), and Nonparticipant (NP). Current physical activity (PA) behaviors were assessed via questionnaire. Dual x-ray absorptiometry (DXA) assessed hip areal bone mineral density (aBMD) and was used with Hip Structure Analysis (HSA) to estimate femoral neck section modulus (FN Z) and hip cross-sectional area (CSA). Peripheral quantitative computed tomography (pQCT) provided stress-strain index (SSI) and bone strength index (BSI) at 38% and 4% midshaft tibial sites respectively. Vertical jump estimated muscle power at age 19. Gender-specific multiple linear regression predicted young adult bone outcomes based on sport participation groups. Mediation analysis analyzed effects of muscle power on relationships between sport participation and bone strength. All analyses were adjusted for current PA. **Results:** For both males and females, bone outcomes for PSPs were greater than bone outcomes for NPs ($P < 0.025$). Bone outcomes for PSPSs were also greater than OSPs in females ($P < 0.025$). Mean differences for PSPs and NPs differed between 6.5% to 15.7%. Muscle power mediated 14% to 27.5% of the effect of sport participation on bone outcomes. **Conclusion:** Former male interscholastic sport participants and female interscholastic power sport participants have

stronger bones than peers even when adjusting for current PA. Muscle power did not fully explain differences in all bone outcomes suggesting that sport participation has additional bone health benefits.

Funding

This work was supported in part by the National Institute of Dental and Craniofacial Research (R01-DE12101 and R01-DE09551), and by the National Center for Research Resources (UL1 RR024979 and M01-RR00059).

Background

Bone strength is defined as resistance to fracture and is a key indicator of bone health throughout the lifespan (1). In clinical and epidemiological studies, bone strength is approximated using measures of bone mass and bone structure (2). Common methods of assessing mass and structure include dual-energy x-ray absorptiometry (DXA) and peripheral quantitative computed tomography (pQCT). DXA uses two-dimensional imaging to measure areal bone mineral density (aBMD) and bone mineral content. When paired with bioengineering software, DXA can provide further information on the quality of bone. One example of this pairing is hip structure analysis (HSA). HSA uses the distribution of mineral mass that lies in a transverse plane to the bone to measure geometric characteristics at that location (3). From there, further indices of bone strength can be derived such as section modulus, which is an indicator of bending resistance in cross section. pQCT, on the other hand, uses three dimensional images of the bone to measure volumetric bone mineral density (vBMD) and to derive indices of structure including bone strength index (BSI), a measure of bone compressive strength. Stress strain index (SSI), an estimate of bone resistance to torsion, can also be derived using pQCT (2). Together, these bone outcomes provide important in vivo information on fracture risk.

In addition to other determinants, such as dietary patterns and genetics, physical activity is causally related to bone strength (4,5). Experimental animal studies and randomized control trials indicate that the most beneficial physical activities for bone are dynamic, short in duration, applied quickly, and are high in load magnitude (6,7). For example, Robling et al. have demonstrated in rat models that bone is more responsive short, intermittent activity bouts compared to a single longer bout, emphasizing the importance of activities that are brief in nature (8). Another rat study displayed the importance of the aspects of quick application and high load magnitudes. Järvinen et al. found that rats exposed to mill walking and sudden impacts had higher cross-sectional moment of inertia values, a measure used to calculate bending stress, compared to sedentary animals or animals that only walked (9). In humans, high load magnitudes are delivered to bone during forceful contacts with the ground or other objects (i.e. impact loading) (10). These loads serve as a signal to induce bone adaptations, and commonly occur during jumping, sprinting, or racquet sports (11,12,13). Importantly, high load magnitudes are also applied when muscle rapidly pulls on bone, such as during power lifting (14) or the up-phase of jumping (15). On the other hand, activities without loads, such as cycling, are not effective at strengthening bone (16).

Sport is widely accessible to children and adolescents through educational institutions. The National Federation of State High School Associations reports 7.9 million interscholastic high school sport participants for the 2016-2017 school year (17). Many types of sport expose participants' bones to both impact and muscle forces (18) making it a valuable method of developing bone strength. Both adolescent and young adult athletes that participate in sports such as basketball, soccer, or gymnastics have stronger bones compared to those that participate in non-impact sports or sedentary peers (16,19,20,21). In addition to sport participation, physical fitness, specifically muscle power, has been shown to be predictive of markers of bone strength (22,23).

Although it is common to classify osteogenic activities and sports into weight bearing (18) or impact (20,21) categories, focusing on sports that primarily emphasize muscle power, for example basketball or volleyball, may be more advantageous. Athletes in these sports may train for muscle power by jump training or explosive weight-lifting. By doing so, they expose their bones to both rapidly applied muscle forces and ground impacts while bettering their performance. On the other hand, impact training, such as repeated box step offs, has no power benefits. In addition, muscle power can be tested in a field setting with a vertical jump (22), whereas impact testing requires laboratory equipment. Therefore, by getting coaches, instructors, parents, and athletes to support the notion of muscle power, participants increase sport performance with the bonus of improved bone strength.

Late adolescence and young adulthood are important osteogenic time periods because clinically-relevant bone sites achieve peak mass accrual and ultimately peak bone strength, during this time (24). Regrettably PA, including participation in sport, decreases from adolescence to young adulthood (25). Consequently, exposure to bone strengthening PA is reduced for many young adults. Therefore, there is value in understanding if bone health benefits associated with sport participation during high school are sustained during young adulthood. To this end, using a longitudinal design and a two-year follow up, we examined the amount of explained variability in young adult bone strength attributed to high school interscholastic sport participation. To better understand how sport contributes to bone health, we tested the potential mediating effect of muscle power on the relationship between high school interscholastic sport participation and young adult bone strength. We hypothesized that interscholastic sport participation during high school would positively predict bone strength in the young adults and that much of the association could be explained by muscle power

Methods

Participant Recruitment and Study Design

The Iowa Bone Development Study (IBDS) is an ongoing, longitudinal study of bone health and health status from childhood through adolescence and young adulthood. Participants for the IBDS were recruited from 1998 to 2001, when subjects were approximately 5 years of age, from a larger group of children (n = 890) that were already participating in the Iowa Fluoride Study. Recruitment for the Iowa Fluoride Study occurred in eight Iowa hospitals between 1992-1994 immediately following birth. Demographic characteristics of the IBDS subject population include being 95% white, with two-thirds of subjects' parents having college degrees (5). Further information about participants' demographic data has previously been discussed (26). This secondary analysis focuses on IBDS participants with assessments during late adolescence and young adulthood, specifically 18 to 21-year-old males and females (mean age 19.7 years old). The Iowa Bone Development Study was approved by the University of Iowa Institutional Review Board (Human Subjects). Minors provided informed written assent with legal caregivers and subjects over the age of 18 providing informed written consent.

Body Height, Weight, and Peak Height Velocity

Research staff trained in anthropometry assessed participants' body height (cm) and body weight (kg) using standardized protocols. Body height was measured using a Harpenden stadiometer (Holtain Ltd, Crosswell, UK), and body weight was measured using a Healthometer physician's scale (Continental, Bridgeview, IL). Participants were weighed and measured without shoes, and data were recorded in tenths of kilograms and in tenths of centimeters, respectively. Maturity offset (years from peak height velocity [PHV]) prediction equations established by Mirwald et al. (27) were used to determine somatic maturity. These equations include age, sex, weight, height, sitting height, and leg length as predictors. Peak height velocity estimates were calculated for all participants using ages 11 and 13 examination data for girls and ages 13 and 15 data for boys, if available. The clinical examination (between ages 11 and 15), which provided an estimate of PHV age that was closest to the actual clinical examination age was used as the best estimate (the Mirwald equation is most precise closest to actual PHV age). If only one PHV estimate was available, it was used. As the cohort aged, years since PHV was used as a measure of biological age.

Questionnaire Assessment of Sport Participation

At approximately age 17 years, participants reported the amount and type of high school interscholastic sport participation. Based on investigator knowledge of sport mechanics, high school sport participation groups were coded as Power Sport Participant (PSP) (member of basketball, cheerleading/poms, football, gymnastics, soccer, and/or volleyball team for at least two seasons), Other Sport Participant (OSP) (member of baseball, cross country/track and field, softball, tennis, and/or wrestling team for at least two seasons or power sport participant for one season), or Nonparticipant (NP) (not a member of a high school power sport team, or one season of other sport, or no reported interscholastic sport participation). Since bone intervention studies suggest that a minimum of seven months is needed for bone adaption (2), we required at least two seasons in a sport that we considered to emphasize power to code a participant as PSP.

Questionnaire Assessment of Physical Activity Behaviors

At follow up, approximately age 19, participants completed the Physical Activity Questionnaire for Adults (PAQ-AD). The PAQ-AD is a seven-day recall questionnaire that asks about general PA, sport participation, exercise, and the intensity of these activities. The PAQ-AD has been shown to be a valid measure of PA when compared to accelerometer measurements of PA (28). The PAQ-AD asks participants about physical activity behaviors using a 1-5 scale with 5 corresponding to higher amounts of activity. Participants' responses to the questions are averaged to give a composite score from 1 to 5. The PAQ-AD was used to adjust all multi-variate analyses for current PA.

Vertical Jump Assessment of Muscle Power

At approximately age 19 years old, participants completed a vertical jump test to test lower body power. Jump height was measured using a Vertec (Questek Corp, Elgin, IL) which has been validated and is strongly correlated (r=0.91) with vertical jump height quantified by a 3-camera motion analyses system (29). We used the Sayers et al. equation to predict muscle power using vertical jump height. The Sayers equation is as follows: (W) = (60.7) × (jump height [cm]) + 45.3 × (body mass [kg] − 2055) (30). This equation uses body weight in part to estimate muscle power and has been validated by comparing estimated muscle power to force platform measured muscle power (Predicted Residual Sum of Squares R^2=0.87) (30). Participants were instructed to perform a squat jump by bending their knees and moving their arms behind them until their knuckles faced the floor, pausing in this squat position so as not to gain any momentum and then jumping as high as possible while reaching up and hitting the Vertec with the dominant arm. After a warm-up, three jumps were measured, and the highest jump height (cm) was recorded.

Dual X-Ray Absorptiometry (DXA) Measurement of Bone Strength

At approximately age 19 years old, trained research staff conducted DXA scans for all participants using the Hologic QDR 4500A DXA (Delphi upgrade) with software V.12.3 in the fan-beam mode, as described previously (5). Briefly, software-specific Global Regions of Interest (ROI) were used to designate the general boundaries of the hip images. The operator reviewed, edited, and confirmed the bone within the ROI box to ensure appropriate bone-edge detection. The DXA measure used in this study was aBMD (g/cm^2) at the total hip. Structural geometry was estimated from hip DXA images using the Hip Structure Analysis program (Hologic Apex 3.0 software). This program is based on the principle first described by Martin and Burr that the mass in a pixel value (g/cm^2 of hydroxyapatite) can be converted to linear thickness (cm) by dividing it by the effective mineral density of a fully mineralized bone (31). A line of pixels traversing the bone axis is thus a projection of the surface area of a bone in cross-section and can yield some of its geometry (3). Specifically, the Hologic software program located the narrowest point of the femoral neck, where bone cross-sectional area (CSA, cm^2) and cross-sectional moment of inertia (cm^4) for bending in the image plane were calculated, from which femoral neck section modulus (FN Z, cm^3) was derived.

Peripheral Quantitative Computed Tomography (pQCT) Measurement of Bone Strength

Tibial measures were acquired using pQCT, software version XCT 6.00 (XCT 2000 or 3000, Stratec, Inc, Pforzheim, Germany), with the Stratec XCT 3000 being used for individuals with a calf circumference greater than 15.5 inches (n = 27). An IBDS calibration study found good agreement between these Stratec models (5). All pQCT scans were acquired by one of three International Society for Clinical Densitometry (ISCD)–certified bone densitometry technologists, and manufacturer-supplied hydroxyapatite phantoms for pQCT were scanned daily for quality assurance. Before scanning, trained technicians used a standard ruler to measure tibial length (mm) from the center of the medial malleolus to the proximal tibial plateau, with the participant resting the lateral side of the foot on the opposite knee. This value was entered into the scanner to standardize the regions of interest as percentages of individual tibia length. A coronal scout view was acquired at the distal end of the tibia, and an anatomical reference line was placed to bisect the medial side of the distal growth plate, or in cases when the growth plate was no longer visible, the medial side of the distal endplate. Moving proximally from the reference line, the scanner was programmed to acquire measures at 4% and 38% of the tibia length, with all pQCT scans acquired using a voxel size of 0.4mm, a 2.2mm tomographic slice thickness, and a scan speed of 20mm/s (32,5).

Bone strength index (mg^2/mm^4), a measure of bone compressive strength, was estimated from total bone measures at the 4% metaphyseal cross-sectional site using interactive contour search mode 3, with the threshold set just above 169 mg/cm^3 in order to separate soft tissue from bone tissue and generate a volumetric total bone density outcome. BSI was calculated with the following formula: BSI (mg^2/mm^4) = total area (mm^2) × (total density (mg/mm^3)^2) (5). Analyses of the 38% cross-sectional site were used when measuring stress strain index (SSI, mm^3), a measure of torsional strength. Cortmode 2 with a threshold of 480 mg/cm^3 was used for SSI, as this is the software default threshold for the strength–strain indices.

Statistical Analyses

Study participants were stratified based on sex and sex-specific means and standard deviations were calculated to describe participants. The Student *t*-test was used to compare female and male mean values. Multiple linear regression was used to predict young adult bone outcomes for males and females separately using height, weight, and high school interscholastic sport group classification as explanatory variables after adjusting for current PA. A generalized linear model using least squares means and F-tests were performed to determine whether differences in bone outcomes existed between the sex-stratified interscholastic high school sport groups. Pairwise comparisons with Bonferroni corrections were used to test the pairwise comparisons. Percent differences between the significantly different mean bone outcomes for the sport groups were calculated. Finally, mediation analysis was performed to describe the causal sequence between sport participation, muscle power, and bone strength outcome. Mediation assumes a precursor variable (interscholastic high school sport participation) has an effect on a mediating variable (jump height) which affects the outcome variable (bone strength) (33). Height, weight, and PAQ-AD score were included as covariates in the mediation analysis models. Jump height was used rather than Watts because the calculation of Watts included weight and therefore created multi-collinearity in our models. Statistical Analysis System (SAS, Cary, NC), version 9.4, was used for the statistical analyses. $P < 0.05$ was specified as representing statistical significance.

Results

Participants

Data from 295 young adults (163 females, 132 males) were obtained. Descriptive statistics of the study participants are shown in Table A1. The mean ± SD age of participants at follow-up was 19.8 ± 0.7 for males and 19.7 ± 0.7 for females and was not statistically different among the sexes. As expected, females had a greater biological age than males since, on average, females begin puberty sooner and reach peak-height velocity sooner than males (7.9 vs 6.1 years, respectively, $P < 0.01$). Compared to females, males were significantly heavier and taller. Males also had significantly greater values for all bone outcomes. In addition, males had greater vertical jump values ($P < 0.01$) and had greater PAQ-AD scores ($P < 0.01$), indicating greater amounts of lower body power and PA. Table A2 displays the breakdown of study participants by sport participation group. Females had 71, 36, and 56 subjects for NPs, OSPs, and PSPs respectively, while males had 64, 22, and 46 subjects for NPs, OSPs, and PSPs respectively.

Bone Strength Prediction from Multiple Linear Regression

The results from the multiple linear regression models are shown in Table A3. The models for bone outcomes using high school sport group were adjusted for height, weight, and PAQ-AD score. Age and biological were not significant predictors and therefore, were not included in the models. All models used Power Sport participation as a reference (coefficient = 0). The coefficient for NP was significant for all bone outcomes in both males

(BSI -23.7; SSI -174; aBMD -0.14; FN Z -0.36; CSA -0.58; P < 0.05) and females (BSI -11.1; SSI -106.0; aBMD -0.07; FN Z -0.15; CSA -0.23; P < 0.05), indicating that being classified as NP resulted in a lower predicted bone outcome value. The coefficient for OSP was not significant in any bone outcomes for males (P > 0.05). In females, however, the OSP coefficient was significant for BSI, SSI, aBMD, and FN Z (BSI -8.46; SSI -93.0; aBMD -0.07; FN Z -0.10; P < 0.05). PAQ-AD coefficients were significant in female BSI, SSI, and FN Z models (BSI 4.58, SSI 50.55; FN Z 0.09; P < 0.05), whereas the coefficients for PAQ-AD were not significant in any bone outcomes for males (P > 0.05). The full models explained 40%, 60%, 46%, 57% and 54% of the variance in male bone outcome for BSI, SSI, aBMD, FN Z, and CSA respectively. Sport group classification specifically accounted for 10%, 2%, 15%, 8%, and 9% of the variability for the same respective bone outcomes. In females, the models explained 36%, 66%, 43%, 65%, and 61% of the variance in BSI, SSI, aBMD, FN Z, and CSA respectively. Sport group classification accounted for 4%, 2%, 8%, 3%, and 3% of the variability for the same respective bone outcomes.

Mean Differences Among Sport Groups

The F-test from the generalized linear model and least squares means indicated significant differences among the means of the sport classification groups for all bone outcomes in males and females (P < 0.05). Table A4 displays the sex-stratified least squares means. Pairwise comparisons with a Bonferroni correction (Figures B1-B5) indicated that in males and females, PSPs had greater mean bone outcomes than NPs (P < 0.025). When comparing OSPs to NPs, males had four outcomes (BSI, aBMD, FN Z, and CSA) that were significant (P value < 0.025). There were no differences in female mean bone outcomes between OSPs and NPs. The percent differences between the mean bone outcomes are shown in Table A5. For PSPs – NPs, the average percent difference for the mean bone outcomes was 12.4% and 8% for males and females respectively.

Mediation Analysis

Table A6 displays the results from the mediation analysis. For this analysis, we grouped PSPs and OSPs for males (any interscholastic sport participation) and NPs and OSPs for females (only power sport participation) due to the results of the regression models and generalized linear models which indicated that male OSPs were similar to PSPs and female OSPs were similar to NPs. The direct effects of any sport participation in males and only power sport participation in females were statistically significant ($P < 0.05$) for all bone outcomes with the exception of male SSI ($P = 0.2283$). The standardized β values indicated that the direct effect of any sport group participation was greater in males than in females (only power sport participation) for BSI, Hip aBMD, FN Z, and CSA (β = 14.69 vs 7.55, 0.11 vs 0.06, 0.26 vs 0.11, 0.43 vs 0.16 respectively). Conversely, the β value for the direct effect of Sport Group Participation was lesser in males for SSI (β = 69.45 vs 77.79) when compared to females. The bootstrap-derived 95% confidence intervals for the indirect effects do not include zero for any of the bone outcomes for either males or females indicating that muscle power is a mediator between sport group participation and bone strength. Besides male SSI, the direct effects of sport participation and the direct effects of muscle power are significant. These results indicated that partial mediation had occurred. In the case of male SSI, muscle power fully mediated increased bone strength.

Discussion

The main purpose of this study was to assess the effect of interscholastic high school sport participation on young adult bone strength. In addition, we performed mediation analysis to analyze muscle power's role in this effect. We found that participating in sports that emphasize powerful movements, such as basketball, volleyball, or gymnastics, predicted young adult indices of bone strength in males and females compared to non-sport participants. The effect on bone strength due to participation in other interscholastic sports was not as clear. Males who participated in other sports had greater bone strength than non-participant peers for all bone outcomes except SSI. However, females who participated in other sports did not have stronger bones than non-sport participants. We have previously shown that on average males in our cohort were more active during adolescence than females (5). The greater amount of total PA in males may have been sufficient when combined with non-power sport participation to increase bone outcomes compared to non-sport participants. In addition, males tend to have greater muscle mass than females (34) adding to the load magnitudes that males' bones experience from muscle forces regardless of speed of muscle movement.

Our results suggest that bone strength associated with high school sport participation is sustained after high school, and presumably, after a reduction in PA. Although we have previously reported that early childhood PA only has limited effects on bone strength during adolescence (35), this current examination focuses on older participants and uses a targeted exposure, namely interscholastic sport participation. Randomized control trials and longitudinal studies of athletes indicate that previous exposure to osteogenic activities leads to maintained bone strength. For example, Gunter et al. (11) performed a 7-month long randomized control jumping intervention trial in prepubertal children and found that even 8 years after the intervention had ceased, the intervention group had significantly greater bone mineral content compared to controls. A study of 8 to 15-year-old female gymnasts by Erlandson et al. (36) observed that even ten years post sport participation, former gymnasts had greater indices of bone strength compared to non-gymnast age matched controls. Kudlac et al. (37) studied female collegiate gymnasts and reported after a 4-year period post-competition, former gymnasts had decreased bone mineral density values compared to training years, but still had stronger bones than age matched controls. Findings in adolescent and young adult males are similar. Nordstrom et al. (38) researched 17-year-old male ice hockey players, badminton players, and non-sport participant controls for 8 years. During the study, 27 athletes ceased training after a mean time period of 3 years, but still had greater femoral neck, total hip, and humeral bone mineral density values compared to controls at follow-up five years later.

The percent differences in bone strength between power sport athletes and non-sport participants which we report are lower than what has previously described. For example, Nikander et al. (39) classified female athletes in their early 20's into either a high-impact loading group (volleyball or hurdling) or an odd-impact loading group (squash, soccer, or speed skating) and compared them to non-athletic age-matched controls. Both athletic groups had more than 20% greater indices for femoral neck aBMD, CSA, and section modulus compared to controls. In a study of adolescent males by Lima et al. (20), similar results were obtained. Study subjects who participated in soccer, gymnastics, or basketball were classified as the impact group and were compared to age-matched controls that only participated in PE classes. The impact group had 17% greater lumbar BMD and

13.6% greater femoral neck BMD. Differences in bone strength can also been seen in tennis players' dominant arms compared to nondominant arms. Haapasalo et al. (13) studied 7 to 17-year old female tennis players and categorized them based on Tanner stages. At all maturity stages, the dominant arms of the tennis players had between 1.6% to 15.7% greater proximal humerus and humeral shaft BMD values than the nondominant arms. As noted earlier, we sorted groups based on power because of the implications for sport performance and public health. This sorting scheme may have led to the lower observed percent differences in bone outcomes since the previously discussed studies sorted groups by impact loads. It may be that impact is more strongly associated with bone adaptation than power. In addition, we did not exclude subjects from the nonparticipant category based on other activities or recreational sport leagues which could confound results.

Our mediation analysis results indicated that vertical jump, a measure of muscle power, partially mediated increased bone strength in athletes, except male SSI. The fact that muscle power did not completely explain bone strength suggests that other characteristics of physical activity during sport are also osteogenic. For example, movement during sport is dynamic and provides atypical bone loading. These characteristics encourage adaptation (39). In addition, most power moves, such as the up-phase in a jump, are followed by impact forces during landing which would also load bone. Therefore, our power sports participants were exposed to muscle forces and ground impacts.

There were several limitations to our study. The study sample was a homogenous group of Midwestern young adults and was not representative of the entire US. Therefore, caution should be used when trying to apply these results to a more diverse population. In addition, there was a limitation in our high school sport participation questionnaire. For example, we did not query specific events in track and field and therefore, could not distinguish between lower osteogenic sports (i.e. distance running, discuss) and higher osteogenic sports (i.e. sprints, jumps/hurdles). Finally, participants in the Iowa Bone Development Study were not randomly selected and, of course, high school sport participation is not random. Adolescents with larger bodies and stronger bones may be more inclined to participate in power sports than peers. Despite the limitations, our study has strengths. Many studies that address sport participation and bone strength are cross-sectional (12,13,18,20,39). However, by using a longitudinal design which included adjustment for current physical activity, we were better able to isolate the effect of high school sport participation on bone strength. Importantly, we used multiple indicators of bone strength, including 3-dimensional pQCT imaging to capture bone structure as well as mass.

In conclusion, participation in any interscholastic sport may contribute to improved bone strength in males. Whereas in females, high school participation in power sports is preferred. Although muscle power clearly contributes to bone strength, other factors associated with sport also contribute. Our results suggest that educational institutions promote sport participation for all students as means to achieve a strong skeleton.

APPENDIX A: TABLES

Table A1. Descriptive Statistics and Sex Comparison

	Males (N=132)	Females (N=163)	t-test
Variable	Mean (SD)	Mean (SD)	p-value
Age at scan, years	19.8 (0.7)	19.7 (0.7)	0.7322
Biological Age, years since age at Peak Height Velocity	6.1 (1.0)**	7.9 (0.9)	<.0001
Scale weight, kg	84.3 (20.0)**	68.7 (18.2)	<.0001
Height, cm	180.3 (7.6)**	166.3 (6.7)	<.0001
Tibial 4% BSI, mg^2/mm^4	147.4 (33.3)**	101.4 (24.0)	<.0001
Tibial 38% SSI, mm3	2180.3 (487.3)**	1541.8 (340.8)	<.0001
Hip aBMD, g/cm2	1.2 (0.2)**	1.0 (0.1)	<.0001
Femoral Neck Z, cm^3	4.4 (0.9)**	3.3 (0.6)	<.0001
Narrow Neck CSA, cm^2	2.3 (0.6)**	1.5 (0.4)	<.0001
Lower Body Muscle Power, Watts	5183.5 (1072.4)**	3486.4 (871.22)	<.0001
Vertical Jump, cm	56.32 (12.0)**	40.0 (7.3)	<.0001
PAQ-AD score, 1-5	2.37 (0.8)**	2.06 (0.7)	0.0007

Data are mean (SD). BSI, bone strength index; SSI, density-weighted polar section modulus stress strain index; aBMD, areal bone mineral density; CSA, cross sectional area; Z, section modulus; PAQ-AD, Physical Activity Questionnaire for Adults. ** $P < 0.01$

Table A2. Participants Stratified by Sport Groups

	NP	OSP	PSP	Total
Males	64	22	46	132
Females	71	36	56	163
Total	135	58	102	295

NP, Nonparticipant; OSP, Other Sport Participant; PSP, Power Sport Participant. PSPs were classified as study subjects who participated in at least two seasons of high school interscholastic basketball, cheerleading, football, gymnastics, soccer, and/or volleyball. Other Sport Participants were study subjects who participated in one season of high school interscholastic power sports or two seasons of baseball, softball, tennis, track and field, and/or wrestling. Nonparticipants were study subjects who participated in one season of high school interscholastic other sports or did not participate in high school interscholastic athletics.

Table A3. Regression Models for Bone Outcomes vs Sport Participation									
		Males				Females			
Dependent	Parameter	Estimate	Standard Error	Pr > |t|	R^2 R^2 change*	Estimate	Standard Error	Pr > |t|	R^2 R^2 change*
Tibia 4% BSI (mg^2/mm^4)	Intercept	-19.32	57.005	0.7352	0.40	-39.19	40.942	0.3400	0.36
	Height, cm	0.6045	0.3355	0.0740	.	0.6024	0.2583	0.0210	.
	Weight, kg	0.6859	0.1270	<.0001	.	0.5334	0.0929	<.0001	.
	PAQ-AD	3.6854	3.0252	0.2254	.	4.5811	2.1757	0.0368	.
	Nonparticipant	-23.70	5.2184	<.0001	0.10*	-11.10	3.5786	0.0023	0.04*
	Other Sport	-3.902	6.5012	0.5494	.	-8.464	4.0384	0.0377	.
	Power Sport	0.0000	.	.	.	0.0000	.	.	.
Tibia 38% SSI (mm^3)	Intercept	-3372	683.88	<.0001	0.60	-2594	426.25	<.0001	0.66
	Height, cm	26.024	4.0203	<.0001	.	20.868	2.6895	<.0001	.
	Weight, kg	11.475	1.5221	<.0001	.	8.9777	0.9677	<.0001	.
	PAQ-AD	-14.59	36.380	0.6891	.	50.545	22.652	0.0271	.
	Nonparticipant	-174.0	62.383	0.0061	0.02*	-106.0	37.257	0.0050	0.02*
	Other Sport	-68.42	78.195	0.3833	.	-93.00	42.044	0.0284	.
	Power Sport	0.0000	.	.	.	0.0000	.	.	.
Hip aBMD (g/cm^2)	Intercept	0.6838	0.2647	0.0110	0.46	0.4615	0.2108	0.0300	0.43
	Height, cm	0.0009	0.0016	0.5787	.	0.0020	0.0013	0.1323	.
	Weight, kg	0.0041	0.0006	<.0001	.	0.0035	0.0005	<.0001	.
	PAQ-AD	0.0176	0.0144	0.2234	.	0.0175	0.0112	0.1207	.
	Nonparticipant	-.1397	0.0242	<.0001	0.15*	-.0768	0.0184	<.0001	0.08*

Table A3. Regression Models for Bone Outcomes vs Sport Participation									
		Males				Females			
Dependent	Parameter	Estimate	Standard Error	Pr > |t|	R^2 R^2 change*	Estimate	Standard Error	Pr > |t|	R^2 R^2 change*
	Other Sport	-.0228	0.0308	0.4596	.	-.0684	0.0208	0.0012	.
	Power Sport	0.0000	.	.	.	0.0000	.	.	.
FN Z (cm^3)	Intercept	-3.617	0.8044	<.0001	0.57	-2.393	0.4436	<.0001	0.65
	Height, cm	0.0276	0.0047	<.0001	.	0.0191	0.0028	<.0001	.
	Weight, kg	0.0115	0.0019	<.0001	.	0.0088	0.0010	<.0001	.
	PAQ-AD	0.0616	0.0437	0.1611	.	0.0936	0.0236	0.0001	.
	Nonparticipant	-.3556	0.0736	<.0001	0.08*	-.1481	0.0388	0.0002	0.03*
	Other Sport	-.1215	0.0935	0.1962	.	-.0975	0.0438	0.0273	.
	Power Sport	0.0000	.	.	.	0.0000	.	.	.
Narrow Neck CSA (cm^2)	Intercept	-2.562	1.2870	0.0487	0.54	-1.767	0.7779	0.0244	0.61
	Height, cm	0.0283	0.0076	0.0003	.	0.0225	0.0049	<.0001	.
	Weight, kg	0.0208	0.0030	<.0001	.	0.0176	0.0018	<.0001	.
	PAQ-AD	0.1301	0.0699	0.0649	.	0.1007	0.0413	0.0160	.
	Nonparticipant	-.5842	0.1177	<.0001	0.09*	-.2341	0.0680	0.0007	0.03*
	Other Sport	-.1722	0.1496	0.2519	.	-.1512	0.0767	0.0506	.
	Power Sport	0.0000	.	.	.	0.0000	.	.	.

Table A3. Regression Models for Bone Outcomes vs Sport Participation									
		Males				Females			
Dependent	Parameter	Estimate	Standard Error	Pr > |t|	R^2 R^2 change*	Estimate	Standard Error	Pr > |t|	R^2 R^2 change*

BSI, bone strength index; SSI, stress strain index; CSA, cross sectional area; FN Z, femoral neck section modulus; PAQ-AD, physical activity questionnaire-adult; R^2 change indicates the percent of the variability in bone outcome specifically accounted for by sport group classification.

Table A4. Sport Groups Means and Pairwise Comparisons							
Dependent	Pr > F[a]	NP	OSP	PSP	NP vs OSP	NP vs PSP	OSP vs PSP
		Mean (SE)	Mean (SE)	Mean (SE)	(p-value)[b]	(p-value)[b]	(p-value)[b]
Males (N=132)		**N=46**	**N=22**	**N=64**			
Tibia 4% BSI (mg^2/mm^4)	<.0001	132.49 (3.97)	152.28 (5.61)	156.18 (3.31)	0.0048	0.0000	0.5494
Tibial 38% SSI (mm^3)	0.0229	2078.29 (47.24)	2183.89 (67.44)	2252.30 (39.80)	0.2032	0.0061	0.3833
Hip aBMD (g/cm^2)	<.0001	1.09 (0.02)	1.20 (0.03)	1.23 (0.02)	0.0004	0.0000	0.4596
FN Z (cm^3)	<.0001	2.12 (0.06)	2.35 (0.08)	2.47 (0.05)	0.0190	0.0000	0.1962
Narrow Neck CSA (cm^2)	<.0001	4.00 (0.09)	4.42 (0.13)	4.59 (0.08)	0.0101	0.0000	0.2519
Females (N=163)		**N=56**	**N=36**	**N=71**			
Tibia 4% BSI (mg^2/mm^4)	0.0039	95.25 (2.66)	99.63 (3.29)	107.25 (2.36)	0.3001	0.0010	0.0626
Tibial 38% SSI (mm^3)	0.0070	1484.15 (27.70)	1516.42 (34.28)	1600.07 (24.64)	0.4641	0.0023	0.0500
Hip aBMD (g/cm^2)	<.0001	0.99 (0.01)	1.01 (0.02)	1.07 (0.01)	0.4855	0.0000	0.0020
FN Z (cm^3)	0.0003	1.43 (0.03)	1.51 (0.04)	1.59 (0.03)	0.0697	0.0001	0.0803
Narrow Neck CSA (cm^2)	0.0014	3.15 (0.05)	3.27 (0.06)	3.40 (0.05)	0.1337	0.0003	0.0893

[a] F-test p-value for overall significance of HS PA group. [b] p-values are reported without adjustment for multiple comparisons. BSI, bone strength index; SSI, stress strain index; aBMD, areal bone mineral

density; FN Z, femoral neck sectional modulus; CSA, cross sectional area; NP, Nonparticipant; OSP, Other Sport Participant; PSP, Power Sport Participant.

Table A5. Percent Differences in Mean Bone Outcomes

	Male PSP – NP % Difference	Male OSP – NP % Difference	Male PSP – OSP % Difference	Female PSP - NP % Difference	Female OSP – NP % difference	Female PSP – OSP % Difference
BSI	15.7	13.0	-	10.4	-	-
SSI	7.7	-	-	6.6	-	-
Hip aBMD	11.4	9.2	-	6.5	-	5.6
FN Z	14.2	9.8	-	9.4	-	-
NN CSA	12.9	9.5	-	7.1	-	-

BSI, bone strength index; SSI, stress strain index; NN CSA, narrow neck cross sectional area; FN Z, femoral neck section modulus; PSP, Power Sport Participant; OSP, Other Sport Participant; NP, Nonparticipant. - indicates no statistical difference between the means.

Table A6. Mediation Analysis with Dichotomized Sport Groups						
	Males			Females		
	β	SE	p-value	β	SE	p-value
Tibia 4% BSI, mg^2/mm^4						
Sport Group to Vertical Jump	6.1500	1.8102	0.0009	2.7971	1.0722	0.0100
Direct Effects of Vertical Jump on BSI	0.9073	0.2251	<.0001	0.8883	0.2223	<.0001
Total effect of Sport Group on BSI	20.2667	4.8432	<.0001	10.0365	3.1346	0.0017
Direct Effect of Sport Group on BSI	14.6865	4.7793	0.0026	7.5517	3.0597	0.0147
Indirect Effects of Sport Group on BSI through Vertical Jump	5.5801	2.0407		2.4848	1.0747	
Bias-corrected 95% CI from bootstrapping	2.3967	10.8235		0.6782	5.2264	
Percent of Total Effect Mediated by Vertical Jump			27.5%			24.8%
Tibia 38% SSI, mm3						
Sport Group to Vertical Jump	5.9618	1.8004	0.0012	2.7971	1.0722	0.0100
Direct Effects of Vertical Jump on SSI	10.0481	2.7127	0.0003	8.2058	2.3368	0.0006
Total effect of Sport Group on SSI	129.351	57.7298	0.0268	100.744	32.6036	0.0024
Direct Effect of Sport Group on SSI	69.4469	57.3660	0.2283	77.7916	32.1650	0.0167
Indirect Effects of Sport Group on SSI through Vertical Jump	59.9043	23.1053		22.9526	10.8676	
Bias-corrected 95% CI from bootstrapping	21.2740	119.949		5.6979	51.0404	
Percent of Total Effect Mediated by Vertical Jump			46.3%			22.8%
Hip aBMD, g/cm2						
Sport Group to Vertical Jump	5.9044	1.8352	0.0016	2.7971	1.0722	0.0100
Direct Effects of Vertical Jump on aBMD	0.0033	0.0011	0.0026	0.0043	0.0011	0.0002
Total effect of Sport Group on aBMD	0.1291	0.0225	<.0001	0.0734	0.0161	<.0001

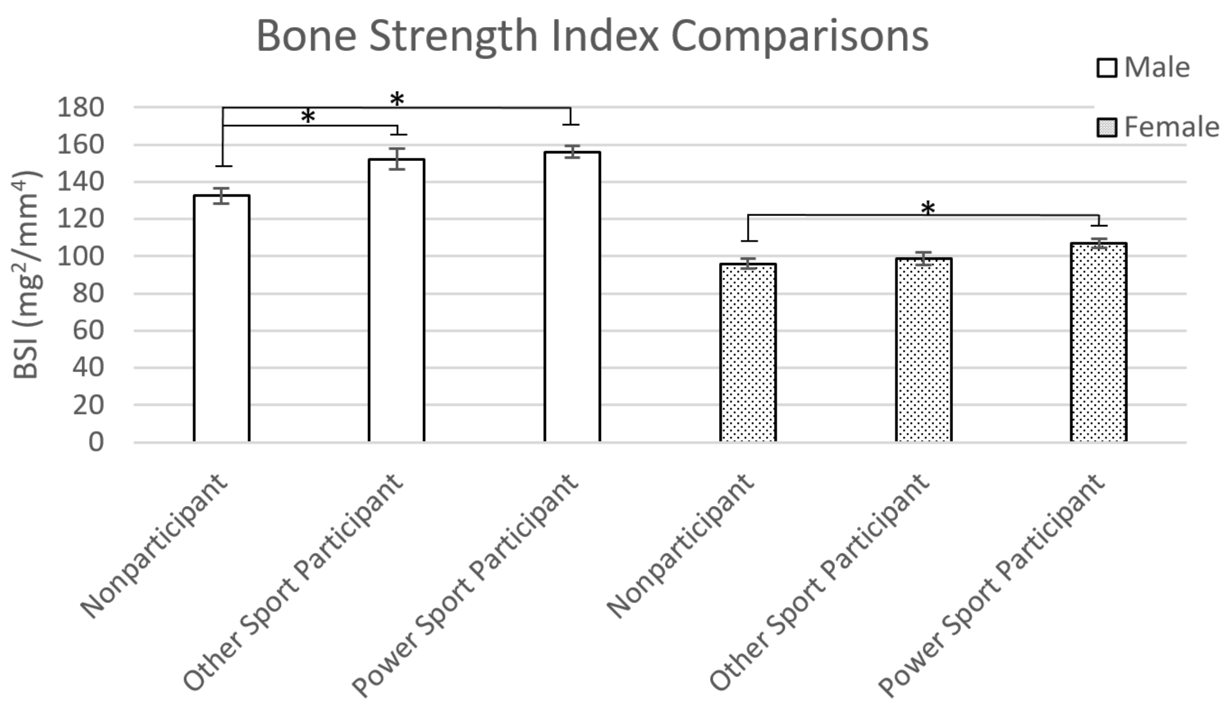
Table A6. Mediation Analysis with Dichotomized Sport Groups						
	Males			Females		
	β	SE	p-value	β	SE	p-value
Direct Effect of Sport Group on aBMD	0.1098	0.0226	<.0001	0.0613	0.0158	0.0002
Indirect Effects of Sport Group on aBMD through Vertical Jump	0.0192	0.0090		0.0121	0.0053	
Bias-corrected 95% CI from bootstrapping	0.0059	0.0439		0.0035	0.0246	
Percent of Total Effect Mediated by Vertical Jump			14.9%			16.5%
Femoral Neck Section modulus, cm^3						
Sport Group to Vertical Jump	5.9044	1.8352	0.0016	2.7971	1.0722	0.0100
Direct Effects of Vertical Jump on FN Z	0.0095	0.0032	0.0038	0.0074	0.0025	0.0031
Total effect of Sport Group on FN Z	0.3172	0.0683	<.0001	0.1277	0.0340	0.0002
Direct Effect of Sport Group on FN Z	0.2609	0.0690	0.0002	0.1069	0.0339	0.0019
Indirect Effects of Sport Group on FN Z through Vertical Jump	0.0563	0.0267		0.0207	0.0098	
Bias-corrected 95% CI from bootstrapping	0.0159	0.1248		0.0052	0.0451	
Percent of Total Effect Mediated by Vertical Jump			17.8%			16.2%
Narrow Neck CSA, cm^2						
Sport Group to Vertical Jump	5.9044	1.8352	0.0016	2.7971	1.0722	0.0100
Direct Effects of Vertical Jump on CSA	0.0180	0.0051	0.0005	0.0141	0.0043	0.0013
Total effect of Sport Group on CSA	0.5318	0.1089	<.0001	0.2006	0.0597	0.0010
Direct Effect of Sport Group on CSA	0.4254	0.1084	0.0001	0.1613	0.0592	0.0071
Indirect Effects of Sport Group on CSA through Vertical Jump	0.1064	0.0441		0.0394	0.0187	

Table A6. Mediation Analysis with Dichotomized Sport Groups						
	Males			Females		
	β	SE	p-value	β	SE	p-value
Bias-corrected 95% CI from bootstrapping	0.0327	0.2162		0.0114	0.0857	
Percent of Total Effect Mediated by Vertical Jump			20.0%			19.6%

BSI, bone strength index; SSI, stress strain index; CSA, cross sectional area; FN Z, femoral neck section modulus. * $P < 0.05$ and ** $P < 0.01$. Covariates included in analysis: weight, height, and PAQ-AD score. Sport groups were dichotomized in this analysis such that PSPs and OSPs were grouped together for males and NPs and OSPs were grouped together for females.

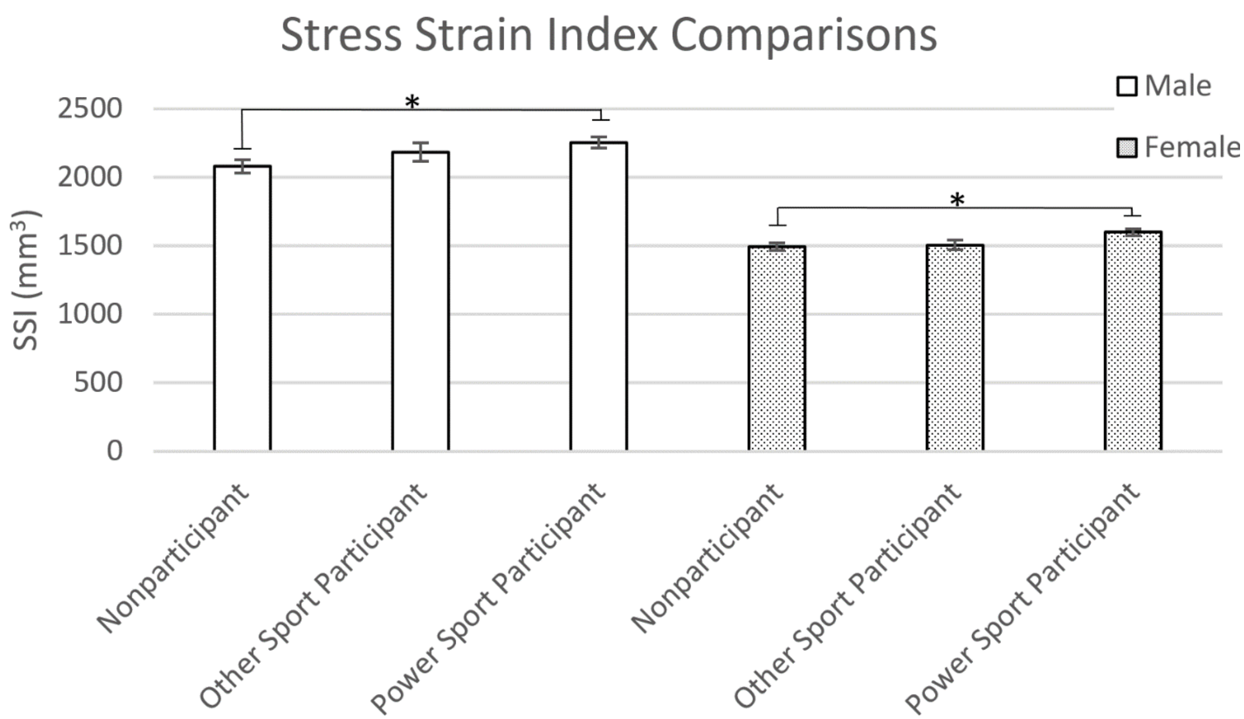
APPENDIX B: FIGURES

Figure B1.



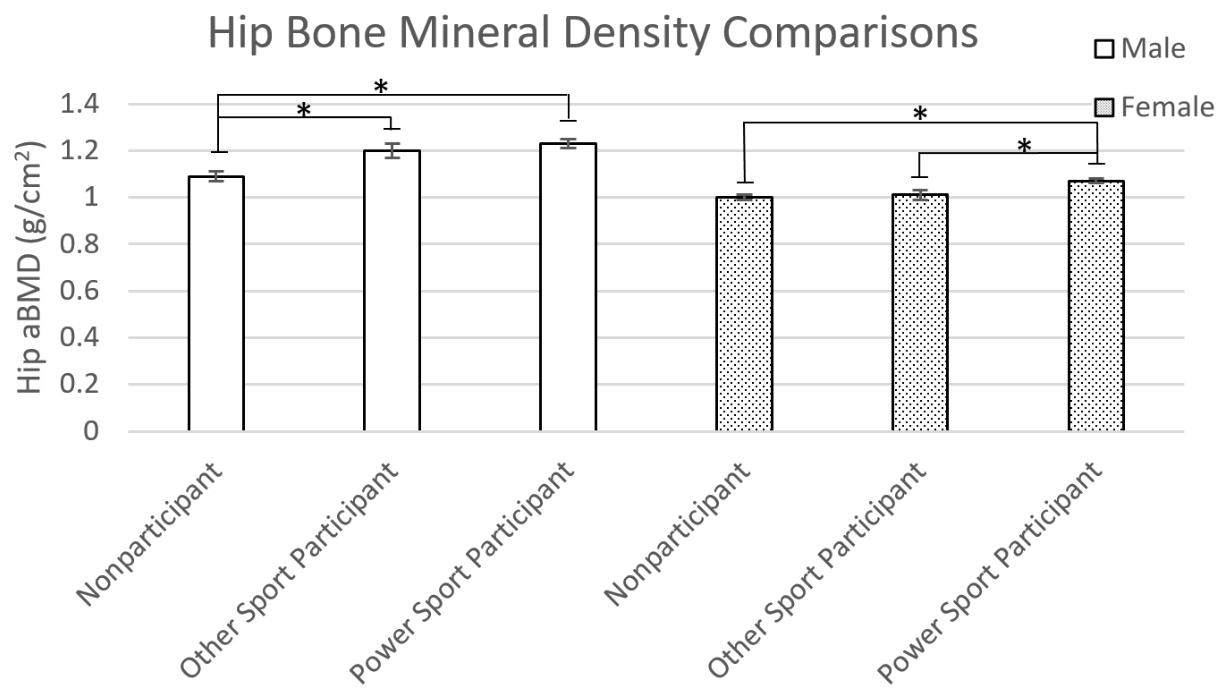
Male and female sport group means and SD with between sport group comparisons for ~age 19 bone strength index (BSI). * P value < 0.025.

Figure B2.



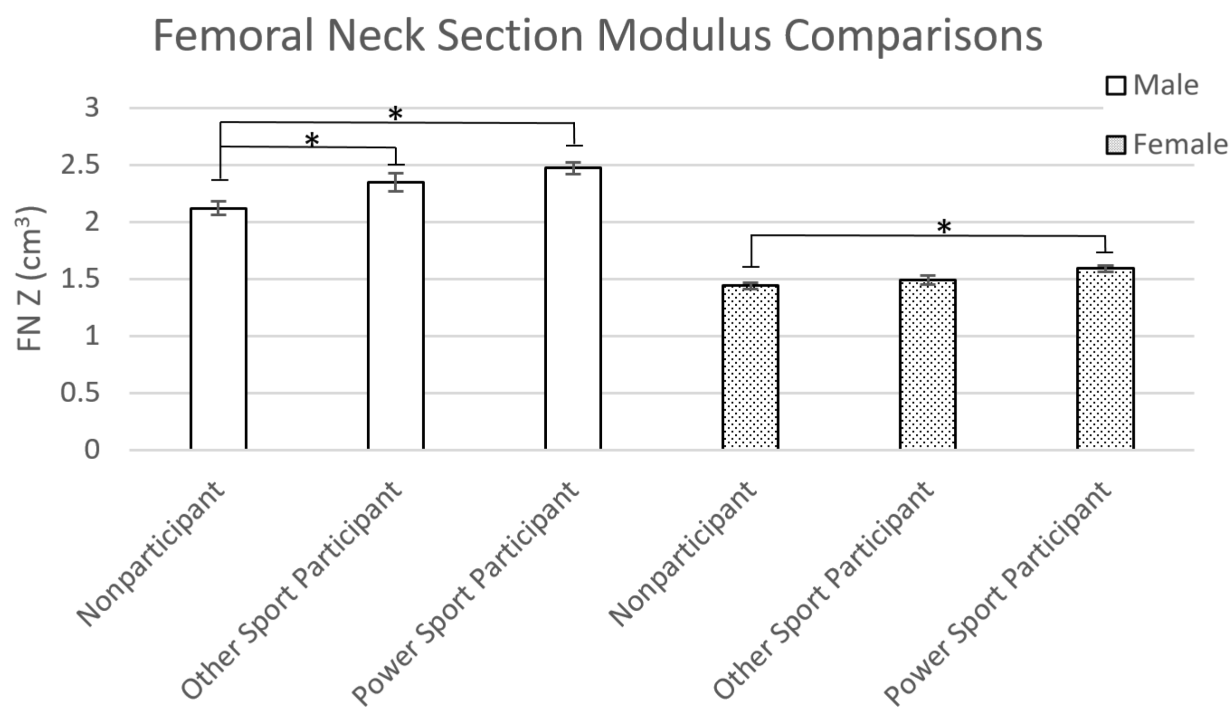
Male and female sport group means and SD with between sport group comparisons for ~age 19 stress strain index (SSI). * P value < 0.025

Figure B3.



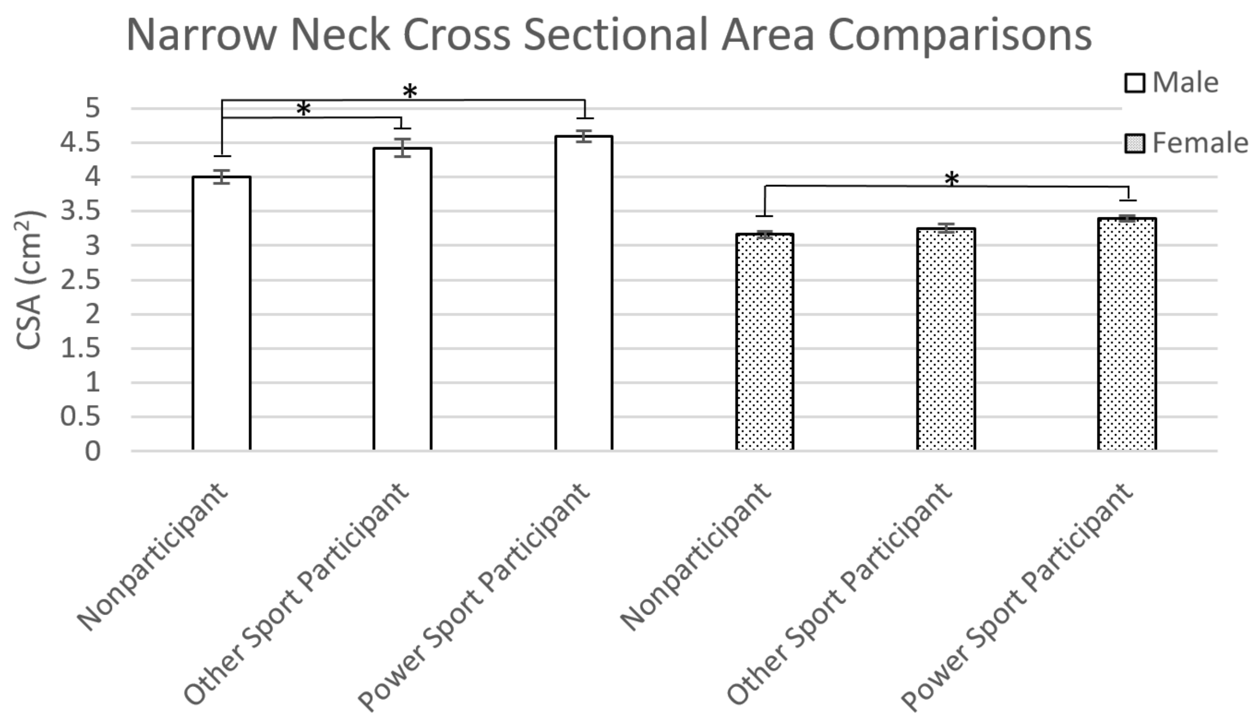
Male and female sport group means and SD with between sport group comparisons for ~age 19 hip areal bone mineral density (aBMD).
* P value < 0.025

Figure B4.



Male and female sport group means and SD with between sport group comparisons for ~age 19 femoral neck section modulus (FN Z).
* P value < 0.025

Figure B5.



Male and female sport group means and SD with between sport group comparisons for ~age 19 narrow neck cross sectional area (CSA). * P value < 0.025

REFERENCES

1. Ammann P, Rizzoli R. Bone Strength and its Determinants. *Osteoporos Int*. 2003; 14(Supplement 3):13-18.
2. Weaver C, Janz K, Klakwarf, H. The National Osteoporosis Foundation's Position Statement on Peak Bone Mass Development and Lifestyle Factors: A Systematic Review and Implementation Recommendations. *Osteoporosis Int.* 2016; 27(4):1281-1386.
3. Beck TJ, Ruff CB, Warden KE, Scott WW, Rau GU. Predicting Femoral Neck Strength from Bone Mineral Data: A Structural Approach. *Invest Radiol*. 1990; 25(1):6-18.
4. Welten D, Kemper H, Post G. Weight-bearing Activity During Youth is a More Important Factor for Peal Bone Mass than Calcium Intake. *J Bone Miner Res*. 1994; 9(7):1089-1096.
5. Janz K, Letuchy E, Burns T, Eichenberger Gilmore J, Torner J, Levy S. Objectively Measured Physical Activity Trajectories Predict Adolescent Bone Strength: Iowa Bone Development Study. *Br J Sports Med*. 2014; 48(13):1032-1036.
6. Turner C, Robling A. Designing Exercise Regimens to Increase Bone Strength. *Exerc Sport Sci Rev*. 2003; 31(1):45-50.
7. Fuchs RK, Bauer JJ, Snow CM. Jumping Improves Hip and Lumbar Spine Bone Mass in Prepubescent Children: A Randomized Controlled Trial. *J Bone Miner Res.* 2001; 16(1):148-156.

8. Robling AG, Hinant FM, Burr DB, Turner CH. Improved Bone Structure and Strength After Long-Term Mechanical Loading is Greatest if Loading is Separated into Short Bouts. *J Bone Miner Res.* 2002; 17(8):1545-1554.

9. Järvinen TL, Kannus P, Sievänen H, Jolma P, Heinonen A, Järvinen M. Randomized Controlled Study of Effects of Sudden Impact Loading on Rat Femur. *J Bone Miner Res.* 1998; 13(9):1475-1482.

10. Guadalupe-Grau A, Fuentes T, Guerra B, Calbert JA. Exercise and Bone Mass in Adults. *Sports Med*. 2009; 39(6):439-468.

11. Gunter K, Baxter-Jones A, Mirwald R. Impact Exercises Increases BMC During Growth: An 8-Year Longitudinal Study. *J Bone Miner Res.* 2008; 23(7):986-993.

12. Rantalainen T, Duckham RL, Suominen H, Heinonen A, Alen M, Korhonen MT. Tibial and Fibular Mid-Shaft Bone Traits in Young and Older Sprinters and Non-Athletic Men. *Calcif Tissue Int.* 2014; 95(2):132-140.

13. Haapasalo H, Kannus P, Sievänen H. Effect of Long-Term Unilateral Activity on Bone Mineral Density of Female Junior Tennis Players. *J Bone Miner Res*. 1998; 13(2):310-319.

14. Nichols DL, Sanborn CF, Love AM. Resistance Training and Bone Mineral Density in Adolescent Females. *J Pediatr*. 2001; 139(4):494-500.

15. Robling, AG. Is Bone's Response to Mechanical Signals Dominated by Muscle Forces? *Med Sci Sports Exerc*. 2009; 41(11):2044-2049.

16. Vlahopoulous D, Barker AR, Ubago-Guisado E. The Effect of 12-Month Participation in Osteogenic and Non-Osteogenic Sports on Bone Development in

Adolescent Male Athletes. The PRO-BONE Study. *J Sci Med Sport.* 2018; 21(4):404-409.

17. National Federation of State High School Associations. *2016-2017 High School Athletics Participation Study*. Indianapolis, IN: National Federation of State High School Associations; 2018.
18. Yung PS, Lai YM, Tung PY. Effects of Weight Bearing and Non-weight Bearing Exercises on Bone Properties Using Calcaneal Quantitative Ultrasound. *Br J Sports Med*. 2005; 39(8):547-551.
19. Taafe DR, Robinson TL, Snow CM, Marcus R. High-Impact Exercise Promotes Bone Gain in Well-Trained Female Athletes. *J Bone Miner Res*. 1997; 12(2):255-260.
20. Lima F, De Falco V, Baima J, Gilberto Carazzato J, Periera R. Effect of Impact Load and Active Load on Bone Metabolism and Body Composition of Adolescent Athletes. *Med Sci Sports Exerc.* 2001; 33(8):1318-1323.
21. Lynch KR, Kemper CG, Turi-Lynch B. Impact Sports and Bone Fractures Among Adolescents. *J Sports Sci.* 2017; 35(24):2421-2426.
22. Janz K, Letuchy E, Burns T, Francis S, Levy S. Muscle Power Predicts Adolescent Bone Strength: Iowa Bone Development Study. *Med Sci Sports Exerc.* 2015; 47(10):2201-2206.
23. Yingling VR, Webb S, Inouye C, O J, Sherwood JJ. Muscle Power Predicts Bone Strength in Division II Athletes. J Strength Cond Res. Published Online: August 29, 2017 (doi: 10.1519 /JSC.0000000000002222).

24. Baxter-Jones AD, Faulkner RA, Forwood MR, Mirwald RL, Bailey DA. Bone Accrual from 8 to 30 Years of Age: An estimation of Peak Bone Mass. *J Bone Miner Res.* 2011; 28(8):1729-1739.

25. Gordon-Larsen P, Nelson MC, Popkin BM. Longitudinal Physical Activity and Sedentary Behavior Trends. *Am J Prev Med*. 2004; 27(4):277-283.

26. Levy SM, Kiritsy MC, Slager SL, Warren JJ. Patterns of Dietary Fluoride Supplement Use During Infancy. *J Public Health Dent*. 1998; 58(3):228-233.

27. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc. 2002; 34 (4): 689–94

28. Copeland JL, Kowalksi KC, Donen RM, Tremblay MS. Convergent Validity of the Physical Activity Questionnaire for Adults: The New Member of the PAQ Family. *J Phys Act Health.* 2005; 2(2):216-229.

29. Leard JS, Cirillo MA, Katsnelson E. Validity of Two Alternative Systems for Measuring Vertical Jump Height. *J Strength Cond Res.* 2007; 21(4):1296-1299.

30. Sayers SP, Harackiewicz DV, Harman EA, Frykman PN, Rosenstein MT. Cross Validation of Three Jump Power Equations. *Med Sci Sports Exerc.* 1999; 31(4): 572-577.

31. Martin RB, Burr DB. Non-invasive measurement of long bone cross-sectional moment of inertia by photon absorptiometry. *J Biomech*. 1984; 17:195-201.

32. Glass NA, Torner JC, Letuchy EM. The relationship between greater pre-pubertal adiposity, subsequent age of maturation and bone strength during adolescence. *J Bone Miner Res.* 2016; 31(7):1455-1465.

33. Mackinnon DP, Fairchild AJ, Fritz MS. Mediation Analysis. *Annu Rev Psychol*. 2007; 58(22):593-614.

34. Poortmans JR, Boisseau N, Moraine JJ, Moreno-Reyes R, Goldman S. Estimation of Total-body Skeletal Muscle Mass in Children and Adolescents. *Med Sci Sports Exerc*. 2005; 37(2):316-322.

35. Francis SL, Letuchy EM, Levy SM, Janz KJ. Sustained Effects of Physical Activity on Bone Health: Iowa Bone Development Study. *Bone*. 2014; 63:95-100.

36. Erlandsen MC, Kontulainen SA, Chilibeck PD, Arnold CM, Faulkner RA, Baxter-Jones AD. Higher Premenarchal Bone Mass in Elite Gymnasts in Maintained into Young Adulthood After Long-Term Retirement from Sport: A 14-Year Follow Up. *J Bone Miner Res.* 2011; 27(1):104-110.

37. Kudlac J, Nichols CF, Sanborn NM, DiMarco NM. Impact of Detraining on Bone Loss in Former Collegiate Female Gymnasts. *Calcif Tissue Int.* 2004; 75(6):482-487.

38. Nordstrom A, Olsson T, Nordstrom P. Sustained Benefits from Previous Physical Activity on Bone Mineral Density in Males. *J Clin Endocrinol Metab*. 2006; 91(7):2600-2604.

39. Nikander R, Sievänen H, Heinonen A, Kannus P. Femoral Neck Structure in Adult Female Athletes Subjected to Different Loading Modalities. *J Bone Miner Res*. 2004; 20(3):520-528.