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The vertical jump test as a health promotion screening tool for predicting bone strength in young adults

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THE VERTICAL JUMP TEST AS A HEALTH PROMOTION SCREENING TOOL FOR PREDICTING BONE STRENGTH IN YOUNG ADULTS

by

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CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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This is to certify that the Master's thesis of

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ABSTRACT

Osteoporosis is one of the most common diseases experienced in the older adult population. This condition is not only costly to manage and treat, particularly so when osteoporotic fractures occur, but also negatively impacts functional health and health-related quality of life for many individuals. This indicates the need for more to be done to prevent osteoporosis from developing initially. While bone mineral density (BMD) testing recommendations are in place for women aged 65 and older and men aged 70 and older to diagnose osteoporosis, there currently are no BMD testing recommendations for preventive or screening purposes in the general, healthy, adult population. One potential screening tool for bone strength is a peak vertical jump test. Peak vertical jump height can be used as a proxy for lower body muscle power, which has been identified as an influential factor in determining bone mass and geometry, both of which are critical aspects of bone strength. This study ascertained the relationship between muscle power and bone strength, as well as the capacity of a peak vertical jump test to identify young adults with below-average areal BMD (aBMD).

A total of 303 young adults (18 to 22 years, *n*=136 males, *n*=167 females) participated in these cross-sectional analyses. DXA was used to assess aBMD for total hip and femoral neck, and DXA images were used to calculate femoral neck section modulus (FN Z) values. Peripheral quantitative computed tomography (pQCT) was used to assess indices of bone strength at the tibia. Cortical bone area (CoA) and density-weighted polar section modulus strength-strain index (SSIp) were assessed at the 38% midshaft site, and bone strength index (BSI) was assessed at the 4% midshaft site. Lower body muscle power was predicted using peak vertical jump height and the Sayers et al.

(1999) equation. Data were analyzed using Pearson bivariate and partial correlations to examine associations among bone strength outcomes and muscle power. Logistic regression was used to examine the probability of below-average bone strength based on muscle power. Receiver Operating Characteristic (ROC) curve analysis was used to show the tradeoff between sensitivity and specificity and to display the accuracy of a peak vertical jump test as an assessment tool for aBMD. Logistic regression indicated the odds ratio of below-average height-adjusted femoral neck aBMD decreased 5.4% for females and 3.6% for males per 50 Watts of power. ROC curve analysis showed the best sensitivity-specificity trade-off for identifying individuals with and without below-average aBMD was 5,038 Watts in males (sensitivity = 73.7%; specificity = 62.4%; AUC = 0.709, 95%CI = 0.572 - 0.847) and 3,261 Watts in females (sensitivity = 71.4%; specificity = 58.9%; AUC = 0.708, 95%CI = 0.586 - 0.829). These cut off values correspond to a vertical jump height of 54.39 cm and 36.16 cm for males and females, respectively. Taken together, the results of these analyses suggest acceptable sensitivity and specificity and moderate discriminate ability for using a measure of muscle power, assessed with a peak vertical jump test, to identify young adults with below-average aBMD.

PUBLIC ABSTRACT

Osteoporosis is a condition when bones decrease in strength, become fragile, and break easily. Osteoporosis can impact an individual's quality of life and their ability to carry out everyday activities. It is recommended that men and women aged 70+ and 65+ undergo (expensive) clinical testing for osteoporosis. Once osteoporosis is diagnosed, it cannot be reversed/cured. Screening for those at-risk for osteoporosis (i.e., those with below-average bone strength) earlier in adulthood would be beneficial, as it would provide the opportunity for individuals to actively take steps to optimize peak bone strength and prevent the decline of bone strength to osteoporotic levels, rather than simply identifying osteoporosis after it is too late. It has been demonstrated that strong muscles and strong bones go hand-in-hand. Having strong, powerful muscles means that bones must be strong in order to withstand the pull that muscles exert. Testing muscle power could be a method for assessing bone strength.

Three hundred and three individuals (18-22yrs; 136 males; 167 females) underwent clinical tests for bone strength and structure, and did a peak vertical jump test to assess muscle power. Relationships between muscle power and bone strength were examined, and probabilities were calculated to see if low muscle power predicted below-average bone strength. Results indicated the odds of having below-average bone strength decreased 5.4% for females and 3.6% for males per 50 Watts of power. These results suggest muscle power (from vertical jump height) to be a reasonably accurate method of identifying young adults with below-average bone strength.

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CHAPTER 1: INTRODUCTION

The International Society of Clinical Densitometry (ISCD) estimates 200 million people worldwide have osteoporosis and 1.5 million people in the United States experience an osteoporotic fracture each year (International Society for Clinical Densitometry [ISCD], 2014). It has been estimated previously that the average annual cost of such a fracture is $8,600 (95% CI, $6,400 to $10,800), adding up to a yearly cost of almost $13 billion in the U.S. (Blume & Curtis, 2010). Given osteoporosis is both non-reversible and one of the most common diseases experienced in American elderly adults (ISCD, 2014), there is a need for more to be done to prevent osteoporosis from developing initially.

Prevention of disease and disability, and early identification of the risk factors that lead to disease or disability, is the primary purpose of the health screening tests administered in clinical and health promotion settings. Clinical screenings, such as mammograms and stress tests, and health promotion screenings, such as assessments of muscular strength and flexibility, aim to identify risk factors and early signs of disease, as well as weaknesses, imbalances and areas in need of improvement. As such, these screens guide proactive clinical treatment and health promotion programming with the goal of optimizing functional health and preventing disease and disability.

Currently, the ISCD recommends bone mineral density (BMD) testing for women aged 65 and older and men aged 70 and older. Early testing is only recommended for those with a family history of or a risk factor for low bone mass, such as low body weight, prior fracture, high-risk medication use, or a disease/condition that is associated with bone loss (ISCD, 2015). BMD screening tests are most commonly performed using

a dual X-ray absorptiometry (DXA) with the goal being to diagnose conditions such as osteopenia (i.e., low bone density) and osteoporosis (i.e., a bone disease characterized by decreased bone mass and density, resulting in increased bone porosity and brittleness) (ISCD, 2015). While the DXA scanning process is short and painless, the scan also involves exposure to low-dose radiation, and can be costly. DXA requires extensive training for personnel and use of expensive equipment and software (ISCD, 2014). For these reasons, BMD tests using DXA can be inaccessible for younger adults who do not meet the qualifications for early screening. There is a need for alternative screening procedures that can identify individuals at-risk for low bone strength at younger ages when steps can still be taken to prevent and/or delay bone mass and geometry from declining to clinically diagnostic levels.

While BMD testing in individuals over 65 years of age is still important due to the possibility of conserving current bone mass and geometry and slowing additional bone loss, osteopenia and osteoporosis are conditions that cannot be reversed once they develop. A screening for bone strength that is appropriate for adults that do not meet the indications for early clinical BMD testing would be a valuable tool in allowing early detection of below-average bone strength in seemingly healthy individuals, especially since a decrease in bone mass and geometry occurs silently and without any physical indications. By the time females reach age 18 and males reach age 20, about 90% of peak bone mass has been established. Peak bone mass can increase until about age 30 in both sexes but then begins to decline slowly thereafter (National Institutes of Health [NIH], 2015). Thus, screening for bone mass and geometry would be particularly valuable during young adulthood, as this is the age range where improvement of bone

mass and geometry is still possible. Identifying risk within this age group would provide individuals with a window of opportunity to optimize peak bone mass and geometry, thereby preventing, or at the very least delaying, a clinical diagnosis of osteopenia or osteoporosis. This is an important tenet of screening, as actual changes can be made once a need for change has been identified. Just as screenings for cardiovascular disease aim to prevent cardiac events from occurring through early detection of risk, a screen for bone strength could help identify risk and guide subsequent referral to physicians and/or fitness professionals for clinical assessment or bone-building and bone-conserving exercise programming, respectively, in an effort to prevent osteopenia, osteoporosis, and other skeletal complications. The ideal screening tool for bone strength would be non-invasive, inexpensive, quick, and easy to administer for clinicians and/or fitness professionals. Developing a screening tool for bone strength requires critical evaluation of the most prominent determinants of bone mass and geometry. Bone strength is a function of both a bone's mass and geometry. Changes in the intrinsic properties, size, or structure/architecture of a bone contribute to the bone's overall strength (Ammann & Rizzoli, 2003). Bone is a dynamic tissue that adapts according to the loads to which it is exposed (Frost, 1987; Frost, 2000; Schoenau & Frost, 2002). Body weight and impact forces have been shown to influence bone mass and geometry (Wolff, 1986; Frost, 1987; Turner, 1998), however, the largest loads placed upon the skeleton come from muscle forces (Schoenau et al., 2002). This is because many muscles of the body work against disadvantageous lever arms due to their anatomical origins and insertions. These unfavorable lever arms require muscles to transmit greater forces to bones per kilogram of body weight than is being moved (Schoenau et al., 2002). While measures of muscle

size have been consistently reported as strong predictors of bone strength (Schoenau et al., 2002; Sumnik et al., 2006), size does not necessarily determine how powerfully/forcefully a muscle can contract and therefore does not fully reflect muscle function, which is primarily influenced by physical activity (Janz et al., 2015). Additionally, assessing muscle size parameters requires invasive and expensive clinical imaging techniques, whereas muscle function may be able to be assessed via physical activity assessments or physical fitness tests.

Muscle forces must be rapid, powerful, and always changing in magnitude and direction in order to stimulate bone adaptation (Turner, 1998). Activities involving maximal-force muscle contractions and/or activities involving rapid accelerations of the body place substantial loads on bones and, therefore, stimulate an increase in bone strength (Schoenau & Frost, 2002). Further, lower body muscle power has been identified as an influential factor in determining bone mass and geometry (Ashe et al., 2008; Baechle & Earle, 2000; Hardcastle et al., 2014; Janz et al., 2015; Schoenau & Frost, 2002). A peak vertical jump test, often used by physical fitness and human performance specialists, is a popular surrogate method for assessing muscle power (Amonette et al., 2012; Hardcastle et al., 2014; Janz et al., 2015; Johnson & Bahamonde, 1996; Munukka et al., 2014; Rantalainen et al., 2009; Rantalainen et al., 2010) and could be an easy, non-invasive, and inexpensive avenue to assess bone strength.

The next section provides a review of the literature that supports the need for this research and justifies the techniques/methods used during data collection and analyses.

CHAPTER 2: LITERATURE REVIEW

The Mechanostat, The Utah Paradigm, Wolff's Law, and The Muscle-Bone Unit

The determinants of bone strength have been researched widely, and several long-standing theories, paradigms, and laws have been developed and subsequently altered over time. In the following text, I will review the literature that has led to our current understanding of the relationships among muscle, bone, and musculoskeletal health.

Bone is a dynamic tissue that responds and adapts to the forces placed upon it in order to efficiently withstand subsequent mechanical stresses and strains (Turner, 1998). Wolff's Law encompasses the overarching idea that "form-follows-function" with respect to bone, and states that changes in a bone's form and/or function lead to subsequent changes in bone's internal and external architecture (Wolff, 1986). This principle provided a basic understanding of skeletal modification and paved the way for future research focusing on the factors that influence bone anatomy and physiology.

The mechanostat theory, proposed by Harold Frost (1987), describes the relationship between loading of bones and subsequent adaptations of bone mass and geometry. The mechanostat theory is a feedback loop that is based on the combination of ideas that mechanical forces and non-mechanical forces (e.g., hormones, diet, paracrine and autocrine effects, age, sex, other cell-level features, etc.) influence bone integrity. This feedback loop is used to determine if, where, and when bone mass and geometry should be increased (Frost, 1987; Schoenau & Frost, 2002). The mechanostat suggests that a group of mechanisms monitor how bone is stressed, integrate this information, and stimulate bone cells (i.e., osteoblasts and osteoclasts) to either increase or decrease bone strength in response to specific levels of mechanical usage (Frost, 1987; Turner, 1998).

When mechanical loading produces strains of great enough magnitude to meet the modeling threshold, an increase in bone strength results (Frost, 1987; Frost, 2000; Frost, 2001). This is known as bone modeling, which is formally defined as "the process of altering the shape of bone by bone resorption and bone deposition" (Plowman & Smith, 2003). When mechanical loading produces strains that are below the modeling threshold, but meet the remodeling threshold, bone remodeling occurs (Frost, 1987; Frost, 2000; Frost, 2001). Bone remodeling is defined as "the continual process of bone break-down (resorption) and formation (deposition of new bone)" (Plowman & Smith, 2003) and can involve bone conservation, when bone is resorbed and then replaced by an equal amount of new bone, or it can involve disuse-mode bone remodeling, when more bone is resorbed than is subsequently laid down, often resulting in a decrease in bone strength (Frost, 1987; Frost, 2000; Frost, 2001).

Much research in bone physiology and musculoskeletal anatomy followed Frost's proposal of the mechanostat. In terms of bone physiology, great strides were made in understanding the determinants of bone strength. Whole bone strength is dependent on several physical factors, including bone properties (e.g., stiffness, density, ultimate strength), bone cross sectional area (mass) and bone location and architecture within the body. Biological factors, such as modeling and remodeling via osteoblast and osteoclast activity, and mechanical strain thresholds were also found to be determinants of mass, architecture, and whole bone strength (Frost, 2000). In terms of muscle physiology, the study of biomechanics contributed to the understanding of how muscle forces influence skeletal integrity. Many muscles of the body work against disadvantageous level arms, due simply to their anatomical origin and insertion attachments. The unfavorable lever

arms created by muscle insertion on bony landmarks require muscles to transmit approximately double the amount of force to bones per kilogram of body weight that is being moved. This led to the understanding that the largest loads placed upon the skeleton come from muscle forces rather than body weight, suggesting muscle forces as strong, influential factors in stimulating bone adaptation and, therefore, strong, influential factors in determining bone strength (Frost, 2000; Schoenau & Frost, 2002). Turner (1998) suggests that short-duration loading of a sufficient magnitude that is dynamic rather than static and is "odd" rather than "routine" stimulates bone cell responsiveness and, therefore, optimizes bone's adaptation to increase in strength. Thus, the muscle forces acting on bone must be rapid, powerful, and always changing in magnitude and direction in order to stimulate bone adaptation. The relationship between muscle and bone led to the idea of a functional "bone-muscle unit," suggesting that muscle strength (either gains or losses) should affect bone strength in the same direction (Schoenau & Frost, 2002). Further, Schoenau and Frost (2002) suggest that activities involving maximal-force muscle contractions and/or activities involving rapid accelerations of the body place substantial loads on bones and, therefore, stimulate an increase in bone strength.

Research has shown the muscle-bone relationship to be consistent at any age (Frost, 2001). In healthy individuals, bone mass and bone strength increase during growth, plateau during young adulthood, and then decline thereafter (Frost, 2001). In fact, about 90% of peak bone mass has been established by the time females reach age 18 and males reach age 20. Peak bone mass has the potential to increase until about age 30 in both sexes, but then begins to slowly decline thereafter (National Institutes of Health

[NIH], 2015). Similarly, muscle strength increases during growth and then plateaus during young adulthood, before declining thereafter; however, the ability to increase muscle strength persists throughout the lifespan. This is particularly important when it comes to conserving bone during adulthood. Research consistently has shown that differences in bone strength mirror differences in muscle strength, which is clear when comparing muscle and bone strength between sexes, as males generally having greater amounts of both (Frost, 2001). Being that the largest loads placed on the body come from muscle forces, and being that muscle forces on bone are required to cause movement of the skeleton, Frost (2001) concluded that the dominant influential factor controlling bone strength is muscle strength. This is further supported by evidence that muscle strength and neuromuscular physiology determine the size of muscles and the size of muscle forces transmitted to bones (Frost, 2000; Frost, 2001, Schoenau & Frost, 2002).

Harold Frost combined these new understandings of bone and muscle physiology with the mechanostat theory to develop the Utah paradigm of skeletal physiology. In general, the negative feedback arrangement of the Utah paradigm is orchestrated by the mechanostat theory and provides an explanation for the relationship between strong muscles and strong bones by describing how the muscle forces (i.e., the mechanical forces) transmitted to bone play a dominant role in controlling the biological mechanisms that influence bone mass and geometry (Frost, 2000). At it's core, the Utah Paradigm has two basic propositions: Proposition 1 states that "Bones have the main purpose of providing only enough strength to keep voluntary physical loads, whether subnormal, normal, or supranormal, from causing spontaneous fractures" (Frost, 2001). This proposition embodies the mechanostat theory, describes how bones adapt to previous and

current mechanical usage, and holds that the mechanical forces caused by muscle contractions primarily are responsible for meeting the thresholds required for stimulating bone adaptation (Frost, 2000; Frost, 2001). Proposition 2 states that "All osteoporoses and osteopenias accompany reduced whole-bone strength" (Frost, 2000). Proposition 2 delves into the relationship between tissue-level biological mechanisms, such as osteoclast and osteoblast activity, and mechanical factors, such as the loads/strains placed on bones, and how these mechanisms work together in determining whole bone strength in response to mechanical use or disuse (Frost, 2000; Frost, 2001). Jee (2000) summarizes the Utah paradigm and the relationship between these mechanisms, stating that the biological mechanisms determining bone strength need effector cells (i.e., osteoblasts and osteoclasts) and non-mechanical factors (e.g., hormones, Calcium, Vitamin D, etc.) in order to influence bone strength. Furthermore, Jee (2000) states that mechanical factors (i.e., muscle forces) guide such biological mechanisms in influencing bone strength, that neural physiology and anatomy dominate the control of biological mechanisms, and that the non-mechanical factors involved can help or hurt but never replace the impact of mechanical forces on determining bone strength.

Bone Adaptation

An understanding of the factors necessary for stimulating adaptations in bone architecture and strength has influenced the design and implementation of exercise interventions and health promotion programming aimed to improve bone health. In the following text, I will review the literature describing the influential and indispensable elements that determine how, if, and when bone adapts.

During a 12-month randomized controlled trial of a unilateral hopping exercise intervention in healthy older men (ages 65-80), Allison et al. (2015) studied the effect of high-impact, odd-loading, osteogenic exercise on cortical and trabecular bone mass at the proximal femur. Study participants were assigned randomly an exercise leg (right or left), with the opposite leg serving as the control, and they completed a single-leg hopping intervention. The exercise intervention involved five sets of 10 hops performed on the assigned exercise leg, with a 15-second rest period between each of the five sets. Subjects were instructed to hop as high and as fast as possible in order to provide an appropriate magnitude and rate of loading to stimulate bone adaptation. They also were instructed to hop in multiple directions, as this provided the odd-loading stimulus necessary for site-specific increases in bone strength due to strain experienced at different parts of bones. Pre- and post-exercise intervention computed tomography (CT) scans of the proximal femur were used to quantify differences prior to and following the intervention. The researchers found a significant increase in cortical bone mineral content (BMC) in the exercise leg compared to the control leg. Not only did they find that the odd-loading impact exercise increased overall cortical mass surface density, cortical density, and endocortical trabecular density, they also found that there were substantially larger increases in the exercise leg at specific regions important in structural integrity of the proximal femur (Allison et al., 2015). These findings demonstrate the positive localized and overall changes in bone strength resulting from an odd-loading exercise of great enough magnitude and short enough duration, described by Turner (1998) as being necessary for bone adaptation.

The study by Allison et al. (2015) provides evidence that a jumping intervention increases bone strength, however, the researchers were unable to conclude which forces, either ground reaction forces (i.e., the force of a body pushing down on the ground and the equal and opposite force of the ground pushing up on a body) or muscle forces, were responsible for stimulating bone adaptation. In addition to the ground reaction forces acting on the proximal femur, the lower-body muscle forces necessary for jumping that acted in the same region of the body must also be considered. The methodology and design of this study did not allow the researchers to control for the influence of muscle forces vs. the influence of ground reaction forces on stimulating localized increases in bone strength. A review of the literature by Robling (2009) examined the most pertinent information regarding mechanical loading and bone adaptation and made the argument that forces produced during muscle contraction, rather than those due to gravitational loading, are the dominant source of mechanical stress that stimulates bone to adapt. This review compiled evidence from studies looking at upper-body limbs and lower-body limbs in an effort to compare the influence of non-weight-bearing and weight-bearing bones of the skeleton, and from studies that were able to control for the influence of muscle forces on bone outcomes.

Robling (2009) describes the work of Daly, Saxon, Turner, Robling, and Bass (2004), which investigated differences in muscle and bone mass in the playing and non-playing arms of tennis players. Daly et al. (2004) found that muscle and bone mass were greater in the playing arm than in the non-playing arm and that muscle area was positively correlated with absolute differences in bone mass, bone size, and bone bending strength. However, the researchers acknowledged that there was still a considerable

portion of the variation in bone size/strength that could not be explained by muscle mass alone.

In another study looking at the relationship between muscle and bone strength in upper-body limbs, Schoenau (2005) investigated the effect of different disease states on muscle forces and bone mass. The results of this study suggested that a bone is typically only as strong as the muscles that pull on it and that, if muscle mass decreases, so too does bone mass (Schoenau, 2005). Under normal, healthy, non-diseased conditions, a strong association was found between bone strength and muscle force or size (Schoenau, 2005). The findings from Daly et al. (2004) and Schoenau (2005) are important in that both studies look at bones and muscles in the limbs of the upper body, which are non-weight bearing in nature and, therefore, are not exposed to ground reaction forces. This supports the argument that muscle forces, rather than gravity, impact, and ground reaction forces, drive bone regulation and adaptation.

Although the limbs of the lower body are subject to weight-bearing loads and are, therefore, exposed to ground-reaction forces, there is evidence to support the primary role of muscle force in driving bone mass regulation. Umemura et al. (1995) studied the effects of explosive muscle contractions on weight-bearing bones in rats. The researchers used food rewards to train rats to jump vertically toward an elevated platform, catch the top edge of the platform with their front limbs, and climb the rest of the way up. This catch-and-climb technique required the rats to contract the muscles of the hind limbs explosively but eliminated the impact loading of the hind limbs upon landing, since the rats pulled themselves onto the platform rather than landing on their hind limbs and absorbing that impact. The researchers found that muscle contraction, in lieu of impact

loading, stimulated an osteogenic response in weight-bearing, hind limb bones (Umemura et al., 1995). These findings provide clear evidence that powerful muscle contractions are capable of stimulating bone adaptation and suggest that muscular power could serve as a good indication of bone strength.

Muscle Mass, Body Size, and Measurements of Bone Strength

In a cross-sectional study of 456 women and 144 men, all of whom were healthy, ambulatory individuals, Wu et al. (2013) studied the interrelationship between muscle and bone. The purpose of this study was to investigate specifically the association between sarcopenia and bone density. Age, sex, physical activity, current medication use and current dietary supplement use information was obtained through questionnaires, and anthropometric measurements (height and weight) were performed. Body mass index (BMI) was calculated from these data and used to classify subjects based on Taiwanese Department of Health criteria. BMD at the femoral neck and lumbar spine were determined by DXA, and subjects were identified as having abnormal BMD (osteoporotic and osteopenic subjects; T-score $\leq$-2.5 to $\leq$-1.0) or normal BMD (T-score >-1.0). Skeletal muscle mass (SM) was estimated using bioelectrical impedance analyses, and SM index (SMI) was calculated by dividing skeletal mass by height squared. An SMI of $\geq$2.0 standard deviations (SD) below the mean SMI for that sex was used to define sarcopenia. Binary logistic regression assessing the association between BMD groups and sarcopenia revealed that individuals with sarcopenia were at a higher risk for low BMD than were individuals in the non-sarcopenia group, and, after controlling for sex and age, that sarcopenia was an independent risk factor for low BMD in women. Additionally, femoral neck and lumbar spine BMD were significantly lower in the

sarcopenia group, suggesting that risk of low BMD increased significantly in the presence of low muscle mass (Wu et al., 2013).

A cross-sectional study by Sumnik et al. (2006) investigated bone mineral mass and muscle cross-sectional area in relation to age, body height, sex, and gynecological history in 130 men (ages 31-60) and 180 pre-menopausal women (ages 30-53) who participated in the Dortmund Nutritional and Anthropometric Longitudinally Designed (DONALD) study. Age, sex, height, drug use, age-at-menarche, oral contraceptive use, numbers of pregnancies/deliveries, and total lactation time information was collected, and peripheral quantitative computed tomography (pQCT) analysis of the non-dominant forearm was performed to gather muscle cross-sectional area and bone mineral mass data. Least squares means and multiple linear regression analyses were run separately for both sexes. The researchers found that both bone mineral mass and muscle cross-sectional area were dependent on height, but not age in adults, suggesting a plateau of factors during young and middle adulthood. With the bone mineral mass-to-muscle cross-sectional area ratio (BMC/MA) serving as the index of the functional muscle-bone unit, they also found that females had a significantly higher BMC/MA ratio than males, probably due to differences in circulating estrogen levels during late puberty. The authors concluded that bone analysis during adulthood should include height-adjusted parameters, as the results suggested that height still was clinically relevant, even though puberty (i.e., the growing period) had ended long ago. The researchers suggested the BMC/MA ratio as a useful variable when analyzing subjects of differing heights, as this ratio is independent of both height and age. However, the use of this ratio as a valid indicator of bone health has yet to be determined (Sumnik et al., 2006).

Limitations of the studies conducted by Wu et al. (2013) and Sumnik et al. (2006) include the cross-sectional study designs used, as well as the use of muscle cross-sectional area as a surrogate for muscle strength. First, the direction of causality (i.e., whether decreased muscle mass causes decreases in BMD or vice versa) is inconclusive based on data that are collected in a cross-sectional manner. Second, although muscle cross-sectional area provides information on muscle size and mass, it does not reflect the functional properties of muscle, specifically contractile velocity, force application, and muscle structure. Therefore, this surrogate measure of muscle function should be viewed with caution when used to investigate its effect on bone strength. The literature describing the relationship between muscle function and bone strength is discussed in greater detail below.

Muscle Power and Bone Strength

The relationships between powerful muscle contractions and bone strength are at the center of this work. In the following text, I will review the literature surrounding the relationship between measures of muscle function, specifically muscle power, and measures of bone strength.

In a cross-sectional observational study of 70 males (mean age 58 years) and 119 females (mean age 56 years), Hardcastle, Gregson, Rittweger, Crabtree, Ward, and Tobias (2014) investigated the role of muscle function in lower body bone strength maintenance during adulthood. Subjects were recruited from The High Bone Mass study, a United Kingdom-based observational study of individuals with unexplained extreme high bone mass (HBM) and unaffected (i.e., non-HBM) family controls. From this study, researchers pooled 113 HBM individuals, as identified by pQCT measures of cortical

bone strength, and 76 HBM controls (relatives and spouses), all of whom had completed a 2-legged jumping test. Pooling HBM cases and HBM controls provided a wide range of bone values in the hopes of maximizing the ability to detect associations between variables. Researchers aimed to assess whether peak jumping power and peak jumping force both were related to bone strength, whether these relationships were greater for power or force in adults, and whether differences in the relationships among peak power, peak force, and bone strength could be explained by their relationships to bone microarchitecture. Data from DXA scans at the lumbar spine and hip were used as an index in identifying HBM cases and HBM controls, and pQCT scans were used to quantify cortical BMD, total bone area, cortical bone area, and cortical bone area/total bone area parameters of the non-dominant tibia at the midshaft. A Leonardo Mechanography Ground Reaction Force Platform (Novotec Medical GmbH, Pforzheim, Germany) was used to assess lower body muscle force (absolute force in kN; relative force in N/kg), power (absolute power in kW; relative power in W/kg), and velocity (m/s), as well as jump height and total body weight during a 2-legged countermovement vertical jump (with brief squat prior to jumping), and during a dominant leg hopping test. Adjustments were made for age, sex, height, and weight when examining relationships among muscle power, muscle force, and bone parameters. Additionally, participants completed the International Physical Activity Questionnaire (IPAQ; short version) to categorize activity levels, and a lifestyle and medical history questionnaire to collect information on smoking status, alcohol use, and diabetes history. Results showed that jump power (kW and W/kg), but not jump force (N/kg), was strongly associated with total hip BMD, and that hopping force, but not jump power, was associated positively

with total bone area, a measure of bone size. Both peak jump power and peak jump force were positively associated with tibial strength-strain index (SSIp), a measure of bone strength during torsion, as assessed by pQCT. Peak jump force, however, was strongly associated, primarily, with total bone area of the midtibia, which suggested a relationship to periosteal expansion, whereas peak jump power primarily was inversely associated with endocortical circumference, which suggested a relationship to endocortical expansion. Although these results reflect differing mechanisms by which peak force and peak power are associated with cortical bone strength, they are consistent in illustrating the positive relationship between measures of muscle function and bone outcomes. Due to the cross-sectional nature of this study, the direction of causality between bone strength and muscle function could not be determined, however, previous research looking at the relationship between bone and muscle changes over time suggests that changes (gains or losses) in muscle strength affect bone, rather than the opposite.

Janz, Letuchy, Burns, Francis, and Levy (2015) studied the use of a simple field measure of muscle power, the vertical jump, in predicting bone strength in a cross-sectional study of 141 male and 162 female adolescents approximately 17 years of age from the Iowa Bone Development Study. The purpose of the study was to assess the association between lower body muscle power and bone strength, and to see if muscle cross-sectional area served as a mediator for this association. The researchers collected anthropometric information, including weight, standing height, sitting height, and leg length, which was used in quantifying somatic maturity using the Mirwald maturity offset prediction equations (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). Vertical jump height was quantified using a Vertec and the Sayers equation was used to predict lower

body muscle power from jump height. Peripheral quantitative computed tomography (pQCT) technology provided indices of whole bone compressive and torsional strength for the tibia at 4% and 66% individual bone length sites. Linear associations among muscle power, muscle cross-sectional area, and bone strength measures were quantified using Pearson bivariate and partial correlation coefficients. Mediation analyses were used to demonstrate causal sequences among muscle power, muscle cross-sectional area, and bone strength outcomes, and bootstrapping was used to construct confidence intervals, which were used to describe indirect effects of muscle power on bone strength. The researchers found statistically significant correlation coefficients ranging from r=0.54 to r=0.78 among muscle power, muscle cross-sectional area, and bone strength, which were reduced to r=0.37 to r=0.69 following adjustment for covariates. Mediation models for female subjects' bone strength index (BSI), strength-strain index (SSI), and cortical bone area (CoA) accounted for a respective 46%, 77%, and 66% of the variance in bone strength, all of which were greater compared to males (38%, 66%, and 54%, respectively). The direct effect of muscle power on bone, as suggested by the nearly identical magnitudes of association between muscle cross-sectional area and bone strength and between muscle power and bone strength, suggests that there is a non-mediated effect between muscle function and muscle size. These findings support the use of an assessment of lower body muscle power as a strong and consistent predictor of bone strength in young adults.

In a cross-sectional study of 51 girls and 63 boys, aged 7.9 to 9.7 years, Baptista, Homens, Carita, Sardinha, and Janz (in press) studied the ability of muscle power to predict BMD. The purpose of this study was to evaluate the accuracy of vertical jump

power in distinguishing children with below average BMD from children with average BMD. Researchers used DXA scan technology to collect BMD data for the whole body-less head (WBLH), the femoral neck, and the radius, as well as fat mass and lean mass measures. Body mass and body height anthropometric measures were collected as well. Vertical jump power (VJP) data was collected by having participants perform a countermovement vertical jump on a contact mat that used flight time to calculate the rise of the center of gravity. Jump height was then used to estimate peak vertical jump power using the equation published by Duncan et al. (2013). While the International Society for Clinical Densitometry (Crabtree et al., 2014) defines "below the expected range for age" to be an areal BMD *Z*-score of -2.0 or lower, "below average" BMD was defined in this study as a WBLH BMD *Z*-score of < -1.0 SD due to the small sample size, and due to the fact that a more conservative cutoff value is often preferable for screening tests, as early detection is the goal of such tools. The researchers found strong and consistent associations between jump power and BMD at all sites, adjusted for height. Additionally, they found that the odds ratio of having below average BMD decreased 1.2% per Watt of power. ROC curve analysis showed that reliable differentiation between children with and without below average BMD occurred up until 735 Watts in boys and 621 Watts in girls, with these values being the lowest power for reliable differentiation. These results not only reflect reasonable sensitivity and specificity for using VJP to identify children with and without below average BMD, but also suggest that a peak vertical jump test is also a cost-effective tool that can be used in screening for below average BMD (Baptista et al., in press).

In a cross-sectional study of 74 community-dwelling women aged 65-75 years, Ashe, Liu-Ambrose, Cooper, Khan, and McKay (2008) looked at the relationships between muscle power and muscle strength on bone strength. Muscle strength was measured by having subjects complete a one-repetition maximum (1RM) using an air-pressured resistance leg press machine, and muscle power was measured by having subjects complete six bilateral leg extensions, each 10% higher in relative intensity, from 40% to 90% of their 1RM. Bone strength was assessed using pQCT imaging at the 50% tibial site on the left tibia, and polar section modulus (mm^3), SSI (mm^3), and cortical volumetric BMD (vBMD; g/cm^3) values were recorded for each subject. Additionally, subjects wore accelerometers for 4 days to objectively measure physical activity. Multi-level linear regression modeling was conducted to examine the independent association of muscle power and strength with the measures of bone strength, controlling for age, height, weight, and physical activity. Pearson correlation coefficients were used to examine the relationships between bone strength measures and muscle power and strength. The results showed a significant correlation between measures of bone strength and muscle power (0.49 SSI; 0.53 section modulus; $p<0.001$), but not muscle strength, and that, after controlling for age, height, weight, and physical activity, muscle power contributed 6.6% ($p<0.007$) and 8.9% ($p<0.001$) of the variance in the SSI value and section modulus value, respectively. There was also a significant association between peak muscle power and mean daily total accelerometer activity counts ($r=0.37$, $p=0.003$) and MVPA ($r=0.26$, $p=0.041$). The authors concluded that muscle power contributed significantly to the variance in estimated bone strength and suggested that training for muscular

strength (Ashe et al., 2008). This begs the question of whether low muscular power can be used to reliably predict low bone strength in the general adult population. If this is the case, the question turns to the most cost-effective, time-effective, acceptable, and reliable method of assessing muscular power in the clinical setting.

Assessing Vertical Jump Height: Tools & Techniques

Leard et al. (2007) used a methodological study design to investigate the validity of the Vertec (Vertec Sports Imports, Hilliard, OH) and Just Jump (Probotics, Huntsville, AL) systems of assessing vertical jump height in comparison to a 3-camera motion analysis system, which served as the criterion reference for the vertical jump. Forty college-aged individuals (26 female, 14 male; mean age 20.7 years) participated in this study. Participants were taught how to perform a countermovement jump and reflective markers detectable by the 3-camera motion analysis system were placed at the base of each subject's sacrum prior to data collection. A Just Jump mat and Vertec apparatus were set up so that each camera of the motion analysis system could capture and record movement of the reflective marker throughout the jump. Participants stood on the Just Jump mat and completed two countermovement jump-and-reach maximal vertical jumps. The results of this study indicated that both the Vertec and Just Jump systems of assessing vertical jump height are highly correlated with the reference 3-camera motional analysis system of measuring vertical jump height.

Leard et al. (2007) point out several factors that can influence the accuracy of the Vertec to measure peak jump height, including an individual's shoulder range of motion in order to reach the highest vane, the test administrator's ability to accurately score and record the number of vanes pushed by the subject during the jump, and the degree of

human error in the jump and reach technique. The Just Jump system can produce more accurate measurements of vertical jump height compared to the Vertec apparatus due to the simplicity of its use, jumping procedures, and scoring. However, the Vertec apparatus provides subjects with a visual target that can influence effort expended and maximum vertical jump height reached, whereas the Just Jump system does not (Leard et al., 2007).

Ford, Myer, Smith, Byrnes, Dopirak, and Hewett (2005) used a randomized, repeated-measures experimental study design to investigate the effect of an overhead goal, acting as an extrinsic motivator, on vertical jump height and lower-body biomechanics during a drop vertical jump. Thirty-five Division I collegiate soccer athletes (18 females, 17 males) completed standing countermovement vertical jump testing that involved dropping off a 31-cm box, followed by a maximal vertical jump during autumn preseason training. Randomly ordered trials of the drop vertical jump test were conducted both with and without an overhead goal. An MX-1 vertical jump trainer provided an external target for the overhead goal trials, while motion and force data were collected for all trials using 8 digital cameras and two force platforms. The MX-1 vertical jump trainer suspends a ball at variable, measured heights above an athlete, who is instructed to grab the ball with both hands at the top of their maximal vertical jump. Ball height was adjusted until subjects performing countermovement vertical jumps could not grab the ball after three trials, with the highest successful jump-and-grab attempt being used for analysis. The results of this study showed that both men and women had greater vertical jump heights when an overhead goal was present compared to when an overhead goal was not present ($p = 0.002$). The authors noted the relevance of

performance on a peak vertical jump test to performance in sport, but stated that "it is an excellent and reproducible indicator of whole-body power," specifically in that the reliability of vertical jump has been reported to be between 0.90-0.99 (Ford et al., 2005). This work concluded that peak vertical jump testing, particularly for athletes, should include an extrinsic/external target as a way to motivate maximal effort during testing (Ford et al., 2005).

Rationale for Choosing the Sayers Equation as the Predictive Model for Muscular Power

Vertical jump height, once quantified, can be used as a proxy for estimating lower body power. Several predictive models for muscular power have been developed using different subject populations, vertical jump techniques, and methods of quantifying jump height. Thus, selecting a model that is appropriate for the overarching aims of this study, while considering subject characteristics and data acquisition techniques/tools, is vital if we want the estimated peak power values to reliably and validly depict true peak power values. In the following text, I will review the literature describing the development and cross-validation of several predictive models for estimating peak muscle power, and provide a rationale for choosing the Sayers et al. (1999) equation as the predictive model for this study.

Sayers, Harackiewicz, Harman, Frykman, and Rosenstein (1999) conducted a cross-validation study of two equations used to estimate peak mechanical power from vertical jump score. The purpose of this study was not only to cross validate the equations developed by Lewis (1974) and Harman et al. (1991), but also to develop a more accurate equation from a larger, heterogeneous population, as well as analyze differences between sexes and jump protocols. Participants recruited for this study were

108 college-aged male and female athletes and non-athletes. Anthropometric measures, including body weight and skinfolds, were assessed for each participant. A force platform was used to quantify the vertical ground reaction forces exerted by each participant during three trials of a maximal height squat jump vertical jump and three trials of a maximal height countermovement vertical jump. The best jump height from each vertical jump protocol was used for analysis. In the squat jump protocol, subjects entered into a preparatory position with knees flexed to approximately 90 degrees and arms swung back so that the knuckles pointed toward the ground. Once in this position, participants paused for a moment before jumping vertically as high as possible. In the countermovement vertical jump protocol, participants rapidly assumed the same preparatory position as in the squat jump protocol, but did not pause in this position before jumping vertically as high as possible. Thus, the countermovement jump was completed in a single, fluid motion and allowed participants to use their downward momentum to initiate the stretch-shortening cycle and propel themselves a greater distance vertically. A Velcro ring placed around the participant's middle finger marked the height of the vertical jump when touched to the vertical jump device. Each participant's standing height was subtracted from the vertical jump height, producing the actual vertical distance jumped. The force platform and associated software analyzed the ground reaction force versus time and was able to determine the power output for each trial. The power output data that were calculated via the force platform were cross-validated with the Lewis (1974) and Harman et al. (1991) equations of estimating peak and average power, which used jump height and body weight data for each subject. Data from the participants in this study were used to develop a new set of regression equations,

which were then compared to the Lewis (1974) and Harman et al. (1991) equations. From there, a final set of equations were derived and cross-validated using Predicted Residual Sum of Squares (PRESS) (Sayers et al., 1999).

Data from the squat jump trials produced the greatest correlations between actual power (measured by the force platform) and estimated power using the Lewis (1974) and Harman et al. (1991) equations. Peak power was underestimated for both squat jump and countermovement jump data in both the Lewis (1974) and Harman et al. (1991) equations. When comparing the original, non-cross-validated regression equations derived from this study's subject population and the resulting PRESS cross-validated regression equation, data from the squat jump protocol trials produced better R^2 and SEE values and, therefore, more accurately predicted peak power output than did data from the countermovement jump protocol trials. Further, smaller SEE values and higher correlations were seen between estimated peak power and actual peak power measured by the force platform for the squat jump trials as compared to the countermovement jump trials. Sayers et al. (1999) suggest this is due to the fact that the squat jump protocol minimizes variation in jumping technique as the pause prior to powerful vertical jump eliminates the possibility of differing speeds and magnitudes of jumping, which is often the case when incorporating a countermovement into a jump. Sayers et al. (1999) concluded that the squat jump equation {Peak Power (W) = 60.7 x (jump height [cm]) + 45.3 x (body mass [kg]) - 2055} should be used to determine peak power rather than the equations developed by Lewis and Harman (Sayers et al., 1999). Additionally, using one equation for both males and females resulted in only a slight difference in peak power output between the sexes and PRESS cross-validation of the regression equations

produced accurate and reliable R^2 and SEE values. Therefore, Sayers et al. (1999) concluded that using separate equations for males and females would be unnecessary. In addition to being validated for both sexes, the Sayers et al. (1999) equation has been validated for use in athletes and non-athletes.

Prior to the development of the Sayer's equation, Johnson and Bahamonde (1996) conducted a cross-sectional study and aimed to develop an equation to predict both peak and average mechanical power for peak vertical jump tests. Previous studies had devised such prediction equations, but had utilized a very small number of subjects and a variety of jump methods. The authors aimed to develop a simple equation using a countermovement jump and reach test in college-aged male and female athletes. A Vertec jump training apparatus was used to measure jump height, and the best jump of each subject's three test jumps was used in the power regression equation. Additionally, a force platform was used to determine power output. After conducting stepwise multiple regressions to predict peak and average mechanical power, the authors found that vertical jump height, mass, and body height were significant and were good predictors of peak and average power in this subject population. Similar to Sayers et al. (1999), this study found that sex was not a significant variable in predicting peak power output, suggesting that a single prediction equation could be used and would be appropriate for both sexes. Although sex was not found to be a significant predictor in the study conducted by Johnson and Bahamonde (1996), it does not mean that differences do not exist between males and females, and the authors suggested that sex differences in power production might be due to differences in size and strength rather than sex itself.

The model developed by Johnson and Bahamonde (1996) was based on data that were collected using a countermovement vertical jump protocol, whereas the data in my study was collected using the squat jump protocol. Further, although the ages of the subjects involved in this study and in my study are very similar, Johnson and Bahamonde (1996) used a homogeneously athletic collegiate population, whereas the subject population involved in my study varies with regard to the type of athletic experience, length of involvement, and level of athletic participation (high school vs. college). For these reasons, the predictive model by Johnson and Bahamonde (1996) will not be used in the proposed study.

A longitudinal study by Canavan and Vescovi (2004) compared the actual peak power assessed using a force platform and the estimated peak power values derived using the Sayers et al. and Harman et al. equations. As rationale for comparing these equations, the authors identified the heterogeneous subject population used by Sayers et al. (1999), comprised of both athletes and non-athletes of both sexes, as a limitation that necessitated examination of the resulting prediction equation. They argued that vertical jump technique and coordination differences could exist among sexes, athletes, and non-athletes and that using such a heterogeneous subject sample for cross-validation with a study using a more narrow subject sample, as is the case in with Harman et al. (1991), is inappropriate. In their investigation, the researchers recruited twenty recreationally trained college-aged females with a minimum of three years of organized basketball participation. Subjects were randomly assigned to a plyometric training intervention group or a control group and performed maximal countermovement vertical jumps on a force platform both before and after the six-week intervention period. Canavan and

Vescovi (2004) found that the Sayers equation overestimated peak power, but suggested that this overestimation could be due to the different methods of quantifying vertical jump height (i.e., jump-and-reach method to collect vertical jump height data by Sayers et al. (1999) vs. use of a force platform to calculate jump height data in the current analysis by Canavan and Vescovi (2004)). The authors concluded that the predictive model developed in their investigation appeared to be highly accurate and provided a more precise estimate of peak power compared to the Sayers et al. (1999) and Harman et al. (1991) formulas (Canavan & Vescovi, 2004). However, data from a very specific subject sample was used to create this regression equation, therefore, limiting the application of this model to broader subject populations.

Although their rationale for developing a new prediction equation is logical when the goal is to tailor calculations to a very specific population, using the predictive model outlined by Canavan and Vescovi (2004) in my proposed study would be inappropriate for several reasons. First, the subject sample used in my study is heterogeneous, comprised of both male, female, athlete and non-athlete subjects. Secondly, vertical jump height data in my study was collected using a Vertec apparatus and a jump-and-reach technique, whereas Canavan and Vescovi (2004) used a force platform to calculate jump height without incorporating any overhead reaching during the maximal jumps. The differences in jump mechanics could very well explain the differences in estimated and measured peak power agreement. Finally, the squat jump protocol was used when collecting vertical jump data from our participants, whereas Canavan and Vescovi (2004), as well as the study that led to the development of the Harman et al. (1991) prediction formula, used the countermovement jump protocol. Although Sayers et al.

(1999) agreed that using the countermovement protocol would not greatly affect the estimation results, they still recommended using the squat jump protocol in order to maintain control and minimize variation in jumping movements between subjects.

Similar to Canavan and Vescovi (2004), Lara-Sánchez, Zagalaz, Berdejo-Del-Fresno, and Martínez-López (2011) hypothesized that a prediction equation that is tailored to specific subject populations will produce more accurate estimations of peak jump power. They argued that subject jump capacity, training, and physical characteristics should be considered, as these factors play integral roles in how precisely power is estimated using prediction equations. This specificity and validity of certain prediction equations was of interest to Lara-Sánchez et al. (2011), as their subject sample was comprised of 921 secondary school students, both males and females, who were approximately 14 years of age at the time of data collection. At this age, males and females are at different stages in their development and, therefore, physical characteristics, jump capacity, and coordination certainly differ. Therefore, the use of tailored prediction equations could be of greater importance in order to obtain more precise estimates of peak power in adolescent populations. In terms of training status and jump ability, tailored prediction equations could be more appropriate when estimating peak power in homogenously athletic/elite-athletic samples. Although the subject sample used in the proposed study is homogenous in terms age (mean age = 19.8 years), it is heterogeneous in terms of sex and athletic status, with both male and female participants with a wide range of athletic experiences and differing durations of engagement in sport. Because these subjects are part of the adult population (based on age), and due to the fact that subjects differ widely in terms of current and previous physical activity engagement,

use of a peak power prediction equation developed for a general, heterogeneous population would be most appropriate when using vertical jump height to estimate peak power. Furthermore, using such an equation would broaden our ability to apply the results of this study to a greater number of individuals, which is a primary goal when developing screening tools.

In conclusion, the Sayer's Equation for predicting muscle power will be used in the proposed study for the following reasons: 1) This equation was developed using a heterogeneous subject population of both males and females, as well as athletes and non-athletes, and was validated separately and deemed appropriate for use in all; 2) This equation recommends using the squat jump protocol when collecting data for predicting peak power, as this method minimizes variation in jump technique and produces better R^2 and SEE values in comparison to data collected using the countermovement jump protocol; 3) This equation was developed using a jump-and-reach vertical jump technique to quantify vertical jump height. Since the proposed study aims to distinguish whether a peak vertical jump test (using the squat jump protocol and Vertec apparatus) can be used as a screening tool to identify young adults (with differing athletic experiences/statuses) with below-average bone strength, using a predictive model that links vertical jump height to muscle power (which is dually linked to bone strength) and reflects the heterogeneous subject sample and methodology used in the proposed study is imperative. Therefore, the Sayer's equation is most appropriate.

Summary and Need for Further Study

The literature review above describes the importance of and relationship between muscle power and bone strength and provides the rationale for the proposed study. What

is unclear is whether a simple test of muscle power (vertical jump) can be used to predict bone strength, which is currently assessed using expensive, time-consuming scans performed in clinical settings. The purpose of this study was to ascertain the relationship between muscle power and bone strength, as well as the capacity of a peak vertical jump test to identify young adults with below-average areal BMD (aBMD). If the relationship between lower body muscle power and bone strength can be clarified, the peak vertical jump test, an easy to administer, cost-effective, time-effective, non-invasive, and acceptable field test for determining lower body muscle power, could have clinical and practical significance as a screening tool in identifying young adults with below-average bone strength. As is the case with other screening tests, positive identification of at-risk individuals could guide referral to a physician for clinical assessment and/or referral to a fitness professional to address bone health-based exercise programming and prescription in an effort to obtain and subsequently maintain greater optimal bone strength. Early identification of at-risk individuals potentially could have significant implications for future osteoporosis prevention and preservation of bone strength and skeletal integrity.

Research Questions

Research Question 1: What is the magnitude of association between peak lower body muscle power (quantified using the peak vertical jump test and Sayers et al. (1999) equation for estimating muscle power) and bone strength (quantified using DXA at the total hip and femoral neck and pQCT at the tibia)?

Research Question 2: Can the peak vertical jump test be used as a screening tool to identify young adults with below-average bone strength?

CHAPTER 3: RESEARCH PAPER

Abstract

While bone mineral density (BMD) testing recommendations are in place for women aged 65 and older and men aged 70 and older to diagnose osteoporosis, there currently are no BMD testing recommendations for preventive or screening purposes in the general, healthy, adult population. One potential screening tool for bone strength is a peak vertical jump test. Peak vertical jump height can be used as a proxy for lower body muscle power, which has been identified as an influential factor in determining bone mass and geometry, both of which are critical aspects of bone strength. This study ascertained the relationship between muscle power and bone strength, as well as the capacity of a peak vertical jump test to identify young adults with below-average areal BMD (aBMD). A total of 303 young adults (18 to 22 years, *n*=136 males, *n*=167 females) participated in these cross-sectional analyses. DXA was used to assess aBMD for total hip and femoral neck, and DXA images were used to calculate femoral neck section modulus (FN Z) values. Peripheral quantitative computed tomography (pQCT) was used to assess indices of bone strength at the tibia. Cortical bone area (CoA) and density-weighted polar section modulus strength-strain index (SSIp) were assessed at the 38% midshaft site, and bone strength index (BSI) was assessed at the 4% midshaft site. Lower body muscle power was predicted using peak vertical jump height and the Sayers et al. (1999) equation. Data were analyzed using Pearson bivariate and partial correlations to examine associations among bone strength outcomes and muscle power. Logistic regression was used to examine the probability of below-average bone strength based on muscle power. Receiver Operating Characteristic (ROC) curve analysis was

used to show the tradeoff between sensitivity and specificity and to display the accuracy of a peak vertical jump test as an assessment tool for aBMD. Logistic regression indicated the odds ratio of below-average height-adjusted femoral neck aBMD decreased 5.4% for females and 3.6% for males per 50 Watts of power. ROC curve analysis showed the best sensitivity-specificity trade-off for identifying individuals with and without below-average aBMD was 5,038 Watts in males (sensitivity = 73.7%; specificity = 62.4%; AUC = 0.709, 95%CI = 0.572 - 0.847) and 3,261 Watts in females (sensitivity = 71.4%; specificity = 58.9%; AUC = 0.708, 95%CI = 0.586 - 0.829). These cut off values correspond to a vertical jump height of 54.39 cm and 36.16 cm for males and females, respectively. Taken together, the results of these analyses suggest acceptable sensitivity and specificity and moderate discriminate ability for using a measure of muscle power, assessed with a peak vertical jump test, to identify young adults with below-average aBMD.

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Background

The International Society of Clinical Densitometry (ISCD) estimates 200 million people worldwide have osteoporosis and 1.5 million people in the United States experience an osteoporotic fracture each year (International Society for Clinical Densitometry [ISCD], 2014). It has been estimated previously that the average annual cost of such a fracture is $8,600 (95% CI, $6,400 to $10,800), adding up to a yearly cost

of almost $13 billion in the U.S. (Blume & Curtis, 2010). Given osteoporosis is both non-reversible and one of the most common diseases experienced in American elderly adults (ISCD, 2014), there is a need for more to be done to prevent osteoporosis from developing initially.

Prevention of disease and disability, and early identification of the risk factors that lead to disease or disability, are the primary purposes of the health screening tests administered in clinical and health promotion settings. Clinical screenings, such as mammograms and stress tests, and health promotion screenings, such as assessments of muscular strength and flexibility, aim to identify risk factors and early signs of disease, as well as weaknesses, imbalances and areas in need of improvement. As such, these screens guide proactive clinical treatment and health promotion programming with the goal of optimizing functional health and preventing disease and disability.

Currently, the ISCD recommends bone mineral density (BMD) testing for women aged 65 and older and men aged 70 and older. Early testing is only recommended for those with a family history of or a risk factor for low bone mass, such as low body weight, prior fracture, high-risk medication use, or a disease/condition that is associated with bone loss (ISCD, 2015). BMD screening tests are most commonly performed using a dual X-ray absorptiometry (DXA) with the goal being to diagnose conditions such as osteopenia (i.e., low bone density) and osteoporosis (i.e., a bone disease characterized by decreased bone mass and density, resulting in increased bone porosity and brittleness) (ISCD, 2015). While the DXA scanning process is short and painless, the scan also involves exposure to low-dose radiation, and can be costly. DXA requires extensive training for personnel and use of expensive equipment and software (ISCD, 2014). For

these reasons, BMD tests using DXA can be inaccessible for younger adults who do not meet the qualifications for early screening. There is a need for alternative screening procedures that can identify individuals at-risk for low bone strength at younger ages when steps can still be taken to prevent and/or delay bone mass and geometry from declining to clinically diagnostic levels.

A screening for bone strength that is appropriate for adults that do not meet the indications for early clinical BMD testing would be a valuable tool in allowing early detection of below-average bone strength in seemingly healthy individuals, especially since a decrease in bone mass and geometry occurs silently and without any physical indications. By the time females reach age 18 and males reach age 20, about 90% of peak bone mass has been established. Peak bone mass can increase until about age 30 in both sexes but then begins to decline slowly thereafter (National Institutes of Health [NIH], 2015). Thus, screening for bone mass and geometry would be particularly valuable during young adulthood, as this is the age range where improvement of bone mass and geometry is still possible. Identifying risk within this age group would provide individuals with a window of opportunity to optimize peak bone mass and geometry, thereby preventing, or at the very least delaying, a clinical diagnosis of osteopenia or osteoporosis. This is an important tenet of screening, as actual changes can be made once a need for change has been identified. The ideal screening tool for bone strength would be non-invasive, inexpensive, quick, and easy to administer for clinicians and/or fitness professionals.

Developing a screening tool for bone strength requires critical evaluation of the most prominent determinants of bone mass and geometry. Bone strength is a function of

both a bone's mass and geometry. Changes in the intrinsic properties, size, or structure/architecture of a bone contribute to the bone's overall strength (Ammann & Rizzoli, 2003). Bone is a dynamic tissue that adapts according to the loads to which it is exposed (Frost, 1987; Frost, 2000; Schoenau & Frost, 2002). Body weight and impact forces have been shown to influence bone mass and geometry (Wolff, 1986; Frost, 1987; Turner, 1998), however, the largest loads placed upon the skeleton come from muscle forces (Schoenau et al., 2002). This is because many muscles of the body work against disadvantageous lever arms due to their anatomical origins and insertions. These unfavorable lever arms require muscles to transmit greater forces to bones per kilogram of body weight than is being moved (Schoenau et al., 2002). While measures of muscle size have been consistently reported as strong predictors of bone strength (Schoenau et al., 2002; Sumnik et al., 2006), size does not necessarily determine how powerfully/forcefully a muscle can contract and therefore does not fully reflect muscle function, which is primarily influenced by physical activity (Janz et al., 2015). Additionally, assessing muscle size parameters requires invasive and expensive clinical imaging techniques, whereas muscle function may be able to be assessed via physical activity assessments or physical fitness tests.

Muscle forces must be rapid, powerful, and always changing in magnitude and direction in order to stimulate bone adaptation (Turner, 1998). Activities involving maximal-force muscle contractions and/or activities involving rapid accelerations of the body place substantial loads on bones and, therefore, stimulate an increase in bone strength (Schoenau & Frost, 2002). Further, lower body muscle power has been identified as an influential factor in determining bone mass and geometry (Ashe et al.,

2008; Baechle & Earle, 2000; Hardcastle et al., 2014; Janz et al., 2015; Schoenau & Frost, 2002). A peak vertical jump test, often used by physical fitness and human performance specialists, is a popular surrogate method for assessing muscle power (Amonette et al., 2012; Hardcastle et al., 2014; Janz et al., 2015; Johnson & Bahamonde, 1996; Munukka et al., 2014; Rantalainen et al., 2009; Rantalainen et al., 2010) and could be an easy, non-invasive, and inexpensive avenue to assess bone strength. This study aimed to ascertain the relationship between muscle power and bone strength, as well as the capacity of a peak vertical jump test to identify young adults with below-average areal BMD (aBMD), defined as a femoral neck aBMD *Z*-score of ≤ -1.0 standard deviation (SD), adjusted for height using the Zemel et al. (2011) population-based approach.

Methods

Participant Recruitment and Study Design

The Iowa Bone Development Study (IBDS) is an ongoing, longitudinal study of bone health throughout childhood, adolescence, and young adulthood (Janz et al., 2014; Janz et al., 2015). Participants for the IBDS were recruited from 1998 to 2001, when subjects were approximately 5 years of age, from a larger group of Midwestern children (n = 890) that had been recruited and were already participating in the Iowa Fluoride Study (Janz et al., 2014; Janz et al., 2015). Original recruitment for the Iowa Fluoride Study occurred in eight Iowa hospitals from 1992 to 1995 immediately following birth. Demographic characteristics of the IBDS subject population include being 95% white, with two-thirds of the subjects' parents having college degrees (Janz et al., 2014; Janz et al., 2015). This secondary analysis focuses on IBDS participants with assessments in

early adulthood, specifically 18 to 22 year old males (n = 136, mean age 19.7±0.7 years) and females (n = 167, mean age 19.7±0.6 years). The Iowa Bone Development Study was approved by the University of Iowa Institutional Review Board (Human Subjects). Participants provided written informed consent.

Body Height and Weight

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, Crymych, UK), and body weight was measured using a Healthometer physician's scale (Continental, Bridgeview, IL) (Janz et al., 2015). Participants were weighed and measured without shoes, and data were recorded in tenths of kilograms and in tenths of centimeters, respectively.

Behaviors and Lifestyle

Behavioral data were collected to better describe the sample. Participants reported which sports they participated in, and the number of years of participation during high school. High school sport participation groups were coded as High Power Participant (member of basketball, cheerleading/poms, gymnastics, volleyball, or soccer team for at least two years), Low Power Participant (member of any high power sports team for 1 year, or ≥3 years total for a combination of participation on the track, football, or tennis team), or No Participation (not a part of high school team for high power sports or low power sports for specified time).

Participants also completed a 24-hour diet recall, from which the Healthy Eating Index-2010 (HEI) score was calculated. The HEI-2010 is a measure of diet quality, assesses how well an individual's diet conforms to the Dietary Guidelines for Americans,

and has been used in research settings to examine potential relationships between health-related outcomes and diet (United States Department of Agriculture [USDA], 2015). Specifically, HEI-2010 is comprised of nine components for adequacy (i.e., sufficient intake of total fruit, whole fruit, total vegetables, greens and beans, whole grains, dairy, total protein foods, seafood and plant proteins, and fatty acids) and three components for moderation (i.e., intakes within, but not in excess of, set limits for refined grains, sodium, and empty calories). Each component is assigned a score (either 5 points or 10 points) based on intake of a specified standard amount. The HEI-2010 has an overall maximum score of 100 points, which is the sum of the twelve, individual components (USDA, 2015).

Dual X-Ray Absorptiometry (DXA)

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 (Janz et al., 2014). 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. DXA measures used in this study included aBMD (g/cm^2) for the femoral neck and 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 (1984) 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. 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 (Beck, Ruff, Warden, Scott, & Rao, 1990). Specifically, the Hologic software program located the narrowest point of the femoral neck, where bone cross-sectional area (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. FN Z is an index of bending strength and represents an important structural construct of bone (Janz et al., 2014). Additionally, total body lean mass (fat-free mass minus BMC; kg) was assessed using DXA.

The International Society for Clinical Densitometry (ISCD) and the World Health Organization (WHO) recommend the femoral neck as the DXA site for diagnosis of osteoporosis in pre-menopausal women and men under 50 years of age. Additionally, the ISCD defines a femoral neck aBMD *Z*-score of -2.0 or lower as "below the expected range for age" for these populations (ISCD, 2015). However, our goal was early detection in a young, healthy population, and in order to detect those at-risk for below-average bone strength, an aBMD cut point that is not yet clinically diagnostic but provides an indication of risk, should be used. Therefore, our analysis used a more conservative approach and defined below-average aBMD as a height-adjusted femoral neck or height-adjusted total hip aBMD *Z*-score ≤ -1.0 standard deviation (SD) (Zemel et al., 2011). Importantly, the height-adjusted *Z*-score of ≤ -1.0 SD cut point was population-specific rather than sample-specific. These height-adjusted *Z*-scores were calculated based on DXA reference data from a heterogeneous cohort of 2,014 healthy Black and healthy non-Black individuals aged 5 to 23 years (Zemel et al., 2011). Sex- and age-specific bone mineral content (BMC) and aBMD reference curves, adjusted for height, were constructed for the total body, total body less head, lumbar spine, total hip,

femoral neck, and forearm skeletal sites. These curves provide important reference values for use in assessing and monitoring bone health in children, adolescents, and young adults (Zemel et al., 2011). In the current analysis, height-adjusted aBMD *Z*-scores for the femoral neck and total hip were used.

Peripheral Quantitative Computed Tomography (pQCT)

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 = 108). A previous calibration study, with all scans acquired at the 4% and 38% tibial sites, found good agreement (1.5% difference for total bone area and density, and <2.2% difference for density-weighted polar section modulus strength-strain index (SSIp)) between these two models (Janz et al., 2015).

There is inadequate evidence supporting the use of the dominant versus non-dominant limb for the bone and muscle measures (Adams, Engelke, Zemel, & Ward, 2014; Zemel et. al., 2008). Therefore, the left leg was scanned, unless there was a history of fracture (<1% of participants). All pQCT scans were acquired by one of two 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 (Glass et al., in press; Janz et al., 2015).

Bone strength index (BSI; 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) (Janz et al., 2015). Analyses of the 38% cross-sectional site were used when measuring SSIp (mm^3) and cortical bone area (CoA; mm^2), both measures of torsional strength. Cortmode 2 with a threshold of 480 mg/cm^3 was used for SSIp, as this is the software default threshold for the strength–strain indices. For CoA, separation mode 2 and a threshold of 710 mg/cm^3 were used, combined with analysis filtering. The 66% cross-section, where muscle is the greatest, was selected as an optimum site for muscle cross-sectional area assessment (MCSA; mm^2, but converted to cm^2 in the present analysis). An initial threshold of -100 mg/mm^3 was used to separate air from skin and to define the limb cross-section in order to assess muscle, independent of bone and other soft tissues. In order to separate subcutaneous fat from muscle and bone, a slightly higher threshold of 40 mg/mm^3 was used. A threshold of 710 mg/cm^3 was used to define the contour of the bone in order to subtract the bone left

within the muscle field. MCSA was defined after marrow voxels below 40 mg/cm^3 had been removed. A trained technician checked all scans for quality and possible movement artifacts at the time of initial scan analysis, followed by a complete review performed by another technician to ensure quality data. Scans that were found to have unacceptable levels of movement at any site or imprecise placement of the reference line were excluded. Two technicians showed high inter-rater reliability with intraclass correlation coefficients (ICC) exceeding 0.98 for all measures, and high test-retest reliability, with ICC exceeding 0.98 for one technician and 0.76 to 0.99 for the second (Janz et al., 2015).

Peak Vertical Jump Power

Peak vertical jump power (Watts [W]) was assessed via a peak vertical jump test, with jump height serving as a proxy for estimating lower body muscle power. Vertical jump height was quantified using a Vertec apparatus (Questek Corp, Elgin, IL). The Vertec has been shown to be valid and strongly correlated (r = 0.91) to 3-camera motion analysis systems, the gold-standard method of measuring vertical jump height (Leard et al., 2007). The Vertec was set at each participant's standing reach height prior to measurement. To set the standing reach, participants were asked to position themselves below the Vertec and reach as high as possible with both arms while keeping the shoulders relaxed and hands overlapped. The bottom vane of the Vertec was adjusted so that it touched the participant's fingertips. Participants then were instructed to perform a squat jump by bending their knees and swinging their arms behind them so that the knuckles pointed toward the floor. Once in the full squat position, participants were instructed to pause momentarily, in an effort to prevent generation of momentum (i.e., prevent a countermovement that could influence the height achieved for the subsequent

jump). Participants then jumped as high as possible while reaching upwards to hit the Vertec vanes with their dominant hand. This protocol was described to the participant and then demonstrated by the test administrator. Participants were allowed two practice jumps to warm up, followed by three measured jumps. The jump with the greatest achieved height (inches) was used for analysis. Vertical jump height (inches) was converted to centimeters (cm) and recorded. The Sayers et al. (1999) equation was used 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). This equation was developed based on force platform and vertical jump-and-reach data collected from a heterogeneous subject population, comprised of 108 college-aged male and female athletes and non-athletes, and has been validated for athletes and non-athletes of both sexes (Sayers et al., 1999).

Statistical Analysis

Descriptive statistics for continuous variable and categorical variable subject characteristics were calculated and reported for both sexes as mean ± SD and median values, respectively. Evaluation of continuous variable mean differences between male and female participants was conducted using independent samples *t*-tests, with distributions having been checked for normality prior to these analyses. Differences in categorical variables between male and female participants were evaluated using the Mann-Whitney U-test, a nonparametric test for comparing median scores. A Chi-square test was used to evaluate sex differences in high school sports participation categories. Pearson bivariate correlations were estimated to examine the strength of linear associations between muscle power and measures of muscle size (i.e., total body lean

mass and MCSA) with femoral neck aBMD, total hip aBMD, FN Z, CoA, SSIp, and BSI for both sexes together, as well as males and females separately. Partial correlation analyses were conducted to remove the effect of body height (cm) from the correlation estimates. A p-value < 0.05 was used to indicate significance for all analyses.

Logistic regression was used to determine, in males and females separately, the probability of below-average aBMD as predicted by muscle power, using a height-adjusted, population-based femoral neck aBMD Z-score of ≤ -1.0 SD as the dichotomous dependent variable. In all logistic regression analyses, 50-Watt increases were utilized in order to scale data more manageable units. Additional logistic regression analyses for both sexes were examined using total body lean mass and MCSA in separate models as the predictor variable, with the femoral neck aBMD Z-score of ≤ -1.0 SD as the dichotomous dependent variable. These analyses were conducted in order to examine how the probability of below-average aBMD differed using measures of muscle size in comparison to a measure of muscle function (i.e., muscle power). In all these analyses, femoral neck aBMD Z-scores of ≤ -1.0 SD were population-generated using Zemel et al.'s (2011) height-adjusted data, rather than using sample-specific data.

Sensitivity analysis was used to assess the proportion of young adults correctly identified as having below-average height-adjusted aBMD, and specificity was used to assess the proportion of young adults correctly identified as not having below-average height-adjusted aBMD. A Receiver Operating Characteristic (ROC) curve demonstrated tradeoff between sensitivity and specificity and displayed accuracy of the peak vertical jump test for estimating aBMD by measuring the area under the curve. A ROC curve plots the true positive rate (sensitivity) against the false positive rate (1 - specificity) for

the different possible cut points (i.e., *Z*-values) of a diagnostic test. Finally, cut point values for muscle power were determined as the reference values below which individuals with below-average height-adjusted femoral neck aBMD *Z*-score ≤ -1.0 SD were identified. It is crucial to determine the optimum balance between sensitivity and specificity while considering the consequences of making both correct and incorrect decisions or classifications. Due to the low-risk consequences of false positive classifications and the safety and appropriateness of the interventions that would be implemented to address below-average bone strength (e.g., exercise counseling, exercise prescription and programming, diet counseling, etc.), a specificity value that is lower than the sensitivity value is defensible. This is because such first-line interventions would not harm, but rather likely benefit, individuals falsely identified as having below-average bone strength. These muscle power cut points then were used to calculate the vertical jump height that corresponded to an aBMD *Z*-score ≤ -1.0 SD (i.e., a vertical jump height below which individuals with below-average aBMD could be identified). A p-value < 0.05 was used to indicate significance. All statistical analyses were performed using SPSS (IBM SPSS Statistics for Mac, Version 23.0. Armonk, NY: IBM Corp.).

Results

Three hundred and three young adults (136 men, 167 women) from the IBDS cohort participated in this study. Participant characteristics are displayed in Table A1. The mean ± SD age of participants was 19.7 ± 0.7 years for males and 19.7 ± 0.6 years for females, and was not significantly different among the sexes. Compared to female participants, male participants were significantly taller and heavier. Males had significantly greater total body lean mass, MCSA at the tibia, and muscle power than

females. Males also had significantly greater femoral neck aBMD (g/cm^2) and total hip aBMD (g/cm^2) than females, but these differences became non-significant once values were transformed into *Z*-scores and adjusted for height. There was a significant difference between males and females for FN Z, assessed by DXA. All pQCT-assessed bone outcomes, presented as raw scores in Table A1, were significantly different between sexes ($p < 0.001$). To more fully describe the study population, differences in the nonparametric, categorical variables (i.e., healthy eating index [HEI] and high school sports participation) were calculated. Median values calculated in the Mann-Whitney U-test are presented for HEI data, and the percentages of participants in each high school sports participation category, split by sex, were assessed with a Chi-square test. Females had significantly higher median value HEI scores ($p <0.001$). An exciting finding was that females had significantly higher high school sport participation scores ($p = 0.003$) (i.e., participated in significantly more high power sports or in a significantly greater number of years of low power sports) compared to males.

Pearson bivariate correlation coefficients and partial correlation coefficients removing the effect of body height between muscle power and bone strength outcomes for males, females, and the total sample (i.e., males and females together) are presented in Table A2. Associations between all variables and muscle power were significant at the $p < 0.01$ level. Pearson correlation coefficients with bone geometry outcomes were highest for muscle power and CoA ($r = 0.737$, males; $r = 0.743$, females; $r = 0.850$, total) compared to muscle power with SSIp and BSI. There was a greater difference in Pearson and partial coefficient values between the sexes for total hip aBMD compared to femoral neck aBMD, although all associations were significant. After removing the effect of

body height (cm) using partial correlations, the magnitudes of association between muscle power and all bone strength outcomes were reduced, but all remained significant at the $p < 0.01$ level. Figure B1 and Figure B2 display the Pearson correlation scatter plots of muscle power against individual bone density outcomes for the femoral neck and total hip, respectively. Figure B3 and Figure B4 display the corresponding partial correlation scatter plots for muscle power against individual bone density outcomes, removing the effect of body height, for the femoral neck and total hip. Figures B5 through B8 display the Pearson correlation scatter plots of muscle power against individual bone geometric outcomes (i.e., FN Z, CoA, SSIp, and BSI), and Figures B9 through B12 display the corresponding partial correlation scatter plots for muscle power against individual bone geometric outcomes, removing the effect of body height, for FN Z, CoA, SSIp, and BSI. Pearson bivariate correlation coefficients between two measures of muscle size (i.e., total body lean mass and MCSA) and bone strength outcomes were also examined and are presented for males, females, and the total sample (i.e., males and females together) in Table A2. Associations for all bone strength outcomes with both total body lean mass and MCSA were significant at the $p < 0.01$ level, however, associations between MCSA and bone strength outcomes more closely resembled those of muscle power than did associations between total body lean mass and the bone strength outcomes of interest.

Binary logistic regression, using dichotomized femoral neck aBMD *Z*-scores of ≤ -1.0 SD (population-generated using Zemel et al. (2011) height-adjusted data) as the dependent variable indicated that the odds of having below-average aBMD decreased 5.4% for females and 3.6% for males per 50-Watt unit of power (Table A3). Of the 303

participants in this study, 21 females and 19 males (12.6% and 14.0%, respectively) were categorized as having below-average aBMD (i.e., a positive result) based on the population-based aBMD *Z*-score of ≤ -1.0 SD, while 146 females and 117 males (87.4% and 86.0%, respectively) were categorized as not having below-average aBMD (i.e., a negative result). ROC curve analysis showed that the best sensitivity-specificity trade-off for identifying individuals with and without below-average aBMD was 5,038 Watts in males (sensitivity = 73.7%; specificity = 62.4%; AUC = 0.709, 95%CI = 0.572 - 0.847) and 3,261 Watts in females (sensitivity = 71.4%; specificity = 58.9%; AUC = 0.708, 95%CI = 0.586 - 0.829) (Figure B13). For the average body mass for males, the 5,038-Watt muscle power cut off corresponded to a vertical jump height of 54.39 cm. For the average body mass for females, the 3,261-Watt muscle power cut off corresponded to a vertical jump height of 36.16 cm.

To compare the site-specific probabilities of being identified as having below-average aBMD as predicted by muscle power, a logistic regression analysis was conducted with population-generated total hip aBMD *Z*-score of ≤ -1.0 SD, adjusted for height using Zemel et al.'s (2011) data, as the dichotomous dependent variable. The results indicated the odds of having below-average aBMD decreased 8.1% for females and 3.0% for males per 50-Watt unit of power (Table A4). Of the 303 participants in this study, 14 females and 12 males (8.4% and 8.8%, respectively) were categorized as having below-average aBMD (i.e., a positive result) based on a population-derived aBMD *Z*-score of ≤ -1.0 SD, while 153 females and 124 males (91.6% and 91.2%, respectively) were categorized as not having below-average aBMD (i.e., a negative result). ROC curve analysis showed that the best sensitivity-specificity trade-off for

identifying individuals with and without below-average total hip aBMD was 5,038 Watts in males (sensitivity = 66.7%; specificity = 59.7%; AUC = 0.668, 95%CI = 0.495-0.841) and 3,044 Watts in females (sensitivity = 78.6%; specificity = 69.9%; AUC = 0.776, 95%CI = 0.664-0.889) (Figure B14). For the average body mass for males, the 5,038-Watt muscle power cut off corresponded to a vertical jump height of 54.39 cm. For the average body mass for females, the 3,044-Watt muscle power cut off corresponded to a vertical jump height of 32.58 cm.

Tables A5 and A6 display logistic regression analyses using two measures of muscle size, in separate models, as the predictor variable with the height-adjusted femoral neck aBMD *Z*-score of ≤ -1.0 SD as the dichotomous dependent variable. Per kilogram increase in total body lean mass, the odds of having below-average aBMD decreased 13.3% for females and 12.9% for males (Table A5), while it decreased 9.9% for females and 8.2% for males per cm^2 increase in MCSA (Table A6).

Discussion

This investigation examined the relationship between muscle power and bone density and geometry, as well as the capacity of a peak vertical jump test to identify young adults with below-average aBMD, defined as a DXA-measured femoral neck aBMD *Z*-score of ≤ -1.0 SD, population-generated using Zemel et al.'s (2011) height-adjusted data. While the ISCD (2015) defines a femoral neck aBMD *Z*-score of -2.0 or lower as "below the expected range for age" for pre-menopausal women and males under 50 years of age, the present analysis defined below-average aBMD as a height-adjusted femoral neck aBMD *Z*-score of ≤ -1.0 SD. Early identification of at-risk individuals allows physicians and other practitioners the opportunity to provide patients/clients with

the preventative tools and necessary knowledge (e.g., exercise counseling, exercise prescription and programming, diet counseling, etc.) to optimize peak bone strength and subsequently prevent or delay age-related loss of bone strength. Therefore, a less conservative *Z*-score cutoff value would be appropriate, since the goal is early detection of below-average bone strength in seemingly healthy individuals, which should be noted as of particular importance as a decrease in bone mass and geometry occurs silently and without any physical indications. Using this cut point can further be rationalized in that the risk of Type I errors is minimized. As is the case with any screening or diagnostic test, it is crucial to determine the optimum balance between sensitivity and specificity while considering the consequences of making both correct and incorrect decisions or classifications. The slightly lower specificity values chosen when determining cut points on the male and female ROC curves are defensible due to the low risk consequences of false positive classifications. This is due to the safety and appropriateness of the first-line interventions that would be implemented to address below-average bone strength (e.g., exercise counseling, exercise prescription and programming, diet counseling, etc.), as such interventions would not harm, but rather would likely benefit, individuals who are falsely identified as having below-average bone strength.

The young adults included in the present analysis would have the ability and time to optimize peak bone mass before the age-related plateau and decline in bone mass begins around age 30 (National Institutes of Health [NIH], 2015). After age 30, such a screen, if determined to be valid in this age group, would still have practical, real-world importance, as conservation of bone mass and prevention of bone mass decline has been shown to occur in individuals of a greater age-range (Allison et al., Ashe et al., 2008;

2015; Frost, 2001; Hardcastle et al., 2014). This is particularly important when working to develop and determine the practical importance of a screening tool, as screens are meant to assess things that can be changed and/or prevented.

By using two different bone property-imaging modalities (i.e., DXA and pQCT), we were able to view the relationships between muscle power and bone density outcomes, and between muscle power and bone geometric/structural properties, therefore providing a more complete illustration of how muscle power influences bone make-up, shape, and function. Pearson and partial correlation coefficients indicated that muscle power was more strongly associated with the geometric properties of bone compared to the density of bone, although all associations were significant (see Table A2). These relations persisted even after the effect of body height had been removed. This is consistent with the site-specific and overall changes in bone that are likely to be influenced by physical activity, as bone adapts and becomes stronger at specific sites that experience stresses of sufficient magnitudes (Allison et al., 2015; Turner, 1998). While aBMD values from DXA give us an idea of a bone's density at the microscopic/mineral level, FN Z, CoA, SSIp, and BSI give us a more macroscopic idea of where that bone's mass is located. Bone density is important in determining bone strength, but can be influenced by multiple factors (e.g., physical activity, hormones, diet, etc.), making it difficult to delineate each factor's contribution to overall bone strength. On the other hand, bone geometry is primarily determined by physical activity, and is specifically dependent upon how, where, and when bone is loaded (Turner, 1998). The sites that experience the greatest stresses must adapt and increase bone mass in order to resist the large bending and compressive forces that they are exposed to, resulting in localized

changes in bone structure, accompanied by improvements in bone strength. This is an exciting relationship that, to our knowledge, has not been previously shown as clearly as it is in the present analysis. This is even more exciting as both muscle power and bone geometry are dependent upon the modifiable behavior of physical activity.

Our findings also suggest that MCSA and total body lean mass, both measures of muscle size, are as closely related to bone strength as muscle power, which is a measure of muscle function (Table A2). While muscle function and size are interrelated, size does not necessarily determine how powerfully a muscle contracts. As measures of muscle size, MCSA and total body lean mass are body composition parameters that are used as surrogates for muscle force/function. Muscle power is a direct measure of muscle function and is primarily determined by physical activity, a modifiable behavior that has been shown to have a strong relationship with bone strength (Janz et al., 2015). The force that muscle exerts on bone during contraction is a primary determinant of how muscle influences bone mass and geometry. Logistic regression was used to determine the odds of below-average height-adjusted femoral neck aBMD as predicted muscle power in males and females separately. For every unit increase in muscle power (50 Watt), the odds of having below-average aBMD decreased 5.4% for females and 3.6% for males (Table A3). Additional logistic regression analyses were conducted for two measures of muscle size (total body lean mass and MCSA) to see how the probability of below-average height-adjusted femoral neck aBMD differed in comparison to muscle power. The odds of having below-average aBMD decreased 13.3% for females and 12.9% for males per unit increase of total body lean mass (kg; Table A5) and 9.9% for females and 8.2% for males per unit increase in MCSA (cm^2; Table A6). The units of

measurement for muscle power, total body lean mass, and MCSA are not standardized and thus the odds ratios from these models cannot be compared at face value. Nagelkerke generalized R-square is used as a goodness-of-fit measure for model comparison. Higher values for Nagelkerke R-square for models with measures of muscle size (i.e., total body lean mass and MCSA) suggest that these measures would be better predictors of below-average femoral neck aBMD than muscle power. While these results are interesting and certainly warrant further investigation, it should be noted that total body lean mass and MCSA were assessed using DXA and pQCT technology, respectively. These clinical imaging modalities are costly, time-consuming, and invasive in comparison to the vertical jump test. Using the vertical jump test and the Sayers et al. (1999) equation as a surrogate for muscle power is the most logical muscle parameter to use for screening, as health-related screening tools should be inexpensive, easy to administer, and non-invasive.

ROC curve analysis is a well-known and established procedure for determining clinical thresholds for screening and diagnostic tests (Zweig & Campbell, 1993). In general, tests with AUCs of 0.50 are considered non-informative, tests with AUCs between 0.60 and 0.70 are considered to have low accuracy, tests with AUCs between 0.70 and 0.90 are considered to be moderately accurate, and tests with AUCs over 0.90 are considered to be highly accurate (Laurson, Eisenmann, & Welk, 2011; Streiner & Cairney, 2007; Swets, 1988). In the present study, sensitivity and specificity analyses revealed acceptable measures for both males and females (sensitivity = 73.7%, males; specificity = 62.4%, males; sensitivity = 71.4%, females; specificity = 58.9%, females), and a moderate discriminate capacity of muscle power for identifying young adults with

below-average height-adjusted femoral neck aBMD (AUC = 0.709, males; AUC = 0.708, females). In the below-average height-adjusted total hip aBMD ROC and sensitivity/specificity analyses, greater between-sex differences were revealed in comparison to femoral neck aBMD ROC and sensitivity/specificity analyses, with low accuracy values for males (sensitivity = 66.7%; specificity = 59.7%; AUC = 0.668, 95%CI = 0.495-0.841) compared to moderate accuracy values for females (sensitivity = 78.6%; specificity = 69.9%; AUC = 0.776, 95%CI = 0.664-0.889) for the total hip. These findings are important because femoral neck aBMD is the DXA site recommended by the ISCD and the World Health Organization (WHO) for diagnosis of osteoporosis in pre-menopausal women and men under 50 years of age. Additionally, the World Health Organization's (WHO) Scientific Group on the Assessment of Osteoporosis at Primary Health Care Level (2004) stated that DXA aBMD data provides the most appropriate prediction of any fracture, while site-specific DXA aBMD data at the femoral neck provides the greatest gradient of risk for hip fracture prediction, which is the most common site of osteoporotic fracture, as well as the fracture site associated with the greatest morbidity and mortality (WHO, 2004).

Baptista et al. (in press) recently examined whether peak vertical jump height, quantified using a force platform, could be used to identify children (aged 7.9 to 9.7 years) with below average whole body-less head BMD. Their findings showed "reasonable" sensitivity and specificity for boys and girls (sensitivity = 63.6%, boys, specificity = 69.2%, boys; sensitivity = 75.0%, girls, specificity = 77.0%, girls), and moderate discriminate ability in identifying boys and girls with below-average BMD (AUC = 0.816, boys; AUC = 0.849, girls). Although all were considered to have

moderate accuracy and discriminate ability, the sex-specific AUC values presented by Baptista et al. (in press) are higher than the sex-specific AUC values using femoral neck aBMD presented in the current analysis. The smaller sample size (n = 114), and younger age range (7.9 to 9.7 years) in the Baptista et al. (in press) study could contribute to the between study differences, as children are within the age range where much growth and development occurs, and our sample of young adults is physically mature

To provide perspective concerning the ROC results, we compare our findings to a statement by the U.S. Preventative Services Task Force (2011) regarding osteoporosis-screening recommendations. This statement identified multiple instruments for predicting risk of low BMD in post-menopausal women as having AUC values between 0.48 and 0.89. These recommendations specifically target older adults in the general U.S. population, without a history of osteoporotic fracture, and the Task Force noted that few instruments have been validated for use in men (U.S. Preventative Services Task Force, 2011). Additionally, Nelson, Haney, Dana, Bougatsos, and Chou (2010) identified 14 risk-assessment instruments of low BMD with AUC values between 0.13 and 0.87, noting that simple instruments (i.e., those with fewer variables) and complex instruments performed similarly in terms of their predictive capacities. This is exciting, as the AUC values reported in the present analysis fall well within this AUC range for osteoporosis screening tests, although our results are specific to a sample of young adults and do not screen specifically for osteoporosis but rather below-average aBMD, which can be an indication of future risk. We also compare our findings to the FITNESSGRAM®, a youth physical fitness assessment tool used in most physical education programs. FITNESSGRAM® has used ROC curve analysis to evaluate fitness levels, assessed by

field tests, based on criterion-referenced standards of the level of fitness needed for good health (Welk, Laurson, Eisenmann, & Cureton, 2011). When developing standards for aerobic capacity, Welk, Laurson, Eisenmann, and Cureton (2011) found "good utility for detecting risk of metabolic syndrome," based on youth aerobic fitness values (AUC = 0.831, boys; AUC = 0.773, girls). A similar study by Laurson, Eisenmann, and Welk (2011) aiming to identify body fat percentage thresholds linked to metabolic syndrome in children found variable discriminate ability of body fat percentage *Z*-scores to identify those positive for the individual risk factors of metabolic syndrome (risk factor AUCs between 0.560-0.956, boys; risk factor AUCs between 0.518-0.919, girls). While FITNESSGRAM® fitness assessments target children and are administered in the physical education settings, the peak vertical jump test as a screen for bone strength would be best administered in health promotion settings, particularly those serving a large population of young adults. An example would be as part of physical activity or fitness courses offered at colleges and Universities, or even at worksite health and fitness centers that offer fitness testing for employees.

Limitations of this study include the homogeneity of the study sample in terms of race and region of residence, as 95% of participants in the current analysis were white, and all were recruited from eight Iowa hospitals. External validity is critical when developing a bone strength-screening tool (and all screening tools, for that matter), since one would expect broad population use. Being able to make generalizations to a general population is valuable and necessary when developing any screening tool, as its real-world applications are more far-reaching when appropriate and accurate for broad population use. Our study provides a starting point to generalize the value of a test of

lower body muscle power to detect bone strength, but further investigation surely is warranted, particularly in more racially and geographically diverse populations. Additionally, coordination, skill, and shoulder range of motion (or lack thereof) could have influenced the participant's ability to execute and achieve a true peak vertical jump height during the peak vertical jump test. In turn, this would impact the participant's estimated muscle power value, and subsequently affect the capacity of muscle power to predict bone strength. Finally, our study used a cross-sectional design and, therefore, we were not able to the determine cause-and-effect regarding the relationship between muscle power and bone density and geometry.

Future research should address the limitations identified for this analysis and continue to examine the capacity of a peak vertical jump field test as a screening tool for identifying adults with below-average bone strength. Further, a longitudinal study, from adolescence through young adulthood and into middle adulthood, could provide insight on how this screening tool's validity tracks throughout different stages of life. Such a study design also could provide information regarding the effect of changes in behaviors/lifestyle, that often accompany increasing age, on objective measures of muscle power, muscle size, and bone density and geometry measures, as well as the capacity of the peak vertical jump test to predict these outcomes. In conclusion, this investigation demonstrates good sensitivity and specificity for both sexes and a moderate discriminate ability of muscle power, quantified using peak vertical jump height and the Sayers et al. (1999) equation, for identifying young adults with below-average aBMD.

APPENDIX A: TABLES

Table A1. Participant Characteristics (136 males, 167 females).

	Males	Females	*p-value*
Age at scan (years)	19.7 ± 0.7	19.7 ± 0.6	0.96
Body weight (kg)	83.7 ± 19.0	68.9 ± 18.0	<0.001
Body height (cm)	180.2 ± 7.6	166.3 ± 6.7	<0.001
Total body lean mass (kg)	60.3 ± 10.5	41.8 ± 7.6	<0.001
Vertical jump height (cm)	57.1 ± 12.3	40.1 ± 7.3	<0.001
Muscle power (Watts)	5199 ± 1069	3501 ± 869	<0.001
Femoral neck aBMD (g/cm^2)	1.06 ± 0.17	0.93 ± 0.13	<0.001
Femoral neck aBMD *Z*-score[a]	0.34 ± 1.11	0.22 ± 1.04	0.33
Total hip aBMD (g/cm^2)	1.17 ± 0.16	1.03 ± 0.13	<0.001
Total hip aBMD *Z*-score[a]	0.46 ± 1.08	0.47 ± 1.00	0.90
FN Z (cm^3)	2.32 ± 0.56	1.52 ± 0.35	<0.001
CoA 38% tibia (mm^2)	364.70 ± 57.22	280.33 ± 42.90	<0.001
SSIp 38% tibia (mm^3)	2169.72 ± 473.67	1548.07 ± 340.22	<0.001
BSI 4% tibia (mg^2/mm^4)	147.51 ± 34.02	101.77 ± 23.91	<0.001
MCSA (cm^2)	84.09 ± 14.11	68.03 ± 10.77	<0.001
Healthy Eating Index	54.35[b]	60.47[b]	<0.001
High School Sport Participation			0.003
High Power Participants[c]	24.3%	43.6%	
Low Power Participants[c]	28.7%	20.2%	
No Participation[c]	47.1%	36.2%	

Data are mean ± SD; [a]Height-adjusted *Z*-score (Zemel et al., 2011); [b]Data for nonparametric variable is median; [c]Data are percentage in sport participation category. aBMD, areal bone mineral density; FN Z, femoral neck section modulus; CoA, cortical bone area; SSIp, density-weighted polar section modulus strength-strain index; BSI, bone strength index; MCSA, muscle cross-sectional area.

Table A2. Pearson bivariate and partial correlations for muscle power, total body lean mass, and muscle cross-sectional area with bone strength outcomes.

	Pearson Correlation Coefficients (*r*)								
	Muscle Power (Watts)			Total Body Lean Mass (kg)			Muscle Cross-Sectional Area (cm^2)		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
Femoral Neck aBMD (g/cm^2)	0.608	0.621	0.682	0.723	0.668	0.729	0.552	0.561	0.641
Total hip aBMD (g/cm^2)	0.584	0.650	0.699	0.710	0.659	0.741	0.554	0.576	0.660
FN Z (cm^3)	0.671	0.720	0.822	0.789	0.782	0.884	0.607	0.615	0.742
CoA 38% tibia (mm^2)	0.737	0.743	0.850	0.797	0.797	0.887	0.651	0.734	0.790
SSIp 38% tibia (mm^3)	0.710	0.744	0.832	0.778	0.824	0.876	0.650	0.715	0.781
BSI 4% tibia (mg^2/mm^4)	0.630	0.613	0.775	0.699	0.637	0.814	0.580	0.627	0.730
MCSA (cm^2)	0.632	0.698	0.775	0.806	0.781	0.856			
Total body lean mass (kg)	0.820	0.896	0.919						
	Partial correlation coefficients with the effect of height removed (*r*)								
	Muscle Power (Watts)			Total Body Lean Mass (kg)			Muscle Cross-Sectional Area (cm^2)		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
Femoral Neck aBMD (g/cm^2)	0.546	0.532	0.530	0.698	0.588	0.627	0.509	0.488	0.499
Total Hip aBMD (g/cm^2)	0.533	0.576	0.554	0.699	0.586	0.643	0.518	0.510	0.522
FN Z (cm^3)[b]	0.512	0.599	0.575	0.682	0.533	0.697	0.546	0.533	0.562
CoA 38% tibia (mm^2)	0.605	0.641	0.646	0.691	0.688	0.713	0.571	0.688	0.640
SSIp 38% tibia (mm^3)	0.537	0.634	0.586	0.640	0.676	0.664	0.558	0.676	0.615
BSI 4% tibia (mg^2/mm^4)	0.561	0.521	0.580	0.654	0.566	0.655	0.511	0.566	0.558

All associations significant: $p < 0.01$

aBMD, areal bone mineral density; FN Z, femoral neck section modulus; CoA, cortical bone area; SSIp, density-weighted polar section modulus strength-strain index; BSI, bone strength index; MCSA, muscle cross-sectional area.

Table A3. Binary logistic regression for below-average height-adjusted femoral neck aBMD with muscle power.

Sex	Measurement	Coefficient	SE	OR	95% CI for OR	*p-value*
Females	Muscle power (per 50 Watts)	-0.056	0.019	0.946	0.911-0.982	0.004
	Constant	1.682	1.192			0.158
Males	Muscle power (per 50 Watts)	-0.036	0.013	0.964	0.940-0.989	0.005
	Constant	1.743	1.242			0.161

Nagelkerke's Generalized R-square: for females = 0.12, for males = 0.11.
aBMD, areal bone mineral density; SE, standard error; OR, odds ratio; CI, confidence interval.

Table A4. Binary logistic regression for below-average height-adjusted total hip aBMD with muscle power.

Sex	Measurement	Coefficient	SE	OR	95% CI for OR	*p-value*
Females	Muscle power (per 50 Watts)	-0.085	0.028	0.919	0.871-0.970	0.002
	Constant	2.873	1.598			0.072
Males	Muscle power (per 50 Watts)	-0.030	0.015	0.970	0.942-0.999	0.046
	Constant	0.636	1.445			0.660

Nagelkerke's Generalized R-square: for females = 0.18, for males = 0.07
aBMD, areal bone mineral density; SE, standard error; OR, odds ratio; CI, confidence interval.

Table A5. Binary logistic regression for below-average height-adjusted femoral neck aBMD with total body lean mass.

Sex	Measurement	Coefficient	SE	OR	95% CI for OR	*p-value*
Females	Total Body Lean Mass (per kg)	-0.142	0.046	0.867	0.793-0.949	0.002
	Constant	3.654	1.730			0.035
Males	Total Body Lean Mass (per kg)	-0.138	0.037	0.871	0.810-0.936	<0.001
	Constant	5.900	1.968			0.003

Nagelkerke's Generalized R-square: for females = 0.14, for males = 0.25.
aBMD, areal bone mineral density; SE, standard error; OR, odds ratio; CI, confidence interval.

Table A6. Binary logistic regression for below-average height-adjusted femoral neck aBMD with MCSA.

Sex	Measurement	Coefficient	SE	OR	95% CI for OR	*p-value*
Females	MCSA (per cm^2)	-0.104	0.029	0.901	0.852-0.954	<0.001
	Constant	4.741	1.790			0.008
Males	MCSA (per cm^2)	-0.085	0.025	0.918	0.875-0.963	0.001
	Constant	4.930	1.865			0.008

Nagelkerke's Generalized R-square: for females = 0.17, for males = 0.20.
aBMD, areal bone mineral density; MCSA, muscle cross-sectional area; SE, standard error; OR, odds ratio; CI, confidence interval.

APPENDIX B: FIGURES

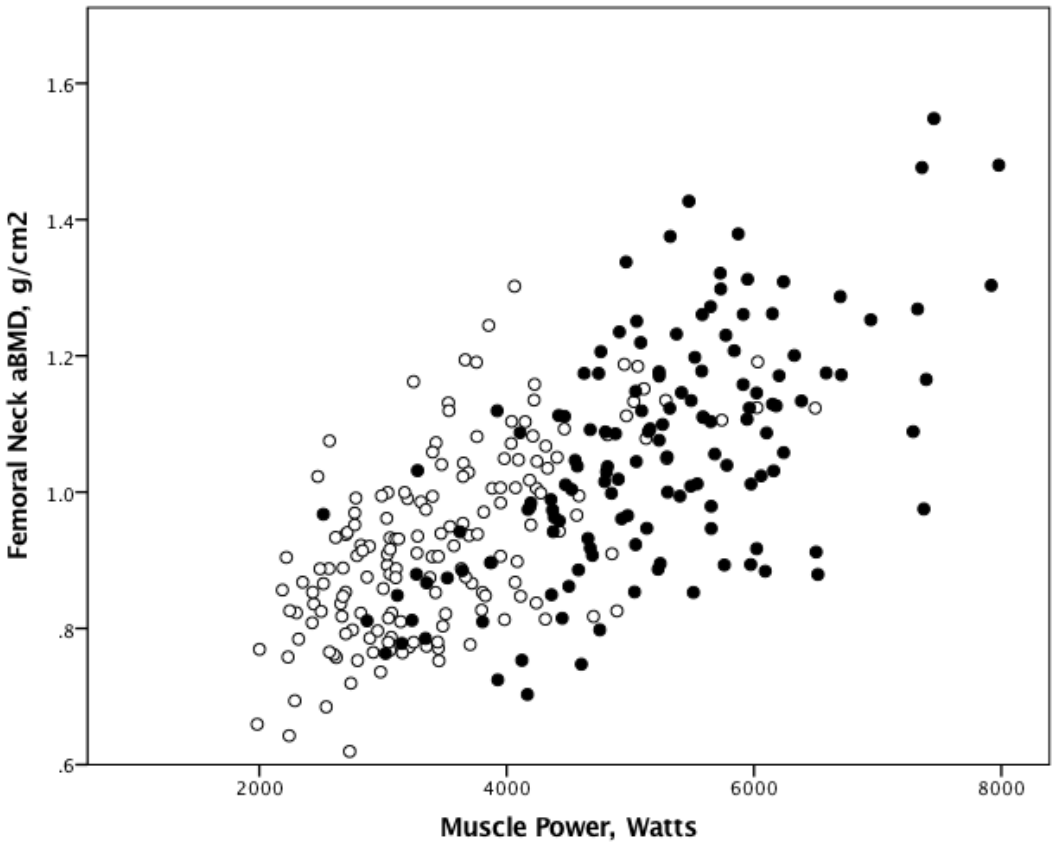

Figure B1. Pearson correlation scatter plot of muscle power against femoral neck aBMD. Males, black dots; Females, white dots. aBMD, areal bone mineral density.

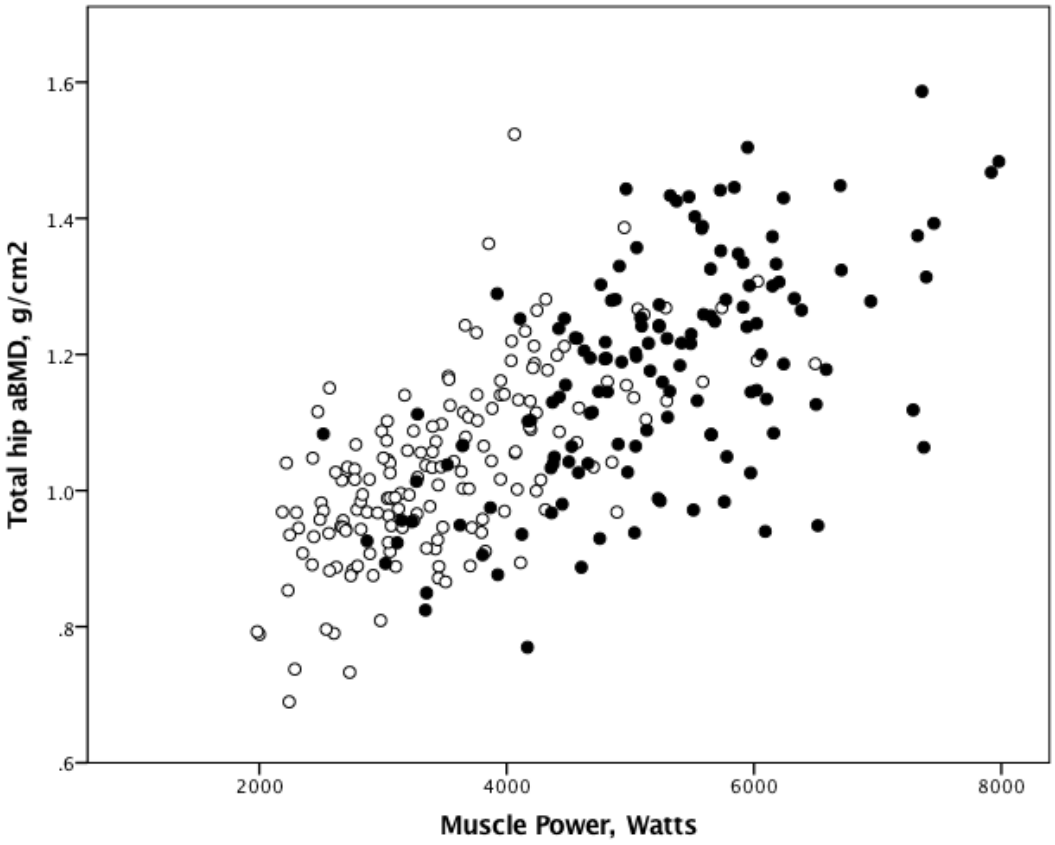

Figure B2. Pearson correlation scatter plot of muscle power against total hip aBMD. Males, black dots; Females, white dots. aBMD, areal bone mineral density.

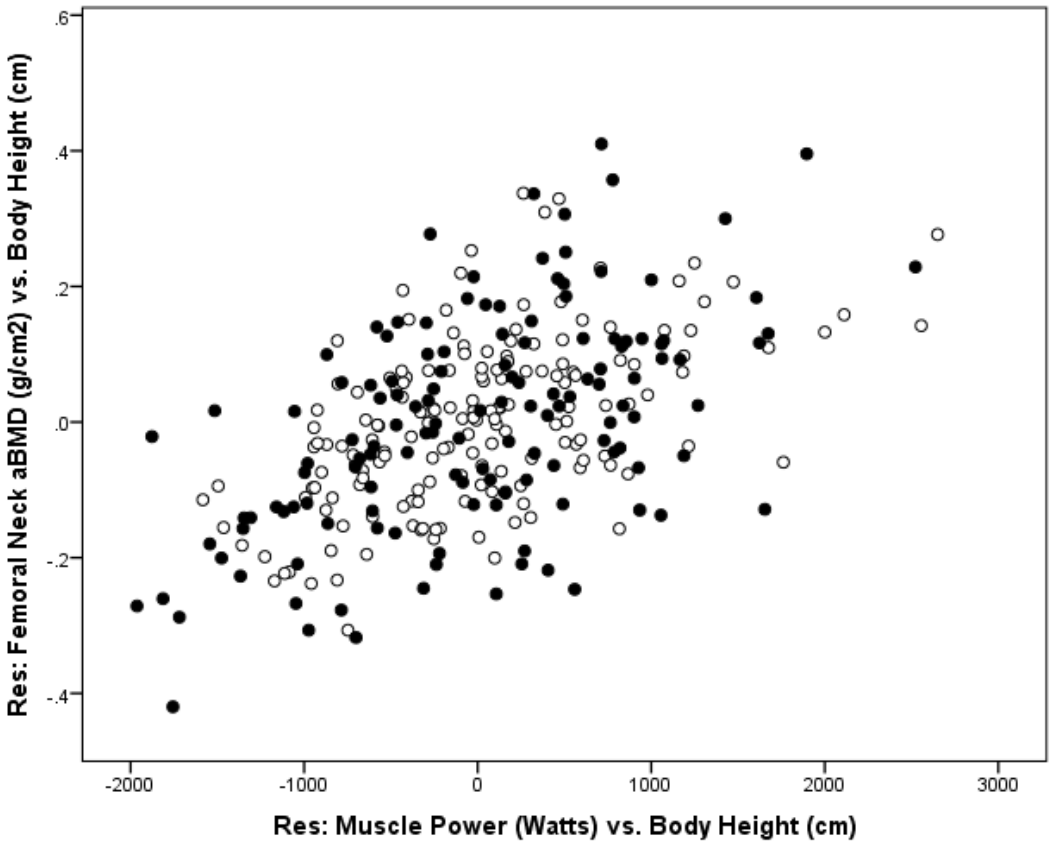

Figure B3. Partial correlation scatter plot of height-adjusted muscle power against height-adjusted femoral neck aBMD. Males, black dots; Females, white dots. aBMD, areal bone mineral density.

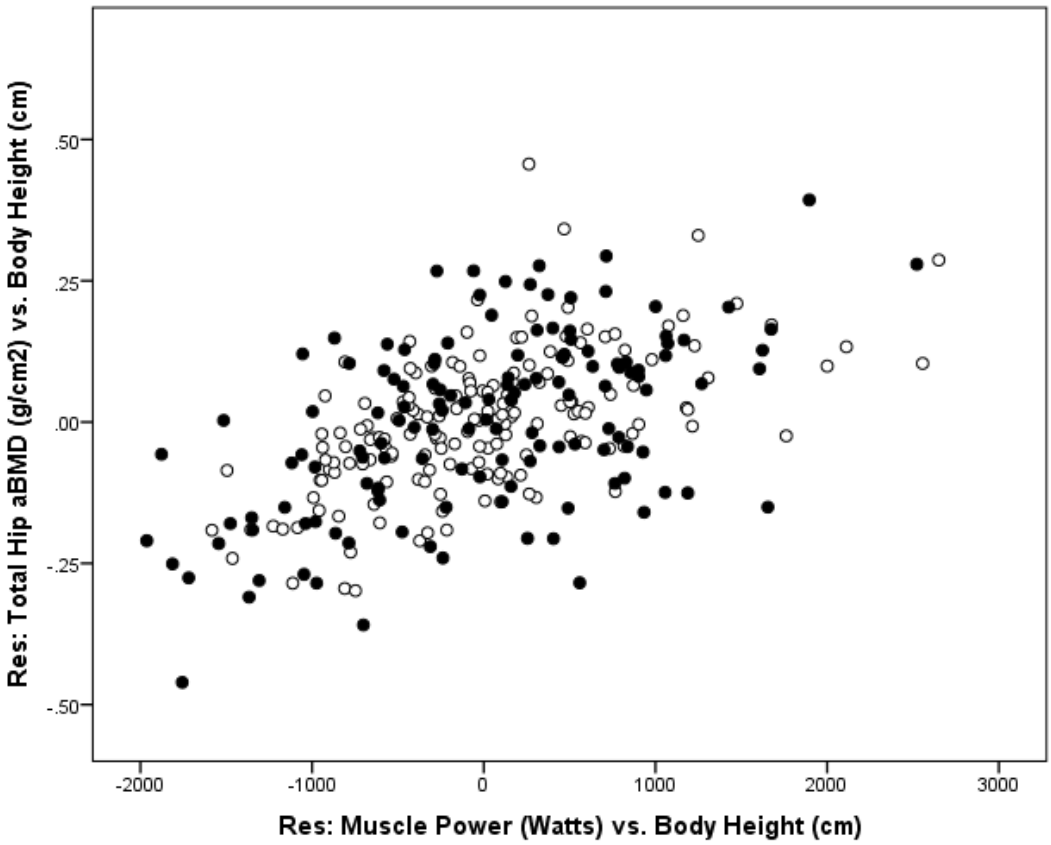

Figure B4. Partial correlation scatter plot of height-adjusted muscle power against height-adjusted total hip aBMD. Males, black dots; Females, white dots. aBMD, areal bone mineral density.

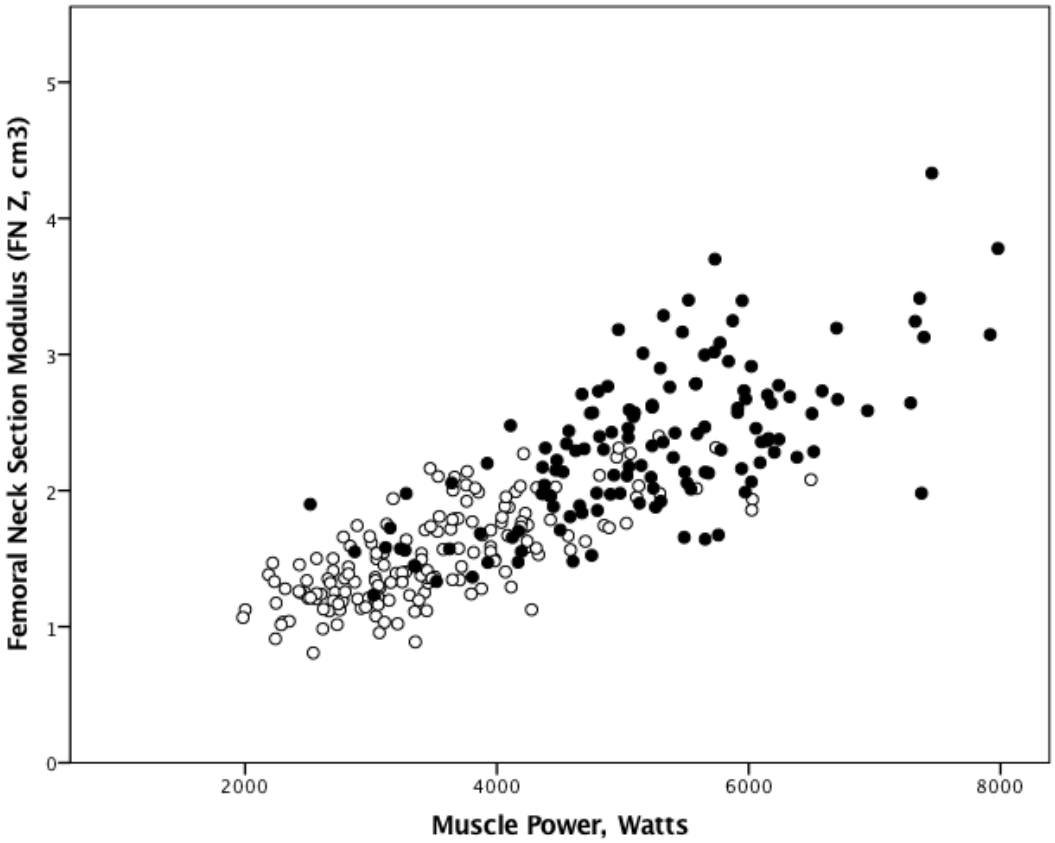

Figure B5. Pearson correlation scatter plot of muscle power against femoral neck section modulus. Males, black dots; Females, white dots.

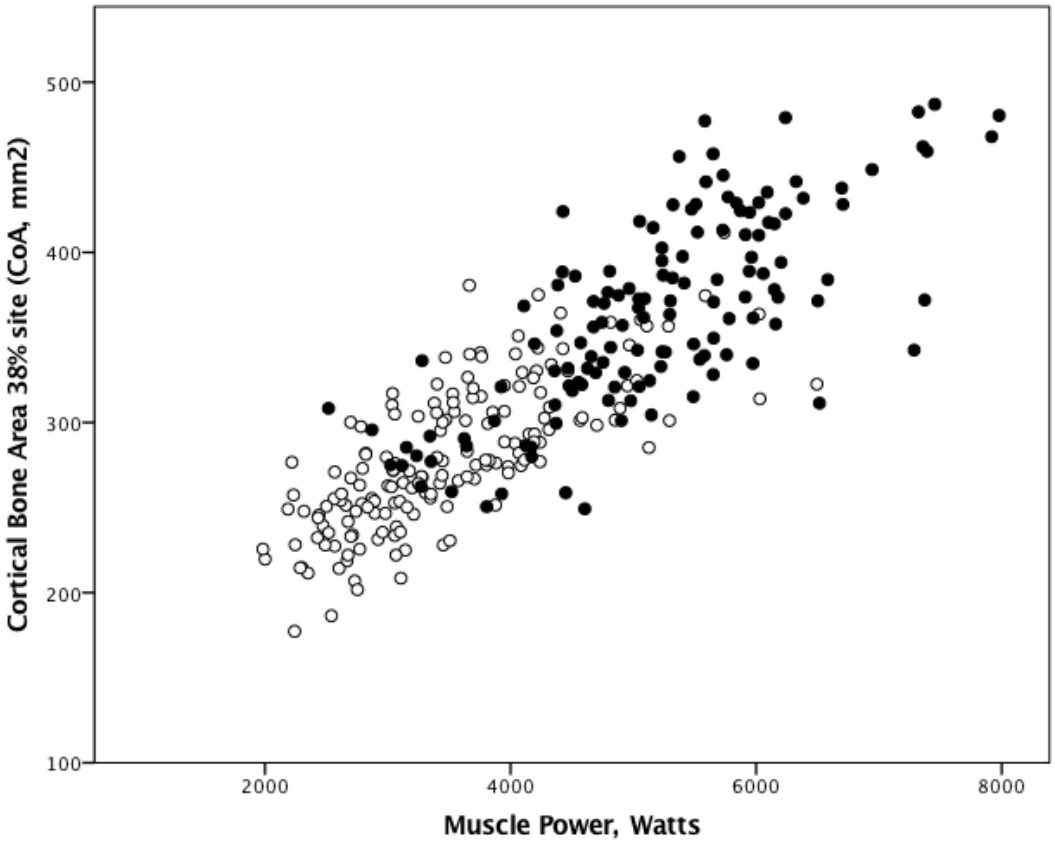

Figure B6. Pearson correlation scatter plot of muscle power against cortical bone area. Males, black dots; Females, white dots.

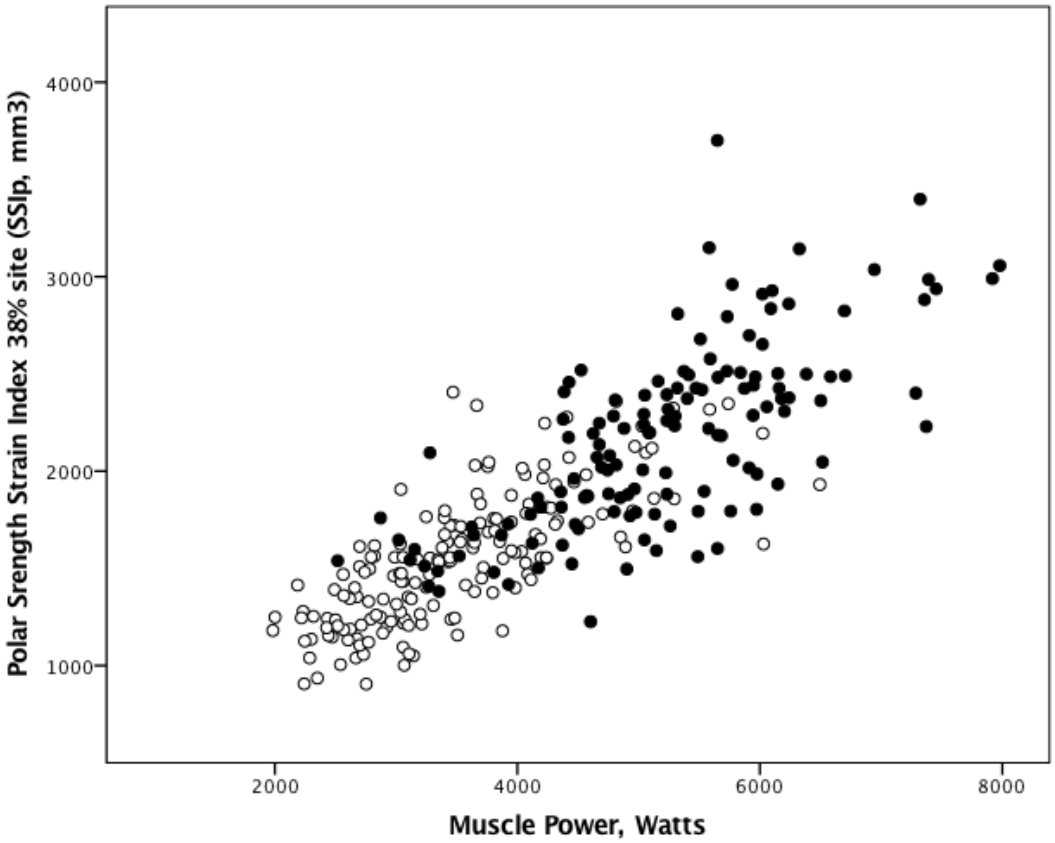

Figure B7. Pearson correlation scatter plot of muscle power against density-weighted polar section modulus strength-strain index. Males, black dots; Females, white dots. SSIp, density-weighted polar section modulus strength-strain index.

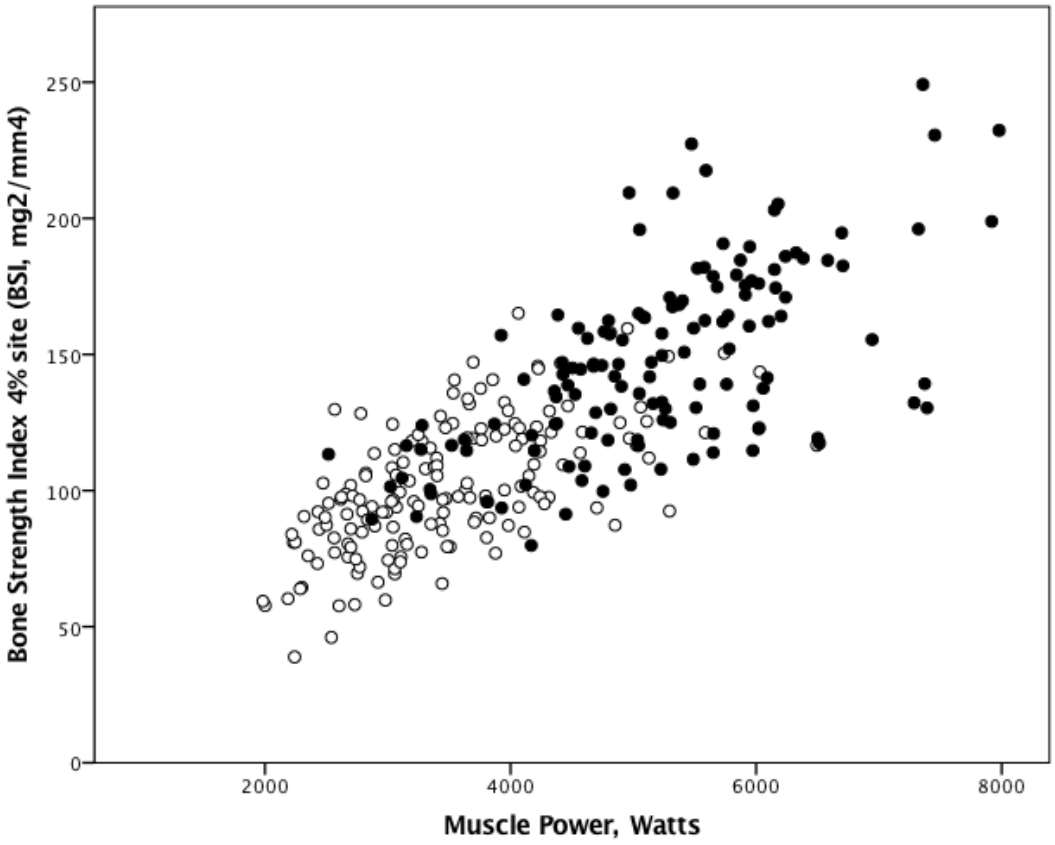

Figure B8. Pearson correlation scatter plot of muscle power against bone strength index. Males, black dots; Females, white dots.

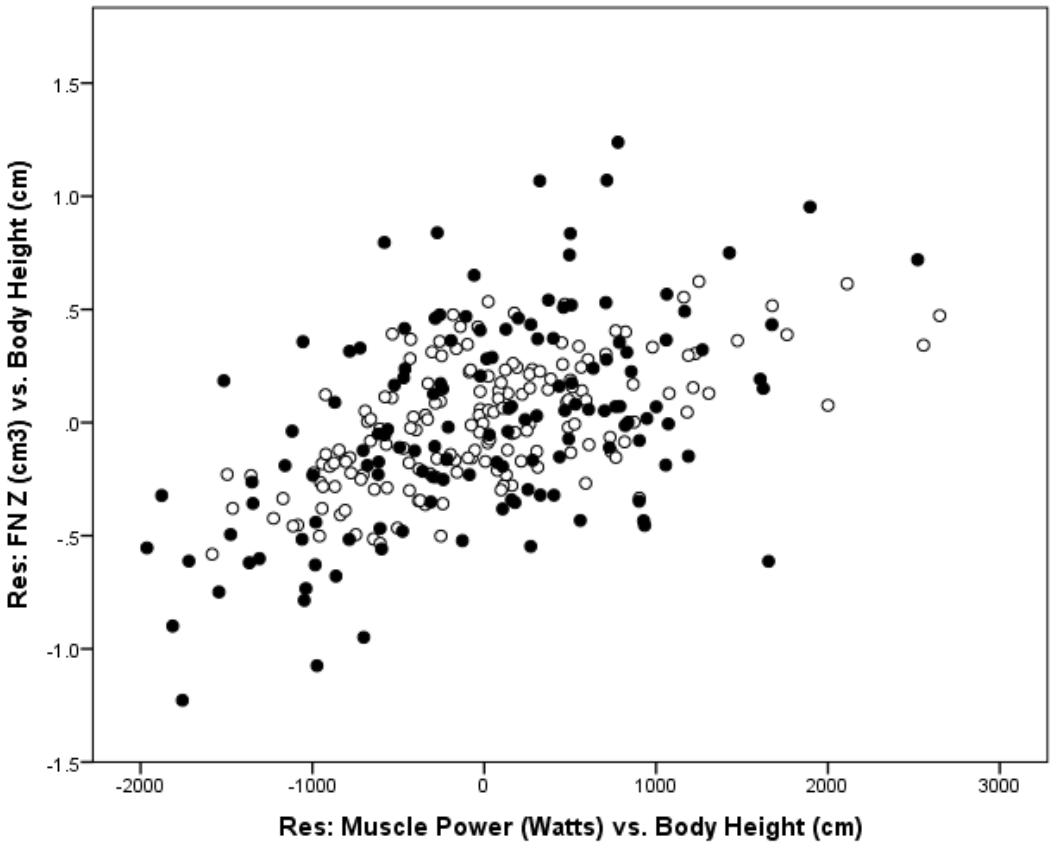

Figure B9. Partial correlation scatter plot of height-adjusted muscle power against height-adjusted femoral neck section modulus. Males, black dots; Females, white dots. FN Z, femoral neck section modulus.

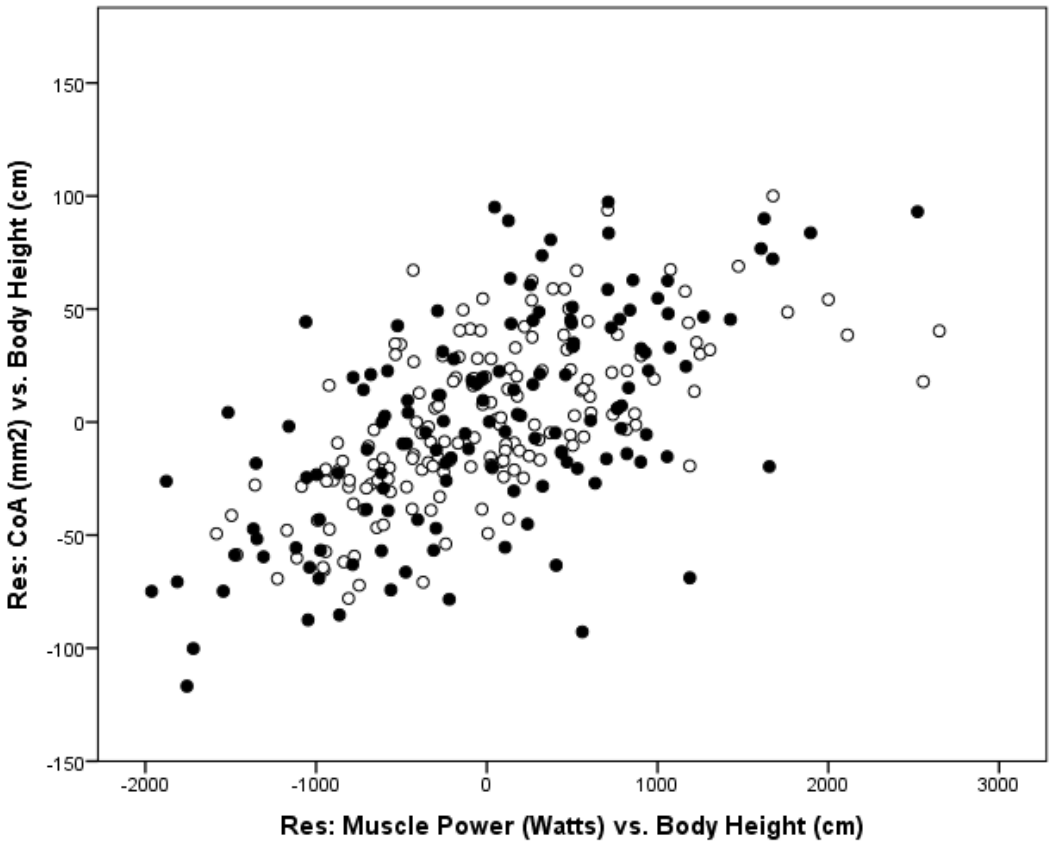

Figure B10. Partial correlation scatter plot of height-adjusted muscle power against height-adjusted cortical bone area. Males, black dots; Females, white dots. CoA, cortical bone area.

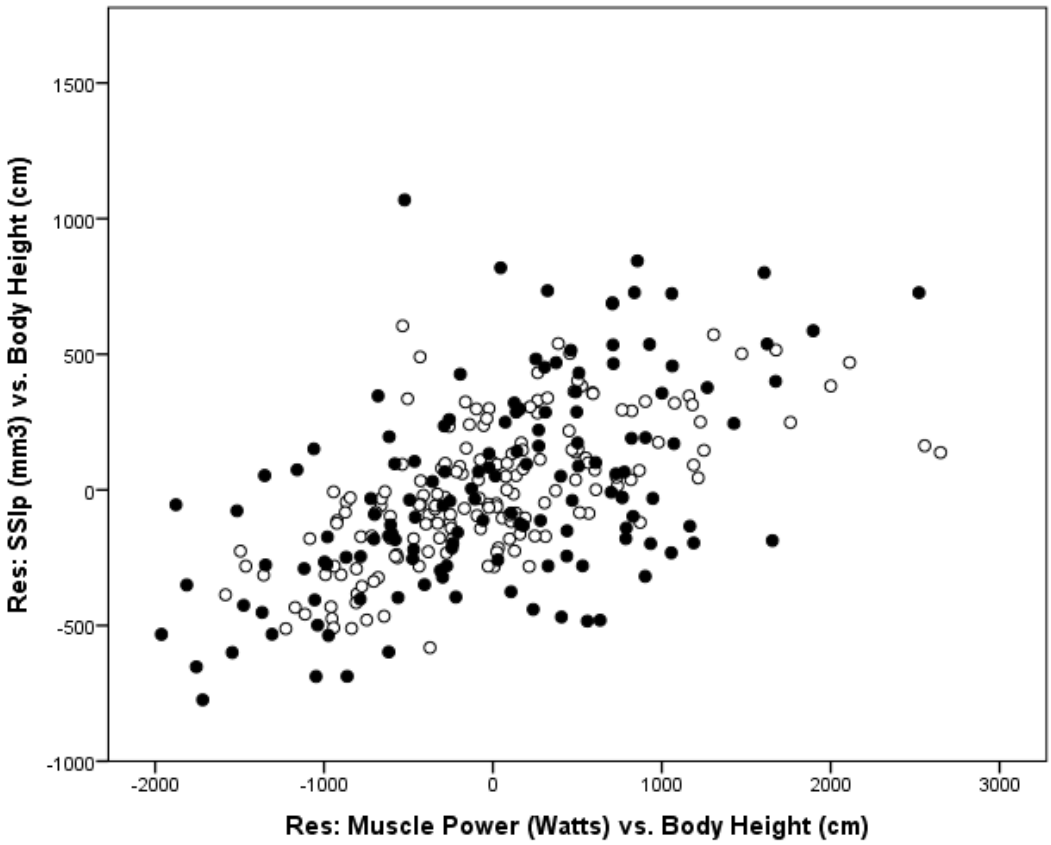

Figure B11. Partial correlation scatter plot of height-adjusted muscle power against height-adjusted density-weighted polar section modulus strength-strain index. Males, black dots; Females, white dots. SSIp, density-weighted polar section modulus strength-strain index.

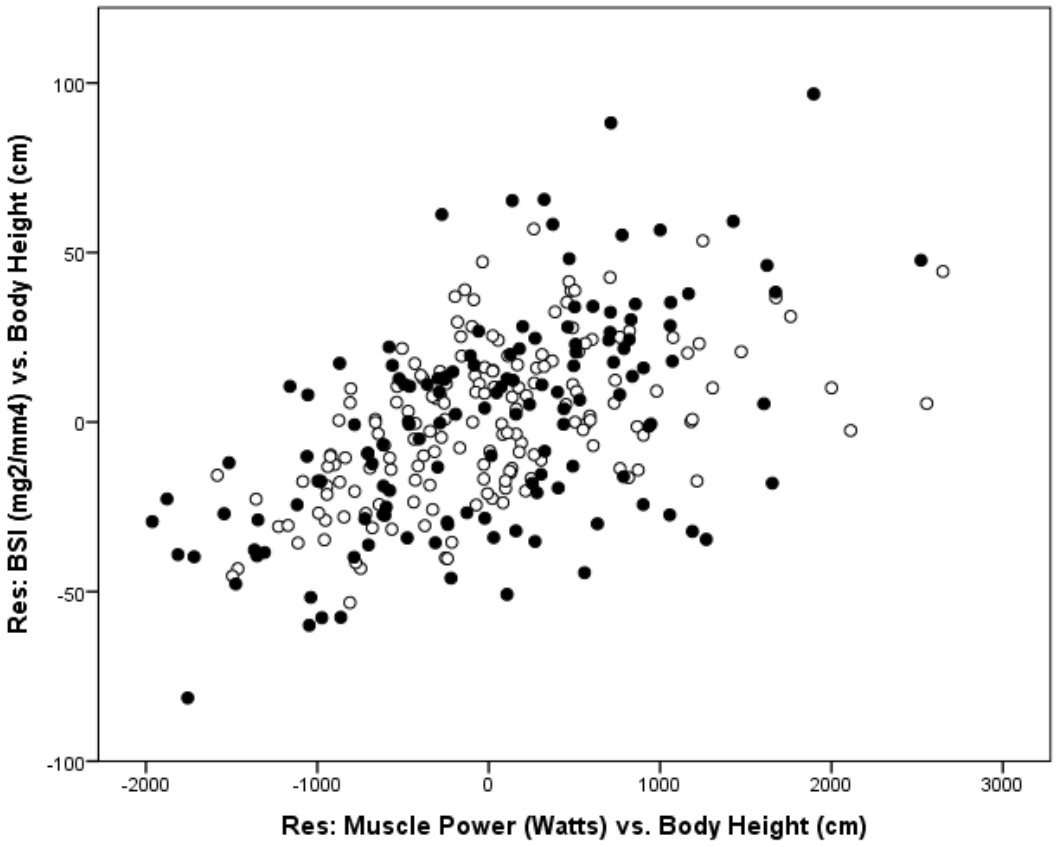

Figure B12. Partial correlation scatter plot of height-adjusted muscle power against height-adjusted bone strength index. Males, black dots; Females, white dots. BSI, bone strength index.

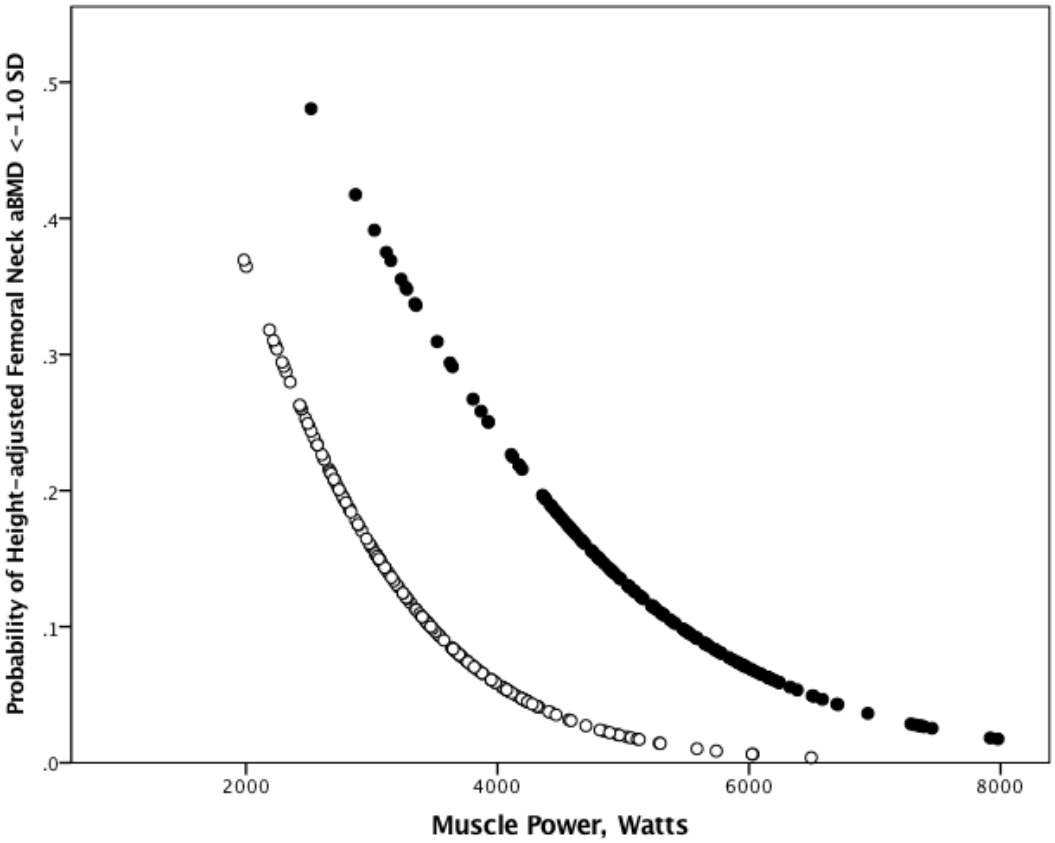

Figure B13. Predicted probability of below-average height-adjusted femoral neck aBMD (*Z*-score of ≤ -1.0 SD) according to muscle power. Males, black dots; Females, white dots. aBMD, areal bone mineral density; SD, standard deviation.

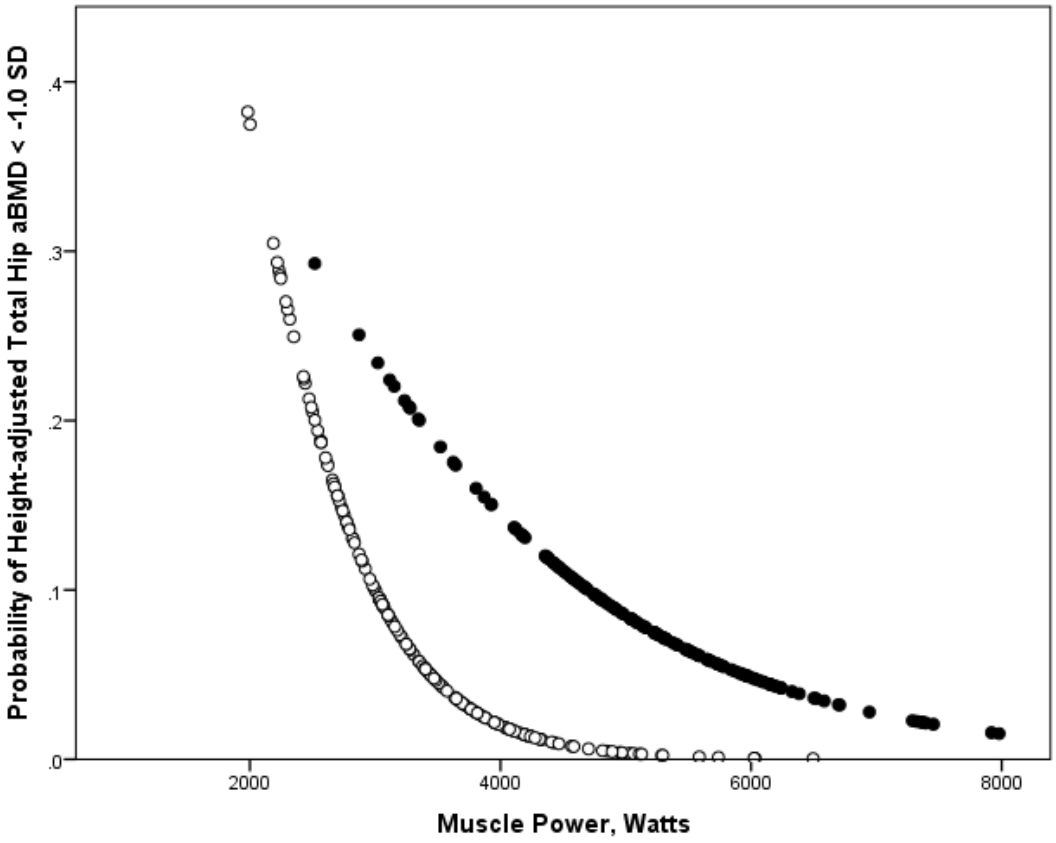

Figure B14. Predicted probability of below-average height-adjusted total hip aBMD (Z-score of ≤ -1.0 SD) according to muscle power. Males, black dots; Females, white dots. aBMD, areal bone mineral density; SD, standard deviation.

REFERENCES

Adams, J. E., Engelke, J., Zemel, B. S., & Ward, K. A. (2014). Quantitative computer tomography in children and adolescents: The 2013 ISCD pediatric official positions. *Journal of Clinical Densitometry, 17*(2), 258-274.

Allison, S. J., Poole, K. E. S., Treece, G. M., Gee, A. H., Tonkin, C., Rennie, W. J., Folland, J. P., Summers, G. D., & Brooke-Wavell, K. (2015). The influence of high-impact exercise on cortical and trabecular bone mineral content and 3D distribution across the proximal femur in older men: A randomized controlled unilateral intervention. *Journal of Bone and Mineral Research, 30*(9), 1709-1716. doi: 10.1002/jbmr.2499

Ammann, P., & Rizzoli, R. (2003). Bone strength and its determinants. *Osteoporosis International, 14*(Suppl 3), S13-S18. doi:10.1007/s00198-002-1345-4

Amonette, W. E., Brown, L. E., De Witt, J. K., Dupler, T. L., Tran, T. T., Tufano, J. J., & Spiering, B. A. (2012). Peak vertical jump power estimations in youths and young adults. *Journal of Strength and Conditioning Research, 26*(7), 1749-1755.

Ashe, M. C., Liu-Ambrose, T. Y. L., Cooper, D. M. L., Khan, K. M., & McKay, H. A. (2008). Muscle power is related to tibial bone strength in older women. *Osteoporosis International, 19*(12), 1725-1732. doi: 10.1007/s00198-008-0655-6

Baechle, T. R., & Earle, R. W. (2000). *Essentials of Strength Training and Conditioning: National Strength and Conditioning Association.* 3rd ed. Champaign (IL): Human Kinetics.

Baptista, F., Homens, P. M., Carita, A. I., Sardinha, L. B., & Janz, K. F. (in press). Peak vertical jump power as a marker of bone health in children. *International Journal of Sports Medicine*.

Beck, T. J., Ruff, C. B., Warden, K. E., Scott, W. W. Jr., Rao, G. U. (1990). Predicting femoral neck strength from bone mineral data: A structural approach. *Investigative Radiology, 25*(1), 6-18.

Blume, S. W., & Curtis, J. R. (2011). Medical costs of osteoporosis in the elderly Medicare population. *Osteoporosis International, 22*(6), 1835-1844. doi:10.1007/s00198-010-1419-7

Canavan, P. K., & Vescovi, J. D. (2004). Evaluation of power prediction equations: Peak vertical jumping power in women. *Medicine & Science in Sports & Exercise, 36*(9), 1589-1593. doi:10.1249/01.MSS.0000139802.96395

Crabtree, N. J., Arabi, A., Bachrach, L. K., Fewtrell, M., El-Hajj Fuleihan, G., Kecskemethy, H. H., Jaworski, M., & Gordon, C. M. (2014). Dual-energy x-ray absorptiometry interpretation and reporting in children and adolescents: The revised 2013 ISCD pediatric official positions. *Journal of Clinical Densitometry, 17*(2), 225-242.

Daly, R. M., Saxon, L., Turner, C. H., Robling, A. G., & Bass, S. L. (2004). The relationship between muscle size and bone geometry during growth in response to exercise. *Bone, 34,* 281-287. doi: 10.1016/j.bone.2003.11.009

Duncan, M. J., Hankey, J., & Nevill, A. M. (2013). Peak power estimation equations in 12- to 16-year-old children: Comparing linear with allometric models. *Pediatric exercise science, 25,* 385-393.

Ford, K. R., Myer, G. D., Smith, R. L., Byrnes, R. N., Dopirak, S. E., Hewett, T. E. (2005). Use of an overhead goal alters vertical jump performance and biomechanics. *Journal of Strength and Conditioning Research, 19*(2), 394-399.

Frost, H. M. (1987). Bone "mass" and the "mechanostat": A proposal. *The Anatomical Record, 219*, 1-9.

Frost, H. M. (2000). Muscle, bone, and the Utah paradigm: A 1999 overview. *Medicine & Science in Sports & Exercise, 32*(5), 911-917.

Frost, H. M. (2001). From Wolff's law to the Utah Paradigm: Insights about bone physiology and its clinical applications. *The Anatomical Record, 262*, 398-419.

Glass, N. A., Torner, J. C., Letuchy, E. M., Burns, T. L., Janz, K. F., Eichenberger Gilmore, J. M., Schlechte, J. A., & Levy, S. M. (in press). The relationship between greater pre-pubertal adiposity, subsequent age of maturation and bone strength during adolescence. *Journal of Bone and Mineral Research.*

Hardcastle, S. A., Gregson, C. L., Rittweger, J., Crabtree, N., Ward, K., & Tobias, J. H. (2014). Jump power and force have distinct associations with cortical bone parameters: Findings from a population enriched by individuals with high bone mass. *Journal of Clinical Endocrinology and Metabolism, 99*(1), 266-275. doi:10.1210/jc.2013-2837.

The International Society for Clinical Densitometry. (2014). *Patient information*. Middletown, CT: Carey, J. J., & Wartenbee, S. R. Retrieved from http://www.iscd.org/patient-information/patient-information/#WhatisOsteo

The International Society for Clinical Densitometry. (2015). *ISCD positions - Adult*. Middletown, CT. Retrieved from http://www.iscd.org/official-positions/2015-iscd-official-positions-adult/

Janz, K. F., Letuchy, E. M., Burns, T. L., Eichenberger Gilmore, J. M., Torner, J. C., & Levy, S. M. (2014). Objectively measured physical activity trajectories predict adolescent bone strength: Iowa bone development study. *British Journal of Sports Medicine, 48,* 1032-1036. doi:10.1136/bjsports-2014-093574

Janz, K. F., Letuchy, E. M., Burns, T. L., Francis, S. L., & Levy, S. M. (2015). Muscle power predicts adolescent bone strength: Iowa bone development study. *Medicine & Science in Sports & Exercise, 47*(10), 2201-2206. doi:10.1249/MSS.0000000000000648.

Jee, W. S. S. (2000). Principles in bone physiology. *Journal of Musculoskeletal Neuronal Interactions, 1,* 11-13.

Johnson, D. L., & Bahamonde, R. (1996). Power output estimate in university athletes. *Journal of Strength and Conditioning Research, 10*(3), 161-166.

Lara-Sánchez, A. J., Zagalaz, M. L., Berdejo-del-Fresno, D., & Martínez-López, E. J. (2011). Jump peak power assessment through power prediction equations in different samples. *Journal of Strength and Conditioning Research, 25*(7), 1957-1962.

Laurson, K. R., Eisenmann, J. C., & Welk, G. J. (2011). Development of youth percent body fat standards using receiver operating characteristic curves. *American Journal of Preventive Medicine, 41*(4S2), S93-S99.

Leard, J. S., Cirillo, M. A., Katsnelson, E., Kimiatek, D. A., Miller, T. W., Trebincevic, K., & Garbalosa, J. C. (2007). Validity of two alternative systems for measuring vertical jump height. *Journal of Strength and Conditioning Research, 21*(4), 1296-1299.

Martin, R. B., & Burr, D. B. (1984). Non-invasive measurement of long bone cross-sectional moment of inertia by photon absorptiometry. *Journal of Biomechanics, 17,* 195-201.

Munukka, M., Waller, B., Multanen, J., Rantalainen, T., Häkkinen, A., Nieminen, M. T., Lammentausta, E., Kujala, U. M., Paloneva, J., Kautiainen, H., Kiviranta, I., & Heinonen, A. (2014). Relationship between lower limb neuromuscular performance and bone strength in postmenopausal women with mild knee osteoarthritis. *Journal of Musculoskeletal and Neuronal Interactions, 14*, 418-424.

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A., & Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine & Science in Sports & Exercise, 34*(4), 689-694.

The National Institutes of Health Osteoporosis and Related Bone Diseases National Resource Center (2015). *Osteoporosis: Peak bone mass in women.* (2015). Retrieved from http://www.niams.nih.gov/Health_Info/Bone/Osteoporosis/bone_mass.asp

Nelson, H. D., Haney, E. M., Dana, T., Bougatsos, C., & Chou, R. (2010). Screening for osteoporosis: An update for the U.S. Preventative Services Task Force. *Annals of Internal Medicine, 153*(2), 99-111.

Plowman, S. A., & Smith, D. L. (2003). Exercise physiology for health, fitness, and performance (2nd ed.). San Francisco, CA: Pearson Education, Inc. publishing as Benjamin Cummings.

Rantalainen, T., Nikander, R., Heinonen, A., Multanen, J., Häkkinen, A., Jämsä, T., Kiviranta, I., Linnamo, V., Komi, P. V., & Sievänen, H. (2010). Neuromuscular performance and body mass as indices of bone loading in premenopausal and postmenopausal women. *Bone, 46*, 964-969.

Rantalainen, T., Sievänen, H., Linnamo, V., Hoffrén, M., Ishikawa, M., Kyröläinen, H., Avela, J., Selänne, H., Komi, P. V., & Heinonen, A. (2009). Bone rigidity to neuromuscular performance ratio in young and elderly men. *Bone, 45,* 956-963.

Robling, A. G. (2009). Is bone's response to mechanical signals dominated by muscle forces? *Medicine & Science in Sports & Exercise, 41*(11), 2044-2049. doi:10.1249/MSS.0b013e3181a8c702

Sayers, S. P., Harackiewicz, D. V., Harman, E. A., Frykman, P. N., & Rosenstein, M. T. (1999). Cross validation of three jump power equations. *Medicine & Science in Sports & Exercise, 31*(4), 572-577.

Schoenau, E. (2005). From mechanostat theory to development of the "functional muscle-bone unit." *Journal of Musculoskeletal Neuronal Interactions, 5*(3), 232-238.

Schoenau, E., & Frost, H. M. (2002). The "Muscle-bone unit" in children and adolescents. *Calcified Tissue International, 70,* 405-407. doi:10.1007/s00223-001-0048-8

Schoenau, E., Neu, C. M., Beck, B., Manz, F., & Rauch, F. (2002). Bone mineral content per muscle cross-sectional area as an index of the functional muscle-bone unit. *Journal of Bone And Mineral Research, 17*(6), 1095-1101.

Streiner, D. L., & Cairney, J. (2007). What's under the ROC? An introduction to receiver operating characteristic curves. *Canadian Journal of Psychiatry, 52*(5), 121-128.

Sumnik, Z., Land, C., Coburger, S., Neu, C., Manz, F., Hrach, K, & Schoenau, E. (2006). The muscle-bone unit in adulthood: Influence of sex, height, age and gynecological history on the bone mineral content and muscle cross-sectional area. *Journal of Musculoskeletal and Neuronal Interactions, 6*(2), 195-200.

Swets, J. A. (1988). Measuring the accuracy of diagnostic systems. *Science, 240*(4857), 1285-1293.

Turner, C. H. (1998). Three rules for bone adaptation to mechanical stimuli. *Bone, 23*(5), 399-407.

Umemura, Y., Ishiko, T., Tsujimoto, H., Miura, H., Mokushi, N., & Suzuki, H. (1995). Effects of jump training on bone hypertrophy in young and old rats. *International Journal of Sports Medicine, 16*(6), 364-367. doi: 10.1055/s-2007-973021.

United States Department of Agriculture/Center for Nutrition Policy and Promotion (2015). *Healthy eating index.* Retrieved from http://www.cnpp.usda.gov/healthyeatingindex

U.S. Preventative Services Task Force. (2011). Screening for osteoporosis: U.S. Preventative Services Task Force recommendation statement. *Annals of Internal Medicine.*

Welk, G. J., Laurson, K. R., Eisenmann, J. C., & Cureton, K. J. (2011). Development of youth aerobic-capacity standards using receiver operating characteristic curves. *American Journal of Preventive Medicine, 41*(4S2), S111-S116.

World Health Organization. (2004). Proceedings from: *WHO scientific group on the assessment of osteoporosis at primary health care level: Summary meeting report.* Brussels, Belgium.

Wolff, J. (1986). *The law of bone remodelling / Julius Wolff; translated by P.G.J. Maquet and R. Furlong.* Berlin; New York: Springer-Verlag.

Wu, C.-H., Yang, K.-C., Chang, H.-H., Yen, J.-F., Tsai, K.-S., & Huang, K.-C. (2013). Sarcopenia is related to increased risk for low bone mineral density. *Journal of Clinical Densitometry, 16*(1), 98-103. doi: 10.1016/j.jocd.2012.07.101

Zemel, B., Bass, S., Binkley, T., Ducher, G., Macdonald, H., McKay, H., Moyer-Mileur, L., Shepherd, J., Specker, B., Ward, K., Hans, D. (2008). Peripheral quantitative computed tomography in children and adolescents: The 2007 ISCD pediatric official positions. *Journal of Clinical Densitometry, 11*(1), 59-74. doi:10.1016/j.jocd.2007.12.006

Zemel, B. S., Kalkwarf, H. J., Gilsanz, V., Lappe, J. M., Oberfield, S., Shepherd, J. A., Frederick, M. M., Huang, Z., Lu, M., Mahboubi, Soroosh, Hangartner, T., & Winer, K. K. (2011). Revised reference curves for bone mineral content and areal bone mineral density according to age and sex for black and non-black children: Results of the bone mineral density in childhood study. *Journal of Clinical Endocrinology and Metabolism, 96*(10), 3160-3169. doi:10.1210/jc/2011-1111.

Zweig, M. H., & Campbell, G. (1993). Receiver-operating characteristic (ROC) plots: A fundamental evaluation tool in clinical medicine. *Clinical Chemistry, 39*(4), 561-577.