THE PENNSYLVANIA STATE UNIVERSITY

SCHREYER HONORS COLLEGE

DEPARTMENT OF KINESIOLOGY

SITE-SPECIFIC EFFECTS OF TENNIS PLAYING ON MUSCLE SIZE AND BONE STRENGTH IN THE DOMINANT ARM OF FEMALE TENNIS PLAYERS

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Spring 2011

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Kinesiology
with honors in Kinesiology

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Abstract

Mechanical loading as experienced while playing tennis induces musculoskeletal adaptations in the dominant arm of tennis players. It is not clear which site in the forearm (radius and ulna) or upper arm (humerus), responds most to loading, and how muscle tissue influences the skeletal adaptations. The aims of this study were: 1) to characterize the site-specific musculoskeletal response to loading and 2) to investigate the relationship between muscle and bone tissues in the upper limbs. Ten female tennis players were recruited from the Penn State Women's Tennis Team (n=5) and from other clubs (n=5). Bone geometric parameters, volumetric bone mineral density as well as estimates of bone strength (SSI, BSI and J) were examined in both the dominant and nondominant arms of the players at several skeletal sites along the forearm (at 4%, 33%, 50%, and 66% of bone length) and upper arm (at 25% and 50% of bone length), using peripheral quantitative computed tomography (pQCT). All bone parameters were therefore obtained at: 4%, 33%, 50%, 66% radius, 4%, 33%, 50%, 66% ulna and 25%, 50% humerus. Muscle cross-sectional area (MCSA) was also determined by pQCT and lean mass of both upper limbs was measured using dual energy X-ray absorptiometry (DXA). The effect of repetitive loading was quantified by examining the relative side-to-side differences between the dominant and nondominant limbs (%Δ). Our findings indicate that the forearm responds more to loading than does the upper arm for MSCA (%Δ 14.8% and 7.7% at the forearm and upper arm, respectively), while the humerus is the bone of the upper limb that shows the greatest adaptation to loading regarding bone strength (%Δ in SSI: 27.7% at the 25% humerus, 13.6% at the 50% radius and 18.1% at the 50% ulna). However, when considering the radius and ulna together as both contributing to forearm bone strength, the side-to-side

differences in bone strength appeared greater in the forearm than the upper arm (i.e. humerus). Side-to-side differences in polar moment of inertia (J), an index of bone's resistance to torsion, ranged from 35 to 37% in the upper arm and 44 to 49% in the forearm (radius + ulna). It was also found that there were differences with regards to bone and muscle asymmetries between the radius, ulna, and humerus. The study indicated a significant relationship between MCSA and bone strength in the playing arm (66% radius $R=0.93$ $p=0.0005$, 50% ulna $R=0.76$ $p=0.01$, 50% humerus $R=0.85$ $p=0.002$) but not the nonplaying arm. This suggests that exercise-induced loading amplifies the relationship between muscle and bone along the dominant arm of tennis players.

In conclusion, repetitive loading seems to exert site-specific effects on bone and muscle tissues. Our findings confirm that loading induces musculoskeletal benefits, which supports the notion that regularly engaging in physical activity positively affects bone health. Further research in this field should examine multiple skeletal sites along the bones of interest in order to gain a true understanding of how these bones respond to exercise. Research in this area could also provide more information on injury prevention, more specifically on the etiology of stress fractures.

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ACKNOWLEDGEMENTS

I would like to take this opportunity to thank everyone who helped me with this project. Without the help of the following people I would have never through this process and I would have never finished this project.

To my thesis advisor, Dr. Gaele Ducher, I would have never made it this far without your constant guidance and support. You were always there to any all of my questions and have been a huge help throughout this entire process. The experience and knowledge that I have gained by working with you are so valuable and I will remember everything forever.

To my other thesis advisor, Dr. Mary Jane DeSouza, thank you for all your support through the work on my project. Thank you also for giving me the opportunity to work and learn in the Women's Health and Exercise Lab. I have learned so much by working in the lab and it will be an experience that I will never forget.

To all the graduate students, undergraduates, and staff that work in the Women's Health and Exercise Lab, I am so glad that I was able to meet and work with all of you. You have all made my experience a more enjoyable one and will always miss my days in Noll Lab. I learn so much everything single time that I walk into lab, and I thank all of you for that.

Finally, to all my friends and family, I would be nowhere without all of your love and support. The friendships that I have made here within my four years at Penn State will last me a lifetime. You are all so special to me, and I would have never made it through this experience without you. Lastly, to my family, I would not be the person that I am today without you. You have all given me to opportunity to excel and have always pushed me to be the best that I can be. I cannot imagine my life without all of you, and I will love you all forever

Chapter 1: Effects of Exercise on Bone Strength - Literature Review

1. Bone health

1.1 Elements of bone health

"Bone must be stiff and able to resist deformation, thereby making loading possible. Bone must also be flexible: it must be able to absorb energy by deforming, to shorten and widen when compressed, and to lengthen and narrow in tension without cracking. If bone is brittle (i.e., too stiff and unable to deform a little), the energy imposed during loading will be released by structural failure--- initially by the development of microcracks and then by complete fracture. Bone must also be light to facilitate movement. A unique feature of bone is that it can serve these contradictory needs of stiffness yet flexibility and lightness yet strength." (from Seeman and Delmas, New Engl J Med 2006).[1]

A key ingredient to living a healthy life is having a strong and healthy skeleton. Bone is the strongest tissue in our body. Bone tissue is able to resist bending, it weighs only one-third as much per unit of volume, and, as outlined by Seeman and Delmas, it is very adaptable towards the loads that it faces.[2]

Significant bone loss occurs with aging in both men and women, leading to skeletal fragility. Osteoporosis is the most common bone disease and is defined by the World Health Organization (WHO) as a "systemic skeletal disease characterized by low bone mass and microarchitectural deterioration of bone tissue, with a constant increase in bone fragility and susceptibility to fracture".[3] Osteoporosis is diagnosed with a bone mineral density (BMD) 2.5 standard deviations below the adult peak mean, as measured by dual-energy X-ray absorptiometry (DXA).[4] It is stated that osteoporosis affects an estimated 75 million people in

Europe, USA, and Japan.[5] Osteoporosis can be caused by disturbances in bone's normal physiology, as typically seen -although not exclusively- during aging.

1.2 Basics of bone physiology

The two processes, bone modeling and remodeling, are essential for the skeleton to mature from a miniaturized form when first created in the fetus.[6] During growth, through remodeling and modeling, adaptations to loading can be achieved. Previous studies on skeletal morphology in elite athletes supports this premise.[7]

1.2.1 Modeling

Bone modeling is a process that leads to changes in size and shape of bone.[8] This process is induced through mechanical forces and occurs predominantly in the growing skeleton.[8] During bone modeling, bone resorption (break down of bone) and bone formation (synthesis of new bone) occur at separate surfaces. These processes are not coupled but are responsible for bone growth from childhood to adulthood. Modeling improves bone strength not only by adding bone mineral mass, but also by expanding the periosteal and endocortical diameters of the bone.[4]

1.2.2 Remodeling

Bone remodeling is a temporally regulated process resulting in the coordinated resorption and formation of skeletal tissue.[8] The two bone cells that create this process are the osteoclasts and osteoblasts. Osteoclasts are bone-resorbing cells while osteoblasts are bone-forming cells. Certain signals attract osteoclasts to sites on the bone which form the bone remodeling units.[9] Osteoclasts complete the resorption of bone within the bone remodeling unit and this new resorbed surface attracts osteoblasts. The osteoblasts fill this area with new matrix and therefore

make new bone.[8] The process can be seen in Figure I.1 below. This process of bone turnover is influenced by a number of factors, which are described in the next two sections.

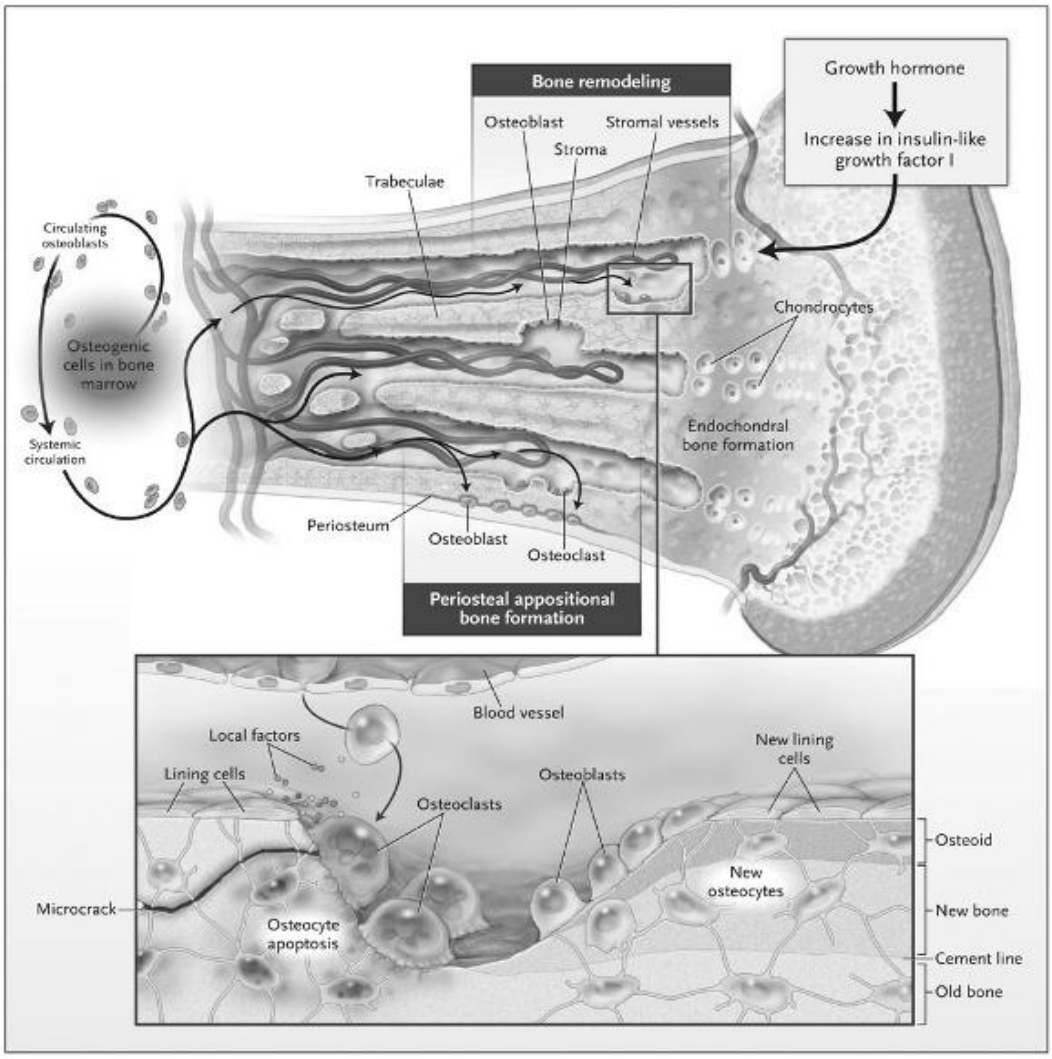

Figure I.1. Cellular processes of modeling and remodeling in a growing bone (from Canalis et al., New Engl J Med 2007).[8]

1.3 Intrinsic factors that affect bone health

Two intrinsic factors that affect bone health include genetic and hormonal influences.

1.3.1 Genetics

Genetic factors explain 60-80% of the variance in bone health.[10] Athletes, in particular, may be genetically disposed to having high BMD, or they may respond more positively to exercise intervention than nonathletes.[4] This could be explained by the gene-environment interaction where genetic factors regulate the response of bone to physical activity.[4]

1.3.2 Hormones

Sex hormones are key regulators of bone health. Estrogen, the major female sex hormone, controls production of cytokines, growth factors, and prostaglandins.[4] Cytokines and transforming growth factor-beta (TGF-beta) are stimulators of bone resorption and osteoclast formation whose levels are depressed by estrogen.[4] Therefore, estrogen limits bone resorption and helps maintain bone mass.[11] Studies on estrogen deficiency show that bone remodeling in the estrogen-deficient early postmenopausal woman is characterized by progressive osteoclastic hyperactivity.[12] This leads to excessive bone turnover and more bone loss. Estrogens are not only important regulator of the female skeleton, but also of the male skeleton as they are required for the process of periosteal bone expansion.[13] Likewise, androgens play an important role in both men and women as they stimulate periosteal bone formation.[13] Other hormones that affect bone include: insulin-like growth factor-1 (IGF- 1) and growth hormone (GH). Growth hormone affects the epiphyseal growth plate especially as a child passes through puberty. This process is mediated by IGF-1.[4] Both these hormones decrease as a person ages, which leads to a decrease in bone formation.[4]

1.4 Extrinsic factors that affect bone health

1.4.1 Nutrition and lifestyle factors other than physical activity

Nutritional factors are known to influence bone physiology and bone health. Research has mainly focused on the role of vitamin D, calcium, and protein. Protein intake has a direct effect on bone as the organic phase of the bone tissue is made of proteins, 90% of which are collagen type I. It also has an indirect effect on bone through its effect on muscles (facilitating hypertrophy), as muscle forces are considered the largest mechanical forces applied on the skeleton.[14] Research shows that supplementation with vitamin D_3 and calcium reduces the risk of hip fractures and other nonvertebral fractures among elderly women.[15] There are also lifestyle factors that affect bone health such as smoking and alcohol. Moderate alcohol intake is not thought to be harmful to bone. However, chronic alcohol abuse is detrimental to bone health, with one of the mechanisms being a direct toxic effect on bone forming cells.[16] Smoking increases the risk of fracture beyond its negative effect on bone mineral density.[17] Although these extrinsic factors associated with diet and lifestyle influence bone health, it is thought that mechanical factors associated with physical activity are the major regulator of bone mass and strength throughout life.[18]

1.4.2. Exercise and its effect on bone health

The effects that exercise has on bone health are of a larger magnitude during childhood and adolescence. Exercise during growth increases bone mass, which translates into an increase in bone width, changes in bone geometry, and to a lower extent changes in volumetric bone density. Building a strong skeleton during youth is thought to decrease fracture risk later in life by maximizing peak bone mass (Figure I.2).[19]

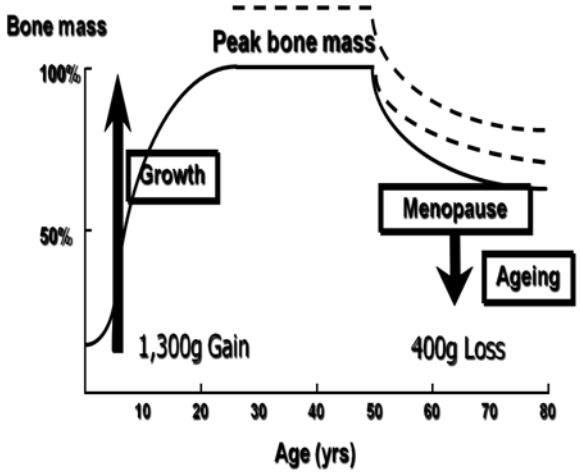

Figure I.2. Changes in bone mass throughout the life span and role of exercise.

Peak bone mass is achieved between 20 to 30 years of age.[20] Bone mass starts to decline soon after peak bone mass, at a slow rate first. Accelerated bone loss occurs around menopause (-2-5%/yr) whereas aging is associated with an overall bone loss of about 1% per year.[20] The dashed lines on Figure I.2 show how exercise can modulate the attainment of peak bone mass and the process of bone loss. Exercising during growth increases peak bone mass which allows bone mass to decline from a higher absolute level before bone loss begins. Exercising later in life may also attenuate aging-related bone loss. Overall regular physical activity may help to build a strong skeleton and to maintain bone strength throughout life, thereby preventing - or at least delaying - osteoporosis and osteoporosis-related fractures.

The model of the mechanostat suggests that an increase in muscle force during growth or in response to increased loading will affect bone mass, as well as the size and shape of bone.[21] It is thought that the muscle forces create the peak forces acting on bone.[22] The mechanostat theory is based on the process of mechanotransduction. Mechanotransduction is a physiological process that transforms the mechanical signal (loading) into a cellular signal (bone cells making new

bone). The overall objective of the mechanostat is to keep the mechanical strains experienced by the bone below a fracture threshold by adjusting the bone structure.[4]

Physiological set points are established which act as thresholds for activation and deactivation of modeling and remodeling.[22] During mechanotransduction, loading causes movements of interstitial fluid within the canaliculae in the bone tissue,[23] which apply forces onto the membrane of osteocytes. These forces transmit signals from the osteocytes to the osteoblasts and osteoclasts which work to form new bone and break down old bone.[4]

2. Bone Strength

One specific determinant of bone health is bone strength. Bones need to be able to support the loads of our daily activities. When bones are not strong, there is a greater risk for fractures. Cross-sectional bone size is a strong predictor of bone strength: the wider the bones, the stronger. More specifically, the resistance of a bone to bending or torsional forces is related to its diameter to the fourth power.[24] The main determinants of bone strength that are measurable in humans using peripheral quantitative computed tomography are shown in Figure I.3.

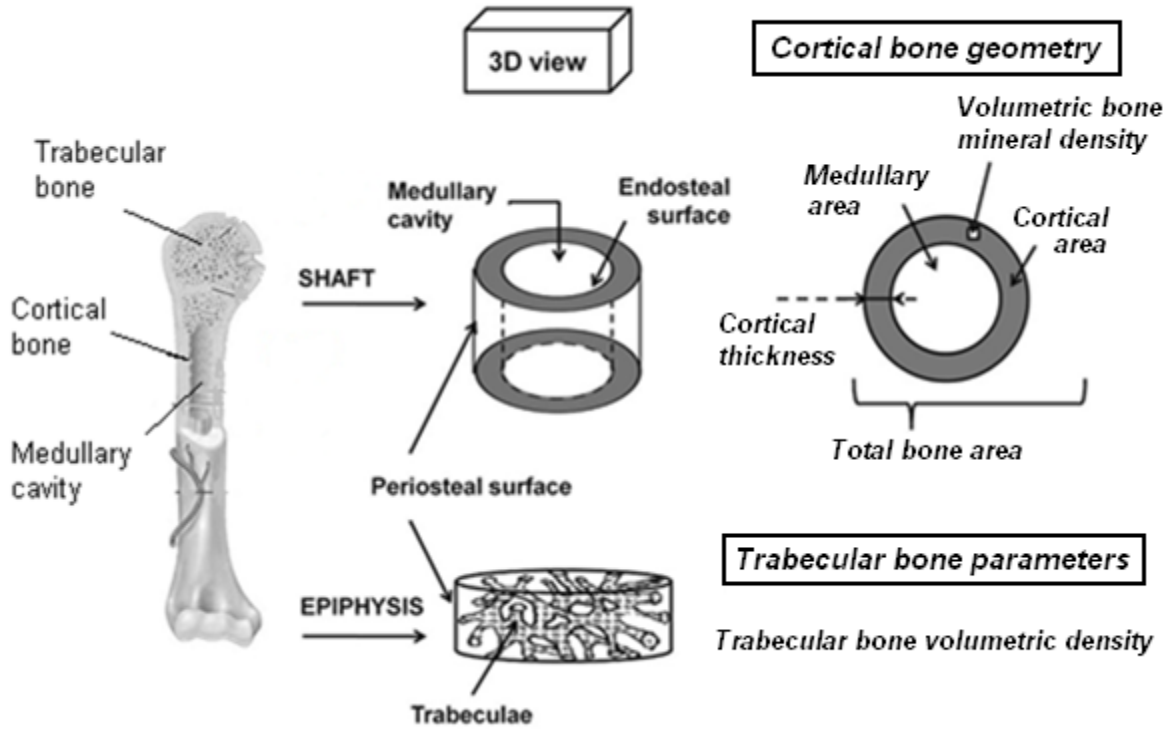

Figure I.3. Visual representation of the cortical and trabecular bone within the humerus, with specific parameters of cortical bone geometry and trabecular bone volumetric density that can be measured in vivo using peripheral quantitative computed tomography (pQCT).

Cortical bone, also known as compact bone, makes up the external part of bones and is a dense calcified tissue. Trabecular bone is found in the extremities of long bones but also in short, flat, and irregular bones. It is made up of a thin network of calcified plates and struts (trabeculae) and is porous. Bone strength is altered in one of two ways, by changing the material properties or by changing the structural properties of bone, through the local stresses which adjust the rates of bone resorption and formation (remodeling).[25] There are material and structural properties of bone which makes it resilient and capable of withstanding constant loading. Material properties include mass, density, stiffness, and strength. Structural properties of bone include size, shape, cortical thickness, cross-sectional area, and trabecular bone micro-architecture (Figure I.3).

Bone strength determines if an individual is susceptible to fracture. The estimation of bone strength requires examining bone geometry. Increases in certain geometric factors such as cortical area or total bone area are associated with changes in the shape and size of the bone. Even a small increase in cross-sectional bone size, without major changes in bone mass, can lead to a marked increase in bone strength (Figure I.4). The peripheral quantitative computed tomography (pQCT) allows researchers to examine bone parameters which provide significant information regarding bone strength. The dual-energy x-ray absorptiometry (DXA) only captures about 70% of bone strength.[26] Additional parameters obtained by pQCT explain about 75-85% of the variance in bone strength.[27, 28]

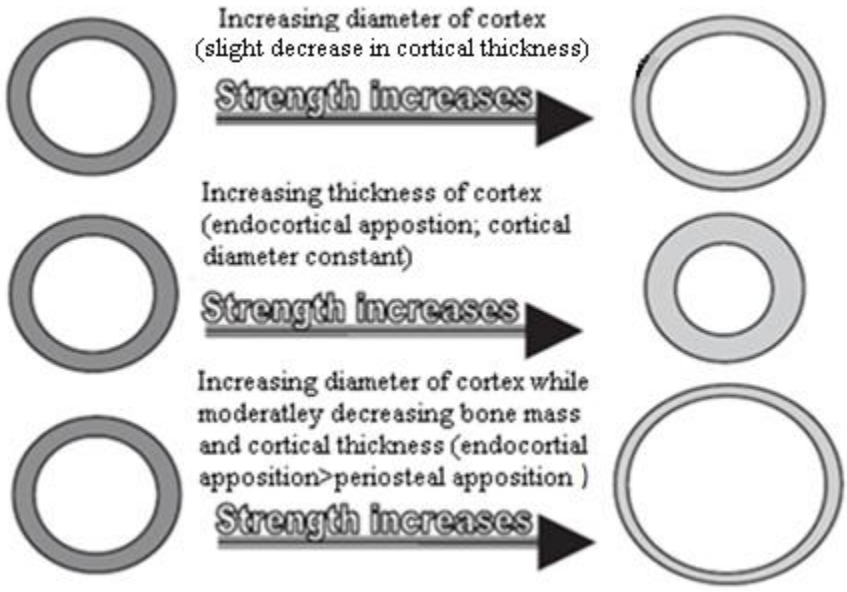

Figure I.4. Changes in bone strength due to adaptations in cortical bone diameter and thickness (modified from Davison et al., Seminars in Arthritis and Rheumatism 2006).[25]

2.1 Estimating Bone Strength

There are certain methods used to measure the determinants of bone strength. Although the dual-energy x-ray absorptiometry (DXA) provides important information such as bone mineral density, three-dimensional imaging techniques such as peripheral quantitative computed tomography (pQCT), and magnetic resonance imaging (MRI) allow investigating bone strength in more depth. Combining data from the DXA and the pQCT multiple parameters regarding bone strength allows investigating bone strength at different skeletal sites.

2.1.1 Dual-energy X-ray absorptiometry (DXA)

The DXA is the most commonly used technique to investigate bone health. The DXA considers the body in two compartments, bone and non-bone, and uses X-ray beams of two distinct energy levels to distinguish the relative composition of each compartment.[4] Results of DXA measurements, bone mineral content (BMC) and areal bone mineral density (BMD) vary at different skeletal sites. The DXA provides an evaluation of bone mass at these sites but it does not assess the architecture of the region or material properties of bone.

The DXA has proven to be efficient for diagnosing osteoporosis and assessing treatment effects.[26] In 2005, the Centers for Medicare and Medicaid Services recognized DXA testing for osteoporosis as one of its key preventive services.[29] Some advantages of using this technique includes its low dose of radiation, the data it provides regarding bone mineral, its large availability and its accessibility with patients.

2.1.2 Peripheral quantitative computed tomography (pQCT)

The pQCT is a small CT machine that measures bone mineral content, total bone area, cortical bone area, volumetric bone mineral density (vBMD) in the trabecular and cortical bone as well as muscle cross-sectional area in a 2 mm thick cross section of the upper or lower limb.

The images obtained from the scan allow discrimination between the trabecular and cortical components of bone, and give precise information on the actual cross-sectional geometry of the bone.[30] The importance of examining bone geometry was emphasized by recent findings which suggest that the effect of mechanical loading on bone can be accentuated during growth, where these effects lead to an increase peak bone mass but also changes in geometry.[31-34]

3. Effects of loading on bone strength

3.1 Models of unilateral loading

The unilateral loading model is often used in research in order to detect how exercise affects bone strength. Racquet sports, in particular, rely on the use of one arm (dominant side) while the other arm (nondominant side) is not exposed to an equal amount of loading. In this model, the nondominant side acts as a control since bones and muscles are exposed to loading due to everyday living, but not to exercise.[35] Comparing the side-to-side differences through this model allows for controlling the influence of confounding variables such as age, gender, height, weight, genetics, and nutrition on bone, because these variables have similar influence on both arms.[36] Unilateral models of loading have been developed in animal research, but equivalents also exist in human studies (unilateral sports).

3.1.1 Animal studies used to test loading effects

A majority of animal studies studying bone health and using unilateral loading were completed in rats. A study conducted on the ulna of rats found that areal BMD (aBMD) and BMC increased by 5.4% and 6.9% respectively, when the ulna was loaded three times per week for 16 weeks.[37] This study also found a 64% increase in the amount of force the bone could

support before failing and a 94% increase in energy to failure.[37] These values suggest that even with minor changes in bone geometry, there could be significant increases in bone strength.

Other animal studies have shown that static loading does not initiate osteogenesis as effectively as dynamic loading. It has been found that the mechanical load needed to start osteogenesis decreases as the loading frequency increases.[37] For instance, when continual loading was applied to the rat ulna at 1, 5, and 10 cycles per second, the greatest mechanical load needed to start osteogenesis decreased from 1820 μstrain at 1 Hz to 650 μstrain at 10 Hz.[38] This shows how increasing the frequency of loading can initiate osteogenesis. These findings from animal studies have helped design exercise guidelines for bone health in humans.

3.1.2 The unilateral model of tennis playing

Tennis has been consistently used as a model to test the effects of loading on muscle and bone tissues. The playing arm of tennis players is subjected to mechanical strains due to the racket vibrations, torsional forces, and muscle contractions that occur while playing. Table I.1 outlines the main findings of several studies that investigated the effects of tennis playing on bone health. Side-to-side differences were reported at the sites that were tested.

Table I.1. Side-to-side differences in bone and muscle parameters reported in studies that use the unilateral model of tennis playing.

Study	Subjects	Age [Starting age of playing]	Method	Sites	Side-to-side differences*				
[39]	105 female players 50 healthy female controls	27.7 ±11.4 (16 ± 9 yrs) 27.2 ±9.2 yrs	DXA Grip strength testing	 Proximal humerus Mid humerus Radial shaft Distal radius	BMC +15.5% +16.2% + 8.5% + 12.5%	Grip Strength +24.2%			
[30]	12 male tennis players 12 controls	29.8±4.8 yrs (9.8±3.0 yrs) 29.8±5.2	pQCT	Humerus 80 % 50 % 20 % Radius 4% 30%	BMC +21.7% +24.6% +27.3% +14.6% +14.2%	ToA +15.8% +17.4% +21.3% +19.4% +17.8%	CoA +11.7% +26.3% +31.9% +11.5% +14.8%	BSI +22.5% +33.7% +36.9% +22.6% +22.1%	Imax +27.1% +39.0% +67.0% NR +34.6%
[40]	47 female tennis players: Prepubertal (n=17) Peripubertal (n=11) Postpubertal (n=19)	 10.4±0.3 (5.7±0.4) 12.2±0.3 (6.5±0.6) 14.5±0.4 (7.1±0.4)	MRI DXA	Humerus 30% 50% 30% 50% 30% 50%	BMC +11-14%	CoA +11.2% +7.7% +16.5% +11.9% +14.5% +12.1%	PsPm +6.7% +6.3% +8.4% +8.9% +7.5% +7.5%	J +14.6% +11.3% +19.2% +16.9% +23.3% +17.0%	
[41]	92 tennis players	46.4± 4.8 (35.7±2.9)	pQCT	Radius 50% 4%	BMC -4.1% +4.9%	SSI -6.4% N/A			
[42]	10 women 6 men	20.1±0.6 (11.6±0.9) 20.2±0.7 (12.8±1.5)	pQCT	Radius 4% 20%	BMC +13.8% +13.3%	SSI N/A +19.1%		CoA N/A +13.5%	

[43]	9 male tennis players 17 nonactive controls	26.2 ± 5.6 24.2 ± 2.8	DXA	Forearm	BMC +21.8%	
[44]	43 male tennis players Prepubertal (n=9) Peripubertal (n= 26) Postpubertal (n=8)	 11.3 ± 0.3 (7.0 ±0.4) 13.9 ± 0.2 (7.1 ±0.4) 17.1± 0.4 (7.3 ±0.8)	MRI DXA	Humerus 50% 30 % 50% 30% 50% 30%	BMC +17.1% +27.5% +18.1%	CoA +12.5% +21.5% +20.1% +32.7% +18.3% +22.5%
[45]	10 men tennis players 10 women tennis players	25.6±5.5 (9.1±3.6) 20.7±1.9 (7.8±2.2)	MRI DXA Grip strength testing	Radius 4%	BMC +16.7% +10.3%	Grip Strength +14.1% +12.5%
[46]	64 female racquet sport players *Young Starters (n=36)* 1993 *Old Starters (n=28)* 1993	 21.6± 7.6 (10.5±2.2) 39.4±10.5 (26.4±8.0)	DXA Grip strength	 Proximal humerus Humeral shaft Distal Radius Proximal humerus Humeral shaft Distal radius	BMC +19.8% +21.3% +15.1% +11.0 % +8.6 % +10.2 %	Grip Strength +22.7% +25.8%

* Side-to-side differences = (Playing arm – Nonplaying arm) / Non playing arm * 100

BMC: bone mineral content; ToA: total area; CoA: cortical area; BSI: basic-strength index; Imax: maximum moment of inertia; SSI: stress-strain index; PsPm: periosteal perimeter; J: polar moment of inertia.

N/A: not applicable; NR: not reported

The asymmetry in bone mineral content (BMC) for adult tennis players ranged from 9% to 27% at the humerus and -4% to 15% at the radius. The asymmetry in cross-sectional bone size (i.e. total area, ToA) ranged from 16% to 21% at the humerus and 18% to 19% at the radius. In contrast, cortical density (CoD) tended to be lower in the dominant arm (asymmetry ranges from -2%- -0.2% at the humerus and -0.2%-0.2% at the radius). The skeletal adaptations translate into improvements in bone strength. Several estimates of bone strength have been used in previous studies. The asymmetry in estimated bone strength ranges from 11% to 67% at the humerus and 6% to 23% at the radius. The ulna has not been investigated in tennis players but it was reported to be the least responding skeletal site to squash-induced loading when compared with the humerus and radius.[47] Previous studies in tennis players who started training during youth showed a 6-10% asymmetry in muscle area at the forearm.[45, 46] Grip strength was 13%-26% greater on the dominant side.[45, 46]

3.2 Effects of repetitive loading on bone strength in humans

Repetitive loading through tennis playing or other forms of physical activity, positively affects bone strength in humans. A study on collegiate gymnasts found an increase in hip and spine BMD during the season and a decrease in BMD during the off-season.[48] The forces that a bone experiences from repetitive loading all impact the processes of modeling and remodeling which leads to a change in bone architecture. However, in contrast to animal studies, little is known about the site-specific response to loading in humans.

3.2.1 Site-specificity of the response to loading

It is proven that loading affects bone but there is little evidence on the site-specific effects of loading on bone geometry and volumetric BMD. Therefore it is important to study the

geometry of bone in order to see which site responds the most to loading. Research in animals has shown that the geometric adaptations of bones are site-specific, but evidence in humans, e.g. tennis players, is scarce.[30] Besides, experimental unilateral loading in animals applies external forces on the bone in a very controlled manner: the bone is immobilized and loading is applied along the same direction, controlling for magnitude, frequency and rate of loading. In contrast, physical activities in humans are likely to induce loads that vary in magnitude, frequency, direction and rate of loading. Therefore, it is unknown if the site-specific response to loading will be as visible in humans as it is in animals.

Bone cross-sectional area was found to be significantly larger in the playing than the nonplaying arm, but the proportion of cortical area and marrow cavity area varied according to bone site.[30] The between-site differences that were found could be attributed to different loading conditions at different skeletal sites.

3.2.2 Mechanisms underlying the osteogenic effect of exercise

Exercise induces different forces that stimulate bone remodeling. In humans, bone strains derive from three sources: ground reaction forces (during weight-bearing activities), joint reaction forces (mainly a function of body or body part moved and its acceleration in gravity) and muscles forces (also varying in proportion to the mass being moved).[49]

3.2.2.1 Muscle forces

Muscle forces are speculated to be the greatest forces placed on bone. Analysis of muscle pull and lever arm suggests that muscle forces acting on the skeleton are generally quite large, usually exceeding peak ground reaction impact forces.[49] However there is little research that

explains why muscle forces would exert the greatest load on bone. Confounding variables such as body size were not necessarily accounted for in previous reports. In order to show how muscle forces dominate the change in bone, it is necessary to show that a decline in muscle mass precedes a decline in bone strength when the muscles are not being used, and it is also important to show that muscle mass increases before bone mass does.[14] This purposed link between muscle and bone is often referred to as the 'functional muscle-bone unit', where changes in muscle mass and strength affect bone mass and strength in the same way.[35] Daly et al. studied 47 pre-, peri-, and postpubertal female tennis players and found that the playing arm had a greater muscle size and bone mass, bone size, and bending strength than the nonplaying arm (side-to-side differences).[35] The percent side-to-side differences in muscle area were also correlated with the side-to-side differences in the bone traits, but the asymmetry in muscle area only accounted for 12-16% of the variance in bone asymmetries.[35] This data supports a causal relationship between muscle and bone, but indicates that other factors are probably involved in exercise-induced skeletal adaptations. Therefore there is a gap in the literature when it comes to explaining how muscles affect bone strength.

3.2.2.2 Impact/Gravitational forces

Impact forces on bone can be anything ranging from kicking a soccer ball to the ball impact forces experienced during a tennis stroke. The ground reaction forces of walking would be considered gravitational forces since gravity pushes down a person allowing them to walk. It was thought that when the racquet hits the ball during a tennis serve, the impact would cause vibrations that would transfer from the racquet to the hand and initiate functional adaptation.[50] Therefore ball impact was thought to have a great impact on bone. However, a study conducted

by Taylor et al. found that ball impact caused a less pronounced increase of bone density than the maximal external should rotation during a tennis serve.[51] Kohrt el al. also found that there is no conclusive evidence from research about which of the muscle forces or gravitational forces play the primary role in controlling bone physiology.[52]

Chapter 2: Study Rationale, Objectives and Hypotheses

Bone health is an essential aspect of human physiology. One way to ensure proper bone health is to load the bones through exercise. Regular physical activity helps to build a strong skeleton that could maintain bone strength throughout life, thereby preventing - or at least delaying - osteoporosis and osteoporosis-related fractures. Playing tennis is one of several osteogenic physical activities that can help build a strong skeleton. Playing tennis is associated with muscle hypertrophy and increased bone strength in the playing (dominant) arm as opposed to the non-playing (nondominant) arm. In young players, this extra bone mineral mass is accompanied by a marked increase in bone size and minor increase in volumetric bone mineral density (vBMD), which is optimal to increase bone strength.[42, 53] Therefore, the model of tennis players (studying the dominant vs. nondominant arms) can be used to study the effects that loading has on bone.

Animal studies have shown that the exercise-induced skeletal benefits are site-specific, i.e. they are not homogeneous along the length of a bone. For example, experiments in rats showed that unilateral loading of the right forearm lead to 25%-increase in bone strength at the distal site but no increase at the proximal site.[54] Moreover, both the ulna and the radius contribute to forearm bone strength, yet only the radius is analyzed in pQCT protocols. It was recently showed that the gymnastics-induced skeletal benefits can be greatly underestimated when considering only the radius.[55] The ulna was more responsive to loading at the proximal forearm.

The site-specific effects of tennis playing on bone strength in the upper limb have not been studied using three-dimensional imaging techniques. Such investigations would provide a

better description of the true skeletal benefits associated with playing tennis. They might also help clarify the cause of overuse injuries such as stress fractures, which tend to occur at the distal humerus in tennis players.

A better understanding of how the skeleton responds to loading also requires the assessment of muscle mass or size. Although muscle forces are thought to be the largest forces applied to the skeleton, there are no reports on how muscle hypertrophy impacts bone strength in the forearm bones and humerus in tennis players. The present project will investigate the musculoskeletal response to repetitive loading by comparing muscle size and bone strength between the playing and nonplaying arms of tennis players using the pQCT imaging technology at different skeletal sites.

Primary Objective: To investigate the skeletal adaptations to repetitive loading in the upper arm (humerus) and forearm (radius and ulna), at different skeletal sites.

Secondary objectives:

1) To investigate the heterogeneity in muscle hypertrophy along the length of forearm and upper arm
2) To investigate the relationship between bone structure and surrounding muscles

Hypotheses:

1) The skeletal benefits at the forearm (radius + ulna) will be similar to, or greater than, the benefits observed in the humerus.
2) Muscle hypertrophy in the forearm will be similar to, or greater than muscle hypertrophy in the upper arm.
3) The skeletal benefits in the dominant arm of female tennis players will be greatest at locations where tennis-induced muscle hypertrophy is the largest.

Chapter 3: Materials and Methods

1. Design

The purpose of this cross-sectional study was to investigate the effects of repetitive loading on bone strength and muscle size in female tennis players. The dominant and nondominant arms of female tennis players were compared. Since the nondominant arm does not experience repetitive loading, it can serve as an internal matched control when investigating musculoskeletal health in the dominant arm. Confounding factors such as genetic, hormonal, nutritional, and lifestyle factors are thought to have the same impact on bone strength and muscle size in both arms; therefore differences between arms can be attributed to loading. The study consists of one visit lasting for 3 hours. Subjects were asked to fill out a questionnaire on their medical history and their training, and then underwent several scans at different sites of their skeleton using dual-energy x-ray absorptiometry (DXA) as well as a peripheral quantitative computed tomography (pQCT).

2. Subjects

Adult female tennis players were offered to participate in this study. Subjects were screened for eligibility using the following inclusion criteria: 1) aged between 18-35 years; 2) had been playing tennis at least twice a week for the past two years. Exclusion criteria included: 1) positive pregnancy test; 2) X-ray procedures using contrast material in the previous 3 days; 3) medical devices that interfere with scan accuracy; 4) wearing external metal objects that cannot be removed; 5) internal metal objects; 6) participants with prosthetics, or other surgical devices

within the body; 7) fracture in the upper limbs in the past 12 months ; 8) taking any chronic medications that affect bone density (e.g. corticosteroids); 9) known bone disorder or chronic disease that affects bone health (e.g. osteogenesis imperfecta, hyperparathyroidism, chronic kidney disease). Before the scans, all female participants were required to provide a urine sample that was tested through an HCG test, in order to test for pregnancy. Participants were members of the University's Women's Tennis Team (n=5), University students (n=3) and members of tennis clubs around the University (n=2). Informed consent was obtained from the participants. The project received approval from the University Institutional Review Board. A total of 10 participants were recruited.

On the day of the study, each participant was explained all the information contained in the informed consent. The participants were able to read the consent form and ask any questions on information that was not clear. Once the informed consent was signed a copy was kept for the investigator's records and a copy was given to the participant.

3. Anthropometry

Body weight was measured on a scale (SECA Model #770 1321134) while the subjects were without shoes and wearing light clothing. Height was measured using a stadiometer (SECA Model #216 1814009). Two measurements were taken and the average of the measurements was recorded. Hand dominance (relevant to tennis playing) and the backhand technique (one-handed vs. two-handed) were recorded. Forearm length was measured from the tip of the olecranon process to the distal end of the ulna styloid process, using a measuring tape. The subjects held their forearm vertical, with the elbow in 90 degrees flexion and measurements of forearm length

were taken twice with a tape. The average of the two measurements was calculated. Due to the difficulty to measure humeral length, we used forearm length as a proxy, as done previously.[56]

4. Grip Strength

Grip strength was measured using a hand-held dynamometer (Grip A, Takei Physical Fitness Test, Takei, Japan). The recommendations by the American Society of Hand Therapists for a standardized position were followed; shoulder adducted and in neutral rotated position, elbow in 90 degrees flexion, forearm semiproned and wrist in neutral resting position.[57] The participant first familiarized with the instrument, grasping the handle, obtaining a good grip, squeezing lightly and watching the corresponding increase in grip strength on the dial. Then the subject was asked to squeeze as hard as possible during 5 sec on a verbal go signal. Three trials for each hand were conducted, alternating hands, and starting with the dominant hand. A rest of at least 1 min was included between two tests on the same hand. The reproducibility of the procedure was tested in 7 subjects. Root-mean-square coefficient of variation for maximal grip strength was 3.6%.

5. Dual-energy x-ray absorptiometry (DXA)

Body composition and bone mineral density were measured by DXA (Lunar iDXA, GE, Muskego, WI, United States). A whole body scan was performed to determine whole body and regional bone mineral density, bone mineral content, fat mass and lean mass. Bone mineral density (BMD, in $g.cm^{-2}$), bone mineral content (BMC, in g) and bone area (in cm^2) were measured on subsequent scans at the lumbar spine (vertebrae L1-L4), both hips and both distal forearms. Three different sites were analyzed on the forearm scans: 1) the most distal portion of the radius (ultradistal radius) about 1.5 cm thick starting at the end plate of the radius; 2) a 2 cm

band that is equal to 1/3 the distance between the styloid process of the ulna and the olecranon; 3) the residual length between the two sites mentioned previously.[58] These three regions, which were defined according to ISCD recommendations, show variation in trabecular bone content. The ultradistal radius that corresponds to the distal epiphysis of the bone is mainly trabecular. The other two regions that correspond to the diaphysis are mainly cortical. In addition, the analysis of the whole body DXA scan provided BMC, BMD, lean mass and fat mass in the dominant and nondominant upper limbs.

6. Peripheral Quantitative Computed Tomography (pQCT)

Bone mass, bone geometry (bone size, thickness of the cortical shell), volumetric bone mineral density, estimates of bone strength as well as muscle cross-sectional area, were measured using pQCT (Stratec XCT-3000 scanner, Stratec Medical, Pforzheim, Germany). The pQCT is able to capture cross-sectional images of bone structure which allowed us to measure the specific parameters relative to bone strength. The pQCT measures the attenuation of an X-ray and automatically transforms this measure into a hydroxylapatite density. For the specific model we used (Stractec XCT-3000), the machine is calibrated so that water is set to 60 mg of hydroxylapatite (HA) and that fat calibrates to 0 mg HA. These measurements of HA correlate to the hydroxylapatite density found in these substances. The manufacturer's phantom was used to calculate attenuation coefficients which are then used to calculate the HA equivalent densities. The phantom itself was calibrated using the European Forearm Phantom (EFP; QRM, Erlangen, Germany). As the machine scans the limb, the X-ray beam goes through the human tissues and a set of 12 detectors, which is located directly opposite to the X-ray beam, gather information regarding the remaining radiation. The lower the remaining radiation, the higher the attenuation of the beam by the bones and soft tissues. The scanner rotates around the region of interest so

that one image is obtained every 15 degrees, over 180 degrees, which by symmetry covers 360 degrees of a full rotation. These different pictures are then integrated by the computer to generate a full cross section of the limb which is depicted in Figure III.1 below. Images were obtained at 6 different sites along the upper limb, as shown in Figure III.1.

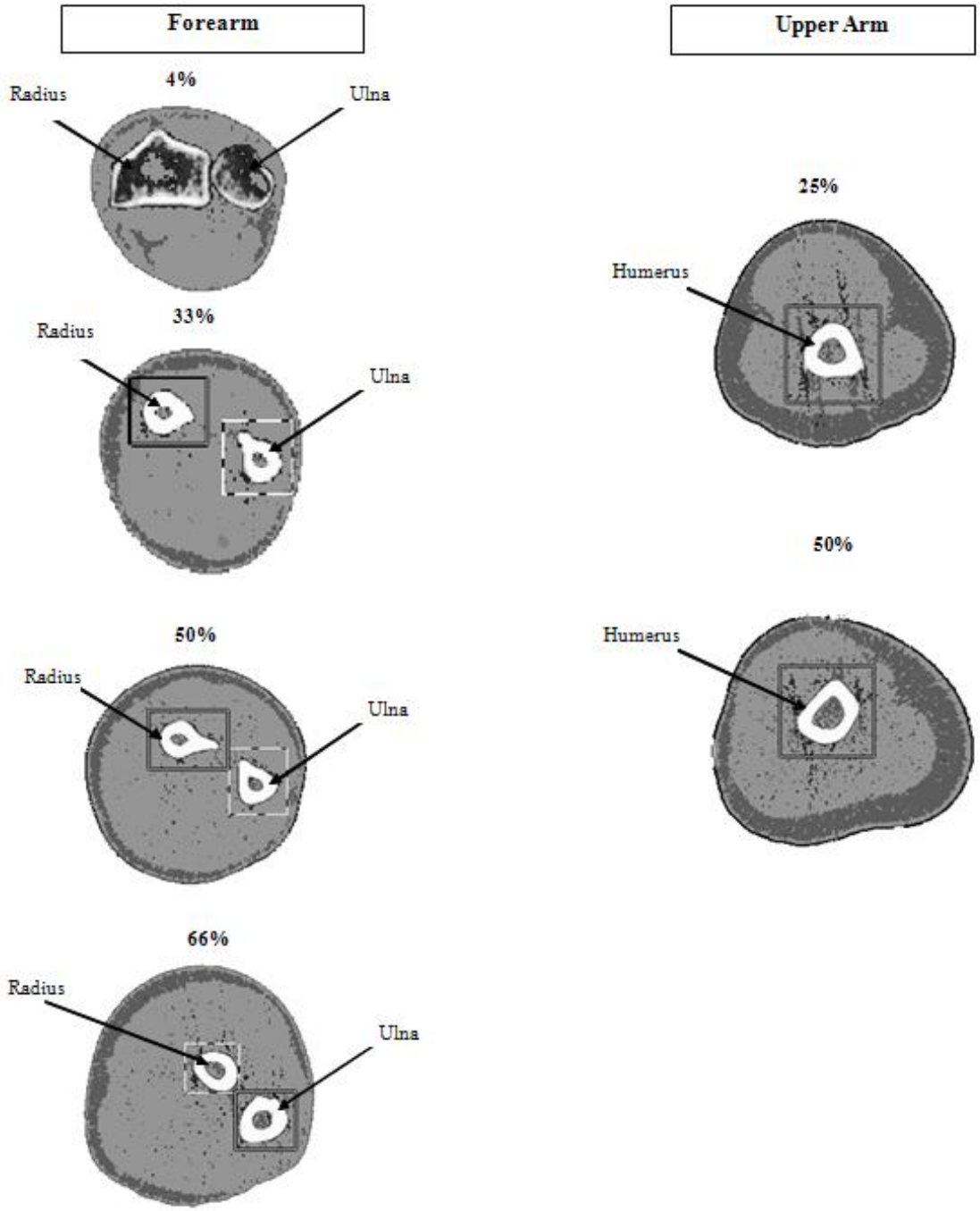

Figure III.1 Examples of cross-sectional pictures obtained from the pQCT. The forearm pictures move from distal (4%) to proximal (66%), as well as the upper arm pictures (25%-50%). The radius and ulna are identified in the forearm pictures and the humerus is identified in the upper arm pictures.

Each subject had both forearms tested as well as each upper arm. A scout view of the distal forearm was performed in order to place the reference line that determines the measurement sites. Six pQCT scans were completed at 4%, 33%, 50%, and 66% of forearm length and at 25% and 50% of the humeral length. Both the radius and the humerus require a certain positioning in order to obtain proper results.

When the subject was ready for pQCT testing, they were placed in a chair next to the machine. The subject then placed their arm through the gantry onto the secure arm holder with the palm of their hand down (prone position). The arm had to be in a horizontal position, with the axis of the bones imaged perpendicular to the gantry of the machine. Figure III.2 indicates the correct position for forearm scanning.

Figure III.2 Proper positioning of the forearm for a pQCT scan.

The positioning for the upper arm was slightly different than that for the forearm. When placing their arm through the gantry, the subject's arm needs to be fully extended. Once the whole arm was in the machine and the patient was in a comfortable position, the arm was secured using black Velcro strips.

The pQCT cross-sections were 2 mm thick, the pixel size was set at 0.6 mm, and the scanning speed was 30 mm/s. These parameters were chosen to minimize the risk of movement artifacts as the participants were required to stay very still during scanning. The same parameters were measured and analyzed at the 25% and 50% sites of the humerus and the 33%, 50%, and

66% sites of the radius and ulna (shaft). Different parameters were measured at the 4% site of the radius and ulna because this site is composed of trabecular bone (epiphysis). Bone parameters measured in the shaft include bone mineral content (BMC, mg/cm), total area (ToA, cm^2), cortical area (CoA, cm^2), average cortical thickness (Ct.Th, mm), cortical density (CoD, mg/cm^3), periosteal perimeter (PsPm, mm), and endosteal perimeter (Es.Pm, mm). At the 4% site of the radius and ulna, BMC (mg/cm), ToA (cm^2), trabecular density (TrD, mg/cm^3) were measured. Muscle cross-sectional area (MCSA, cm^2) was also measured at the 25% and 50% sites of the humerus and the 33%, 50%, and 66% sites of the radius.

Several estimates of bone strength were calculated, either based on parameters of bone geometry only, or combining bone geometry and volumetric density. Estimates of bone strength based on bone geometry only include the minimum moment of inertia (I_{min}, cm^4), maximum moment of inertia (I_{max}, cm^4), and the polar moment of inertia (J, cm^4). I_{min} and I_{max} represent the distribution of bone material about the planes of least and most bending resistance, respectively. They estimate the ability of the bone structure to resist bending in orthogonal planes. J is the sum of I_{min} and I_{max}, and estimates the ability of the bone structure to resist torsion. In addition, the ratio between both moments of inertia (I_{max}/I_{min}) provides an indication of diaphyseal shape, with an Imax/Imin ratio closer to one representing a more circular bone cross-section.[59] Other indices combine both bone geometry and volumetric density. The stress-strain index (SSI, mm^3) in the shaft and the bone strength index (BSI, mg^2/mm^4) in the epiphysis are calculated as previously described.[53]

All of these parameters were measured in both the dominant and nondominant arms and the relative side-to-side difference was calculated for each parameter.

7. Medical History Questionnaire

All subjects were asked to fill out a questionnaire that included information regarding demographics and basic medical history. There were different sections to the questionnaire including demographics and medical history, menstrual cycle history, bone health and fracture history. The demographics and medical history section dealt with ethnicity, currents illnesses, and history of smoking. The menstrual cycle questions were specific regarding age of menarche, any times when menstruation stoped for a certain length of time, and the use of oral contraceptives. The bone health and fracture history section collected information regarding stress fractures, other fractures, family history of osteoporosis, history of injuries, and history of bone density tests.

8. Training History Questionnaire

The training history questionnaire included information regarding the current and past physical activity survey, as well as a table to gather information regarding tennis training. Hand dominance (relevant to tennis playing) and the backhand technique (one-handed vs. two-handed) were also evaluated using the questions in this section.

9. Statistical Analysis

The analysis of the pQCT images and calculation of bone and muscle parameters were performed using the manufacturer's software package (version 6, Stractec Medical, Pforzheim, Germany). Statistical analysis software (PASW Software 18, SPSS Inc.) was used to analysis the data from the surveys, anthropometry, DXA, and pQCT combined. The data shown in tables is shown as mean ± standard error. Normality of the parameters was tested by the Kolmogorov-

Smirnov test. Two-tailed paired samples t-tests were used to compare the parameters at the dominant and nondominant forearms. One sample t-tests were used to test for the significance of the relative side-to-side differences against zero. The relative side-to-side differences were shown as the percentage of the nondominant value ($\Delta\%$ = (dominant – nondominant) / nondominant × 100). Absolute side-to-side differences were calculated as the dominant value minus the nondominant value. Pearson correlation analysis was performed to examine statistical relationships between muscle cross sectional area and bone strength.

Chapter 4: Results

The effects of playing tennis on muscle size and bone strength were assessed in ten subjects along with measures of tennis playing history. Descriptive characteristics about the subjects are given in Table IV.1. All subjects were right-handed and 6 had a history of fracture. One subject had 3 previous fractures, two subjects had 2 previous fractures, and 3 subjects each had one. Only one subject sustained a stress fracture that was most likely caused by tennis playing (site: humerus). All subjects had a one-handed forehand and 9 had a double-handed backhand with 1 having a single-handed backhand.

Table IV.1. Anthropometry and training characteristics in the female tennis players (n=10).

	Female Tennis Players			Minimum	Maximum
Age (yrs)	22.5	±	1.8	18.5	33.7
Height (cm)	167.4	±	1.5	159.8	174.9
Weight (kg)	64.9	±	3.0	56.0	84.5
Lean body mass (kg)	44.5	±	1.6	39.5	55.4
Percent body fat (%)	26.8	±	1.4	21.2	36.6
Starting age for training (yrs)	9.0	±	0.7	4.0	12.0
Current Training Volume (hrs)	11.7	±	2.9	1.0	22.5
Max Training Volume (hrs)	18.6	±	2.4	6.0	30.0
Years of Training (yrs)	13.4	±	2.0	7.5	25.7

Data are given as mean ± SE

Bone Asymmetry

The skeletal benefits gained from repetitive loading at the forearm (radius + ulna) and at the humerus were examined through certain bone parameters. Additional parameters were gathered and can be found in tables A.1, A.2, and A.3 in the appendix. The reproducibility of the pQCT parameters was tested by analyzing 7 scans performed twice. Root-mean-square coefficient of variation for pQCT parameters ranged from 1.32 to 2.40% in the shaft, 1.83 to 2.92% for parameters in the epiphysis, and 2.76% for MCSA.

Side-to-side differences in bone parameters at different skeletal sites in response to loading are shown in Figure IV.1 (a. estimated bone strength, b. total area, c. polar moment of inertia and d. maximum moment of inertia). The graphs represent the average relative difference between the dominant and nondominant arms with error bars expressing the 95% confidence interval. Confidence intervals not crossing the horizontal axis (zero) indicate that the side-to-side difference was significantly different from zero.

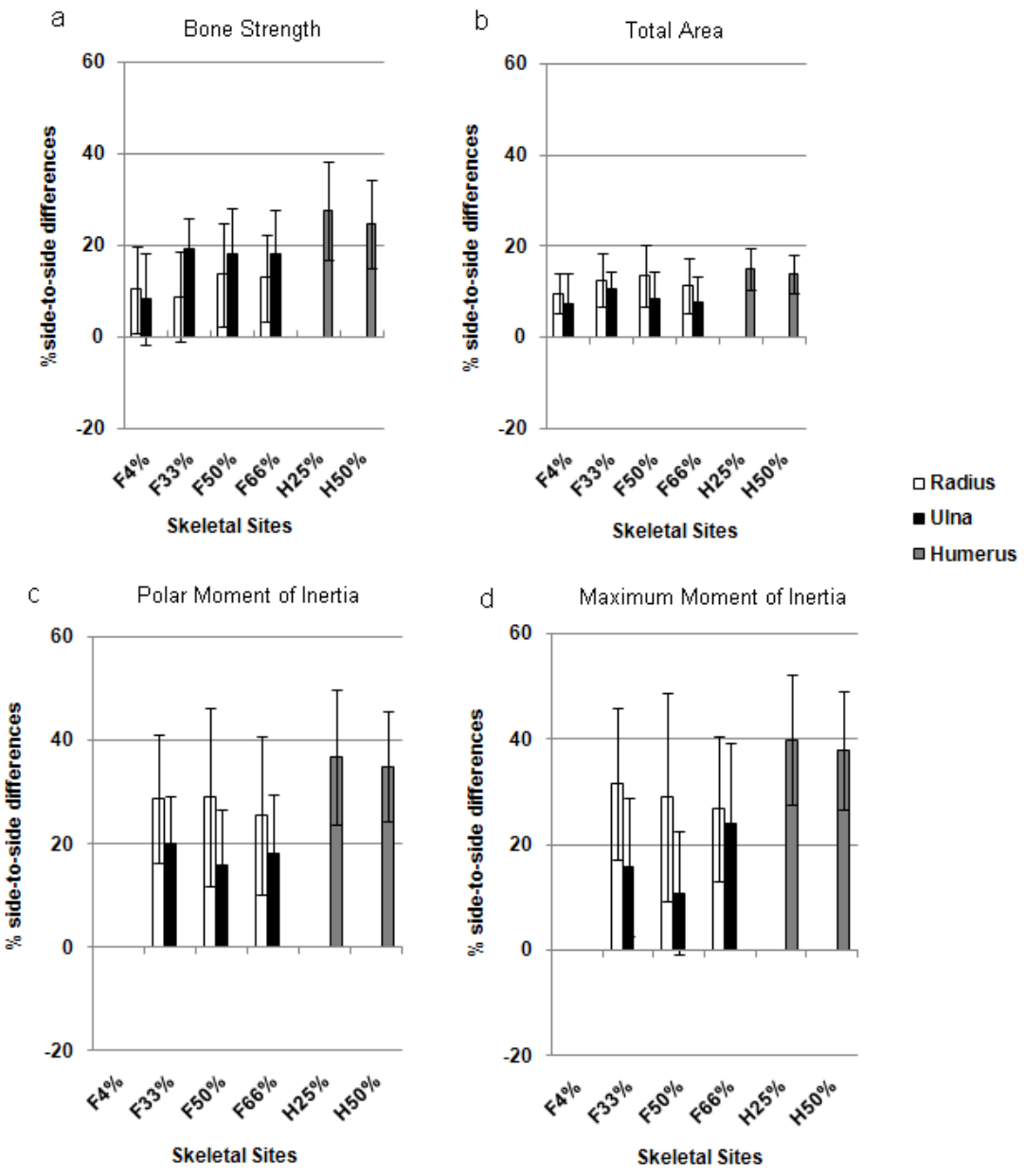

Figure IV.1a-d. Relative side-to-side differences in estimated bone strength (SSI and BSI), total area, polar moment of inertia, and maximum moment of inertia in response to repetitive loading at various sites along the forearm (F, with data at the radius and ulna) and humerus (H).

Preliminary comparison of the osteogenic response to loading between the 3 bones indicates that the humerus is the skeletal site that seemed to respond the most to loading. There were slight differences between the radius and the ulna for each parameter. However, if the results of the radius and ulna were added together, the forearm is not that different from the upper arm in terms of bone asymmetries. When considering estimates of bone strength such as SSI or J, the forearm actually shows larger bone asymmetries than the upper arm. The range for side-to-side differences for SSI at the humerus was 24.7-27.7% and the range for the forearm was 28.0-31.7%. For J, the range for side-to-side differences at the upper arm was 35-36.8% and the range at the forearm (radius + ulna) was 43.7-48.8%. Correlations were not found between the bone asymmetries in the upper arm and the bone asymmetries in the forearm.

Paired sample t-tests were used to compare the largest side-to-side difference in the upper arm with the largest side-to-side difference in the forearm for several bone parameters. No significant difference was found between bone strength, total area, polar moment of inertia, or maximum moment of inertia at the two most responsive sites along the arm, i.e. U33% and H25% ($p=0.21$).

Paired samples t-tests were also used to compare the relative differences of the parameters between the radius and ulna, the humerus and radius, and the humerus and ulna. The only significant difference found between the radius and ulna was trabecular density (TrD) at the 4% site ($p=0.043$). The radius and ulna were only compared to the humerus at the 50% site since the 50% site was scanned in the forearm and the upper arm. The only significant difference found between the humerus and the radius was SSI ($p=0.021$). There were four significant differences found between the humerus and the ulna: cortical area ($p=0.002$), bone mineral

content (p=0.004), maximum moment of inertia (p=0.0005), and polar moment of inertia (p=0.0005).

Training history was found to have an impact on the magnitude of the relative side-to-side differences for some bone parameters. At the 50% and 66% sites of the radius, the side-to-side difference in polar moment of inertia showed a significant relationship with current hours of tennis playing per week (R=0.67 p=0.03 and R=0.64 p=0.04, respectively). Also, the relationship between SSI and maximum training volume at the 25% site of the humerus was borderline significant (R=0.60 p=0.07).

Muscle hypertrophy in the upper arm and forearm

The benefits in muscle size gained from repetitive loading in the forearm and the upper arm were examined through muscle cross-sectional area (MCSA) and upper limb lean mass (Table A.1, see appendix). Increase in muscle cross-sectional area in response to loading is shown in Figure IV.2.

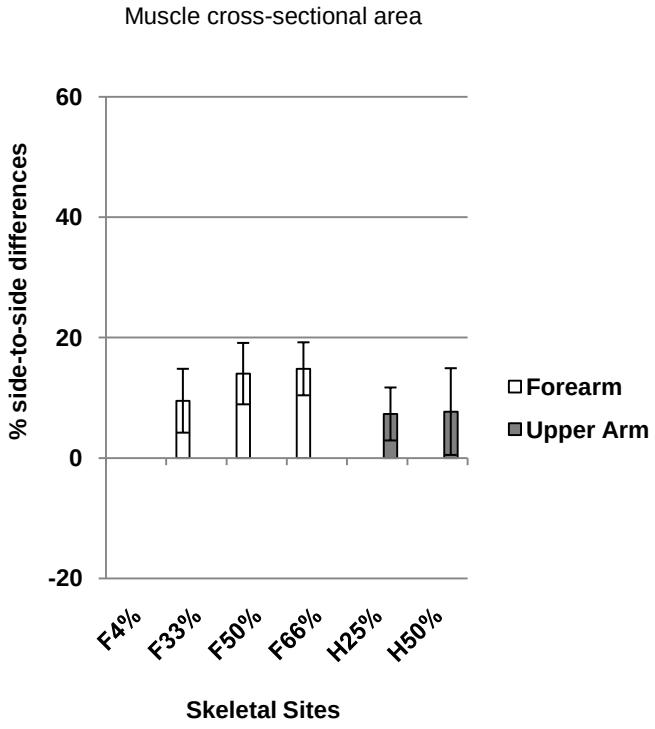

Figure IV.2. Relative side-to-side difference in muscle cross-sectional area in response to repetitive loading at various sites along the forearm (F) and upper arm (H).

The 50% site seemed to show the largest response to repetitive loading for MCSA in the upper arm (Figure IV.2). The site with the greater response in MCSA along the forearm was 66% (Figure IV.2). A paired t-test showed that the 66% forearm had a larger side-to-side difference in MCSA than the 50% upper arm ($p=0.05$), indicating that loading increases MCSA more so in the forearm than the upper arm.

Pearson correlation analysis found that the percent difference between the dominant and nondominant arms for grip strength negatively correlated with the relative differences in MSCA at the radius 50% and 66% sites and the ulna 50% and 66% sites.

Muscle-bone relationship

The effects of muscle size on bone were examined by looking at certain parameters. These parameters include bone strength (SSI, BSI), total area (ToA), and muscle cross-sectional area (MSCA). Muscle cross-sectional area was positively correlated with bone strength on the dominant side (R values ranged from 0.79 to 0.93, $p<0.05$). On the nondominant side, only the 66% site of the radius showed significant correlation between SSI and MCSA. There were no correlations between the relative side-to-side differences for MCSA and the side-to-side differences in any of the bone parameters. However, at the 50% forearm, the relationship between the side-to-side difference in MCSA and the side-to-side difference in SSI was borderline significant (radius $R=0.57$, $p=0.09$ and ulna $R=0.61$, $p=0.06$). The correlations are shown in table IV.2 below. Figure IV.3 shows the muscle-bone relationship at the 66% site of the dominant forearm (using bone strength at the radius and the ulna).

Table IV.2. Correlation values obtained from the Pearson product-moment correlation coefficients between muscle cross-sectional area (MCSA) and estimated bone strength (SSI). Correlations were testing the relationship between muscle and bone, and the relative side-to-side differences between muscle and bone.

	Dominant	**Nondominant**	**Side-to-side differences**
	MSCA-SSIpol	MSCA-SSIpol	MSCARelDiff-SSIpolRelDiff
Radius			
66%	R = 0.93 p = 0.0005**	R = 0.79 p = 0.007**	R = 0.008 p = 0.98
50%	R = 0.88 p = 0.001**	R = 0.57 p = 0.09	R = 0.07 p = 0.85
33%	R = 0.79 p = 0.007**	R = 0.35 p = 0.33	R = -0.14 p = 0.70
Ulna			
66%	R = 0.66 p = 0.04*	R = 0.31 p = 0.38	R = 0.32 p = 0.36
50%	R = 0.76 p = 0.01*	R = 0.46 p = 0.18	R = 0.61 p = 0.06
33%	R = 0.72 p = 0.02*	R = 0.56 p = 0.09	R = 0.48 p = 0.16
Humerus			
50%	R = 0.85 p = 0.002**	R = 0.51 p = 0.14	R = 0.008 p = 0.98
25%	R = 0.75 p = 0.01*	R = 0.49 p = 0.15	R = -0.17 p = 0.63

*p<0.05
**p<0.01

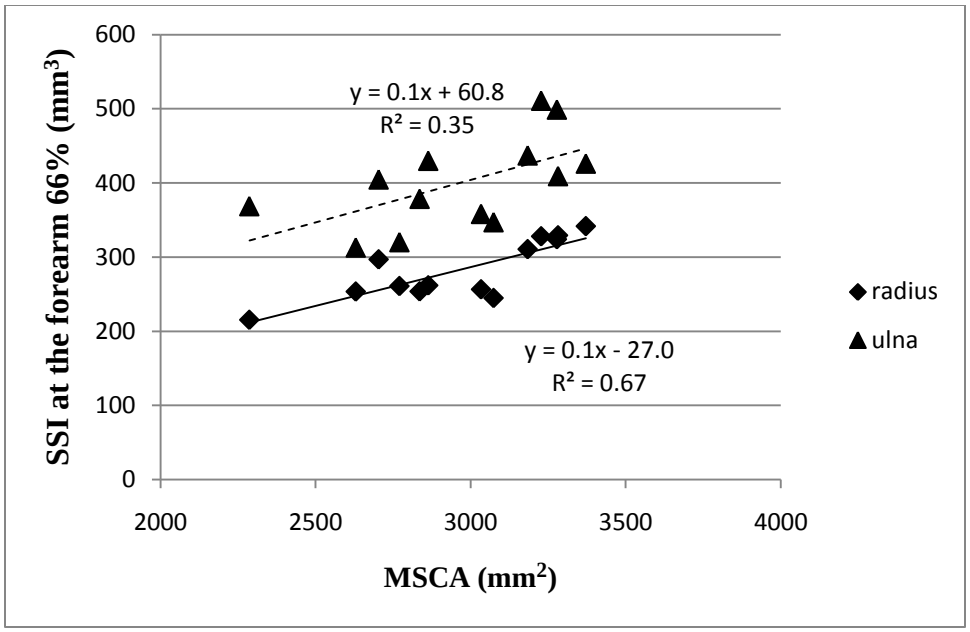

Figure IV.3. The muscle bone relationship for the radius and the ulna at the 66% site along the forearm.

The R^2 values shown in Figure IV.3 show that the coefficient of determination for the radius (R^2=0.67) is about two times stronger than the coefficient of determination for the ulna (R^2=0.35). Although slightly weaker (r between 0.65-0.92), these correlations were still significant after controlling for height.

Chapter 5: Discussion

Our findings indicate that the forearm responds more to loading than the upper arm in terms of muscle cross-sectional area (MSCA), while the humerus is the bone of the upper limb that shows the greatest adaptation to loading regarding bone strength. It was also found that there were differences with regards to bone and muscle parameters between the radius, ulna, and humerus. The study indicated a significant muscle-bone relationship in the playing arm.

The skeletal benefits were larger at the humerus compared with the radius or ulna for bone parameters such as bone mineral content and bone strength. However, if the results of the radius and ulna were added together, the forearm is not that different from the upper arm in terms of bone asymmetries. Side-to-side differences for bone mineral mass and strength ranged from 15-40% in the humeral shaft. These findings are consistent with previous studies in tennis players who started training during growth, [30, 39, 46] showing an 8.5-39% asymmetry in bone parameters at the humerus.

An explanation for this finding could be that the humerus is the only bone in the upper arm while both the radius and ulna bear the loads in the forearm. The loading experienced in the forearm would be shared between the radius and the ulna while in the upper arm the humerus would receive the impact of loading by itself.[60] During a fall or a situation where a big impact force is placed on the forearm, the radius and ulna would both respond. Interestingly, when adding the bone asymmetries of the radius and ulna for SSI and J at all sites, the ranges are slightly greater than bone asymmetries ranges found in the humerus. The fact that the loading is shared between the radius and ulna could also explain the smaller asymmetry seen in the ulna and radius between the side-to-side differences. This suggests that the upper arm and the forearm have similar exercise-induced skeletal response to loading.

The 25% site (distal region) of the humerus is the skeletal site that responds the most regarding bone morphology to loading. Figure V.1 shows an example of the bone asymmetry between the nondominant and dominant arms at the 25% site of the humerus.

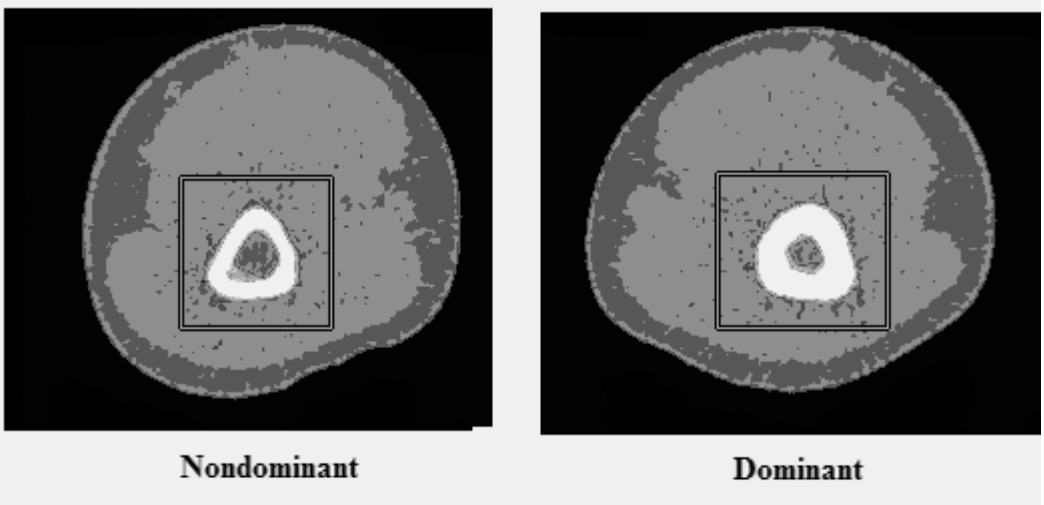

Figure V.1 Images about from the pQCT humerus scan on the dominant and nondominant arms of a female tennis player, at the humeral 25%. This player was 18 years old and has been playing tennis for 10 years. The relative side-to-side difference in BMC was 56.7%, in total area it was 26.0%, and in polar moment inertia it was 71.7%.

Side-to-side differences for bone mineral mass and strength ranged from 15-40% at the 25% site of the humerus. This was the largest asymmetry found for any site. These findings are consistent with another study conducted in tennis players who started training during growth and showing a 21-67% asymmetry in bone parameters at the 20% humerus site.[30] In this study, the distal humerus (20% site) was also the most responsive site to loading when compared to the 80% and 50% site of the humerus and the 4% and 30% sites of the radius.

An explanation for this could be the due to the shape of the humerus. The shape of the humerus was found to be circular due to the shear stresses that are placed on the bone from

torsional loading (especially during the tennis serve).[60] The shear stresses that are placed on the bone are applied on the whole cross-section; therefore the most efficient bone shape that would resist torsional deformation would be circular. The second phase of the tennis serve includes maximum external shoulder rotation. During this phase, the torsion of the humerus induces humeral hypertrophy which increases bone apposition along the humerus.[51] Therefore the circular shape of the humerus allows the bone to better handle the torsion during playing and especially during the serve. This leads to increased bone apposition along the humerus.

Another objective was to clarify if the muscle hypertrophy in the forearm would be similar to or greater than the muscle hypertrophy in the upper arm. The side-to-side differences in muscle cross-sectional area (MCSA) were larger at the forearm than the upper arm. The differences for MSCA ranged from 9.5-14.8% at the forearm. Previous studies in tennis players who started training during youth showed a 6-10% asymmetry in muscle area at the forearm.[45, 46] The side-to-side differences for MCSA averaged ~7% in the upper arm which is consistent with the literature that shows a range from 7%-8% in the upper arm as well.[35] The site that had the largest side-to-side difference was 66% at the forearm. Figure V.2 and V.3 show muscle attachments along the bones of the forearm and upper arm. The muscle attachments could provide an explanation for the site-specific skeletal response to loading.

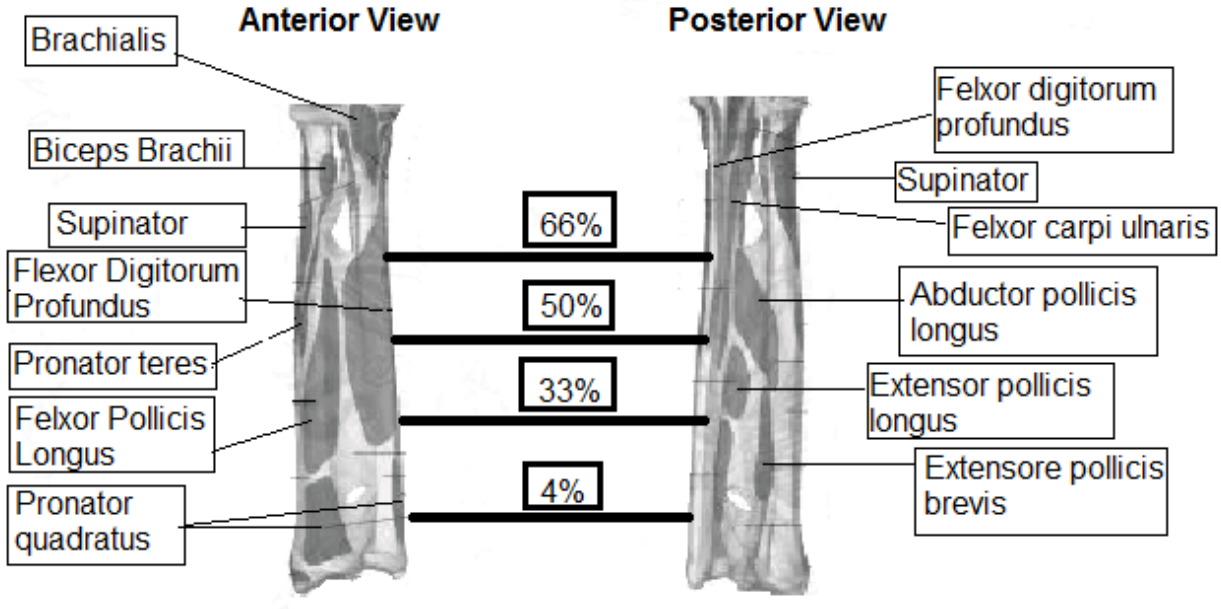

Figure V.2. Anatomical representation of the muscle attachments along the forearm bones: the radius and ulna.

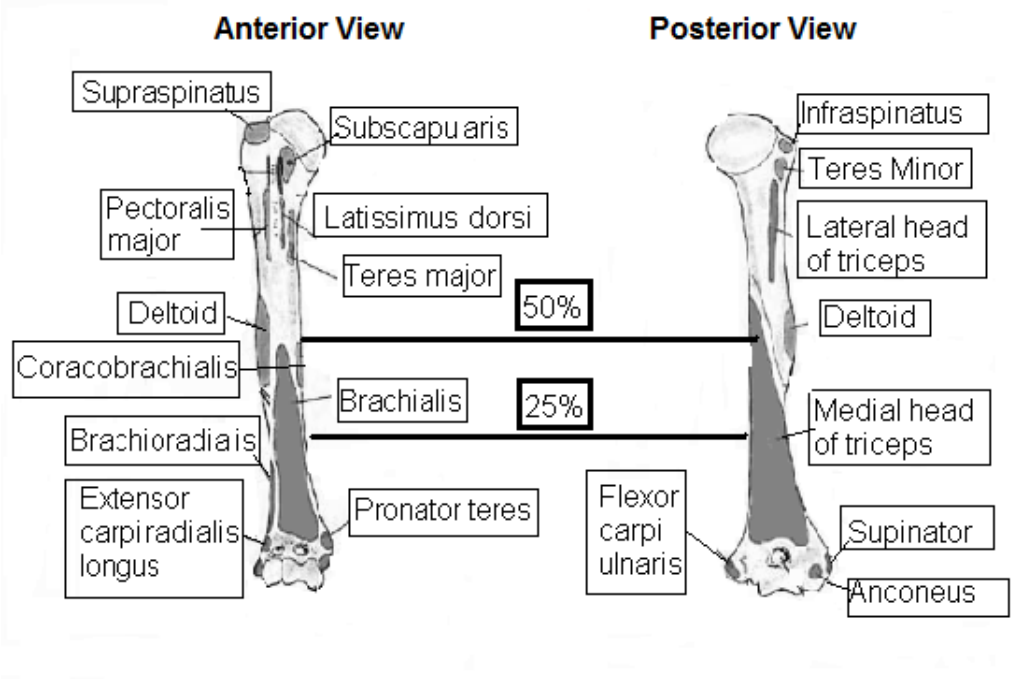

Figure V.3. Anatomical representation of the muscle attachments along the upper arm bone, the humerus.

This could be explained by the fact that the musculature at that proximal site of the forearm is a lot bigger than the musculature at the more distal sites. There are three layers of muscle that all gain size as they move proximally up the forearm. These muscle attachments are shown in Figure V.2. The dominant arm of tennis players is frequently in use which means that these muscles are submitted to mechanical strains as well. This could lead to greater muscle hypertrophy on the dominant side compared with the nondominant side. The humerus on the other hand has a very different musculature.

The difference between the relative asymmetries in muscle cross-sectional area at the 25% and 50% sites of the humerus was very small. In Figure IV.2, the relative difference for MSCA was only slightly larger at the 50% site than at the 25% site of the humerus. An explanation for this could be the lack of change in musculature around the humerus as you move proximally. Each skeletal site has its own muscle attachments. Since the musculature between the two sites is not different, it would explain the little variance in the relative side-to-side differences between the sites.

A third objective was to test whether the skeletal benefits in the dominant arm of female tennis players would be the greatest at locations where tennis-induced muscle hypertrophy was the largest. It is known that a muscle-bone relationship exists throughout the entire body. We noticed that exercise-induced loading seemed to amplify the relationship between muscle and bone along the dominant arm of tennis players. Previous studies indicate that a strong muscle-bone relationship also exist in the nondominant arm of tennis players.[61] It is unclear why we did not find this relationship in our sample. By looking at the data, the site that seemed to show the largest response in MSCA was the forearm 66%. This is also to the site that had the strongest

correlation between MSCA and bone strength (SSI) according to Table IV.2. However it seems that the skeletal benefits gained from loading are larger at the upper arm rather than the forearm. However, if the results of the radius and ulna are added together, they were greater than the results found in the upper arm. The upper arm also showed a smaller muscle hypertrophy than the forearm. Therefore a muscle-bone relationship along the whole dominant arm of female tennis players does seem to exist but the strength of the relationship varies between sites.

There were a number of limitations in this study. First and foremost, the small sample size of only ten players definitely limited the power of the study and prevents the generalizability of the results. With a small sample size, it is hard to obtain significant results and to relate the results to the overall population. The characteristics of the population were also limiting. The population only consisted of females, training regimes were homogeneous, and the age range was narrow. All these factors may limit the inter-individual variability in the data. Also, playing tennis is not the only factor that explains the side-to-side differences between the dominant and nondominant arm of tennis players. There are other impact forces and other mechanisms which could lead to a difference between the arms such as the preferential use of the dominant arm in daily tasks, including physical tasks. Therefore having a control group for the study would have helped controlling for some of these other factors. Another area where this study is limited is the fact that the bones in the forearm and upper arm are not perfectly straight. When scanning these bones, we cannot control for their curvature and therefore the pictures obtained from the scans are not perfectly perpendicular to the long axes of the bones. Depending on where the image is obtained, results for bone parameters could have been affected. One final area where this study is limited has to do with the estimation of bone strength. Estimates of bone strength are based on the assumption that the bones have a cylindrical shape, which is true for the shafts of some long

bones (humerus) but not others (tibia). The estimation of bone strength may be more difficult in the ulna due to the variability of the interoesseous membrane.[62] The ulna does not have a cylindrical shape which could affect the estimates of bone strength that were found in this study. It was also found that J is not an accurate indicator of torsional rigidity when sections depart too far from circularity (I_{max}/I_{min} ratio>1.5), according to.[63] Some of the skeletal site in this study do show an I_{max}/I_{min} ratio>1.5 such as the dominant 50% humerus site and both the dominant and nondominant 33% site of the radius.

Chapter 6: Conclusion

In conclusion, repetitive loading seems to exert site-specific effects on bone and muscle tissues. Our findings confirm that loading induces musculoskeletal benefits, which supports the notion that regularly engaging in physical activity positively affects bone health. We found that the forearm had a greater response in muscle while the upper arm had a greater response in bone parameters. A strong correlation was found between muscle and bone in the dominant arm of the tennis players. The absence of such correlation in the nondominant arm is unclear. This suggests that other factors than muscle size alone are likely to affect bone strength.

Further research in this field should examine multiple skeletal sites along the bones of interest in order to gain a true understanding of how these bones respond to exercise. Research in this area could also provide more information on injury prevention, more specifically on the etiology of stress fractures.

Chapter 7: Resources

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Appendices: List

Appendices 1: Additional Results

Table A1. Side-to-side differences for forearm length, DXA-derived musculoskeletal parameters, pQCT-derived muscle cross-sectional area (CSA), and grip strength in the arms of ten female tennis players.

		Dominant		Nondominant		% Difference (95% CI)
Forearm Length (cm)		26.7 ± 0.4		26.2 ± 0.4		1.7 (0.7, 2.7)**
DXA-derived musculoskeletal parameters						
Upper limb BMC (g)		166.50 ± 4.72		143.70 ± 3.85		16.05 (10.47, 21.64)***
Upper limb BMD ($g.cm^{-2}$)		0.755 ± .0165		.681 ± .0134		10.960 (6.198, 15.004)***
Upper limb lean mass (kg)		2.1 ± 0.1		1.9 ± 0.7		8.9 (5.7, 12.2)***
pQCT-derived muscle CSA (mm^2)						
Upper arm	$H_{50\%}$	2604.0 ± 122.0		2423.0 ± 98.3		7.7 (0.5, 14.8)*
	$H_{25\%}$	2370.0 ± 80.4		2212.0 ± 75.8		7.3 (2.9, 11.7)**
Forearm	$R_{66\%}$	2920.0 ± 110.4		2539.0 ± 67.3		14.8 (10.4, 19.1)***
	$R_{50\%}$	2427.0 ± 97.9		2125.0 ± 63.9		14.0 (8.9, 19.1)***
	$R_{33\%}$	1639.0 ± 64.7		1496.0 ± 50.0		9.5 (4.2, 14.8)**
Grip Strength (N)		323.2 ± 15.5		263.4 ± 18.3		25.6 (12.9, 38.4)***

[a] Data are mean ± SE

[b] Mean percent differences between dominant and nondominant were assed using single sample t-tests with a population mean of 0. Significance is indicated by * $p<0.05$, ** $p<0.01$, *** $p<0$

BMC: bone mineral content; BMD: bone mineral density

Table A2. Side-to-side differences for specific bone parameters at different sites along the radius and ulna.

		Radius			Ulna		
		Dominant[a]	**Nondominant[a]**	**% Difference (95% CI)[b]**	**Dominant[a]**	**Nondominant[a]**	**% Difference (95% CI)[b]**
66%	BMC (mg/cm)	101.6 ± 2.6	92.5 ± 3.1	10.4 (4.1, 16.8) **	135.3 ± 3.8	123.7 ± 3.5	9.6 (4.1, 15.1) **
	ToA (cm^2)	140.6 ± 6.2	126.5 ± 5.2	11.4 (5.3, 17.6) **	162.5 ± 4.9	151.1 ± 3.9	7.7 (2.2, 13.2) *
	CoA (cm^2)	76.4 ± 2.4	69.8 ± 2.5	10.0 (3.3, 16.7) **	102.2 ± 2.7	93.8 ± 2.4	9.1 (4.7, 13.5) ***
	Ct.Th (mm)	2.2 ± .1	2.1 ± .08	4.1 (-1.9,10.2)	2.8 ± .06	2.7 ± .07	5.6 (3.6, 7.7) ***
	Ps.Pm (mm)	42.0 ± .90	39.8 ± .82	5.5 (2.6, 8.4) **	45.1 ± .69	43.5 ± .57	3.7 (1.1, 6.3) *
	Es.Pm (mm)	28.1 ± 1.4	26.5 ± 1.0	6.0 (1.4, 10.6) *	27.4 ± .78	26.7 ± .7	2.6 (-1.4, 6.6)
	CoD (mg/cm^3)	1112 ± 10.0	1116 ± 7.4	-0.4(-1.6, 0.9)	1139 ± 5.6	1134 ± 7.1	0.4 (-0.5, 1.3)
	SSI (mm^3)	284.7 ± 13.1	254.5 ± 13.6	12.9(3.5, 22.4) *	398.6 ± 17.7	339 ± 13.7	18.1 (8.3, 27.8) **
	I_{max} (cm^4)	1231 ± 87.2	983.3 ± 69.4	26.8 (13.0, 40.6)**	1851 ± 106.9	1512 ± 85	23.9 (8.4, 39.3) **
	I_{min} (cm^4)	851.5 ± 57.0	727.5 ± 57.0	19.4 (5.5, 33.4) *	1292 ± 81.7	1161 ± 53.7	10.9 (1.9, 19.9) *
	I_{max}/ I_{min}	1.5 ± .05	1.4 ± .03	6.7 (-1.0, 14.4)	1.5 ± .07	1.3 ± .05	11.7 (1.7, 21.6) *
	J (cm^4)	2083.0 ± 139.9	1710.8 ± 123.8	25.6(10.4, 36.8) **	3142.5 ± 177.4	2673.4 ± 132.0	18.1 (6.5, 29.7) **

50%	BMC (mg/cm)	116.3 ± 3.2	102. 4 ± 2.8	13.9 (6.8, 20.9) **	116.8 ± 3.0	109.2 ± 2.4	7.1 (1.6, 12.6) *
	ToA (cm^2)	133 ± 4.0	117.5 ± 3.5	13.6(6.8, 20.4) ***	131.4 ± 4.2	121.4 ± 4.0	8.5 (2.6, 14.5) **
	CoA (cm^2)	90.0 ± 2.4	78.4 ± 2.2	15.2 (7.3, 23.1) **	89.3 ± 2.4	83.0 ± 2.0	7.9 (1.9, 13.8) *
	Ct.Th (mm)	2.8 ± .05	2.8 ± .07	8.7 (3.1, 14.3) **	2.8 ± .06	2.7 ± .07	3.1 (-1.5, 7.7)
	Ps.Pm (mm)	0.8 ± .62	38.4 ± .59	6.5 (3.3, 9.7) ***	40.6 ± .65	39.0 ± .65	4.1 (1.3, 7.0) **
	Es.Pm (mm)	23.2 ± .73	22.1 ± .57	4.8 (0.6, 9.1) *	22.9 ± .69	21.8 ± .88	5.6 (.07, 11.1) *
	CoD (mg/cm^3)	1141 ± 5.3	1147 ± 5.9	-0.4 (-1.2, 0.4)	1142 ± 6.0	1147 ± 7.5	-0.4(-1.2, 0.5)
	SSI (mm^3)	237 ± 9.9	211 ± 9.8	13.6 (2.4, 24.7) *	266 ± 12.8	225.9 ± 8.8	18.1(8.1, 28.0) **
	I_{max} (cm^4)	1538 ± 109.3	1229 ± 98.0	29.1 (9.3, 48.8) **	1466 ± 123.4	1336 ± 114	10.9 (-0.9, 22.7)
	I_{min} (cm^4)	720.8 ± 35.8	557.3 ± 28.3	30.6 (15.9, 45.3) ***	786.2 ± 47.5	622 ± 38.8	28.5 (9.2, 47.9) **
	I_{max}/ I_{min}	2.1 ± .09	2.2 ± 0.1	-1.4 (-10.1,7.3)	1.9 ± 0.1	2.2 ± 0.2	-11.6 (-24.2, 1.0)
	J (cm^4)	2258.8 ± 139.6	1785.8 ± 120.2	29.1 (11.8, 46.3) **	2252.5 ± 154.9	1957.8 ± 135.9	15.8 (4.9, 26.8) **
33%	BMC (mg/cm)	106.5 ± 3.6	96.0 ± 3.15	11.1 (6.4, 15.7) ***	94.7 ± 3.0	87.4 ± 2.4	8.3 (4.5, 12.2) ***
	ToA (cm^2)	118 ± 4.6	106 ± 4.6	12.6 (6.7, 18.5) ***	109 ± 3.5	98.7 ± 3.3	10.6 (6.8, 14.5) ***
	CoA (cm^2)	80.8 ± 2.8	72.8 ± 2.3	11.1 (5.8, 16.4) ***	72.5 ± 2.2	66.9 ± 1.9	8.6 (4.0, 13.2) **
	Ct.Th (mm)	2.7 ± .07	2.6 ± .04	4.2 (0.6, 7.9) *	2.5 ± .05	2.4 ± .07	2.4 (-2.0, 6.9) ***

	Ps.Pm (mm)	38.5 ± .8	36.3 ± .8	6.0 (3.3, 8.8) ***	37.0 ± .58	35.2 ± .59	5.1 (3.3, 7.0) ***
	Es.Pm (mm)	21.6 ± .8	20.1 ± .8	7.6 (2.2, 13.1) *	21.4 ± .57	19.9 ± .77	8.0 (3.6, 12.4) **
	CoD (mg/cm^3)	1170 ± 4.6	1173 ± 6.6	-0.3 (-0.9, 0.4)	1136 ± 6.1	1140 ± 5.8	-0.3(-0.7, 0.01)
	SSI (mm^3)	224.2 ± 12.1	209 ± 13.5	8.8 (-1.1, 18.7)	207.4 ± 9.3	174.1 ± 7.0	19.2(12.4, 26.0) ***
	I_{max} (cm^4)	1054 ± 98.9	817 ± 86.4	31.5 (17.1, 45.8) ***	921.4 ± 87.5	807.8 ± 80.8	15.8 (2.7, 29.0) *
	I_{min} (cm^4)	652 ± 42.8	526 ± 36.0	25.2 (13.2, 37.1) ***	543.7 ± 25.9	421.7 ± 19.2	29.4 (20.7, 38.1) ***
	I_{max}/ I_{min}	1.6 ± .07	1.5 ± .07	5.2 (-2.3, 12.7)	1.7 ± 0.1	1.9 ± 0.1	-10 (-20.7, 0.8)
	J (cm^4)	1705.5 ± 140.0	1342.6 ± 121.8	28.8 (16.3, 41.3) ***	1465.1 ± 107.4	1229.5 ± 93.7	20.0 (10.6, 29.4)
4%	BMC (mg/cm)	123 ± 4.6	112 ± 3.5	9.8 (4.4, 15.1) **	59.2 ± 3.7	55.1 ± 3.1	7.4 (1.8, 13.0) *
	ToA (cm^2)	387 ± 13.0	354 ± 13.2	9.6 (5.2, 14.0) **	187 ± 11.3	174 ± 9.3	7.2(0.2, 14.2) *
	TrD (mg/cm^3)	194 ± 7.2	192 ± 6.5	1.1(-3.1, 5.3)	232.5 ± 12.5	217 ± 12.5	7.8 (1.7, 13.8) *
	BSI (mg^2/mm^4)	39.3 ± 2.1	35.7 ± 1.7	10.3(0.9, 19.8) *	19.0 ± 1.7	17.8 ± 1.6	8.4 (-1.6, 18.4)

[a] Data are mean ± SE

[b] Mean percent differences between dominant and nondominant were assed using single sample t-tests with a population mean of 0. Significance is indicated by * $p<0.05$, ** $p<0.01$, *** $p<0$

BMC: bone mineral content; ToA: total area; CoA: cortical area; Ct.Th: cortical thickness; Ps.Pm: periosteal perimeter; Es.Pm: endosteal perimeter; CoD: cortical density; SSI: stress-strain index; I_{max}: maximum moment of inertia; I_{min}: minimum moment of inertia; I_{max}/I_{min}: ratio between both moments of inertia; J: polar moment of inertia; TrD: trabecular density; BSI: basic-strength index

Table A3. Side-to-side differences for specific bone parameters at different sites along the humerus.

		Humerus		
		Dominant[a]	**Nondominant[a]**	**% Difference (95% CI)[b]**
50%	BMC (mg/cm)	260.9 ± 7.0	220.5 ± 6.5	18.7 (11.8, 25.6)***
	ToA (cm^2)	323.6 ± 10.5	285.0 ± 10.3	13.8 (9.6, 18.1)***
	CoA (cm^2)	203.2 ± 6.0	168.7 ± 4.5	20.8 (12.7, 28.8)***
	Ct.Th (mm)	4.0 ± 0.1	3.5 ± .08	15.5 (6.5, 24.6)**
	Ps.Pm (mm)	63.7 ± 1.0	39.0 ± 0.6	6.7 (4.7, 8.7)***
	Es.Pm (mm)	38.7 ± 1.4	38.0 ± 1.2	1.8 (-3.9, 7.5)
	CoD (mg/cm^3)	1140.4 ± 6.2	1148.0 ± 6.1	-0.6 (-1.8, 0.5)
	SSI (mm^3)	1129.8 ± 53.2	911.8 ± 45.4	24.7 (15.2, 34.2)***
	I_{max} (cm^4)	8037.0 ± 512.3	5857.0 ± 365.9	38.0 (26.8, 49.2)***
	I_{min} (cm^4)	4805.0 ± 391.7	3700.0 ± 287.6	30.9 (18.3, 43.5)***
	I_{max}/ I_{min}	1.7 ± 0.1	0.1 ± 0.1	6.2 (-1.8, 14.1)
	J (cm^4)	12842.3 ± 851.9	9556.7 ± 606.0	35.0 (24.3, 45.7)***
25%	BMC (mg/cm)	254.1 ± 8.5	202.8 ± 6.1	25.8 (16.0, 35.6)***
	ToA (cm^2)	290.5 ± 11.3	252.4 ± 8.1	15.0 (10.4, 19.5)***
	CoA (cm^2)	196.8 ± 6.7	154.2 ± 4.6	28.3 (16.7, 39.9)***
	Ct.Th (mm)	4.2 ± 0.1	3.4 ± 0.1	24.3 (12.2, 36.3)***
	Ps.Pm (mm)	60.3 ± 1.2	56.3 ± 0.9	7.2 (5.1, 9.3)***
	Es.Pm (mm)	34.1 ± 1.2	35.0 ± 0.9	-2.7 (-7.7, 2.3)
	CoD (mg/cm^3)	1160.6 ± 5.9	1162.4 ± 5.5	-0.2 (-1.1, 0.8)
	SSI (mm^3)	968.2 ± 47.2	761.4 ± 36.3	27.7 (17.0,38.3)***
	I_{max} (cm^4)	5845.0 ± 441.6	4161.4 ± 258.7	39.9 (27.6, 52.3)***

	I_{min} (cm^4)	4781.6	±	315.6	3616.6 ± 239.1	33.4 (18.3, 48.5)***
	I_{max}/ I_{min}	1.2	±	0.0	1.2 ± 0.0	5.6 (-0.4, 11.5)
	J (cm^4)	10626.5	±	744.6	7778.1 ± 489.1	36.8 (23.7, 49.9) ***

[a] Data are mean ± SE

[b] Mean percent differences between dominant and nondominant were assed using single sample t-tests with a population mean of 0. Significance is indicated by * p<0.05, ** p<0.01, *** p<0.0

BMC: bone mineral content; ToA: total area; CoA: cortical area; Ct.Th: cortical thickness; Ps.Pm: periosteal perimeter; Es.Pm: endosteal perimeter; CoD: cortical density; SSI: stress-strain index; I_{max}: maximum moment of inertia; I_{min}: minimum moment of inertia; I_{max}/I_{min}: ratio between both moments of inertia; J: polar moment of inertia

Appendices 2: Research Materials

Informed Consent Form for Biomedical Research
The Pennsylvania State University

Title of Project: Effects of Tennis Playing on Muscle Size and Bone Strength

Principal Investigator: Gaele Ducher, PhD
123 Noll Laboratory, Department of Kinesiology
Penn State University
University Park, PA 16802
(814) - 867- 4151
gxd25@psu.edu

Coordinator: Jaclyn Smulofsky
(732)- 299-0833
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Co-Investigator(s): Mary Jane De Souza, PhD
mjd34@psu.edu

Nancy Williams, PhD
niw1@psu.edu

Location of Project: Women's Health and Exercise Laboratory, Department of Kinesiology, Noll Laboratory, Penn State University, University Park, PA ; the General Clinical Research Center, Penn State University, University Park, PA and Department of Nutritional Sciences, Chandlee Laboratory, Penn State University, University Park, PA

1. Purpose of the study:

The purpose of this research is to study the site-specific effects of tennis playing on muscle size and bone strength in adult tennis players. The effect of repetitive loading will be assessed by comparing the playing arm, which is submitted to repetitive impacts and muscle contractions, with the nonplaying arm. The site-specific effects of tennis playing on bone strength in the upper limb (humerus in the upper arm, radius and ulna in the forearm) have not been studied using three-dimensional imaging techniques. Such investigations would provide a better description of the true skeletal benefits associated with tennis playing. A better understanding of how the skeleton responds to exercise requires the assessment of muscle mass, size and strength. The project will also investigate the relationship between muscle and bone tissues and how these two tissues respond to exercise.

2. Procedures to be followed:

Questionnaires: You will be asked to fill out a questionnaire regarding your general medical history (e.g. fracture history) and physical activity history.

Basic anthropometry and muscle strength: you will be weighed on a digital scale in a T-shirt and shorts. Your height will be measured using a stadiometer. Grip strength will be assessed in both arms using a hand-held dynamometer. The length of your forearms will be measured using a plastic tape.

DXA scans: You will undergo five DXA scans. You will first undergo a whole body DXA scan in order to determine your body composition (muscle and fat mass). This scan takes about five minutes. You will be required to lie still on an un-enclosed padded bed. A detector contained in a small narrow arm passes slowly backwards and forwards over the body site being measured. We ask you to wear clothes that do not contain any metal (such as metal zippers). If your clothing does contain significant metal pieces you will be asked to wear T-shirt and shorts for the scan. Four more scans will be performed at different sites (lumbar spine, hip, dominant forearm and nondominant forearm) to measure your bone mineral density. These last four scans are quicker (approximately 20 to 30 seconds each). The whole scanning process will take about half an hour.

pQCT scans: Muscle size and bone strength of the upper arm and forearm will be measured using a peripheral quantitative computed tomography (pQCT) machine that obtains 3-dimensional images of your arm. Both the dominant and nondominant arms will be assessed. You will sit on a chair and put your arm inside the machine, which will then take pictures of your arm from several angles. You will be asked to remove your watch and jewelry before doing the scan. The scans will cause no pain or discomfort other than having to remain still. In total, six pictures will be taken (four in your forearm and two in your upper arm). The whole procedure (6 pictures in the right arm and 6 pictures in the left arm) takes about an hour.

3. Discomforts and risks:

DXA and pQCT scans: The Dual Energy X-ray Absorptiometry (DXA) bone density procedure and the peripheral quantitative computed tomography (pQCT) bone strength procedure exposes an individual to a small amount of radiation where the X-ray beam crosses the body. This radiation exposure is not necessary for your medical care and is for research purposes only. Prior to these tests if you are a woman, as a precaution, we will perform a pregnancy test. This test will require you to provide a sample of urine. A pregnancy test is done before the DXA and pQCT scans because you will be exposed to a small amount of radiation which may be unhealthy for an unborn baby.

> *DXA scans:* The total dose for the five scans (total body, hip, spine and both forearms) is equivalent to a whole body radiation dose of about 3.0 millirem. A millirem is a unit of whole-body radiation dose. For comparison purposes, the average person in the United States receives a radiation exposure of 300 millirem per year from natural background sources, such as from the sun, outer space, and from radioactive materials that are found naturally in the earth's air and soil. A dose of 3.0 millirem is less than you would receive from 4 days of natural background radiation.

pQCT scans: The dose from one pQCT arm scans is equivalent to a whole body radiation exposure of 0.2 millirem. A dose of 0.2 millirem is less than you would receive from 6 hours of natural background radiation. Since the protocol includes 3 sets of scans in each arm, the radiation dose will amount to 1.2 millirems, which is less than 2 days of natural background radiation.

The total radiation dose for the protocol will amount to 3.0+1.2= 4.2 millirem, which is less than what you would receive from 6 days of natural background radiation.

4. Benefits: Benefits of participating in this project include a thorough check-up of your musculoskeletal health, which comprises a measurement of your bone mineral density and your body composition (muscle mass and fat mass). You will receive an individual report including the major outcomes of the project (body composition and bone health), as well as normative data for comparison.
The benefits to society include a better description of the true skeletal benefits associated with playing tennis. They might also help clarifying the causes of overuse injuries such as stress fractures.

5. Duration/time of the procedures and study: The whole procedure will only require one session lasting about 3 hours.

6. Alternative procedures that could be utilized: None

7. Statement of confidentiality: All participant records will be held confidential. Code numbers will be used to store and secure all data that will be collected. Only the investigators listed above will have access to your identity and will be able to access the data.

The Pennsylvania State University's Office for Research Protections, the Institutional Review Board, and the Office for Human Research Protections in the Department of Health and Human Services may review records related to this research study. All records associated with your participation in the study will be subject to the usual confidentiality standards applicable to medical records (e.g., such as records maintained by physicians, hospitals, etc.). In the event of any publication resulting from the research, no personally identifiable information will be disclosed.

8. Right to ask questions: Please contact Dr Gaele Ducher at (814)-867-4151 with questions, complaints or concerns about this research. You can also call this number if you feel this study has harmed you. If you have any questions, concerns, problems about your rights as a research participant or would like to offer input, please contact The Pennsylvania State University's Office for Research Protections (ORP) at (814) 865-1775. The ORP cannot answer questions about research procedures. Questions about research procedures can be answered by the research team.

9. Voluntary participation: Your decision to be in this research is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise.

10. Injury Clause: In the unlikely event you become injured as a result of your participation in this study, medical care is available. It is the policy of this institution to provide neither

financial compensation nor free medical treatment for research-related injury. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

11. Abnormal Test Results: In the event that abnormal bone scan test results are obtained, you will be made aware of the results in 3-5 days and recommended to contact your private medical provider for follow-up. Abnormal results only apply to the DXA scans as there are no norms or reference data for the pQCT scans and grip strength. If your bone mineral density is below the norms, you will be informed and advised to go and see your primary care physician to discuss this further.

You must be 18 years of age or older to take part in this research study. If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent form for your records.

_____ _____

Participant Signature Date

_____ _____

Person Obtaining Consent Date

ANTHROPOMETRY

ID:_____Date:_____

1. Weight: _____ kg

2. Height: 1._____ cm 2._____ cm Average_____ cm

3. Playing Arm? □ Right □ Left

4. Double-handed forehand? □ Yes □ No

5. Double-handed backhand? □ Yes □ No

6. Are you ambidextrous? □ Yes □ No

If Yes, please indicate for which activities you would use your nonplaying arm (e.g. writing, physical work)

_____

_____

6. Grip Strength (3 trials, circle the best result)

Playing Arm _____ / _____ / _____ Nonplaying Arm _____ / _____ / _____

7. Forearm length: Right 1._____ cm 2._____ cm Average_____ cm

Left 1._____ cm 2._____ cm Average_____ cm

8. Comments:

_____

_____

_____

PENNSTATE 1855

ELIGIBILITY

Subject ID:

Date: __ __ / __ __/ __ __

To be filled out by participant prior to each scan:

Screening Questions:	
Have you had any X-ray, MRI or CT procedures within the last 3 days which used: ▪ Iodine, barium, other contrast media or nuclear medicine isotopes	Yes ☐ No ☐ Not sure ☐
Do you have any of the following medical devices in your body: ▪ Ostomy, prosthetic, or surgical devices ▪ Pacemaker leads ▪ Radioactive seeds ▪ Radiopaque catheters/tubes	Yes ☐ No ☐ Not sure ☐
Are you wearing: ▪ Metal buttons, snaps, or zippers ▪ Glasses or jewelry	Yes ☐ No ☐ Not sure ☐
Do you have any of the following foreign (e.g. metal) objects in your body: ▪ Shrapnel, buckshot ▪ Metal plates or joints ▪ Piercings ▪ Other (specify):	Yes ☐ No ☐ Not sure ☐
Do you meet general health guidelines: ▪ Healthy ▪ Well-hydrated	Yes ☐ No ☐ Not sure ☐
<u>If you are a woman:</u> Did you provide a urine sample for a urinary pregnancy test?	Yes ☐ No ☐ Not sure ☐

I certify that the information given above is true and correct to the best of my knowledge.

_____ _____

Research Staff Date

PENNSTATE 1855

ELIGIBILITY

Subject ID:

Date: __ __ / __ __/ __ __

To be filled out by research staff prior to each scan:

Participant's Birthdate_____

Height (cm): _____ Weight (kg):_____ BMI (kg/m^2):_____

Results of the pregnancy test:

☐ Not applicable (explain:_____)

☐ Negative

☐ Positive

OUTCOME OF ELIGIBILITY CHECKLIST

Review questions above:

- ***If any shaded boxes in the Screening Questions are checked, the volunteer is NOT eligible.***
- ***Obtain more information on any Screening Questions that have a "Not sure" box checked. Write clarification notes on the form to document eligibility status based on response.***
- ***If pregnancy test is positive, the volunteer is NOT eligible.***

☐ ELIGIBLE ☐ NOT ELIGIBLE

1. DEMOGRAPHICS AND MEDICAL HISTORY

Directions: Please answer the following 18 questions about your medical history and some general information, directly onto the survey. If you have any questions, ask one of the investigators.

ID_____Date:_____

1. Age: _____ years Date of Birth: ____ / _____ / 19_____
2. Gender: M □ F □

3. Racial Category: (please check *ONLY* one)

□ Aboriginal/First Nations/Inuit
□ Black/Caribbean
□ Asian
□ Latin American
□ Middle Eastern
□ South-Asian
□ White/Caucasian/European
□ Other

4. Are you currently under a doctor's care? □ Yes □ No

If yes, please describe the reason.
_____

5. Please describe any current illness or conditions:
_____

6. Please indicate in the following table if you take any medications and/or supplements on a regular basis (e.g. asthma medication, calcium supplements…)

Medications/Supplements	Brand	Dose	Times per Week	For What Condition?

7. Do you currently smoke? □ Yes □ No

If yes, how many cigarettes do you smoke per day? _____

8. Did you smoke in the past? □ Yes □ No

If yes, for how long? _____

WOMEN ONLY (MEN Please go to section 3)

2. MENSTRUAL CYCLE HISTORY

Directions: Estrogens are known to have a strong influence on bone health. This section of the questionnaire aims at collecting information on your menstrual history because it may have affected your bone health. Please answer the following 22 questions about your menstrual cycle status and history directly onto the survey. If you have any questions, please to not hesitate to ask one of the investigators.

1. How old were you when you first menstruated?
I was _____ years old when I first menstruated.

2. If you recall, approximately how much did you weigh when you first menstruated?
My weight at that time was _____(lbs)

3. Have you ever given birth? (check only one)
□ *I have never given birth* (skip to # 5)
□ *I have given birth, and I was _____yrs old* (please answer #4)

4. If the answer to #3 is YES, indicate how many births_____; date(s)_____

5. Have you, in the past, gone for any length of time without menstruating regularly?
□ *Yes* (please answer # 6, # 7, and # 8)
□ *No* (skip to # 9)
if yes, for how long _____

6. If the answer to # 5 is YES, do you remember how old you were at that time?
□ *Yes, I was _____years old* (please answer # 7 and # 8)
□ *No, I don't remember how old I was* (please answer # 7 and # 8)

7. If the answer to # 5 is YES, what were the circumstances (e.g., exercising excessively, dieting, or other stressors) that were present during this time?

□ *I don't remember any unusual circumstances during that time* OR
*The circumstances were:*_____

8. If the answer to # 5 is YES, do you remember your approximate weight at the time?
□ *Yes, I weighed _____ pounds/kilograms.*
□ *I don't remember my weight at that time.*
□ *My weight at that time was approximately _____ pounds.*

9. Currently, what is the average length of your menstrual cycle (from the beginning of menstrual flow [menses] to the beginning of the next menstrual flow [menses])?
My average cycle length is _____days

10. Currently, for how many days do you typically experience menstrual flow each cycle?
□ *1 day* □ *2 days* □ *3 days* □ *4 days* □ *5 days* □ *> 5+ days*

11. In the past 3 months, estimate how many menstrual cycles you have had?
I have had _____cycles in the past 3 months

12. In the past 6 months, estimate how many menstrual cycles you have had?
I have had _____cycles in the past 6 months

13. In the past 9 months, estimate how many menstrual cycles you have had?
I have had _____cycles in the past 9 months

14. In the past 12 months, estimate how many menstrual cycles you have had?
I have had _____cycles in the past 12 months

15. Are you currently taking oral contraceptives?
□ *Yes* (please answer # 16)
□ *No* (skip to # 17)

16. If the answer to #15 is YES, how long have you been taking oral contraceptives?
□ *< 3 months* □ *3- 6 months* □ *6-12 months* □ *1-1.5 years* □ *> 1.5 years*

17. If the answer to #15 is NO, have you taken oral contraceptives in the past? If so, how old were you when you took them?
□ *Yes, I have taken oral contraceptives in the past when I was_____ years old.*
□ *No, I have not taken oral contraceptives in the past.*

18. Have you ever taken oral contraceptives for irregular periods? □ Yes □ No

19. Have you ever taken oral contraceptives OR other hormones for amenorrhea (absence of menses). □ Yes □ No

If yes, please explain:

20. Have you ever had any of the following surgical procedures (check all that apply):

- □ *Hysterectomy*
- □ *Oophorectomy (removal of one or both ovaries)*
- □ *Tubal ligation*
- □ *Other gynecological procedure(s) (please list)*

_____
_____

21. Have you ever had a miscarriage? □ Yes □ No

22. Have you ever had an episode where you had no period for 3 months or longer? □ Yes □ No

If yes, for how long?_____

Was this the first episode? □ Yes □ No

If no, please explain_____

3. BONE HEALTH AND FRACTURE HISTORY

Directions: Please fill out the following questions and chart(s) regarding your bone health history directly onto the survey. If you have any questions, please do not hesitate to ask any of the investigators.

A. HISTORY OF STRESS FRACTURES

A stress fracture is an overuse injury often caused by repetitive impacts to your bones (such as doing a lot of repetitive exercise like training for a marathon), rather than a sudden high impact (such as a fall or an accident).

1. Have you ever had a stress fracture?

□ Yes □ No □ Don't Know

If you ticked Yes, answer question #2.

If you ticked No or Don't Know, go to section B. (History of Other Fractures).

2. Please fill out the chart below regarding your stress fracture(s). Record the site of the stress fracture, whether or not the fracture was diagnosed by a doctor, and whether or not the stress

fracture was diagnosed using an x-ray, CT scan or MRI. If you don't know the answers to any of these questions, write "don't know".

What bone or limb did you fracture?	Was this stress fracture diagnosed by a doctor? If yes, please state date (or year)	Was this stress fracture diagnosed by a x-ray, CT scan, or MRI?	What caused the stress fracture?

B. HISTORY OF OTHER FRACTURES

This section deals with fractures that are not stress fractures, i.e. they occurred after a low, moderate or high-impact (fall, contact when playing sport, car accident…).

1. Have you ever had a fracture?

□ Yes □ No □ Don't Know

If you ticked Yes, answer question #2.

If you ticked No or Don't Know, go to the next section (History of Other Injuries).

2. Please fill out the chart below regarding your fracture(s). Record the site of the fracture and whether or not the fracture was diagnosed by a doctor. Most fractures would be diagnosed using a standard x-ray. If you don't know the answers to any of these questions, write "don't know".

What bone (or limb) did you fracture?	Was this fracture diagnosed by a doctor? If yes, please state date (or year)	Was this fracture diagnosed by a x-ray?	What caused the fracture?

HISTORY OF OTHER INJURIES

1. In the past 12 months, have you had to refrain from training due to an injury other than a fracture (sprain, muscle tear…)? □ Yes □ No

If you ticked yes, answer question 2**,** and if you ticked no, proceed to the next section (History of Bone Density Tests)

2. Please describe the injury(s) below. If you don't know, write "don't know"

Describe the Injury	Did this injury occur as a result of exercise training (yes/no)	How long you were unable to exercise for.	How much exercise training were you doing at the time?

HISTORY OF BONE DENSITY TESTS

1. Have you ever had a bone density test? □ Yes □ No
   If yes, were you diagnosed with low bone density? □ Yes □ No
   If yes, did you get prescription medication? □ No □ Yes (name:_____)
   If yes, are you taking it currently? □ No □ Yes (dose:_____)

FAMILY HISTORY OF OSTEOPOROSIS

1. Does your mother/grandmother have a history of osteoporosis? □ Yes □ No
2. Does your mother/grandmother have a history of broken bones (fractures)? □ Yes □ No
3. Does your father/grandfather have a history of osteoporosis? □ Yes □ No
4. Does your father/grandfather have a history of broken bones (fractures)? □ Yes□ No
5. Any other significant family history of osteoporosis that you are aware of?□ Yes □ No

If yes, which member of your family?_____

4. CURRENT AND PAST PHYSICAL ACTIVITY SURVEY

Directions: Please answer the following questions regarding your current and past physical activity habits.

TENNIS

1. Please fill out the following table regarding your **tennis training schedule**. Start with your current training schedule and then detail your training schedule during the previous years.

Age (yrs)	Sessions / week?	Total Hours / week? (include competitions)	Do you practice the whole year round? (YES/NO)	Competitions (Please give grade if yes)
Your age today: ___				

1 year ago / Age ___				
2 years ago / Age ___				
3 years ago / Age ___				
4 years ago / Age ___				
5 years ago / Age ___				
6 years ago / Age ___				
……..				

2. Has there been any time longer than two consecutive months when your training for tennis has been interrupted? □ Yes □ No

If yes: How old were you when your training was interrupted? _____

How long was your training schedule interrupted? _____

Why was your training interrupted (e.g. injury)? _____

OTHER ACTIVITIES

1. With respect to activities **other than tennis,** please state the following (please include activities such as gym work):

Age	Activity	Months per year	Days per week	Hours per session	Years Spent Playing this sport
Example	Basketball	12	2	1	3

2. Do you participate in some forms of resistance training (ie. lifting weights at the gym)? (If you go to the gym regularly and do weight training but also some aerobic training (cycling, running, walking, rowing), please consider **only the time when you lift weights** for this particular section, not the aerobic work).

□ Yes □ No

If yes, how many training sessions of resistance training do you do at the gym per week and how long are these sessions usually?

Number of sessions: _____ / week

Duration of an average session: _____min / session

Do you usually do exercises on the upper body, lower body or both?

□ Upper body only □ Lower body only □ Both upper and lower body

For how long have you been doing resistance training? _____ Years

Academic Vita

Jaclyn P. Smulofsky
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State College, PA 16801
(732)-299-0833

Permanent Address
28 Nashua Drive
Marlboro, NJ 07746
(732)-780-3798

EDUCATION

The Pennsylvania State University: Schreyer Honors College, University Park, PA
Bachelor of Science in Kinesiology
Honors in Kinesiology
Option Movement Science
Graduate May 2011

THESIS

Site-specific effects of tennis playing on muscle size and bone strength in the dominant arm of female tennis players
Supervised by: Dr. Gaele Ducher and Dr. Mary Jane DeSouza

RELATED EXPERIENCE:

Women's Health and Exercise Lab, Noll Laboratory, University Park, PA
Research Assistant Fall 2009-present

- Organize data, aliquot samples, and help run various studies
- Created thesis project comparing the response of loading on dominant and nondominant arms of female tennis players

Penn State Department of Biology, University Park, PA
Physiology Laboratory Teaching Assistant Fall 2010

- Teach and mentor students in one laboratory section the different aspects of Physiology
- Prepare for labs, grade papers, and hold office hours each week

Free Motion Rehabilitation Center, Howell, NJ
PT Aid May-July 2009, May-July 2010

- Observed therapists and helped patients perform exercises
- Supplied cold packs, hot packs, and helped set up the electrical stimulation machine

Special Strides Therapeutic Riding Center, Monroe, NJ
Sidewalker June 2010

- Helped stabilize patients while riding horses
- Assisted with therapeutic practices for riders suffering from disabilities

Rusk Institute of Rehabilitation Medicine, New York, NY
Student Physical Therapy Volunteer June 2009-July 2009

- Observed therapists in a pediatric and an orthopedic inpatient setting
- Helped patients with their daily activities and assisted with personal exercise routines

LEADERSHIP AND EXTRACURRICULAR ACTIVITES

National Service Sorority: Gamma Sigma Sigma Fall 2008-Fall 2010

- Participate in and organize various community service activities

National Society of Collegiate Scholars Fall 2008-present

Human Health and Development Honor Society Fall 2008-Spring 2009

- Attend monthly meetings and participate in community service events each semester

Penn State Dance Marathon
Rules and Regulations Committee Member Fall 2007-Spring 2008

- Responsible for security and regulations throughout the dance marathon weekend

Operations Committee Member Fall 2008-Spring 2010

- Help fundraise for the largest student run philanthropy in the world
- Assisted with set-up, tear-down, and event activities

Kinesiology Club
Kinesiology Peer Student Mentor Fall 2008-Spring 2009

- Mentored a lowerclassmen majoring in Kinesiology

Fresh Start Day of Service
Fresh Start Team Leader Fall 2009

- Lead a group of Freshmen students through a day of community service events and bonding activities

AWARDS

Dean's List: Fall 2007, Spring 2008, Fall 2008, Spring 2009, Fall 2009, Spring 2010, Fall 2010