The Relationship of Gymnastics Participation in Childhood and Adolescence

to Skeletal Development and Maintenance

A Thesis Submitted to the College of

Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of Doctor of Philosophy

In the College of Kinesiology

University of Saskatchewan

Saskatoon, Saskatchewan

By

Marta Christine Erlandson

ABSTRACT

Osteoporosis, through its association with age-related fracture, is a major public health concern worldwide. Although osteoporosis was once considered a disease of the elderly, it is now recognized as a condition that has childhood antecedents. The capacity of bone to adapt is the greatest before puberty because of a higher rate of modeling and remodeling. Therefore, the amount of bone gained during childhood and adolescence has the potential to impact lifetime skeletal health. Children who participate in greater amounts of physical activity have greater bone mineral accrual in adolescence as well as a greater peak bone mass in young adulthood. Structured impact loading during growth also positively influences bone parameters. However, the intensity, duration and frequency of loading that is required to elicit skeletal benefits are not well established. Furthermore, although structured physical activity during growth has been hypothesized to delay or prevent the risk of osteoporosis and related fracture later in life there is no clear evidence of a persisting benefit once the loading stimulus has been removed. Therefore, the objective of this thesis was to investigate low-level impact loading during growth and skeletal development as well as to determine the influence of the withdrawal of the loading stimulus on adult bone parameters. Two studies were necessary to realize this objective. The findings should help to determine whether adolescent and adult bone health benefits from structured physical activity during growth. If this is found to be the case then structured gymnastic activity could be promoted as an effective means to optimize adult bone mass, structure and estimated strength.

Study 1: The purpose of study one was to investigate whether the differences previously reported in the skeleton of competitive female gymnasts (high level gymnastics exposure) are also demonstrated in young children with a current or past participation history in recreational or precompetitive gymnastics (low level gymnastics exposure). One hundred and sixty three children (30 gymnasts, 61 ex-gymnasts, and 72 non-gymnasts) between 4 and 6 years of age were recruited and measured annually for four years. Total body (TB), lumbar spine (LS) and femoral neck (FN) bone mineral content (BMC) was measured by dual energy x-ray absorptiometry (DXA) at each measurement occasion. Bone mass, density, structure and estimated strength was determined using peripheral quantitative computed tomography (pQCT) at the radius and tibia during the third measurement occasion. Multilevel random effects models were constructed and used to predict differences in TB, LS and FN BMC between groups while controlling for differences in body size, physical activity and diet. Analysis of covariance (covariates of sex, age and height) was used to investigate differences in bone content, density, area, and estimated strength at the radius and tibia. Gymnasts had 3% more TB and 7% more FN BMC than children participating in other recreational sports at the fourth measurement occasion ($p<0.05$). Gymnasts were also found have 6-25% greater adjusted BMC, volumetric bone mineral density and estimated strength at the distal radius compared to non-gymnasts ($p<0.05$). These findings suggest that recreational and precompetitive gymnastics participation (low level gymnastics exposure) is associated with greater bone parameters. This is important as beginner gymnastics skills are attainable by most children and do not require a high level of training. Low-level gymnastics skills can easily be integrated into school physical education programs potentially impacting skeletal health.

Study 2: The purpose of study 2 was to assess whether the previously reported greater bone mineral content in premenarcheal gymnasts was maintained 10 years after the cessation of participation and removal of the gymnastics loading stimulus. In 1995, thirty elite premenarcheal female gymnasts were recruited into a study investigating the role of high impact physical activity on bone mass in childhood and compared to 30 non-gymnasts. In 2009-2010 gymnasts and non-gymnasts (n=60) were re-contacted and 25 retired gymnasts and 22 non-gymnasts consented to participate. Total body, LS, and FN BMC was assessed at both measurement occasions by DXA. Bone geometric and densitometric parameters were measured by pQCT at the radius and tibia in 2009/10. ANCOVA was used to compare gymnasts' and non-gymnasts' bone parameters while controlling for differences in age, body composition and maturation. Gymnasts had significantly greater size adjusted TB, LS, and FN BMC (15, 17, and 12%, respectively) at 12 years of age (1995) ($p<0.05$). At follow-up, retired gymnasts also had significantly greater size adjusted TB, LS, and FN BMC (13, 19 and 13%, respectively) ($p<0.05$). Furthermore, retired female gymnasts had greater bone area, content and estimated strength at the radius and greater BMC and estimated strength at the tibia compared to non-gymnasts ($p<0.05$). Premenarcheal gymnasts have bone benefits that were apparent in adulthood after long-term removal of the gymnastics loading stimulus. Low level gymnastics exposure was associated with greater bone parameters in childhood. If these benefits can be maintained, as is suggested in retired competitive gymnasts, recreational gymnastics participation has the potential to positively impact lifetime skeletal health.

ACKNOWLEDGEMENTS

This thesis is dedicated to my parents Martin and Cheryl for their unending support and encouragement and for always believing in me. They have endured all the ups and downs that the process of writing a thesis yields, from tears in oatmeal and minor mental breakdowns to the joy of receiving scholarships, having manuscripts accepted and producing a final product. I owe you both a special thank you for the numerous rounds of proof reading you have had to endure – mom for all your grammatical and 'english teacher' help and dad for all your assistance with the scientific aspect. We all knew that one degree wasn't going to be enough, but after 10 years and three degrees I think I am done. I appreciate all the time and energy you have devoted to guiding and aiding me to this place in my educational journey – thank you!!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVATIONS

aBMD	Areal Bone Mineral Density (g/cm^2)
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
APHV	Age at Peak Height Velocity
BMC	Bone Mineral Content (g)
BSI	Bone strength index (mg^2/mm^4)
Ca^{2+}	Calcium (mg)
CoA	Cortical bone area (mm^2)
CoC	Cortical bone mineral content (g/cm)
CoD	Cortical volumetric bone mineral density (mg/cm^3)
CoTHK	Cortical wall thickness (mm)
DXA	Dual energy X-ray Absorptiometry
EGYM	Ex-gymnast Group
FA	Forearm
FM	Fat mass (kg)
FN	Femoral Neck
Gym	Gymnast Group
Ht	Height (cm)
IU	International Units
LL	Lower leg
LM	Lean mass (kg)
LS	Lumbar Spine
MCSA	Muscle cross-sectional area (mm^2)
MedA	Medullary area (mm^2)
NGym	Non-gymnast Group
NPAQ	Netherlands Physical Activity Questionnaire
N	Number of participants
PA	Physical Activity
PAQ-AD	Physical Activity Questionnaire for Adults
PAQ-C	Physical Activity Questionnaire for Children
PBMAS	Pediatric Bone Mineral Accrual Study (University of Saskatchewan)
PHV	Peak Height Velocity
pQCT	Peripheral Quantitative Computed Tomography
QCT	Quantitative Computed Tomography
SD	Standard Deviation
SSIp	Polar Stress strain index (mm^3)
SSIx	Bone bending strength in the x axis (mm^3)
SSIy	Bone bending strength in the y axis (mm^3)
TB	Total Body
TBLH	Total Body Less Head
ToA	Total bone area (mm^2)
ToC	Total bone mineral content (g/cm)

ToD	Total volumetric bone mineral density (mg/cm^3)
TrA	Trabecular bone area (mm^2)
TrC	Trabecular bone mineral content (g/cm)
TrD	Trabecular volumetric bone mineral density (mg/cm^3)
vBMD	Volumetric Bone Mineral Density (mg/cm^3)
Vit D	Vitamin D (IU)
Wt	Weight (kg)
% Fat	Percent body fat
♂	Male
♀	Female

CHAPTER 1: Introduction

1.0 Introduction

Osteoporosis is the most common bone disorder in the world and a major cause of loss of independence in the elderly; approximately 60% of women and 30% of men over the age of 50 will suffer from an osteoporotic fracture in their remaining lifetime (US Department of Health and Human Services, 2004). In Canada, it is estimated that as many as 2 million individuals suffer from osteoporosis (Osteoporosis Canada, 2010). Osteoporosis, through its association with age-related fractures, is a cause of longstanding pain, functional impairment, disability and death in the elderly, and a major contributor to medical care costs worldwide (Cummings et al., 2002; Oliver et al., 2007). The direct medical costs for this disease are estimated to be $1.9 billion per year in Canada and are expected to continue to rise as the Canadian population ages (Osteoporosis Canada, 2010).

Although the consequences of poor skeletal health are mainly observed later in life, and fracture prevention has been directed at delaying the rate of age-related bone loss, the most effective time to influence skeletal health appears to be at the opposite end of the lifespan. The capacity of bone to adapt is greatest before puberty because a higher rate of modeling and remodeling during growth promotes adaptation in bone size, shape, and mineralization (Bass, 2000). Therefore, understanding the determinants of childhood and adolescent bone mineral accrual is imperative. Many factors influence skeletal development during childhood and adolescence, including genetics, sex, body composition, diet and physical activity (Khan et al, 2001). Of the modifiable factors that influence the skeleton, such as nutrition and exercise, it has been hypothesized that

1

weight bearing physical activity during growth has the greatest potential to influence peak bone mass and subsequently the public health burden of osteoporosis. Peak bone mass can be defined as the amount of bone present at the end of skeletal maturation and is an important determinant of osteoporotic fracture risk (Bonjour et al., 1994; Bonjour et al., 2009). Children with greater levels of habitual physical activity have greater bone mineral accrual in adolescence (Bailey et al., 1999) and greater peak bone mass in young adulthood (Baxter-Jones 2008); however, the mode as well as the intensity, duration, and frequency of activity that is optimal or beneficial for accretion of bone mineral is not well established. Furthermore, little is known of the effect of habitual or structured physical activity on bone geometry, which is important because bone strength has been found to increase independent of changes in bone mass (Adami et al., 1999; Robling et al., 2006).

Gymnastics training results in unique high mechanical loading to the skeleton and thus provides an excellent model for assessing structured weight bearing physical activity and bone mass, density, structure and estimated strength (Daly et al., 1999, Proctor et al., 2002). The majority of studies have demonstrated that competitive female gymnasts have greater areal bone mineral density (aBMD, g/cm^2) and bone mineral content (BMC, g) when compared to other athletic and non-athletic populations (Caswell et al., 1996; Laing et al., 2002; Zanker et al., 2003; Nickols-Richardson 2000; Proctor et al., 2002; Robinson et al., 1995; Bass et al., 1998). Furthermore, total and regional aBMD is greater in gymnasts with higher exposure to gymnastics, i.e. greater hours or years of training (Scerpella et al., 2003, Laing et al., 2005). Studies examining gymnasts' bone parameters have generally focused on competitive athletes who had been systematically training for at least 2 years and who trained a minimum of 10 hours per week year round. However,

competitive gymnastics is a high level sport and participation is limited to a select number of skilled individuals. Recreational gymnastics, on the other hand, is attainable by most children and does not require a high level of training. However, less is known about recreational and precompetitive gymnastics participation (i.e., low-level gymnastics exposure) and bone parameters.

Although it has been hypothesized that attaining a high peak bone mass early in life may prevent the risk of osteoporosis and related fracture risk later in life there is no clear evidence of a persisting benefit of structured physical activity during growth on adult bone mass, density, structure or estimated strength once the loading stimulus has been removed. Currently, the best evidence linking structured childhood physical activity and bone health in adulthood is based on cross-sectional and short-term prospective studies in former competitive athletes. Cross-sectional studies of former athletes who started training in childhood suggest that bone gains achieved during the younger years may be maintained into adulthood; however, exercise during growth remains an unproven investment as an evidence-based means to prevent osteoporotic fracture (Pollock et al., 2006).

Retired artistic female gymnasts provide a unique model to examine the influence of structured childhood physical activity on adult bone health. As previously stated, young competitive gymnasts have greater aBMD and BMC when compared to other athletic and non-athletic populations (Proctor et al., 2002; Robinson et al., 1995; Bass et al., 1998). Furthermore, retired artistic gymnasts have significantly higher aBMD values compared to non-athlete controls with differences ranging from 5-22% (Kirchner et al., Bass et al., 1998, Zanker at al., 2004, Pollock et al., 2006). This suggests that potential

bone gains from participation in high impact youth sport persist into adulthood after removal of the high-load stimulus. However, to date, no known studies have examined structured high impact activity in childhood and adolescence and followed the same individuals into adulthood after cessation of sport participation and withdrawal of the ostoegenic stimulus to determine if and how much of the increased bone mineral content is maintained compared to a group of normal healthy controls.

The overall goal of this thesis was to investigate low exposure, structured impact loading activity during childhood and subsequent bone development and determine the long-term influences of childhood and adolescent sport participation on adult bone health. A gymnastics model was utilized and two studies were required to achieve these two objectives. The first study explored whether the differences previously reported in the skeleton of elite competitive female adolescent gymnasts (high-level gymnastics exposure) are also demonstrated in young children with a current or past participation history in recreational or precompetitive gymnastics (low-level gymnastics exposure). The second study investigated whether the previously reported benefit of premenarcheal gymnastics training on bone mineral content (Faulkner et al., 2003) was maintained 14 years later, after retirement from sport and removal of the gymnastics loading stimulus. The findings from these two studies will help to determine the exposure required for bone health benefits, as well as identify whether structured physical activity during growth can be promoted as an effective means to optimize adult bone mass, structure and estimated strength. The specific objectives and hypotheses for each study are described below.

1.1 Study 1: Low-level gymnastics exposure and bone development in 4-10 year olds: A four-year longitudinal study

Objectives:

1) Determine the influence of low-level gymnastics exposure on bone mineral accrual from 4-10 years of age.

2) Compare bone mass, volumetric density, structure and estimated strength between recreational and precompetitive gymnasts and children involved in other non-gymnastic recreational sports.

Hypotheses:

1) Young male and female gymnasts, with low levels of gymnastics exposure, would have greater bone mineral accrual than non-gymnasts.

2) Young gymnasts would have greater bone mass, structure and estimated strength compared to non-gymnasts.

1.2 Study 2: Premenarcheal gymnastics participation and adult bone mass, density, structure and estimated strength

Objective:

1) Compare adult bone mass, density, structure and estimated strength between retired premenarcheal female gymnasts and non-gymnasts, after 10 years of retirement from gymnastics.

Hypotheses:

1) Retired gymnasts would have greater bone mass, areal and volumetric density, size, and estimated strength compared to non-gymnasts.

CHAPTER 2: Review of Literature

2.1 Introduction

Osteoporosis and related fractures are a major public health concern and the prevalence is expected to increase dramatically over the coming decades, primarily due to an ageing population. By the year 2041 the annual economic impact of hip fractures alone is projected to be $2.4 billion in Canada (Wiktorowicz et al., 2001). Although osteoporosis was once considered a disease of the elderly, it is now recognized as a condition that has childhood antecedents (Faulkner and Bailey, 2007). While genetics play an important role in the attainment of peak bone mass and strength, accounting for up to 85% of inter-individual variance, lifestyle factors such as physical activity and diet are also important determinants of bone health. However, the long-term implications of these factors on adult bone health are not yet well defined. In this literature review the following topics will be described: the growing burden of osteoporosis on the health care system, bone biology, bone imaging modalities, and the determinants of skeletal health including genetics, hormonal status, nutrition, body composition and impact loading. The influence of habitual and structured childhood physical activity and specifically gymnastics training on skeletal development and maintenance will also be discussed.

2.2 Osteoporosis

Osteoporosis is the most common bone disorder in the world. It is estimated that approximately 200 million people worldwide are affected and the prevalence is expected to continue to increase primarily due to an ageing population (Cooper C, 1999). In Canada, it has been predicted that as many as 2 million individuals live with osteoporosis

(Osteoporosis Canada, 2010). That equates to one in four women and at least 1 in 8 men over the age of 50, in Canada, suffering from osteoporosis (Osteoporosis Canada, 2010). It is a major cause of loss of independence in the elderly with approximately 60% of women and 30% of men over the age of 50 suffering from an osteoporotic fracture in their remaining lifetimes (US Department of Health and Human Services, 2004). Osteoporosis has often been referred to as a 'silent disease' because bone loss occurs without symptoms and has no signs until a fracture occurs. It is defined as a disease process characterized by low bone mass and micro architectural deterioration of bone tissue leading to enhanced bone fragility and a subsequent increase in fracture risk (The Consensus on Development Conference, 1993). Figure 2.1 is a 3-D rendition of a section of vertebral bone illustrating the difference in architecture between a young healthy bone and an osteoporotic bone.
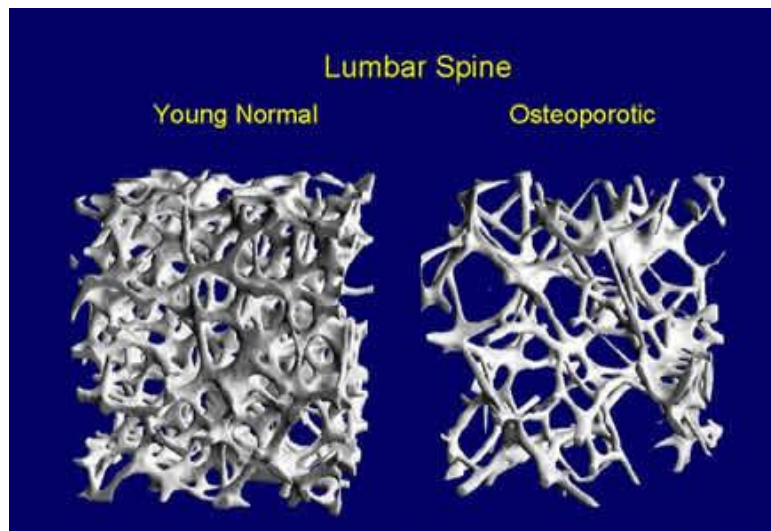
Figure 2.1 – A section of healthy young lumbar spine vertebrae and a section of osteoporotic lumbar spine vertebrae. From Scanco µCT website (retrieved on September 12, 2010 www.scanco.ch/documentation/imagesanimations/animations.html)

The greatest clinical consequence of osteoporosis is fracture. Kanis et al. (2001) define osteoporotic fractures as any fracture occurring at a site associated with low aBMD. It is estimated that up to 80% of all fractures in individuals over the age of 50 can be attributed to osteoporosis (Bessette et al., 2008; Milton et al., 1992) and that 50 million people, worldwide, suffer from osteoporotic fractures (Johnell and Kanis, 2006). The most common fracture sites are the hip, spine, and distal forearm. Fractures related to osteoporosis often entail a number of serious complications, which in turn lead to an enormous expense and high mortality rates (Lorrain et al., 2003). After suffering a hip fracture 20% of individuals die within the first year, 40% are unable to walk independently, and 60% require long-term care (Cooper et al., 1993; Magaziner et al., 1990; World Health Organization, 2003). Another important consideration of osteoporotic fracture is the economic burden, which includes both direct (i.e., health care expenditure) and indirect (i.e., lost earnings and equipment) costs. The cost to the Canadian health care system of treating osteoporosis and the fractures it causes is currently estimated to be $1.9 billion annually and these costs are expected to continue to rise as the Canadian population ages (Osteoporosis Canada, 2010).

The burden of osteoporosis has largely been assessed in terms of fracture incident and economic costs; however, the physical, psychological and social consequences of osteoporotic fractures must also be considered when quantifying the impact of this disease. For example, it is estimated that only one half of individuals who suffer an osteoporotic hip fracture will ever regain the ability to perform normal life activities (Lorrain et al., 2003). Individuals with these fractures often have a reduced ability to perform daily household and self-care activities such as cooking, vacuuming, bathing and

dressing (Huang et al., 1996; Papaioannou et al., 2008). In a large multi-center Canadian study Adachi and colleagues (2001; 2003) found that health-related quality of life decreased in women and men following an osteoporotic fracture and that this health-related quality of life impairment was long term. In a survey of women aged 75 years and over, 80% of women said they would rather be dead than experience the loss of independence and poor quality of life that results from a hip fracture (Salkeld et al, 2000). It has been suggested that unless decisive steps for preventive intervention are taken a catastrophic global epidemic of osteoporosis seems inevitable (Riggs and Melton, 1995; World Health Organization, 2003).

2.2.1 A Pediatric Concern?

Although the consequences of poor skeletal health are mainly observed later in life, and fracture prevention has been directed at delaying the rate of age-related bone loss, the most effective time to influence bone health appears to be at the opposite end of the lifespan. Childhood and adolescence is a particularly important period because the skeleton undergoes rapid change due to the process of growth, modeling and remodeling (Bass 2000). The amount of bone gained during this period of accelerated bone accrual impacts greatly on lifetime skeletal health (Bailey, 2000). As discussed, osteoporosis is an age-related metabolic bone disorder characterized by low bone density and structural deterioration of bone tissue. Low bone mass in older adulthood may be the result of accelerated bone loss during ageing or a failure to reach an adequate peak bone mass during the growing years.

It has been suggested that a 10% increase in peak bone mass would delay the onset of osteoporosis by 13 years, while a 10% reduction in age-related bone loss would only delay the onset by 3 years (Bonjour et al., 2007). As such it is imperative to maximize the attainment of peak bone mass in childhood and adolescence to prevent or delay osteoporosis and related fracture later in life. Obtaining and maintaining high levels of bone mineral density is the single best defense against osteoporosis. For example, a 10% increase in adult bone mineral content at the femoral neck (hip) reduces the risk of fracture at that site by one half (Cumming et al., 1993; US Department of Health and Human Services; 2004). Therefore, understanding the determinants of childhood and adolescent bone mineral accrual are imperative.

2.3 Bone Biology

Bone is a dynamic tissue that continually adapts to produce a structure strong enough to support the functional needs of the skeleton without fracture. The skeleton serves as a framework for the body, acts as a protector of vital organs, and facilitates movement by acting as a sequence of lever arms. Skeletal bone also plays an integral role in body processes such as immune function and calcium and phosphate homeostasis. Bone is composed mainly of type I collagen embedded with calcium hydroxyapatite (Khan et al., 2001). The relative amount of mineral in the collagen matrix varies according to the function and age of the bone (younger individuals have less mineralization) and is a major determinant of bone strength. Bone is a remarkable structure comprised of a strength greater than oak, brick, or even concrete (Einhorn, 1996), a bending resistance as effective as cast iron yet weighing only one-third as much

per unit of volume, and a flexibility that allows for absorption of sudden impacts without fracture (Forwood, & Burr, 1993).

There are two types of bone tissue in the human body: cortical (compact) bone and trabecular (cancellous) bone. The skeleton is comprised of approximately 75-80% cortical bone and 20-25% trabecular bone. An important differentiation between cortical and trabecular bone is in the manner in which the bone matrix and cellular elements are arranged. These differences permit the two types of bone to function differently. Cortical bone is a densely arranged tissue that forms the outer surface of all bones and is primarily found in the shaft of long bones. It functions to provide structure and ensures the integrity of the skeleton. Trabecular bone is a spongy lattice-like structure made of horizontal and vertical interconnecting plates called trabeculae. It is found primarily at the ends of long bones and within the vertebral bodies. Trabecular bone is architecturally adapted to withstand mechanical stress and is more responsive to the metabolic demands of the skeleton because of its higher surface area to volume ratio. Trabecular bone turnover is approximately 26% per year versus 3% in cortical bone (Khan et al, 2001).

2.3.1 Changes in Bone due to Normal Growth, Development, and Maturation

Growth is the attainment of size of a given tissue by an increase in number of cells (hyperplasia), size of cells (hypertrophy), or an increase in cellular matrix. It is the expression of the genetic program and is under the control of the endocrine system (Ohlsson et al., 1993). The growth of the skeleton determines the size and proportion of the body. This process is tightly regulated. During growth, both bone geometry and material composition are modified to produce a mechanically competent skeletal

structure (Kontulainen et al., 2007). Long bones grow in length through the process of endochrondal ossification. This occurs at the growth plate, a cartilaginous region located between the epiphysis and metaphysis of long bones (Figure 2.2). The growth plate (epiphyseal plate) is a narrow band made up of two regions: the proliferating cartilage zone and the cartilage hypertrophy zone. Multiplication of cartilage cells and elaboration of intercellular matrix occur in the cartilage proliferation zone. In the proceeding zone, cartilage cells are arranged into columns, which mature and calcify. Ossification (replacement of cartilage with bony tissue) then occurs in the metaphysis. This process continues throughout childhood and rapidly accelerates during the adolescent growth spurt in height. After the adolescent growth spurt, the rate of cartilage cell proliferation slows and eventually stops. The epiphyseal plate completely ossifies (fuses) usually in the early twenties (earlier in girls than boys) and the bone can no longer grow in length.
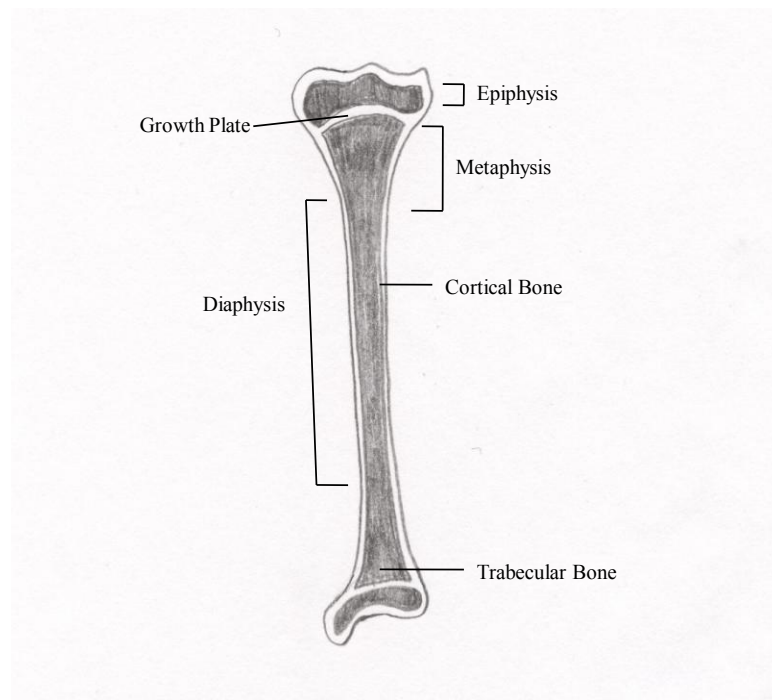
Figure 2.2 – Schematic view of a growing bone adapted from Khan et al. 2001.

Long bones also grow in size (width) and redistribute mass further from the central axis through the process of modeling. The diameter of a bone enlarges through appositional growth on the outer (periosteal) surface of the bone. Bony tissue is deposited on the periosteal surface and resorbed on the inner (endosteal) surface (Parfitt, 1994). These two processes act together to increase bone size and enlarge the medullary cavity, which in turn increases bone's resistance to bending and prevents the cortical shell from becoming excessively thick and too heavy for efficient locomotion. The timing and rate of increase in bone girth is related to both pubertal development and sex (Kontulainen et al., 2007). Whereas epiphyseal plates usually fuse between 18-25 years of age and longitudinal growth ceases, circumferential growth occurs throughout life. Three types of bone cells are primarily involved in the modeling, formation, and resorption of bone. Osteoblasts are the bone cells that produce the bone matrix, osteocytes are mature bone cells embedded deep within the bone, and osteoclasts are the bone cells responsible for bone resorption or removal of old bone.

The Saskatchewan Pediatric Bone Mineral Accrual Study (PBMAS) was one of the first studies to describe the developmental pattern of bone accretion from childhood through adolescence and into young adulthood (Bailey et al., 1997; Baxter-Jones et al., 2008). PBMAS showed that bone mineral content (BMC) increases linearly with increasing age throughout childhood, with no apparent gender difference. In early adolescence girls appear to have slightly greater BMC than boys, which is likely a reflection of the earlier timing of the female adolescent growth spurt (12 years of age). Boys have their adolescent growth spurt approximately two years later, around 14 years of age, and continue to increase BMC through late adolescence when girls have ceased

(Figure 2.3). The magnitude of the BMC gain in adolescence is greater in males than females; combined with the longer period of accrual in males this results in males having more BMC than females in adulthood. Bone mineral density (BMD) follows a similar pattern of accrual, with females peaking approximately two years before males. Bone mineralization increases progressively in early childhood and then accelerates in adolescence before reaching a plateau in early adulthood. Bailey (1997) reported that by the age of peak height velocity both males and females have attained approximately 90% of their adult stature and 60-70% of their adult femoral neck (hip), lumber spine and total body BMC.
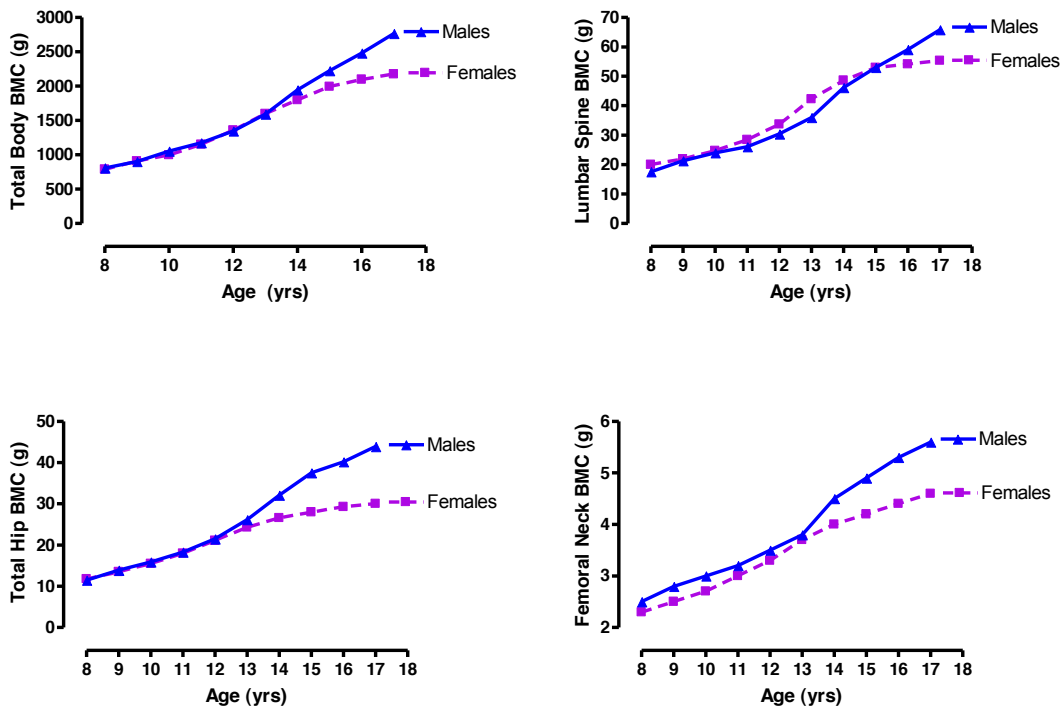
Figure 2.3 –Bone mineral accrual for the total body, lumbar spine, total hip, and femoral neck in males and females. Adapted from Faulkner et al., 1996.

In addition to growing in length and width, skeletal tissue is continually modeled and remodeled to maintain its shape and integrity. Modeling is an organized cell activity that allows bone to grow and adjusts bone strength through the addition and resorption of bone at separate anatomical sites (Frost, 1990). Bone modeling involves independent actions of osteoblasts and osteoclasts. Accretion occurs without prior resorption and results in a net gain of bone tissue (Frost, 1990). Bone modeling is most active in childhood and tends to subside after skeletal maturity. It fits a growing bone's architecture to the mechanical demands of physical activity, body weight, and neuromotor function (Frost, 1990).

Bone remodeling and repair may involve a change in the shape or internal architecture of a bone or a change in the total amount of mineral deposited in the skeleton. This is achieved though a constant process of bone deposition and bone resorption (Frost, 1989; Parfitt, 1996). Bone remodeling differs from modeling in that osteoblasts and osteocasts do not act independently, but rather are coupled and bone resorption and formation occur at the same spot on the bone surface. Together, the osteoblasts, osteocytes, and osteoclasts make up basic multicellular units (BMU) where the process of remodeling occurs within cortical and trabecular bone (Frost, 1989). Remodeling is a continuous process throughout life and provides a mechanism whereby fatigue-damaged bone is replaced with new bone, ion homeostasis is maintained, and bone is reinforced for increased stress.

The balance between modeling and remodeling differs between the growing and adult skeleton. In the former, modeling is the dominant mode and bone deposition occurs at a more rapid rate than bone resorption. During modeling seen in early childhood and

through to late adolescence, osteoblastic activity exceeds osteoclastic activity resulting in larger, heavier and denser bones. Bone remodeling begins to be the dominant mode in adulthood, where bone mass is at an equilibrium undergoing a constant and equal removal of old bone and renewal with newly formed bone. This equilibrium exists between bone formation and resorption until the fourth or fifth decade of life, when resorption occurs at a more rapid rate resulting in a net loss of bone. In women, bone loss begins at approximately 45 years of age and occurs at an average rate of 1% per year until age 65 when the rate plateaus (Lorrain et al., 2003).

2.4 Bone Imaging Techniques

Measuring the properties of bone has long been a challenge for musculoskeletal researchers. Areas of interest often include bone's size and shape (anatomy), strength (biomechanics), and metabolic activity (biochemistry and physiology) as well as the development and adaptation capabilities of bone (Khan et al., 2001). As previously stated, bone is a highly dynamic tissue that continually adapts through a process of resorption of existing bone and formation of new bone. This process of bone turnover, in humans, begins in utero and continues throughout our lives changing bone mass, density, structure and strength. Therefore, it is essential that we have modalities to measure these properties of interest in living humans.

Imaging plays an important role in assessing bone parameters. Various measurement techniques have been used including: radiographic density, single photon absorptiometry, dual energy X-ray absorptiometry, broad band ultrasound, magnetic resonance imaging, and computed tomography. Currently, dual energy X-ray

absorptiometry (DXA) is the most widely used technique for assessing bone because of its low short-term precision error, low radiation exposure, and its capacity to measure multiple skeletal sites (Miller et al., 1995). DXA is planar measurement. It provides a measure of BMC (g) and areal BMD (g/cm^2). DXA measures all bone mineral within a given area but does not assess its spatial orientation or alignment. So although it evaluates bone mineral, it cannot measure bone structure, architecture or material properties. DXA allows for the measurement of bone mass (BMC) but cannot assess the shape of the bone (geometry or structure).

Quantitative computed tomography (QCT), on the other hand, provides a three-dimensional measure of bone. It determines volumetric density (mg/cm^3) rather then areal density and is able to distinguish between trabecular and cortical bone (Genant et al., 1996; Griffith et al., 2010). However, one of the disadvantages of QCT is its relatively high radiation dose. Recently, the use of peripheral quantitative computed tomography (pQCT) has become popular as it alleviates some of the previous QCT issues. It is a small purpose-built scanner to measure BMC, volumetric bone density, and geometry of the peripheral skeleton. Because pQCT is used only for the appendicular skeleton the radiation level is very low (Genant et al., 1996; Griffith et al., 2010). Compared to DXA pQCT has improved the estimate of bone strength as it measures both structure and volumetric density (Ashe et al., 2006; Griffith et al., 2010; Lochmuller et al., 2002). This shift from planar two-dimensional to three-dimensional analysis allows a more precise characterization of bone health.

2.5 Determinants of Bone Health

Many factors influence the accumulation of bone mineral during childhood and adolescence as well as maintenance of skeletal integrity in adulthood. These include genetics, sex, hormonal status, body composition and lifestyle factors such as diet and physical activity (Khan et al, 2001).

2.5.1 Genetics and Sex

The development of osteoporosis has a strong genetic component. The mechanism by which genetics governs bone development and rate of bone loss has not been well established; however, family and twin studies suggest that genetic factors may account for up to 85% of the variance in peak bone mass (Bounjour et al., 2007; Arden et al., 1997; Hopper et al., 1998). Bone geometry is also known to have a substantial genetic component. Men and women with a maternal history of hip fracture have been shown to not only have less aBMD at the hip but also thinner femoral cortices (Looker and Beck, 2002). The Framingham study, a large population-based osteoporosis study, has been examining the association between genetics and geometric indices of the hip in men and women (Denissie et al., 2007; Kiel et al., 2007). The authors found that proximal femur bone geometric indices were under moderate to strong genetic influence (heritability ranging from between 0.28 and 0.70) independent of body size (Demissie et al., 2007).

During growth, the skeletal response to modifications in environmental factors can also vary considerably between individuals (Bounjour et al., 2007). This inter-individual difference in response to increased physical activity or dietary supplementation may be related to genetic variation. For example, it has been suggested that athletes may

be genetically predisposed to having higher bone mineral density or may respond more positively to physical activity intervention than non-athletes (Khan et al., 2001). This may explain why cross-sectional studies of athletes' bone parameters reveal substantial differences between athletes and controls, whereas physical activity interventions in the general population, aimed at increasing bone mass, find much smaller difference between exercisers and controls.

Early in life there is little difference in bone size, mass, or geometry between the sexes (Bailey et al., 1999; Faulkner et al., 1996; Janz et al., 2007; Janz et al., 2010; Khan et al., 2001). During the pubertal years, linear growth and skeletal mass accumulation is greater in males than females resulting in larger, longer bones and higher bone mineral density in males (Faulkner et al., 1996). For example, cortical bone size has been found to increase, on average, 10% more in boys than girls at the tibia (Kontulainen et al., 2005). Both sexes experience age-related gains in bone strength; however, the larger bone size in males during the peripubertal and pubertal years results in a greater strength benefit (Schoenau et al., 2001). Bone loss is also different between males and females, with women losing more bone through life than men (Krall et al., 1997; Riggs et al., 2000). Hence women are more susceptible to osteoporosis and related fracture (World Health Organization, 2003).

2.5.2 Hormonal Status

The endocrine system regulates bone metabolism through the release of hormones. Many hormones are involved in the regulation of bone development including: estrongen, progesterone, growth hormone, insulin-like growth factor I, and

20

corticosteroids (Khan et al., 2001). Estrogen plays a key role in skeletal health by binding to the estrogen receptor on the osteoblast, limiting bone resorption. It is essential for both bone accrual and maintenance of a healthy bone balance in adulthood. The onset of the pubertal period is associated with a rise in serum estrogen in both males and females (Riggs et al., 2002; Jarvinen et al., 2003). This rise in estrogen is believed to alter the stress-strain set point in bone, increasing the sensitivity of bone to mechanical stimulation (Lee & Lanyon, 2004). Thus, when estrogen levels are increased a similar mechanical stimulus would result in greater bone adaptation in the high versus low estrogen state.

Earlier maturing individuals experience this rise in serum estrogen at a younger age compared to those who mature later and thus have a prolonged period of increased sensitivity. As such it has been suggested that individuals who mature earlier will emerge from adolescence with greater bone mass and estimated strength compared to those individuals who mature later. Two longitudinal studies have prospectively assessed the influence of maturational or pubertal timing on bone development. Findings from these studies suggest that early maturating females accrue approximately 50 g more bone mineral content by young adulthood (Jackowski et al 2010; Chevalley et al., 2009a). Earlier maturing females also have greater estimated bone strength at the radius and tibia (Chevalley et al., 2008; Chevalley et al., 2009b). Furthermore, retrospective observations in premenopausal women suggest an inverse relationship between aBMD and age at menarche (Rosenthal et al., 1989; Ito et al., 1995). However, the influence of maturational timing on the development of bone in males is less well defined with some studies suggesting a positive effect of early maturation and others reporting no effect of maturation (Glisanz et al., 2010; Jackowski et al., 2010; Kindblom et al., 2006).

Estrogen also plays an essential role in women for the maintenance of healthy bones. When the production of estrogen declines bone density decreases and fracture rates increase (Bradford et al., 2010). Around the time of menopause, estrogen levels decrease resulting in an accelerated phase of bone loss (The ESHRE Capri Workshop Group, 2010). The estrogen deficiency causes an imbalance between bone resorption and formation such that the amount of bone removed during the remodeling cycle slightly exceeds what is being replaced (The ESHRE Capri Workshop group, 2010). This menopausal bone loss increases the risk of osteoporosis and related fracture (Cummings et al., 1998; Huang et al., 2007; Sacco and Ward, 2010).

2.5.3 Nutrition

Nutrition is a modifiable determinant of bone that plays an important role in both skeletal development and maintenance. A number of nutritional factors have been linked to bone health. For example, adequate intakes of calcium and vitamin D are considered important for optimizing bone health during growth. During the pubertal growth spurt, rates of modeling and remodeling accelerate increasing calcium requirements; however, the amount required for optimal accrual is unclear (Specker and Vukovich, 2007). Calcium is a fundamental component of bone and as such is recognized as an essential nutrient for bone accrual. The skeleton serves as a storage site for excess calcium and also as a supply of calcium during times of need. Therefore, if dietary calcium intake is insufficient bone mass, and subsequently strength, may be compromised. Carter et al. (2001) found that calcium intake was a predictor of bone mineral content in adolescent males. Similarly, other studies have found that calcium supplementation during the

growing years increases bone mineral accrual by 1-3%; however, the benefits tend to disappear upon removal of the calcium supplementation (Johnston et al., 1992; Bonjour et al., 1997; Lloyd et al., 1993; Lee et al., 1997). In a review of the literature Cummings (1990) concluded that evidence from cross-sectional, longitudinal, and intervention studies suggest that dietary calcium may not influence bone parameters in young and middle aged adults. Even the strongest proponents of calcium supplementation for bone health concede that the evidence for a relationship between bone density and calcium is inconclusive (Nordin and Heaney, 1990). This may be related to the decreased calcium requirement in adulthood due to lower rates of bone turnover. However, calcium supplementation in postmenopausal women may help to attenuate bone loss and decrease fracture rates (Bischoff-Ferrari et al., 2008; Daniele et al., 2004; Karkkainen et al., 2010; Tranquill et al., 1994).

There may also be a synergistic relationship between calcium ingestion and physical activity on bone health; mechanical loading is necessary to stimulate bone modeling and remodeling and calcium is a required substrate for bone mineralization (Specker and Vukovish, 2007). Specker and Binkley (2003) found that calcium intake modified BMC and bone geometry in response to structured physical activity in young children. However, consistent with calcium supplementation trials the benefits to bone mass did not persist after the intervention had ceased (Binkley and Specker, 2004).

Vitamin D is a vital nutrient that supports numerous functions critical to overall health. It is essential for calcium regulation and thus bone metabolism. The main source of vitamin D is sunlight; therefore, the risk of deficiency is greatest for individuals living in countries with limited sunlight exposure, such as Canadians in the winter months.

Vitamin D deficiency may result in an increase in bone resorption resulting in diminished bone density (McClung and Karl, 2010). El Hajj-Fuleihan et al. (2006) found that vitamin D supplementation had a positive effect on musculoskeletal parameters in girls and that this effect was greatest prior to menarche. Similarly, Viljakainen et al. (2006) found a positive effect of vitamin D supplementation in young females. Total hip BMC was 14.3% greater in the girls receiving a low dose supplementation and 17.2% higher in girls receiving a high does of vitamin D compared to the unsupplemented group (Viljakainen et al., 2006).

In a recent review Cranney et al. (2008) found positive associations between vitamin D status and bone mineral content and density throughout the lifespan. Lappe et al. (2008) found vitamin D in combination with calcium supplementation reduced the risk of stress fractures by 20% in a group of young healthy female naval recruits. Furthermore, vitamin D in combination with calcium supplementation has also been suggested to decrease the number of hip and vertebral fractures in older women (Chapuy et al., 1992; Karkkainen et al., 2010). However, other studies have found no effect of vitamin D supplementation on bone parameters (Ward et al., 2010; Molgaard et al., 2010). Inconsistent results were also reported in a meta-analysis of the effect of vitamin D supplementation on fracture prevention (Bischoff-Ferrari et al., 2005). Studies are needed to clarify the role of both calcium and vitamin D on lifetime skeletal health.

2.5.4 Body Composition

Body composition can be divided into a number of relevant compartments and tissue masses. This can be done anatomically (fat, lean, bone, residual) or chemically

(water, lipid, protein) (Khan et al., 2001). Body composition is mainly compromised of two anatomical tissue components: lean mass and fat mass (Lui et al., 2010). The relative proportion of each of these soft tissue types that comprise total body weight can vary widely between individuals and can impact skeletal health. For example, high body weight may be protective for the skeleton whereas low body weight, particularly in elders, is a major risk factor for fracture (Rosen and Klibanski, 2009).

Body weight has been identified as a primary predictor of BMC, BMD, and estimated bone strength (Fricke et al., 2009; Hage et al., 2010; Langsetmo et al., 2010; Saito et al., 2005). It has been suggested that individuals with a higher body weight have higher bone mass (Reid, 2008). A number of studies have reported an association between body weight in childhood and bone mass in adulthood (Blum et al., 2001; Cooper et al., 1995; Saito et al., 2005). Cooper et al. (1995) found significant correlations between weight at 1, 5, and 10 years of age and BMC at the lumbar spine and femoral neck at 21 years of age. Similarly, Saito and colleagues (2005) found weight gain from birth to 1.5 years of age and 9-12 years of age was associated with BMC at the lumbar spine and femoral neck in female university students 18-21 years of age. Weight at the time of menarche has also been found to be associated with aBMD in premenopausal women (Blum et al., 2001). In contrast, overweight adolescent girls (body mass index (BMI) ≥ 25) have greater estimated bone strength at the hip (Hage et al., 2010) but similar size adjusted aBMD values compared to normal weight girls (Hage et al., 2009) suggesting no effect of body weight on bone mass.

A higher BMI has a positive influence on bone health in Canadian men and women 25 years of age and older (Langsetmo et al., 2010). However, cross-sectional

studies have demonstrated that body weight may be a more important predictor of aBMD

in older compared to younger populations. Postmenopausal women who were at least

10% above their ideal body weight had significantly greater aBMD than did

postmenopausal women of a normal body weight, a phenomenon not observed in

premenopausal women (Ribot et al., 1987). It has been suggested that body weight

accounts for approximately 30% of the variance in elderly men and women aBMD,

making it one of the best determinants of bone density (Hannan et al., 1992; Nguyen et

al., 2000). Furthermore, moderate excess body mass (body mass index ≥ 25) significantly

reduces vertebral postmenopausal bone loss (Tremollieres et al., 1993).

Body weight is largely made up of two components: fat mass (FM) and lean mass

(LM or fat-free mass). The relative contribution of these two compartments to the

variation in bone mass has not been well established. There may be gender specific

differences in the influence of FM and LM on bone development. For example, LM was

found to be a strong determinant of total body aBMD in adolescent males while FM was

a stronger predictor in adolescent females (Hage et al., 2009). In a cross-sectional study

of children 6-18 years of age Ackerman and colleagues (2006) found that fat mass was a

determinant of BMC in all girls but only in prepubertal boys. In contrast, in a longitudinal

study of bone development Baxter-Jones et al. (2003) found that FM did not predict

BMC in either boys or girls. Confounding this relationship is an age-related change in

body composition (the relative contribution of FM and LM to total body weight). For a

given body size, measured by either lean mass or height, postmenopausal women with

greater fat mass have greater aBMD (Ho-Pham et al., 2010). While in children, despite a

greater lean mass for height, total body BMC for lean mass was reduced in heavier

children, suggesting that fat mass may inhibit bone accrual (Dimitri et al., 2010). Increased fat mass was also associated with reduced aBMD and smaller bone size independent of lean mass in men 25-45 years of age (Taes et al., 2009). Therefore, while total body weight is generally found to be positively associated with bone parameters; the relative contribution of fat and lean mass to bone health remains unclear.

2.5.5 Physical Activity/Impact Loading

Physical activity is another modifiable determinant of bone health. Habitual weight bearing physical activity has been widely reported to have beneficial effects on bone parameters (American College of Sports Medicine, 2004; Bailey et al., 1997; Baxter-Jones et al., 2008; Daly, 2007; Janz et al., 2010; Slemenda et al., 1991). In accordance with Wolff's Law, it is generally accepted that a bone will adapt to the load applied in order to maintain efficiency in providing structural and functional support to the skeleton without injury or fracture (Frost, 1990). The adaptation of bone to such loading is to increase size, change geometry and increase the amount of mass within the periosteal envelope (Ward et al., 2005). When a mechanical load is placed on a bone it causes a slight deformation or "strain" which is resisted by intermolecular bonds "stress". For a given bone structure, the loads to which bone is subjected will determine the strain. An increased load, such as the increased use of the upper and lower extremities in gymnastics landings, will increase the strain on the bone. Bone cells detect strain and respond by changing the bone structure to lessen the strain placed on the bone (Lanyon and Rubin, 1984; Frost, 1990).

Generally studies have demonstrated that habitually physically active individuals of all ages have better bone parameters compared to less active individuals (American College of Sports Medicine, 2004; Bailey et al., 1997; Bakker et al., 2003; Baxter-Jones et al., 2008; Hamilton et al., 2008; Janz et al., 2006; Janz et al., 2010; Recker et al., 1992; Rideout et al., 2006; Salamone et al., 1996). Furthermore, exercise intervention has been found effective for attenuating age-related bone loss and decreasing fracture risk (deKam et al., 2009; Kelley et al., 2001; Kelley et al., 2002; Feskanich et al., 2002; Moayyeri et al., 2010). However, the capacity of bone to adapt its mass to activity has been suggested to be greatest before puberty because of a higher rate of modeling and remodeling processes that promote adaptations in the size, shape, and mineralization of bone to accommodate loads (Bass, 2000). Weight-bearing physical activity during growth may help to maximize peak bone mass by increasing the amount of bone mineral deposited and thus may lower the risk of osteoporosis and related fracture (Frost 1987, Prafitt, 1994). Appropriate mechanical loading during the critical period of rapid skeletal growth and modeling in children and adolescents appears important for future skeletal health (Grimston, et al., 1993). However, before recommendations regarding the role of physical activity can be made, more prospective research is needed to determine if the higher bone mass attained in childhood and adolescence is maintained upon removal of the osteogenic stimulus thus impacting adult skeletal health.

2.6 Childhood Physical Activity and Skeletal Health

The growing skeleton responds to increases in everyday physical activity by increased bone mineral accrual (Bailey et al., 1999). In one of the first studies on the

influence of habitual physical activity on areal bone mineral density, Slemenda and colleagues (1991) examined 59 pairs of monozygotic twins (n=118) and found, in normal children 5-14 years of age, total hours of weight bearing activity correlated significantly with bone density at the radius and hip. In contrast, non-weight bearing activities, such as swimming and biking, had no association or in some cases a negative correlation with aBMD (Slemenda et al., 1991). Slemenda et al. (1991) also found that children with physical activity levels one standard deviation above the mean (2.7 h/day) were likely to emerge from adolescence with 5-10% greater bone mass. The authors concluded that a moderate increase in the level of regular weight-bearing physical activity among children and adolescents was associated with a moderate, but important, increase in skeletal mass (Slemenda et al., 1991). In a subsequent 3-year observational study of the same cohort, the authors found a 4-7% greater increase in hip aBMD for prepubertal children in the highest, compared to lowest, quartile of physical activity (Slemenda et al., 1994). These findings indicate that children involved in the greatest volume of normal everyday physical activity had greater bone mass than children who participated in less habitual physical activity. This highlights the importance of mechanical loading for optimizing bone accrual during growth.

More recently, in a longitudinal study assessing bone development in childhood (the Iowa Bone Development Study) Janz and colleagues found that habitual physical activity at 5 years of age was associated with greater bone mineral content at 8 and 11years of age (Janz et al., 2006; Janz et al., 2010). Three hundred and thirty-three children were measured at 5, 8 and 11 years of age. Physical activity was assessed using accelerometers and total body, lumbar spine, and hip bone mineral content was assessed

using DXA. Minutes spent engaged in moderate to vigorous physical activity at 5 years of age predicted bone mineral content at 8 and 11 years of age after adjustment for current height, weight, age, maturity and physical activity (Janz et al., 2010). Boys and girls in the highest quartile of physical activity at age 5 had 4-14% more BMC at 8 and 11 years compared to those in the lowest quartile of physical activity at age 5 (Janz et al., 2010). Janz and colleagues (2007) also found that bone geometry at the hip was associated with physical activity in a cross-sectional analysis of 468 children 4-12 years of age from the Iowa Bone Development Study. Moderate to vigorous physical activity assessed by accelerometer was a positive independent predictor of femoral neck area and estimated strength in boys and girls (Janz et al., 2007). Children who participated in the highest quartile of physical activity had 3-5% greater estimated strength at the hip compared to children in the lowest quartile (Janz et al., 2007).

Additional evidence for the beneficial effect of everyday physical activity on bone mineral accrual is apparent in PBMAS, a six-year longitudinal study of Canadian children. Bailey et al. (1999) investigated the influence of physical activity on bone mineral accrual during the adolescent years. Longitudinal data was available for 60 boys and 53 girls. BMC was measured using dual energy X-ray absorptiometry and physical activity was assessed via a questionnaire. Physical activity groups (physically inactive, average activity, and physically active) were formed based on the score derived from the physical activity questionnaire. Children in the highest quartile, the most physically active, accrued more bone during the two years around peak bone mineral accrual. This resulted in 17% greater total body, 18% greater lumbar spine, and 11% greater femoral neck BMC in the active girls one year after peak BMC velocity compared to the least

active girls. Slemenda and colleagues (1994) in the study described above also found that physical activity was associated with more rapid mineralization in prepubertal children and reported a 29% increase in bone mineral content at the lumbar spine in the three years around the onset of puberty. However, only if these bone mineral benefits are maintained can mechanical loading during growth be purported to have clinical significance in preventing or delaying the risk of osteoporosis later in life.

The Saskatchewan Pediatric Bone Mineral Accrual Study (PBMAS) described above (Bailey et al., 1999) was one of the first studies to prospectively collect longitudinal data from childhood through adolescence and into young adulthood allowing for the opportunity to determine whether the bone mass benefits of habitual physical activity during adolescence are maintained in adulthood (Baxter-Jones et al., 2008). Eighty-two females and 72 males had longitudinal measures from childhood through to young adulthood. The most active children were found to accrue 9-17% more bone through the adolescent growth spurt compared to less active children (Bailey et al., 1999). Males and females who were the most active in adolescence maintained this bone benefit into adulthood (Baxter-Jones et al., 2008). Males classified as active in childhood were found to have 8% greater total body, 11% greater total hip, and 9% greater femoral neck BMC in adulthood compared to individuals classified as either inactive or moderately active in childhood (Baxter-Jones et al., 2008) (Figure 2.4). Likewise, active adolescent females had 9% greater total hip and 10% greater femoral neck BMC in young adulthood (Baxter-Jones et al., 2008) (Figure 2. 4). This longitudinal study provides evidence for the hypothesis that habitual physical activity during childhood and adolescence positively impacts bone health in young adulthood.
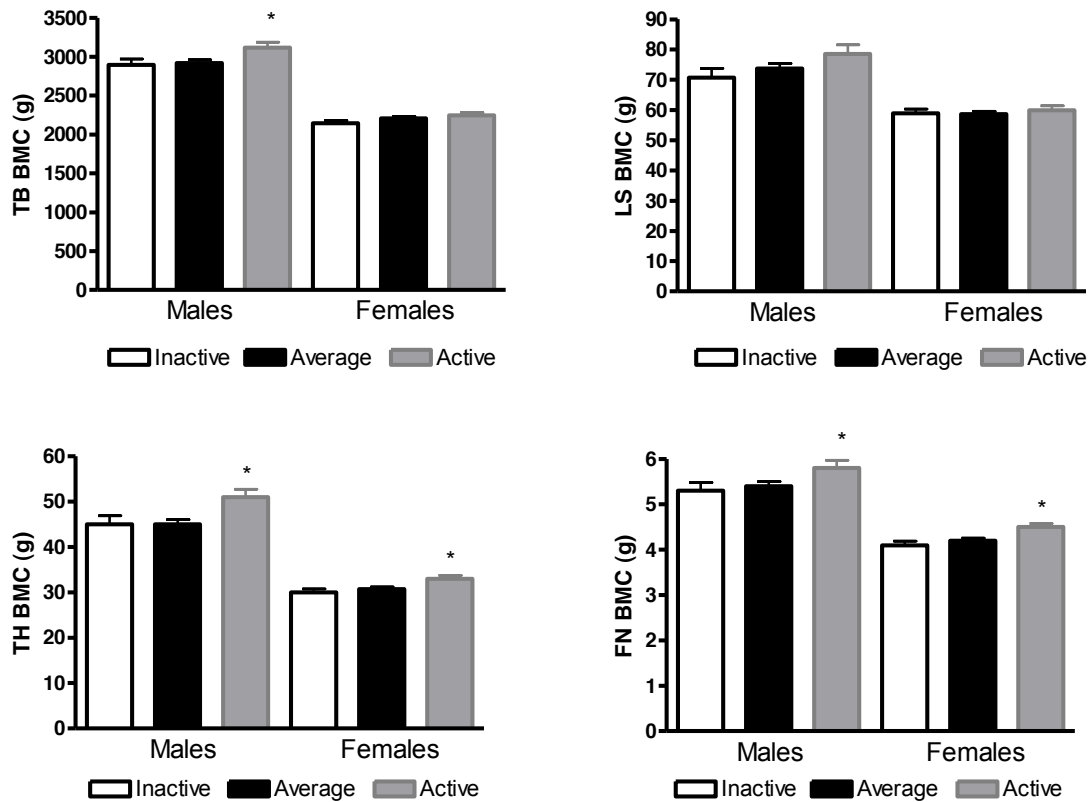
Figure 2.4 – Adjusted total body, lumbar spine, total hip and femoral neck BMC in adulthood based on physical activity level during childhood and adolescence. Means adjusted for age, maturity, height, weight, physical activity, calcium intake and BMC at 1 year after peak height velocity. Adapted from Baxter-Jones et al. 2008.

Physical activities that preferentially stress one side of the body over the other provide a unique model for studying the influence of mechanical loading on the growing skeleton (Bailey et al., 1996). The unloaded side of the body is used as an internal comparison allowing for the only true control of inter-individual genetic, nutritional, and hormonal differences. Any differences in bone parameters can thus be attributed to the

different loading patterns of the two limbs. This model of study allows for investigation of the suggestion that individuals with greater BMC and aBMD excel at sports and that it is predisposition rather than training that results in the observed increases in BMC and aBMD in athletic populations.

Haapasalo and colleagues (1994) examined 19 female Finnish national level squash players (aged 25.4 ± 4.0 years) and 19 healthy Finnish women (aged 25.4 ± 3.9 years). The squash players had been actively training for approximately 6 years (2-12 years) and trained four times a week for 75 minutes each session. BMC and aBMD were measured at six different sites in the upper arm using dual energy X-ray absorptiometry. The squash players exhibited significantly higher BMC and aBMD values at all sites measured for their dominant playing arm compared to their non-dominant arm. Controls also had greater BMC and aBMD in their dominant arm. However, these side-to-side differences were significantly greater in the squash players than the controls. Significantly larger side-to-side differences (average 22%) were also found in players who started their training before or during menarche than those who started 1 or more years after the event (9%).

Similarly, Kannus et al. (1995) compared the BMC of 105 female national level tennis and squash players and 50 healthy female controls using DXA. The tennis and squash players were divided into six groups according to the biological age (years from menarche) they started training. Compared to the control group, the tennis and squash players had significantly larger side-to-side differences in BMC (3.2-4.6% versus 8.5-16.2%, respectively). Furthermore, players who started their career before or at menarche exhibited a difference 2-4 times higher than those who started after menarche. Kannus

and colleagues (1995) recommended that physical activity should be started no later than puberty to be maximally effective for bone gains.

Kontulainen at al (2002) used pQCT to further examine a subset (n=64) of the tennis and squash players from the Kannus et al. (1995) cohort and found that those individuals who began training before menarche not only had 8-22% greater estimated bone strength at the radius and humerus compared to the control group, but that they also had 8-14% greater estimated strength compared to those athletes who began training after menarche. This further supports the assertion that bone is most responsive before puberty. Kontulainen et al. (2002) found that the increased strength benefit from racquet sports participation was primarily due to periosteal enlargement of the bone cortex in females. Haapasalo et al. (2000) also found an increase in bone size in the dominant arm of national level male tennis players (n=12, mean age of 30 years), leading to a subsequent increase in bone strength.

The increased bone mineral density, bone size and estimated strength found in the dominant playing arm of racquet athletes from unilateral studies support the assertion that bone parameters increase as a result of structured physical activity. The non-playing arm is used as a control for genetics, diet, hormonal, and other variables that have been suggested as alternative explanations to the increases in bone observed in athletes involved in impact-loading sports. These findings suggest that the loading from physical activity, and not genetics, is responsible for the greater bone parameters.

Strategies that increase the acquisition of bone mass during childhood and adolescence may help protect skeletal integrity and reduce the risk of osteoporosis in later life (Zanker et al., 2003); however, the mode of physical activity as well as the intensity,

duration, and frequency of exercise that is optimal or beneficial for accretion of bone mineral is not well established. Taaffe et al. (1995; 1997) suggest that high-magnitude mechanical loads are more osteogenic than low-intensity loads and that the significance of number of cycles, or repetitions, is relatively modest. A general principle underlying the prescription of exercise to promote bone health is Wolff's law, which states that bone accommodates the forces applied to it by altering its amount and distribution of mass (Frost, 1990). However, Wolff's law did not propose any principles as to how bone adapted to these mechanical loads. Frost (1987) proposed a minimum effective strain (MES) hypothesis for the process of bone adaptation to mechanical loading. The MSE theory suggests that there is a strain level within bone that has to be exceeded for any changes in bone architecture to occur. The strain magnitude dictates and stimulates the remodeling, modeling, or repair responses of bone tissue (Frost, 1987). The strain, mechanical stimulus, required for bone remodeling and maintenance of bone turnover is lower than the strain required to elicit a modeling response where bone is added and structurally altered. Stains below this set-point fail to elicit a response and result in resorption exceeding bone formation, leading to a net loss of bone mass and subsequently a decrease in bone strength (Frost, 1987).

From the studies reviewed above it can be suggested that the ability of bone to adapt to mechanical loading is much greater during growth. Adolescence is the only time in life when bone is added in substantial amounts to the inside as well as the outside of bone (Parfitt, 1994). The clinical significance of increased bone accrual, as demonstrated above, if retained into older adulthood, can be easily seen.

2.7 Gymnastics Training and Bone Health

As further investigations were undertaken to determine the type of structured physical activity most conducive to bone accrual, gymnastics training received significant attention. Gymnastics training results in unique high mechanical loading to the skeleton and thus provides an excellent model for assessing the influence of physical activity on bone mass, density, structure and strength (Daly et al., 1999, Proctor et al., 2002). The majority of studies have demonstrated that competitive female gymnasts have greater aBMD and BMC when compared to other athletic and non-athletic populations (Bass et al., 1998; Caswell et al., 1996; Laing et al., 2002; Nickols-Richardson 2000; Proctor et al., 2002; Robinson et al., 1995; Zanker et al., 2003). Furthermore, retired female gymnasts provide an interesting model to investigate the influence of childhood and adolescent mechanical loading on adult bone health.

2.7.1 Gymnasts Growth and Development

As shown above structured weight bearing physical activity is positively associated with increased bone accrual; however, there are also some concerns about the potential negative effects that intensive physical training may have on a child's growth and development. For example, it has been suggested that intense training at a young age adversely affects the growth and maturation of young female gymnasts (Caine et al., 2001; Daly et al., 2000; Daly et al., 1998; Weinmann et al., 1999). Therefore, the influence of high intensity structured physical activity on growth and development will be discussed briefly.

The influence of structured physical activity on the growth and development of children has been an area of interest for over 100 years. Studies performed in the early 20th century suggested that physical activity in males had a stimulatory effect on statural growth; for example, young male athletes were observed to be taller and stronger than their age matched non-athletic peers. More recently; however, much of the literature suggests that the reason some elite young athletes are taller and stronger than their peers is not due to a stimulatory effect of training, but more likely related to the timing of maturation; that is, early maturers may self-select into sports where their increased size and strength are advantageous such as in basketball and football (Baxter-Jones et al., 1995; Malina, 1994; Malina 1998; Theintz et al., 1989).

In contrast, the opposite is likely true for the sport of gymnastics where a small lightweight physique is favorable for performance success. Confounding this, has been the suggestion that the high intensity and volume required for elite gymnastics training at an early age may adversely affect a child's statural growth. High-level gymnastics training has been suggested to delay or retard the growth spurt in gymnasts' lower extremities resulting in reduced stature (Theintz et al., 1993). In contrast, it has also been suggested that the short stature observed in elite gymnasts is partly due to selection of individuals with reduced leg length and that it is the trunk length rather than leg length that is being compromised (Bass, et al., 2000; Caine, et al., 2001). While others suggest no influence of elite gymnastics training on final adult stature (Erlandson et al., 2008). Thus, the influence of intensive gymnastics training on growth is still controversial.

The question as to whether gymnastics training has a positive or adverse effect on the growth and development of young children, has received considerable attention in the

popular press. In some instances gymnastics training has been associated with negative impacts on young females' sexual maturation. For example, the tempo of growth has been found to be slower in gymnasts compared to other athletes in the later stages of sexual maturation (Erlandson et al., 2008). Age at menarche has also been found to be later in gymnasts compared to other athletic groups and non-sporting controls (Beunen et al., 1999; Claessens et al., 1992; Erlandson et al., 2008). However, mothers' of gymnasts also have a later age at the attainment of menarche, suggesting a familial tendency toward later maturation (Baxter-Jones et al., 1994). Participation in gymnastics training has also been shown to have a positive influence on body composition development, including increased bone mineral accrual, increased lean tissue development and decreased fat mass development (Laing et al., 2002; Nickols-Richardson et al., 1999). The impact of gymnastics training on bone development and maintenance is presented below.

2.7.2 Premenarcheal Gymnastics Training

In keeping with the available evidence presented in the previous sections suggesting that the skeleton is most responsive to exercise before puberty, studies have been directed at assessing the bone parameters of prepubertal/premenarcheal gymnasts. Results from both cross-sectional and longitudinal studies support the positive influence of gymnastics training on bone accrual during growth. The studies listed below examine the relationship between gymnastics participation and BMC and aBMD in premenarcheal/prepubertal children and adolescents.

2.7.2.1 Cross-Sectional Studies

Courteix and colleagues (1998) compared elite premenarcheal athletes involved in a sport requiring significant impact loading (gymnastics) to athletes involved in a non-impact bearing sport (swimming). The sport groups consisted of 10 swimmers (aged 10.5 ± 1.4 years) and 18 gymnasts (10.4 ± 1.3 years) who had performed at least 3 years of high-level sport training (8-12 h/wk for swimmers and 10-15 h/w for gymnasts). Thirteen girls (10.7 ± 1.0 y) involved in fewer than 3 hours per week of activity served as a non-sporting control group. There were no significant differences between the groups with regard to age, height, weight, or body composition; however, gymnasts had significantly higher aBMD values, by 11-33% at the radius, lumbar spine and femoral neck compared to both swimmers and controls. Similarly, Cassell et al. (1999) compared gymnasts and swimmers, 7-9 years of age, to non-athletic controls and found that after controlling for differences in body weight, gymnasts had significantly greater total body aBMD compared to swimmers and controls, 10% and 8% respectively.

Nickols-Richardson et al. (2000) observed premenarcheal gymnasts (n=16), 8-13 years of age, who had been training for an average of six years and compared them to age, height and weight matched non-gymnast controls (n=16). Gymnasts were found to have significantly higher aBMD at the total hip (12%), femoral neck (14%), trochanter (12%), Ward's triangle (31%), and lumbar spine (13%). Similarly Dyson et al. (1997) reported that elite premenarcheal female gymnasts, 7-11 years of age, had significantly greater aBMD at the femoral neck and trochanter, 8% and 16% respectively. Dowthwaite et al., (2006; 2007) found female gymnasts 7-12 years of age had significantly greater aBMD and BMC compared to non-gymnasts at the lumbar spine,

forearm, and femoral neck (7-20%). Zanker et al. (2003) also found female gymnasts, 7-8 years of age, had significantly greater (8-10%) lumbar spine, forearm and total body aBMD compared to non-gymnasts. The gymnasts in the Dowthwaite et al. (2006; 2007) Zanker et al. (2003) studies had been training regularly for 2-4 years and trained approximately 6-10 hours per week.

Studies examining gymnasts' bone parameters have generally focused on competitive athletes who had been systematically training for at least two years and who trained a minimum of 10 hours per week year round. More recently, low-level gymnastics exposure has also been suggested to result in bone benefits. Scerpella et al. (2003) found that young females, 7-11 years of age, who engaged in 1-8 hours per week of gymnastics training had 4% greater total body and 7% greater forearm aBMD compared to children who did not participate. Laing et al. (2005) also found that recreational gymnastics participation, low-level gymnastics exposure, had a beneficial effect on bone parameters. The authors found that 4-8 year old girls (n=65) participating in one hour per week of recreational gymnastics, at baseline, gained more aBMD at the lumbar spine and bone area at the forearm over two years compared to children participating in non-gymnastics activities (Laing et al., 2005). Laing et al. (2005) stated that their findings suggest that beginner level gymnastics skills may be adequate stimuli for enhancing gains in bone mineral and size. This is important because while competitive gymnastics is a high level sport and participation is limited a select number of skilled individuals; recreational gymnastics is attainable by most children and does not require a high level of training. Furthermore, while competitive gymnastics training has

been suggested to have negative impacts on growth and development, this is not the case in recreational level gymnasts.

The majority of previous literature has focused on females; there is limited research focusing on gymnastics training and male bone development. Daly et al. (1999) were the first to assess male competitive gymnasts' bone parameters; they found that male gymnasts had a greater increase in calcaneal bone parameters compared to controls over 18-months, 12.8% vs 7.2% respectively. However, they used ultrasound and assessed broadband ultrasonic attenuation (BUA). The precise skeletal properties reflected by BUA have not been well established and ultrasound does not directly measure either bone structure or material properties; therefore, caution should be taken when interpreting these results. Only one study has examined the influence of competitive gymnastics training on male bone parameters using DXA. Zanker et al. (2003) found no significant differences in aBMD between male gymnasts and non-gymnasts at the total body, lumbar spine and femoral neck. However, Zanker et al. (2003) only examined 10 male gymnasts which may be influencing the results.

These cross-sectional studies demonstrate that greater aBMD is seen in female gymnasts, even as young as four to seven years of age. However, the cross-sectional research design makes it difficult to conclude that the higher aBMD observed is the result of gymnastics training and not genetics or other environmental factors. Furthermore, many of the studies have a low participant number which may be influencing results. Prospective longitudinal studies may provide a better means to assess the impact of child and adolescent gymnastics training on bone parameters.

2.7.2.2 Longitudinal Studies

Laing and colleagues (2002) compared a small number of female gymnasts (n=7) to age, height, and weight matched active controls. The girls were 8-13 years of age at baseline and were followed for a period of three years. At baseline and year three, gymnasts were training an average of 11.7 and 17.9 hours per week, respectively. The control group had never participated in gymnastics training; however, they were competitive in other activities such as basketball, soccer, softball, and tennis. At baseline gymnasts had 6% greater total body, 15% greater lumbar spine and 14% greater femoral neck aBMD. The main finding was that over the 36-months, gymnasts continued to improve total body and hip aBMD as well as lumbar spine and total body BMC. At year three gymnasts had 12% higher total body, 19% higher lumbar spine and 23% higher femoral neck aBMD compared to the active non-gymnasts.

Bass et al. (1998) followed 37 prepubertal elite female gymnasts (aged 10.4 ± 0.3 years) and 17 skeletal age, height, and weight matched controls for 12 months. In cross-sectional analyses, the aBMD of the prepubertal gymnasts was 0.7-1.9 standard deviations higher at weight-bearing sites than the predicted mean in the controls. During 12 months of training, the gymnasts had a 30-85% greater increase in aBMD than the controls at the total body, spine and legs. Volumetric density was calculated (g/cm^3) using a geometric formula. The estimated volumetric BMD also increased significantly in the prepubertal gymnasts, but not in the controls. The authors concluded that increases in aBMD achieved by vigorous structured physical activity during puberty were large and could potentially reduce fracture risk in adulthood by 2- to 4-fold.

In a similar study, Courteix et al. (1999) found a higher annual gain in bone mineral at the loaded sites in prepubertal gymnasts 12 years of age. Fourteen gymnasts, training 12-15 hours per week for at least three years prior to study initiation were compared to 15 non-exercising children and six swimmers training 5-6 hours per week. Gymnasts had significant greater lumbar spine, femoral neck, and radius aBMD compared to non-gymnasts both at baseline (11%, 14%, and 13%, respectively) and follow-up (12%, 15%, and 17%, respectively). The percentage change in aBMD from baseline to follow-up also tended to be greater in gymnasts; however, the difference was not statistically significant.

Young female gymnasts have been found to not only have increased cross-sectional aBMD and BMC values at the lumbar spine, femoral neck, radius, and total body; these young athletes have also been found to increase aBMD at a greater rate than non-gymnasts. These findings suggest that participation in gymnastics training in childhood may assist to maximize peak bone mineral accrual (Nickols-Richardson et al., 1999). However, information on prepubertal gymnastics training and male bone parameters is lacking.

2.7.3 Collegiate-Level (Postmenarcheal) Gymnastics Training

Several researchers have also examined college-aged female gymnasts (Bemben et al., 2004; Fehling et al., 1995; Nichols et al., 1994; Proctor et al., 2002; Robison et al., 1995). Studies of post-pubertal gymnastics training consistently demonstrate significantly greater bone parameters in the gymnasts compared to non-gymnasts. These cross-sectional and longitudinal studies are reviewed in detail below.

2.7.3.1 Cross-Sectional Studies

Proctor and colleagues (2002) compared the aBMD of 25 elite female collegiate gymnasts (aged 18-25 years old) to a group of 25 sedentary controls. The two groups were matched for body weight; however, the gymnasts were significantly younger (-1.4 y) and shorter (-4.6 cm) than the controls. BMC and aBMD were assessed using dual energy X-ray absorptiometry. The gymnasts were significantly leaner than the controls, as evident by a lower percent body fat and greater lean body mass. The gymnasts were also found to have significantly greater bone mineral density at all sites measured, despite presenting numerous factors that contradict increased aBMD such as delayed menarche, irregular menstrual cycles, and possible eating restraint. Total body aBMD was 8% higher in gymnasts with 17-19% differences in the lumbar spine, proximal femur, and forearm. The controls demonstrated the typical pattern of slightly greater mineralization in their dominant arm, whereas a bilateral difference was not evident in the upper limbs of gymnasts. The lack of a bilateral difference in gymnasts supports the theory that the high aBMD values observed in the gymnasts are primarily due to the impact loading activity.

Fehling et al (1995) also examined college-aged female gymnasts. They compared the bone mineral density of collegiate female athletes in impact loading sports, volleyball (n=8) and gymnastics (n=13), to active loading swimmers (n=7), and group of sedentary controls (n=17). The volleyball players and gymnasts had significantly greater aBMD compared to both swimmers and controls at the lumbar spine, femoral neck, Ward's triangle, total body, right leg, and pelvis. Gymnasts had significantly greater forearm aBMD compared to all groups, despite demonstrating a higher prevalence of

menstrual disturbances (olio/amenorrhea). There were no differences in aBMD between the swimming group and the control group at any site. These results suggest that the type of mechanical loading (i.e., impact vs. active) plays an integral role in influencing aBMD and that this enhancement appears to be site specific.

Similarly, Nichols et al (1995) compared college-aged gymnasts to other collegiate athletes participating in impact loading sports (basketball, volleyball, and tennis) as well as a non-athletic control group. The sport groups had significantly greater aBMD than the non-athletic control group at the lumbar spine (8.7%), femoral neck (10.4%), and total body (7.5%). However, there was no significant difference between gymnasts and the other sports groups' aBMD values. In contrast, Bemben and colleagues (2004) reported that collegiate gymnasts had significantly greater aBMD at the total body, lumbar spine and femoral neck compared to collegiate level cross-country runners, despite a greater prevalence of menstrual dysfunction in the gymnasts. Robinson et al (1995) also observed collegiate level gymnasts and runners compared to a group of non-exercising controls. They found that gymnasts had significantly higher aBMD at the femoral neck (10.3%) compared to controls and significantly higher aBMD at total body, lumbar spine and femoral neck compared to runners (6%, 16% and 19%, respectively). This bone benefit was found despite 47% of gymnasts reporting the occurrence of either oligo- or amenorrhea (Robinson et al., 1995).

These cross-sectional studies in college-aged female gymnasts found greater aBMD values in gymnasts compared to other athletic and non-athletic populations, with the exception of one study. Nichols et al (1995) found similar bone parameters between gymnasts and other impact loading college athletes at the lumbar spine, proximal femur

and total body; however, the gymnasts in this study were significantly younger, shorter, and lighter than non-gymnasts which may be influencing the findings. The greatest benefit of gymnastics participation would appear to be at the hip (10-20%) and the forearm (17%). This may be related to the loading pattern from gymnastics training of repetitive landings on the both the arms and legs. However, once again the cross-sectional research design makes it difficult to conclude that the higher aBMD observed is the result of gymnastics training and not genetics or other environmental factors.

2.7.3.2 Longitudinal Studies

There are few studies that longitudinally examine the influence of collegiate level or postmenarcheal gymnastics training. Bemben and colleagues (2004) tracked college gymnasts (n=12) and cross-country runners (n=10) over a six-month period. Gymnasts participated in apparatus specific training six days per week as well as weight training 3-4 times per week and the cross-country runners trained six days per week logging more than 65 kilometers a week. At baseline and follow-up gymnasts had significantly greater total body, lumbar spine and femoral neck aBMD. However, there was no change in aBMD values during the training season from baseline to the six-month follow-up measure. These findings are in contrast to the observed benefit of gymnastics training on premenarcheal bone parameters. This suggests that while gymnastics training in childhood and adolescence during the period of accelerated bone accrual may help to optimize peak bone mass, postmenarcheal training may not further influence bone parameters.

Similarly, Nichols et al (1994) followed collegiate gymnasts (n=11) and a group of sedentary controls (n=11) during a 27-week training period. Gymnasts trained

approximately 20 hours per week while the sedentary control group participated in less than three hours per week of physical activity. At the first measurement occasion gymnasts had significantly greater lumbar spine (7.8%) and femoral neck (9.6%) aBMD compared to the control group. After 27-weeks of training gymnasts were found to have a significantly greater increase in lumbar spine aBMD (1.3%) compared to the controls. There was no difference between groups in the change in femoral neck aBMD from the first to second measurement occasion. The first measure in the present study was taken at the beginning of the training season after a period of rest from the previous year; therefore, the observed increase in lumbar spine aBMD may be an artifact of a previous detraining effect because the lumbar spine trabecular bone is more metabolically active than the femoral neck cortical bone.

2.7.4 Retirement from Gymnastics Training

With regard to previous gymnastics training, former female gymnasts have higher site-specific aBMD values, suggesting that physical activity habits during growth may have long-lasting benefits on bone health (Pollock et al., 2006). The following section will discuss the cross-sectional and longitudinal studies of former gymnasts in more detail.

2.7.4.1 Cross-Sectional Studies

Zanker and colleagues (2004) studied past gymnastics participation and adult bone mass. They compared 18 former female gymnasts and 18 women who had never participated in structured sport or exercise, and explored the relationship between aBMD of these former gymnasts and their duration of retirement from sport. The gymnasts had

initiated training between five and 11 years of age and had trained continuously for between six and 14 years. They had retired between the ages of 15 and 22. The gymnasts displayed a broad range of duration of retirement (3-12 years) and a wide age range (20-32 years). The gymnasts had also adopted a sedentary lifestyle following retirement from gymnastics. Adoption of a sedentary lifestyle was defined as the absence of regular participation in structured exercise and a habitual physical activity level that fell below the UK recommendations of 30 min of moderate intensity activity on at least five days of the week. The retired gymnasts displayed significantly higher aBMD at all measurement sites, which ranged in magnitude from 6% for total body to 11% for the total hip. In addition, there was no significant decline of aBMD with increasing duration of retirement from gymnastics training and competition.

Bass et al. (1998) also observed significantly higher aBMD measures in a group of former elite female gymnasts when compared to a group of age and weight matched controls, an average of eight years after retirement from sport and removal of the osteogenic stimulus. The gymnasts began training at a mean age of eight years and trained 14-19 hours per week for an average of 10 years. Retired gymnasts had 6-16% greater aBMD at the total body, lumbar spine, femoral neck, and forearm compared to the control group. Furthermore, bone benefits did not diminish with increasing duration of retirement. Similarly, Kirchner et al. (1996) reported that retired college gymnasts (n=18) who had initiated training at a mean age of 12 years had significantly higher aBMD values at the lumbar spine (16%), femoral neck (18%), and total body (9%) when compared to a group of age, height and weight matched controls. These results suggest

that past participation in premenarcheal or collegiate-level gymnastics may provide a residual effect on adult aBMD.

2.7.4.2 Longitudinal Studies

Kudlac et al (2004) were the first to prospectively observe changes in aBMD in retired female collegiate gymnasts. Female collegiate gymnasts (n=10) were measured at the beginning of their final competitive year and then again approximately four years later. Gymnasts had significantly greater BMC and aBMD at the total body, femoral neck, trochanter and total hip in their final year of gymnastics competition as well as four years after retirement when compared to non-gymnasts (Kudlac et al., 2004). They also found that aBMD declined at a similar rate in both gymnasts and non-gymnasts at the hip (approximately 0.72-1.9% a year); however gymnasts had a greater decline at the lumbar spine compared to non-gymnasts (Kudlac et al., 2004). Despite the greater decline in the gymnasts' lumbar spine aBMD the values were still greater, although not significantly so, than the non-gymnasts at both measurement occasions. The similar rate of bone loss at the hip between gymnasts and non-gymnasts is promising; if the decline continues at the same rate retired gymnasts will always have greater aBMD compared to non-gymnasts potentially reducing fracture risk.

Pollock et al. (2006) also prospectively examined the impact of retirement from gymnastics on adult bone parameters. The primary finding was that retired competitive female gymnasts had significantly higher total body (9.9%), lumbar spine (11%), femoral neck (11.6%), and arm (13.8%) aBMD compared with non-gymnasts 24 years after retirement from gymnastics training and competition. Furthermore, in their nine-year follow-up of these former college gymnasts approaching menopause there were no

significant differences between gymnasts and controls in percent change of aBMD for total body, lumbar spine, total proximal femur, femoral neck, and forearm. These results suggest that an elevated bone mass in former female gymnasts is retained despite current activity level and years of retirement.

Recently, Scerpella et al. (2010) prospectively observed young female gymnasts who trained at least 6 hours per week for two years prior to age at menarche. Gymnasts then ceased participating in gymnastics by one year post menarche. Ex-gymnasts were found to have greater aBMD and BMC at the radius 4-9 years post-menarche compared to non-gymnasts. The authors state that this longitudinal analysis provides the first preliminary evidence of prolonged, postmenarcheal retention of skeletal benefits attributed to mechanical loading during childhood. However, Scerpella et al. (2010) only observed 6 ex-gymnasts and 14 non-gymnasts which may be influencing the results.

In summary, the findings from both the cross-sectional and longitudinal studies of retired female gymnasts suggest that the higher aBMD values reported in premenarcheal and college-aged active gymnasts are at least partially retained in early- to mid-adulthood. These bone benefits may potentially decrease the risk of osteoporosis and related fracture as these women age. However, little is unknown of gymnasts' bone geometry, which is important as bone strength has been found to increase after exercise intervention independent of changes in mass (Adami et al., 1999; Robling et al., 2006).

2.7.5 Gymnastics Training and Bone Geometry

The majority of studies that have evaluated gymnastics participation and bone development as well as the influence of retirement from gymnastics on bone parameters

have focused on areal BMD and bone mineral content as measured by dual energy x-ray absorptiometry. Areal BMD is dependent on bone size; when comparing children whose bones may be changing size rapidly, confusion can result about the magnitude of change in aBMD during the growing years (Compston, 1995). The amount of bone mineral and area do not change at the same rate in growing children. Therefore, the influence of size dependent variables can lead to over or underestimation of aBMD in children and adolescents.

Assessment of aBMD and BMC with exercise studies is also limited because important changes in the structural properties of bone may occur which are undetected by DXA. DXA provides a reasonable overall description of bone status, but overlooks structural alterations that can influence bone strength (Jarvinen et al., 1999). There is limited information on gymnastics training and bone geometry, structure and estimated strength. The two studies examining premenarcheal gymnasts and the one study investigating the influence of retirement from gymnastics training on bone geometry are discussed in detail below.

As previously stated, pQCT provides a 3-D measure of bone and allows for the distinction between cortical and trabecular bone. Using pQCT Dyson et al. (1997) were the first to study gymnasts' bones structural properties. They examined elite premenarcheal gymnasts (n=16) 7-11 years of age who trained a minimum of 15 hours per week and had been training for at least two years prior to the measurement occasion. Competitive gymnasts had significantly greater total, cortical, and trabecular vBMD (20%, 16%, and 27%, respectively) at the distal radius when compared to non-gymnasts. Similarly, Ward et al. (2005) examined the effect of competitive gymnastics participation

51

on bone mass, volumetric density, and geometry in both males and females. Forty-four gymnasts, 5-12 years of age, were compared to a non-gymnast control group (n=42). Gymnasts had greater total and trabecular vBMD at the distal radius (17% and 21%, respectively) and distal tibia (5.7% and 4.5%, respectively). At the radial and tibial shafts gymnasts had greater bone area (9.2% and 5.3%, respectively) which resulted in greater estimated bone strength at both sites (13.6% and 5.4%, respectively).

Eser et al. (2009) compared retired elite female gymnasts (n=30, mean age of 23 years) to a moderately active group of non-gymnasts (n=30, mean age of 25). To be included retired gymnasts had to have trained at least six hours per week for four years during childhood and adolescence. The gymnasts had been retired on average for six years (3-18 years). Bone geometric and densitometry parameters were measured by pQCT. Gymnasts were found to have significant geometric benefits at the forearm. Gymnasts had greater total cross-sectional area at the distal radius (25%) and greater total and cortical cross-sectional area at the radial (32% and 13%, respectively) and humeral (19.7% and 24.1%, respectively) shaft sites. Gymnasts also had greater BMC (16-24%) at the radius and humerus. Relative differences between retired gymnasts and non-gymnasts were much smaller in the lower limb. However, gymnasts still had significantly greater (8-11%) BMC and total cross-sectional area in the tibial and femoral shafts and greater volumetric trabecular density (7%) and BMC (8%) at the distal tibia.

Findings from these studies suggest that changes in bone density and geometry are site specific. Therefore, studies assessing bone parameters using DXA only may be underestimating the influence of gymnastics training on bone parameters in childhood and adolescence as well as the impact of previous gymnastics participation on adult bone

health. Both Ward et al. (2005) and Dyson et al. (1997) observed gymnasts who were engaged in competitive rather than recreational level gymnastics classes and who had high and extremely high levels rather than low levels of gymnastics exposure. The influence of low-level gymnastics exposure on bone geometry is currently unknown. There is also limited information on male gymnasts bone parameters. Furthermore, to date no study has prospectively examined premenarcheal gymnasts and followed the same individuals upon retirement from sport and removal of the gymnastics stimulus to determine if and how much of the benefit is maintained.

2.8 Summary

Habitual and structured physical activity during growth may contribute to the prevention of osteoporosis by increasing bone strength through an increase in bone size and mass. Total hours of regular weight bearing activity have been found to correlate significantly with BMC and aBMD in normal children. Furthermore, dramatic increases in bone parameters as a result of structured high impact loading have been observed in the years surrounding peak bone mineral accrual.

Gymnastics training involves unique high mechanical loading on the skeleton. These loading forces are up to ten times body weight on the hands and feet with over 700 foot contacts and over 100 hand contacts in a typical four-hour training session (Mafukidze, 2000). Because of this high loading, gymnasts are an optimal population to study structured physical activity and bone adaptation. From the literature presented above it is evident that elite premenarcheal and collegiate-aged female gymnasts have greater aBMD and BMC compared to both athletic and non-athletic populations, and this

benefit, at least in part, is retained upon retirement. However, less is known of recreational and precompetitive gymnastics participation (low-level gymnastics exposure) and bone parameters. Furthermore, gymnasts' bone geometric properties have not been studied.

Little research has been conducted examining impact loading activity in general and specifically gymnastics training and male bone parameters. Osteoporosis in elderly men is becoming a major public health problem (Szulc and Delmas, 2007). Currently 25-30% of fragility fractures occur in men (Baron et al., 1996) and post fracture morbidity and mortality are higher in men than women (Fransen et al., 2002). As the incidence of osteoporosis in males continues to increase it is important to find ways to combat this disease in both genders.

Therefore, the goal of this thesis was to investigate low-level gymnastics exposure and bone development in young males and females as well as determine the influence of childhood and adolescent gymnastics participation on adult bone health. I designed two studies, recruited participants, collected the data, analyzed results and developed four manuscripts to address these goals. An outline of the four manuscripts that will be presented is described below. The findings from these two studies will help to determine if adolescent and adult bone benefits from structured physical activity during growth. If this is the case structured gymnastics activity can be promoted as a potential means to optimize adult bone mass, structure and estimated strength. However, long-term prospective studies are required which follow retired female gymnasts as they approach menopause and bone lose accelerates to better understand the impact of premenarcheal gymnastics participation on osteoporosis and related fracture risk.

Study 1 – Low-level gymnastics exposure and bone development in 4-10 year olds: A four-year longitudinal study

Manuscript 1: Bone mineral accrual in 4 to 10 year old recreational, precompetitive gymnasts: A 4-year longitudinal study

Manuscript 2: Precompetitive and recreational gymnasts have greater bone density, mass and estimated strength at the distal radius in young childhood

Study 2 - Premenarcheal gymnastics participation and adult bone mass, density, structure and estimated strength

Manuscript 1: Elite premenarcheal gymnasts have higher bone mass in childhood and adolescence that is maintained after long-term retirement from sport: A 14-year follow-up

Manuscript 2: Former elite premenarcheal gymnasts exhibit site-specific skeletal benefits in adulthood after long-term retirement.

CHAPTER 3 – Low-Level Gymnastics Exposure

3.1 Study 1 - Bone mineral accrual in 4 to 10 year old recreational, precompetitive gymnasts: A 4-year longitudinal study

3.1.1 Abstract

Competitive female gymnasts have greater bone mineral measures than non-gymnasts. However, less is known about recreational and/or precompetitive gymnasts. The purpose of this study was to investigate whether the differences previously reported in the skeleton of competitive female gymnasts (high level gymnastics exposure) are also demonstrated in young children with a current or past participation history in recreational or precompetitive gymnastics. One hundred and sixty three children (30 gymnasts, 61 ex-gymnasts, and 72 non-gymnasts) between 4 and 6 years of age were recruited and measured annually for four years (not all participants were measured at every occasion). Total body (TB), lumbar spine (LS) and femoral neck (FN) bone mineral content (BMC) was measured by dual energy x-ray absorptiometry (DXA). Multilevel random effects models were constructed and used to predict differences in TB, LS and FN BMC between groups while controlling for differences in body size, physical activity and diet. Gymnasts had 3% more TB and 7% more FN BMC than children participating in other recreational sports at year four ($p<0.05$). No differences were found at the LS between groups and there were no differences between ex-gymnasts' and non-gymnasts' bone parameters ($p>0.05$). These findings suggest that recreational and precompetitive gymnastics participation is associated with greater BMC at the total body and femoral

neck. This is important as beginner gymnastics skills are attainable by most children and do not require a high level of training. Low level gymnastics skills can easily be implemented into school physical education programs potentially impacting skeletal health.

3.1.2 Introduction

Gymnastics training results in unique high mechanical loading to the skeleton and therefore provides an excellent model for assessing weight bearing physical activity and bone mineral development. The majority of studies have demonstrated that competitive adolescent, collegiate and retired female gymnasts have greater aBMD and BMC when compared to other athletic and non-athletic populations (Bass et al., 1998; Nickols-Richardson et al., 1999; Pollock et al., 2006; Proctor et al., 2002; Robinson et al., 2005; Zanker et al., 2004). Furthermore, total and regional aBMD is greater in gymnasts with higher exposure to gymnastics, i.e. greater hours or years of training (Laing et al., 2005; Scerpella et al., 2003). Studies examining gymnasts' bones have generally been cross-sectional and focused on adolescent female competitive athletes who had been systematically training for at least 2 years and who trained a minimum of 15 hours per week (Bass et al., 1998; Daly et al., 2005; Proctor et al., 2002; Robinson et al., 2005). Although competitive adolescent gymnasts are known to have greater bone strength in adolescence, little is known about their bone properties in young childhood. In addition, competitive gymnastics is a high level sport and participation is limited to a select number of skilled individuals. Recreational gymnastics, on the other hand, is attainable by most children, starts at a very young age and does not require a high level of training. However, less is known about recreational and/or precompetitive gymnastics participation (i.e. low level gymnastics exposure) and male and female bone mineral accrual during childhood.

To our knowledge only one study has examined recreational gymnastics participation and bone accrual. Laing et al. (2005) found that 4-8 year old girls

participating in one hour of recreational gymnastics per week gained more aBMD at the lumbar spine and bone area at the forearm over two years compared to children participating in non-gymnastic activities. However, it is well documented that aBMD does not adequately adjust for bone size which is particularly problematic when examining growing children and may lead to underestimation of the impact of gymnastics participation on bone mineral accrual (Faulkner et al., 2003; Prentice et al., 1994). There is also a paucity of research examining gymnastics participation, both at the competitive and recreational level, and male bone mineral accrual. Therefore, the aim of this study was to investigate whether the differences previously reported in the skeleton of competitive adolescent female gymnasts are also demonstrated in young children with a current or past participation history in recreational or precompetitive gymnastics. We hypothesized that young male and female gymnasts, with low levels of past or current gymnastics exposure (on average 1.5 hours per week at baseline), would have greater bone mineral accrual than children involved in non-gymnastic recreational sports.

3.1.3 Methods

3.1.3.1 Study design: Participants were part of a mixed-longitudinal study performed at the University of Saskatchewan between 2006 and 2010. At study entry 3 cohorts were identified; 4, 5 and 6 years of age. Data was collected annually for 4 years. Additional participants were recruited during the second and third years of data collection to increase participant numbers at different ages. Because there were overlaps in ages between the clusters, it was possible to estimate a consecutive 6 year developmental pattern (4-10yrs) over a shorter 4 year period.

Participants were excluded if they had any condition that prevented them from performing exercise safely or any condition known to affect bone development (ie., heart conditions, neurological or musculo-skeletal problems). Informed consent was obtained from all parents or guardians and verbal assent was obtained from all children. This study was approved by the University of Saskatchewan's Biomedical Research Ethics Board (Bio 06-111) (Appendix A).

3.1.3.2 Participants: One hundred and seventy-eight participants were recruited. To be included in the present analysis participants required complete anthropometric, body composition and life style data; 163 participants (92%) fulfilled these requirements and are presented here. Table 3.1.1 provides a breakdown of eligible participants by age and sex for each testing year; it should be noted that not all participants were present at every testing occasion. Of the 163 participants, 95% were Caucasian, 2% Asian and 3% other (biracial). Gymnasts were recruited from the recreational and precompetitive programs of three competitive gymnastics clubs in Saskatoon, Saskatchewan and the University of Saskatchewan's recreational gymnastics program. Gymnasts had participated in gymnastics for forty-five minutes or more per week for at least one term (4 months) at study initiation. The study was designed to examine the influence of gymnastics participation on bone development; however, since some of the gymnasts who were participating in gymnastics at study initiation subsequently did not participate further (no participation in the previous four months) a sub-group of ex-gymnasts was identified in year two. Therefore, the ex-gymnast group includes individuals who were classified as gymnasts at baseline but were not participating in subsequent follow-up years. Parents of

gymnasts and ex-gymnasts reported how many hours per week their children participated in gymnastics. This represents the current participation hours for gymnasts; however, as ex-gymnasts had not participated in gymnastics for the previous four months, their hours of training is a representation of participation prior to cessation of gymnastics. Non-gymnasts were recruited from other recreational sport programs, such as swimming lessons and summer soccer, basketball, T-ball and sports 'r' fun sport camps, at the University of Saskatchewan. Non-gymnasts had no exposure to gymnastics stimulus. Thus three gymnastic status groups were identified: gymnasts, ex-gymnasts and non-gymnasts.

Table 3.1.1 Mixed longitudinal study design with number of males (females) measured at each test year by age category

	Test year				
Age	2006-2007	2007-2008	2008-2009	2009-2010	Total
4	22(23)		4(2)		26(25)
5	23(22)	15(15)	7(5)	6(2)	51(44)
6	13(21)	23(20)	12(15)	7(8)	55(64)
7	5(11)	16(18)	20(16)	18(15)	59(60)
8		4(12)	15(17)	21(17)	40(46)
9			6(16)	13(16)	19(32)
10				4(13)	4(13)
Total	63(77)	58(65)	64(71)	69(71)	254(284)

3.1.3.3 Chronological Age and Anthropometrics: The chronological age of each child was recorded to the nearest 0.01 year by subtracting the decimal year of the participant's date of birth from the decimal year of the day of testing. Anthropometric measurements included standing height and weight. Heights were recorded to the nearest millimeter using a wall mounted stadiometer (Holtain Limited, Britain) and body mass to the nearest 0.5 kilogram using a digital scale (Tanita Corporation, Model 1631, Japan). All measures

were performed twice and if the difference was greater than 0.4 a third measure was recorded. The mean or median was then reported depending on whether two or three measures were recorded, respectively (ISAK, 2001). All measures were performed by the same Canadian Society for Exercise Physiology-Certified Exercise Physiologist.

3.1.3.4 Physical Activity and Dietary Assessment: Physical activity was assessed using the previously validated Netherlands Physical Activity Questionnaire (NPAQ) (Janz et al., 2005; Montoye et al., 1996) (Appendix B). Parents were asked to report their child's current physical activity level. The NPAQ proxy report includes items about activity preferences and everyday activity choices rather than a specific recall of physical activity (Janz et al., 2005). Questionnaire responses range from 7 (low physical activity) to 35 (high physical activity). Calcium and vitamin D intake were assessed through the use of a 24-hour recall questionnaire (Appendix C). Dietary data were analyzed using the Food Processor and Nutritional Software version 8.5 (ESHA research software, Salem, Oregon). The 24-hour recall has been suggested as a suitable method to assess individual nutrient intakes of children (Whiting et al., 1993).

3.1.3.5 Dual Energy X-ray Absorptiometry: Body composition measurements were performed using a Hologic Discovery Wi dual energy X-ray absorptiometry (DXA) scanner. Three different scans were performed; total body, lumbar spine, and femoral neck. The TB scans are presented as TB and TB less head (TBLH). The International Society for Clinical Densitometry recommends that head be excluded when calculating bone mass measurements of the total body in children and adolescents (Gordon et al.,

2008); however, the majority of previous research has reported TB BMC with the head included therefore, both methods are presented here. Bone mineral content (g), lean mass (kg) and fat mass (kg) were derived from the scans. All scans were administered and analyzed by a certified radiology technologist. Quality control phantom scans were performed daily. The coefficients of variation (CV%) for these measures from our laboratory, based on duplicate measures in 30 young healthy female university students (20-30 yrs), were 0.5% for whole body BMC, 0.7% for lumbar spine BMC and 1.0% for the proximal femur BMC. Fat and lean tissue mass were assessed from the total body scans. Our laboratory has determined coefficients of variation for these measures to be 3.0% and 0.5% respectively.

3.1.3.6 Statistical Analysis: Variables are presented as means and standard deviations (SD). Group differences (gymnasts vs ex-gymnasts vs non-gymnasts) for height, weight, total body fat mass, total body lean mass, calcium, vitamin D, and physical activity were assessed in each age category by analysis of variance and Bonferroni post hoc. Group differences (gymnasts vs non-gymnasts) in TB, TBLH, LS and FN BMC were assessed using ANCOVA (covariates: age, sex, height, weight, physical activity, calcium and vitamin D) at the first testing occasion (2006-2007). Statistical analysis was performed using SPSS software version 18.0 and alpha was set at 0.05

For the longitudinal analyses, hierarchical (multilevel) random-effects models were constructed using a multilevel modeling approach (MlwiN version 1.0, Multilevel Models Project; Institute of Education, University of London, UK). A detailed description of multilevel modeling is presented elsewhere (Baxter-Jones et al., 2004). In

brief, bone mineral accrual and bone area was measured repeatedly within individuals (level 1 of hierarchy) and between individuals (level 2 of hierarchy). Analysis models that contain variables measured at different levels of hierarchy are known as multilevel regression models. Specifically the following additive, random effects multilevel regression models were adopted to describe the developmental changes in bone mineral accrual and bone area.

$$y_{ij} = \alpha + \beta_j x_{ij} + k_1 z_{ij} + \ldots k_n z_{ij} + \mu_j + \varepsilon_{ij}$$

where y is the bone mineral content or bone area parameter on measurement occasion i in the jth individual; α is a constant; $\beta_j x_{ij}$ is the slope of the time component (age centered around 7 years) for the jth individual; and k_1 to k_n are coefficients of various explanatory variables (e.g., height, physical activity, hours of training, etc.) at assessment occasion i in the jth individual. Dummy variables were created for gymnastic groups with non-gymnasts as the reference category. These are the fixed parameters in the model. Both μ_j and ε_{ij} are random quantities, whose means are equal to zero; they form the random parameters in the model. They are assumed to be uncorrelated and follow a normal distribution, and thus their variances can be estimated; μ_j is the level 2 (between-subjects variance) and ε_{ij} the level 1 residual (within-individual variance) for the ith assessment of bone mineral content in the jth individual. Models were built in a stepwise procedure, i.e., predictor variables (k fixed effects) were added one at a time, and the log likelihood ratio statistics were used to judge the effects of including further variables (Baxter-Jones et al., 2004).

The predictor variable coefficients (fixed variables in Table 3.1.4) were used to predict BMC (g) accrual with age for total body, femoral neck and lumbar spine. Height,

weight, and physical activity scores were controlled in the prediction equations using sex specific averages shown in Table 3.1.2.

3.1.4 Results

At the first measurement occasion, gymnasts (n=77) participated approximately 1.5±1.2 hours per week in gymnastics and had been training for 1.0±1.1 years. At the last measurement occasion (2010), gymnasts (n=30) were, on average, participating in gymnastics for 4.6±4.2 hours per week and had been training for 4.6±1.3 years. Ex-gymnasts (n=61) had participated in gymnastics for approximately 1.6±1.7 hours per week for approximately 2.3±1.1 years. Anthropometric, body composition, and dietary data as well as physical activity scores are presented in Table 3.1.2. There were no significant differences ($p > 0.05$) between groups for the variables presented, with the exception of gymnasts who were significantly shorter than both ex-gymnasts and non-gymnasts (n=72) at 6 years of age ($p < 0.05$).

Table 3.1.2 Descriptive statistics of chronological age-related anthropometric, body composition and life style data for gymnasts, non-gymnasts and ex-gymnasts

	Age (yrs)						
	4	5	6	7	8	9	10
Non-Gymnasts							
N	22	40	54	49	37	26	7
Ht (cm)	105.4±4.1	110.0±4.7	116.7±5.5	121.5±5.8	126.3±5.6	133.7±6.9	134.9±4.7
Wt (kg)	17.6±1.3	19.8±2.4	21.8±2.8	23.7±3.1	26.1±3.5	30.7±4.8	34.0±4.0
TB Fat (kg)	4.3±0.8	4.7±1.4	4.5±1.3	4.6±1.3	5.1±1.7	6.3±2.3	8.4±2.8
TB lean (kg)	12.2±1.0	13.8±1.8	15.8±2.2	17.4±2.5	19.4±2.7	22.5±3.6	23.4±3.0
Calcium (mg)	906±232	1038±491	1031±444	1091±605	919±550	904±330	1021±775
Vit D (IU)	189±129	231±152	200±140	190±137	185±179	212±129	202±151
PA score	24.4±3.9	24.8±3.5	25.4±3.9	25.5±3.8	24.8±4.1	24.8±5.0	25.6±2.5
Gymnasts							
N	9	13	18	17	10	8	3
Ht (cm)	103.5±3.9	107.1±5.0	113.4±4.2[a,c]	119.9±5.2	124.9±5.1	128.9±5.7	134.0±5.3
Wt (kg)	18.0±3.1	18.7±2.7	21.0±3.3	23.8±4.6	26.8±5.5	28.9±9.0	28.5±3.1
TB Fat (kg)	4.1±1.3	4.3±0.7	4.4±1.2	4.6±1.4	5.4±2.3	6.1±4.8	4.4±0.7
TB lean (kg)	12.7±1.8	13.2±1.8	15.5±2.4	17.7±3.2	19.6±3.2	21.0±3.9	22.1±1.9
Calcium (mg)	908±380	1097±426	975±427	1041±417	761±358	938±208	773±104
Vit D (IU)	194±122	198±110	200±152	159±122	130±96	116±91	318±138
PA score	25.6±3.0	25.7±2.9	25.4±3.0	25.8±2.7	26.0±5.0	24.4±3.8	26.7±4.2
Ex-Gymnasts							
N	20	42	47	53	39	17	7
Ht (cm)	104.4±5.1	111.2±6.1	117.9±6.2	122.7±6.6	129.6±7.0	133.6±7.4	134.2±7.3
Wt (kg)	18.1±2.7	20.5±3.6	23.4±4.5	24.9±4.1	28.2±5.2	30.1±5.5	29.9±4.8
TB Fat (kg)	4.2±1.2	4.7±1.7	5.1±2.2	4.8±2.0	5.7±2.4	6.0±2.7	5.3±2.0
TB lean (kg)	12.9±1.7	14.5±2.4	16.8±2.6	18.5±3.0	20.6±3.5	22.2±3.6	22.5±3.3
Calcium (mg)	1146±468	1090±479	1011±424	1014±447	1030±410	1119±533	666±321
Vit D (IU)	244±176	222±137	228±203	209±156	196±152	190±79	159±79
PA score	24.8±2.9	24.9±2.6	25.0±3.2	25.8±3.4	26.0±3.5	26.2±2.9	27.6±3.3

Variable mean±SD, *Ht* height, *Wt* weight, *TB* total body, *Vit D* vitamin D, *PA score* Netherlands physical activity score
[a]Gymnasts significantly different than Non-gymnasts
[b]Ex-gymnasts significantly different than Non-gymnasts
[c]Gymnasts significantly different than Ex-gymnasts

Table 3.1.3 summarizes the results from the first year of testing (2006-2007). There were no differences between gymnasts and non-gymnasts unadjusted (data not shown) and adjusted bone mineral content at any site measured ($p>0.05$).

Table 3.1.3 Adjusted bone mineral content values for gymnasts and non-gymnasts at the first testing occasion (2006-2007) (covariates: age, sex, height, weight, physical activity, calcium, vitamin D)

	Gymnasts (n=77)	Non-Gymnasts (n=63)
TB BMC (g)	686.3±5.5	675.0±6.0
TBLH BMC (g)	429.2±3.3	421.4±3.7
FN BMC (g)	8.4±0.2	8.2±0.2
LS BMC (g)	15.8±0.2	15.3±0.2

Adjusted marginal mean ± SEE (standard error of the estimate) of bone mineral content in grams. *TB* – Total body, *BMC* – Bone Mineral content, *TBLH* – Total body less head, *FN* – femoral neck, *LS* – Lumbar spine.

Table 3.1.4 summarizes the results from the multilevel models for TB, TBLH, FN, and LS bone mineral content development. The model for total body bone mineral content indicated that once age centered (1 year predicts 16.6 ± 4.3 g of BMC), height (1 cm predicts 7.6 ± 0.9 g of BMC), weight (1 kg predicts 7.1 ± 1.2 g of BMC), vitamin D (1 IU predicts 0.03 ± 0.1 g of BMC) and sex (females have 17.5 ± 7.7 g less BMC than males) were controlled, there was a significant independent gymnastic group effect (Table 3.1.4, Figure 3.1.1). Gymnasts had on average 27.9 ± 10.9 g more TB BMC than non gymnasts (p<0.05); there was no significant difference between ex-gymnast and non-gymnast TB BMC (Table 3.1.4, Figure 3.1.1). Hours of gymnastic training was also added to the model but was not a significant independent predictor of BMC accrual (p>0.05). There were also no significant gymnastic group by age centered interactions (p>0.05). The model for total body BMC with the head excluded (TBLH) resulted in

similar findings: when age centered, height, weight were considered gymnasts had on average 22.0 ± 6.3 g more TBLH BMC than non-gymnasts ($p<0.05$). However of note, sex was not a significant predictor for the TBLH model. Similar findings were also noted at the FN; when age centered, height, weight, sex, and physical activity were controlled. Gymnasts had 0.15 ± 0.06 g more BMC than non gymnasts ($p<0.05$); no significant differences were found between ex-gymnasts and non-gymnasts ($p>0.05$) (Table 3.1.4). No significant difference was found at the lumbar spine between the groups ($p>0.05$) when age, height, and weight were controlled (Table 3.1.4, Figure 3.1.1). The multilevel models for TB, TBLH, FN, and LS bone area revealed no significant differences between groups in bone area development when adjusted for age, height, and weight ($p>0.05$) (data not shown).

Table 3.1.4 Multilevel regression analysis of total body, total body less head, femoral neck, and lumbar spine BMC development (g)

Variable	Total Body BMC	TB Less Head BMC	Femoral Neck BMC	Lumbar Spine BMC
		Fixed Effects		
Constant	-304.2±92.8	-346.0±62.0	-1.7±0.6	-16.1±2.9
Age Centered	16.6±4.3	13.2±2.9	0.04±0.03	-0.06±0.1
Age Centered^2	1.0±0.6	2.0±0.5	0.01±0.006	NS
Sex	-17.5±7.7	NS	-0.09±0.04	NS
Height	7.6±0.9	5.7±0.6	0.02±0.006	0.25±0.03
Weight	7.1±1.2	7.4±0.9	0.02±0.007	0.17±0.04
Vitamin D	0.03±0.01	NS	NS	NS
Calcium	NS	NS	NS	NS
Physical Activity	NS	NS	0.01±0.004	NS
Hours Trained	NS	NS	NS	NS
Gym vs NGym	27.9±10.9	22.0±6.3	0.15±0.06	NS
XGym vs NGym	NS	NS	NS	NS
		Random Effects		
Level 1				
Constant	788.7±70.9	454.1±40.9	0.06±0.005	0.89±0.08
Level 2				

	Constant	Age Centered	Constant	Age Centered	Constant	Age Centered	Constant	Age Centered
Constant	2984.1±383.1	431.3±88.4	1428.1±187.9	274.6±49.7	0.05±0.009	0.007±0.003	2.7±0.36	0.41±0.09
Age Centered	431.3±88.4	82.7±32.8	274.6±49.7	46.8±19.2	0.007±0.003	0.007±0.002	0.41±0.09	0.07±0.03

Fixed-effect values are estimated mean coefficients ± SEE (standard error estimate) of bone mineral content in grams. Random effects values are estimated mean variance ± SEE (bone mineral content) in grams^2. Age Centered (Age – 7) yrs; Sex (0=male, 1=female); Height, cm; Weight, kg; Vitamin D, IU; Calcium, mg; Physical Activity (7-low to 35-high). *TB Less Head* – Total body BMC – Head BMC, *Gym*- gymnasts group, *NGym*- non gymnasts group, *XGym* - ex-gymnasts group; NS (p>0.05), not significant and variable removed from the final model.
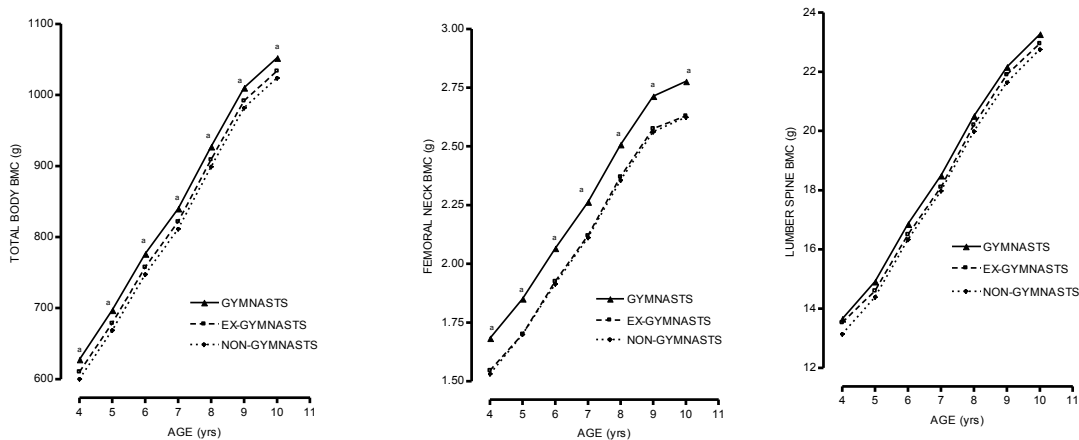
Figure 3.1.1 – Predicted total body, femoral neck and lumbar spine BMC development in gymnasts, non-gymnasts and ex-gymnasts from the multilevel regressions (Table 3.1.3). The *triangle* on the graph represents gymnasts, the *square* is ex-gymnasts and the *asterisk* is non-gymnasts. Height, weight and physical activity were held constant using values obtained from Table 3.1.2.
[a]Gymnasts significantly different than non-gymnasts

Age centered was added as both a fixed and random coefficient. The random effects coefficients describe the two levels of variance [within individuals (level 1 of the hierarchy) and between individuals (level 2 of the hierarchy)]. For all three BMC models, the significant variances at level 1 of the models indicate that BMC was increasing significantly at each measurement occasion within individuals (Estimate > 2*SEE; p <0.05) (Table 3.1.3). The between individuals variance matrix (level 2) for each model indicated that individuals had significantly different BMC growth curves, both in terms of their intercepts (constant/constant, $p < 0.05$), and the slopes of their lines (age/age, p <0.05). The variance of these intercepts and slopes were positively and significantly correlated (constant/age, p <0.05) in all models. The variance between individuals was therefore different at different ages.

70

3.1.5 Discussion

This is the first prospective study to examine low level gymnastics exposure (on average 1.5 hours per week at baseline) and bone mineral accrual in young males and females. The aim was to investigate the development of bone mineral content to determine if the advantages reported in the skeleton of competitive adolescent female gymnasts with high level gymnastics exposure were also apparent in young children with a current or past participation history in recreational or precompetitive gymnastics. The main finding was that recreational and precompetitive male and female gymnasts had significantly greater total body and femoral neck bone mineral content compared to children engaged in other recreational sports.

A cross-sectional comparison of the gymnasts versus non-gymnasts at the first year revealed no significant differences between groups for any bone parameter. However, in the longitudinal analysis it was found that by year four, recreational and precompetitive gymnasts had 3% more total body and 7% more femoral neck bone mineral content than children participating in other recreational sports when body size, physical activity and diet were considered. This suggests that one year of gymnastics participation at the recreational level was not sufficient to change these bone parameters (ie. a longer duration of stimulus is required). The majority of ex-gymnasts ceased participating in gymnastics between the first and second measurement occasions which may be contributing to the lack of difference observed between ex-gymnasts and non-gymnasts in the current cohort. Conversely it may be that DXA is not a sensitive enough measure to detect differences from one year stimulus compared to a longer duration. This is supported by the cross-sectional analysis of peripheral quantitative computed

71

tomography (pQCT) data in this cohort which found that both gymnasts and ex-gymnasts had greater bone mineral content at the distal radius at year three (Section 3.2). There was also no difference in bone area between groups once adjusted for age, height and weight, suggesting that individuals have an appropriate bone area for their size. This finding is consistent with the pQCT data in this cohort, which also found no differences in bone area between gymnasts, non-gymnasts and ex-gymnasts (Section 3.2).

The greater total body and FN BMC observed in these young male and female gymnasts is consistent with, though on a smaller magnitude to, the findings previously reported in competitive adolescent, collegiate and retired female gymnasts (Bass et al., 1998; Dowthwaite et al., 2007; Nickols-Richardson et al., 1999; Nickols-Richardson et al., 2000; Pollock et al., 2006; Proctor et al., 2002; Robinson et al., 2005; Zanker et al., 2004). The lower magnitude response is not unexpected as total and regional aBMD has been shown to be greater in gymnasts with higher exposure to gymnastics (i.e. greater hours or years of training) suggesting a dose response relationship between loading and bone mass (Laing et al., 2005; Scerpella et al., 2003). However, despite the fact that the current cohort is young and had a low level of gymnastics exposure they had greater TB and FN BMC suggesting that recreational and precompetitive gymnastics participation is beneficial at this young age. The greater BMC also supports Laing's et al. (2005) assertion that the stimuli received during introductory classes is sufficient to increase bone mass compared to other recreational sports.

Laing et al. (2005) were the first to examine beginner level female gymnasts and bone accrual. They found 4-8 year old girls participating in recreational gymnastics classes showed a significantly greater increase in lumbar spine aBMD and forearm bone

area over two years compared with girls not participating in gymnastics (Laing et al., 2005). The authors suggested that beginning level gymnastics skills performed in introductory classes seem to be adequate stimuli for enhancing gains in both bone mineral and size. However, it is well documented that aBMD does not adequately adjust for bone size, which is particular problematic when assessing growing children (Faulkner et al., 2003). Therefore, in the present study a size correction was applied directly to the DXA measured BMC by adjusting for the participants' height and weight at each measurement occasion in the multilevel model. The current study is also unique in that it assessed male as well as female recreational and precompetitive gymnasts.

The majority of previous literature has focused on females; there is limited research focusing on gymnastics training and male bone development. Daly et al. (1999) were the first to assess male competitive gymnasts; they found that male gymnasts had a greater increase in calcaneal bone parameters compared to controls over 18-months, 12.8% vs 7.2% respectively. However, they used ultrasound and assessed broadband ultrasonic attenuation (BUA). The precise skeletal properties reflected by BUA have not been well established and ultrasound does not directly measure either bone structure or material properties; therefore, caution should be taken when interpreting these results. To our knowledge, only one study has examined the influence of competitive gymnastics training on male and female bone parameters using DXA. Zanker et al. (2003) found that females had 8-10% greater aBMD at the TB, LS and forearm; however, there was no significant difference between male competitive gymnasts and non-gymnasts at any site. The authors did observe a trend toward a higher TB and forearm aBMD in males (Zanker et al., 2003). This is in contrast to the present study where male as well as female

gymnasts had greater TB and FN BMC. Zanker et al. (2003) suggested that the lack of a significant difference between male gymnasts and non-gymnasts may be related to their lower level of cumulative high-impact weight bearing activities compared to the female gymnasts. However, the male gymnasts in the Zanker et al. (2003) study trained 4-6 hours per week and had been training for 1-2 years which is greater than the current cohort at baseline and comparable to the hours of training after 4 years of participation. The present study findings as well as those by Laing et al. (2005) would suggest that the loading received in the Zanker et al. (2003) study should have been sufficient to produce significant benefits on the skeleton. The discrepancy in results may be related to the fact that Zanker et al. (2003) only examined 10 male gymnasts thus they may have simply been underpowered to observe the impact of lower gymnastics exposure on bone parameters.

As previously stated this study observed greater TB and FN BMC in the young male and female gymnasts compared to children engaged in other sports; however, there was no difference in LS BMC between the groups. This is in contrast to the cross-sectional comparisons of competitive adolescent, collegiate, and retired female gymnasts who have been reported to have higher total body as well as regional bone mineral measures when compared with other athletic and non-athletic populations of similar age, height and weight (Bass et al., 1998; Laing et al., 2001; Nickols-Richardson et al., 1999; Nickols-Richardson et al., 2000; Pollock et al., 2006; Proctor et al., 2002; Robison et al., 2005; Zanker et al., 2004). Laing et al. (2001) reported that female gymnasts of age 8-13 years had higher aBMD at the total body, femoral neck and lumbar spine, by 6%, 14%, and 15% respectively. The lack a significant difference between groups at the lumbar

spine may be related to the young age of the gymnasts in the current cohort. The appendicular skeleton (i.e. femoral neck) has been found to grow more rapidly and accrue more bone before puberty while axial skeleton (i.e. lumbar spine) growth is accelerated during puberty (Bass et al., 1999). Therefore, differences in LS BMC in the current cohort may become apparent as they approach puberty and axial skeletal growth accelerates. Alternatively it may also be that the loading experienced from low level gymnastics exposure is insufficient to increase BMC at the lumbar spine compared to other recreational activities. The gymnasts in the previously described study were competitive gymnasts who were training, on average, 11.7 hours per week and had been training for approximately 5.9 years (Laing et al., 2002).

Competitive gymnasts have greater total and regional aBMD and BMC and this persists after retirement from training and competition in former collegiate gymnasts (Pollock et al., 2006; Zanker et al., 2004). As such competitive gymnastics training and high level gymnastics exposure may potentially delay or prevent osteoporosis and related fractures. However, competitive gymnastics is a high level sport and participation is limited to a select number of skilled individuals. Zanker et al. (2003) stated that due to the great skill and physical and mental demands of competitive gymnastics it would be unrealistic to prescribe this activity to children as a possible prophylactic to osteoporosis in adulthood. Recreational gymnastics or low level gymnastics skills, on the other hand, are attainable by most children and do not require a high level of training. Recreational gymnastics involves the development of spatial and body awareness, muscular strength and neuromuscular coordination. Low level gymnastics skills can easily be implemented

into school physical education programs; thus, most children may benefit from this training.

Assessment of bone mineral content with exercise studies is limited because important changes in the structural properties of bone may occur and go undetected. The primary outcome in this section, BMC, does not account for changes in the shape or structure of bone. As previously stated, this is important as bone strength has been shown to significantly improve independent of changes in bone mass (Adami et al., 1999; Robling et al., 2006). Modeling during growth can alter endosteal and periosteal dimensions, and measures of the structural properties of bone in addition to bone mineral and may have provided valuable additional information (Petit et al., 2002). Therefore, the impact of recreational and/or precompetitive gymnastics participation on bone strength may be underestimated without measurements of bone structure. This is supported by Jarvinen et al. (1999) who suggest that while DXA provides a reasonable overall description of bone status, it overlooks structural bone alterations which can largely and independently influence bone strength. Investigations of bone structural adaptation are required to better understand the effect of both competitive and recreational gymnastics training on bone development. The influence of recreational gymnastics participation on bone geometry will be presented in section 3.2.

There are some other limitations to this study. The mixed-longitudinal design does not allow for a cause-effect assessment of current or past gymnastics participation on bone parameters. Well controlled prospective studies starting before the initiation of gymnastics participation are required to definitively answer whether the greater bone mineral measures are the result of cumulative exposure to gymnastics or present before

the initiation of participation. Detailed information about the types of exercises undertake by the gymnasts at the four different centers was not available, therefore, it was not possible to quantify the loading experienced by these young recreational and precompetitive gymnasts. The high activity level of the non-gymnast group may be reducing or even masking the positive influence of gymnastics participation on bone mineral accrual. The non-gymnasts in the current cohort were participating in other recreational sports (such as soccer, T-ball, basketball and karate) which may lead to increased loading in a similar manner as gymnastics at the lumbar spine and femoral neck. This is supported by similar and high physical activity scores across the groups. More active children may emerge from adolescence with 5-10% greater bone mass, depending on the skeletal site (Slemenda et al., 1991); therefore, if the non-gymnasts in the current cohort have greater activity levels and bone mass than average the impact of recreational and precompetitive gymnastics participation on bone parameters may actually be greater than the difference reported in the current cohort.

In summary, when compared to other physically active children, recreational and precompetitive gymnasts had greater total body and femoral neck bone mineral content. These findings are important as recreational gymnastics skills are attainable by most children and do not require a high level of training. Low level gymnastics skills can easily be implemented into school physical education programs and thus most children may benefit from this training, potentially developing greater total body and femoral neck BMC. This training could have a potential impact in primary osteoporosis and fracture prevention. However, investigations of bone structural adaptation are required to better

understand the effect of both competitive and recreational gymnastics training on bone development.

3.1.6 Acknowledgments

3.2 Study 2 - Precompetitive and recreational gymnasts have greater bone density, mass and estimated strength at the distal radius in young childhood

3.2.1 Abstract:

Competitive gymnasts have greater bone mass, density and estimated strength. The purpose of this study was to investigate whether the differences reported in the skeleton of competitive gymnasts are also apparent in young recreational and precompetitive gymnasts. 120 children (29 gymnasts, 46 ex-gymnasts and 45 non-gymnasts) between 4-9 years of age (mean=6.8±1.3) were measured. Bone mass, density, structure and estimated strength were determined using peripheral quantitative computed tomography (pQCT) at the distal (4%) and shaft (65%, 66%) sites in the radius and tibia. Total body, hip and spine bone mineral content (BMC) was assessed using dual energy x-ray absorptiometry (DXA). Analysis of covariance (covariates of sex, age, and height) was used to investigate differences in total bone content (ToC), total bone density (ToD), total bone area (ToA), and estimated strength (BSI) at the distal sites and ToA, cortical content (CoC), cortical density (CoD), cortical area (CoA), cortical thickness (CoTHK), medullary area (MedA) and estimated strength (SSIp) at the shaft sites. Gymnasts and ex-gymnasts had 5% greater adjusted total body BMC and 6-25% greater adjusted ToC, ToD and BSI at the distal radius compared to non-gymnasts ($p<0.05$). Ex-gymnasts had 7-11% greater CoC and CoA at the radial shaft and 5-8% greater CoC and SSIp at the tibial shaft than gymnasts and non-gymnasts ($p<0.05$). Ex-gymnasts also had 12-22% greater ToC and BSI at the distal tibia compared to non-gymnasts ($p<0.05$). This data suggests that recreational and precompetitive gymnastics participation is associated with greater bone strength.

3.2.2 Introduction

Gymnastics training results in uniquely high mechanical loading to the skeleton and therefore provides an excellent model for assessing the influence of loading on bone mass, density, structure and strength (Daly et al., 1999; Proctor et al., 2002). The majority of studies have demonstrated that competitive gymnasts have greater areal bone mineral density (aBMD, g/cm^2) and bone mineral content (BMC, g) when compared to other athletic and non-athletic populations (Bass et al., 1998; Proctor et al., 2002; Robinson et al., 1995). After four years of recreational gymnastics participation greater BMC was also observed in the present cohort at the total body and femoral neck (Section 3.1). Furthermore, total and regional aBMD is greater in gymnasts with higher exposure to gymnastics, i.e. greater hours or years of training (Scerpella et al., 2003). However, the impact of gymnastics loading on the adaptation of bone geometry is not well established (Dowthwaite et al., 2009). Competitive gymnasts commence systematic training from an early age (approximately 7-8 years of age) and often train in excess of 20 hours per week, year round (Daly et al., 2005). Studies examining gymnasts' bone parameters have generally focused on athletes who had systematically trained for at least 2 years and who trained a minimum of 15 hours per week (Bass et al., 1998; Proctor et al., 2002; Robinson et al., 1995). However, less is known about recreational and precompetitive gymnastics participation (i.e. low level gymnastics exposure) and bone size, bone mass, (volumetric) bone mineral density and estimated bone strength.

Young competitive female gymnasts have greater total, trabecular and cortical volumetric density (g/cm^3) at the distal radius compared to non-gymnasts, when assessed by peripheral quantitative computed tomography (Dyson et al., 1997; Ward et al., 2005).

Competitive gymnasts also have greater total and trabecular vBMD at the distal tibia as well as greater estimated bone strength at the radial and tibial shafts (Ward et al., 2005). The greater estimated bone strength at the distal sites was related to bone density, whereas at the shaft a greater bone area explained the strength benefit (Ward et al., 2005). Importantly, recent evidence suggests that these benefits in bone structure and estimated strength appear to be maintained into adulthood long after retirement, on average 6 years, from gymnastics training (Eser et al., 2009). This potentially decreases the risk of osteoporotic fracture later in life. To our knowledge only one study has examined recreational gymnastics participation and bone accrual. Laing et al. (2005) found that 4-8 year old girls participating in one hour of recreational gymnastics gained more areal bone mineral density at the lumbar spine and bone area at the forearm over two years compared to children participating in non-gymnastic activities. However, little is known in regard to bone mass, volumetric density and bone strength estimates in gymnasts under 7-8 years of age, prior to commencement of systematic competitive training. Therefore, the aim of this section was to investigate the influence of low level gymnastics participation on bone mass, size, volumetric density and estimated strength. We hypothesized that young gymnasts with low and extremely low levels of gymnastics exposure would have greater bone mass, density and estimated strength at the radius and tibia.

3.2.3 Methods

3.2.3.1 Participants: Participants were from a mixed-longitudinal study investigating the influence of gymnastics participation on bone development in young childhood (2006-

2010). The study design and participants are described in detail above 3.1.3.2 (pg 59-61). A subset (n=120, 89%) of the original cohort from year three (2008-2009) (Table 3.1.1) are included in this cross-sectional comparison. Children were 4-9 years of age (6.8 ± 1.3yrs) at the time of measurement. Our sample size justification was based on the findings from a similar cohort by Ward et al (2005). We calculated that a minimum of 6 participants per group would be needed for detecting a 17% difference in total density at the distal radius with 80% power.

3.2.3.2 Chronological Age, Biological Age and Anthropometrics: The chronological age of each child was recorded to the nearest 0.01 year by subtracting the decimal year of the participant's date of birth from the decimal year of the day of testing. Anthropometric measurements included standing height, sitting height and weight. Heights were recorded to the nearest millimeter using a wall mounted stadiometer (Holtain Limited, Britain) and body mass to the nearest 0.5 kilogram using a digital scale (Tanita Corporation, Model 1631, Japan). Left tibia length was measured from base of the medial malleolus to the superior margin of the medial epicondyle and left ulna length was measured from the distal tip of the styloid process to the proximal endplate using an anthropometric caliper (Rosscraft Lufkin, Canada). All measures were performed twice and if the difference was greater than 0.4 cm a third measure was recorded. The mean or median was then reported depending on whether two or three measures were recorded, respectively (ISKA, 2001). All measures were performed by the same Canadian Society for Exercise Physiology-Certified Exercise Physiologist.

The range of variability between individuals of the same chronological age in maturity may be large especially as individuals approach their adolescent growth spurt; therefore, it is essential that maturity or biological age is considered when examining children's growth (Mirwald et al., 2002). Age at peak height velocity (APHV) is a biological age maker that reflects the maximum growth in stature during a one year time interval in childhood and acts as an indicator of somatic maturation. It is a maturational landmark which is easily assessed, does not require invasive procedures and occurs in both males and females. APHV was estimated for all participants who were 8 years of age or older at the time of measurement using Mirwald et al.'s (2002) maturity offset equation. The equation is only accurate for children 8 years or older; therefore, it was not used on the younger participants. The coefficient of determination (R^2) is 0.92 for males and 0.91 for females.

3.2.3.3 Physical Activity and Dietary Assessment: Physical activity was assessed using the previously validated Netherlands Physical Activity Questionnaire (NPAQ) (Janz et al., 2005; Montoye et al., 1996) (Appendix B). Parents were asked to report their child's current physical activity level. The NPAQ proxy report includes items about activity preferences and everyday activity choices rather than a specific recall of physical activity (Janz et al., 2005). Questionnaire responses range from 7 (low physical activity) to 35 (high physical activity). Calcium and vitamin D intake were assessed through the use of a 24-hour recall questionnaire (Appendix C). Dietary data were analyzed using the Food Processor and Nutritional Software version 8.5 (ESHA research software, Salem,

Oregon). The 24-hour recall has been suggested as a suitable method to assess individual nutrient intakes of children (Whiting et al., 1993).

3.2.3.4 Peripheral Quantitative Computed Tomography (pQCT): Cross-sectional slices (2.4±1mm) of the left radius and tibia were measured by pQCT (XCT-2000; Stratec Medizintechnik GmbH, Pforzheim, Germany). The participant's arm and then leg were placed in an air cast and the cast was inflated to assist with stabilization and decrease movement artifacts (Figure 3.2.1). A scout scan was performed to visualize the distal growth plate and a reference line was placed on the medial point of the distal endplate (Figure 3.2.1). The forearm was scanned at the distal and shaft sites, 4% and 65% of the limb length proximal to the reference line, respectively. The lower leg was scanned at the 4% (distal) and 66% (shaft) sites. All measurements were performed by the same trained technician and a voxel size of 0.4 mm was used for all sites at a scan speed of 20 mm/s.
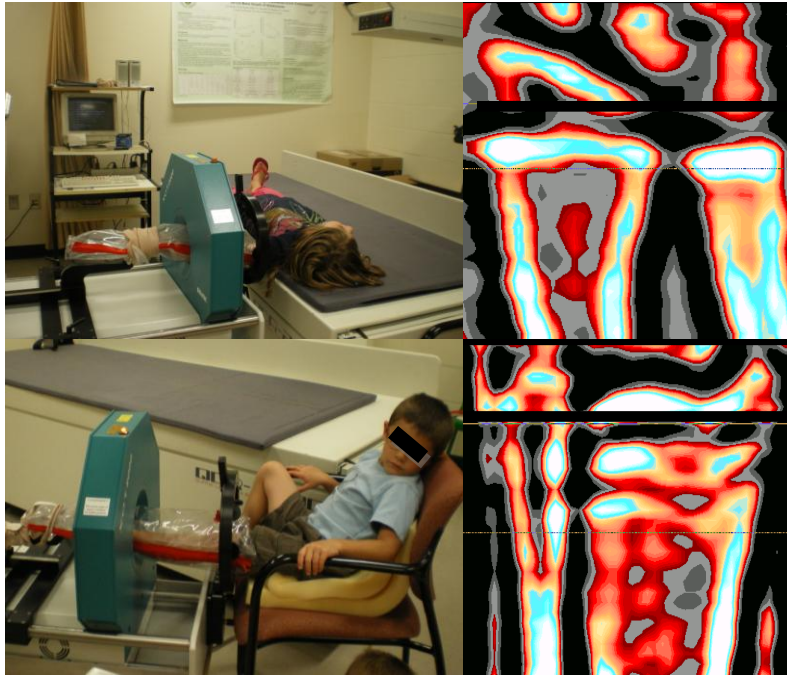
Figure 3.2.1 – Limb placement in pQCT gantry and placement of reference line on medial point of distal end plate

Analyses were performed with manufacturer provided software (XCT, version 5.4). Scans were analyzed using contour mode 1 with a threshold of 280 mg/cm^3 (to separate bone from soft tissue) at the distal site. Bone properties at the shaft sites were analyzed using separation mode 4 with a threshold of 280 mg/cm^3 and 540 mg/cm^3 (to separate cortical bone from marrow). Thresholds were selected based on line analysis. Muscle cross-sectional area (MCSA) was calculated by subtracting total bone area from total limb area. Limb area was analyzed using contour mode 1 and a threshold of 30 mg/cm^3 (to separate muscle from fat tissue) (XCT, 2007). The laboratory coefficients of variation (CV%$_{RMS}$), based on duplicate measures in 65 healthy adult volunteers, for MCSA, bone density, content, area and strength indices at the radius and tibia ranged from 1.8-6.3%.

The distal metaphysis (4%) was used to determine total bone area (ToA), total volumetric bone density (ToD) and total bone content (ToC). Total bone area (ToA),

cortical bone area (CoA), cortical volumetric density (CoD), cortical content (CoC), cortical wall thickness (CoTHK) and medullary area (MedA) were assessed at the shaft site in the radius and tibia (65%, 66% respectively). Medullary area was calculated by subtracting cortical area from total bone area. Bone strength index (BSI) was calculated (ToA x ToD^2) as a measure of estimated compressive strength at the distal site and polar stress-strain index (SSIp) was derived from the shaft measurements as a surrogate for bone torsional strength (XCT, 2007; Lochmuller et al., 2002; Kontulainen et al., 2008). Images found to contain movement artifacts were excluded from analysis if bone edge detection was impeded (n=15). A total of 5 distal radius, 7 radial shaft and 3 tibia scans (including both distal and shaft) were removed from analysis due to movement.

3.2.3.5 Dual Energy X-ray Absorptiometry: Body composition measurements were performed using a Hologic Discovery Wi dual energy X-ray absorptiometry scanner. Three different scans were performed; total body, lumbar spine, and proximal femur (hip). Bone mineral content (g), lean mass (kg), and fat mass (kg) were derived from the scans. All scans were administered and analyzed by a certified radiology technologist. Quality control phantom scans were performed daily. The coefficients of variation (CV%) for these measures from our laboratory, based on duplicate measures in young healthy female university students (20-30 yrs), were 0.5% for total body BMC, 0.7% for lumbar spine BMC and 1.0% for the proximal femur BMC. Fat and lean tissue mass were assessed from the total body scans. Our laboratory has determined coefficients of variation for these measures to be 3.0% and 0.5%, respectively.

3.2.3.6 Statistical Analysis: Variables are presented as means and standard deviation (SD). Group differences (gymnasts vs. ex-gymnasts vs. non-gymnasts) for age, height, weight, lean mass, fat mass, MCSA, physical activity, vitamin D (VitD), and calcium (Ca^{2+}) were assessed by Analysis of Variance (ANOVA). Mean differences (and their 95% Confidence Intervals) for pQCT and DXA outcomes across groups were assessed by Analysis of Covariance (ANCOVA). In order for comparison with the findings of Ward et al. (Ward et al., 2005) in competitive gymnasts of a similar age and gender composition; we included sex, age and height as covariates. Correlations between hours of training and bone parameters were assessed using Bivariate Pearson correlations. All analyses were performed using SPSS version 17.0. Alpha was set as $p<0.05$.

3.2.4 Results

Anthropometric, body composition, and dietary data as well as physical activity scores are presented in Table 3.2.1 (29 gymnasts (20 females, 9 males), 46 ex-gymnasts (20 females and 26 males) and 45 non-gymnasts (26 females, 19 males)). Gymnasts trained significantly more hours per week for more years than ex-gymnasts (p<0.05). There were no significant differences (p>0.05) between the groups for the remaining variables presented in Table 3.2.1 apart from some of the nutrition variables. Male and female gymnasts and ex-gymnasts had significantly greater vitamin D intakes compared to non-gymnasts (p<0.05). Female gymnasts and ex-gymnasts, and male ex-gymnasts also had significantly greater calcium intakes compared to non-gymnasts (p<0.05). There were no significant differences between groups in biological age for those children aged 8 years and above ($p>0.05$). Female non-gymnasts (n=11) were 1.9 years from PHV,

gymnasts (n=8) were 2.4 from PHV and ex-gymnasts (n=9) were 2.1 years from PHV

(*p*>0.05*)*. Male non-gymnasts (n=6) were 4.1 years from PHV and gymnasts (n=7) were

4.0 years from PHV (*p*>0.05); all individuals classified as male ex-gymnasts were under

8 years of age and therefore, were considered pre-pubertal.

Table 3.2.1 – Anthropometric, body composition and lifestyle data for gymnasts, ex-gymnasts and non-gymnasts

	♂ Gym n=9	♂ XGym n=26	♂NGym n=19	♀ Gym n=20	♀XGym n=20	♀ NGym n=26
Age (yrs)	5.65±1.53	6.58±1.15	6.84±1.24	7.06±1.11	7.41±1.04	6.94±1.45
Height (cm)	116±12	121±10	120±9	120±8	125±6	121±10
Weight (kg)	23.4±5.2	25.7±6.0	23.7±4.4	23.4±5.0	26.6±4.8	24.4±4.9
TB FM (kg)	4.8±1.6	4.8±2.2	4.4±1.3	4.7±1.9	6.4±2.5	5.5±2.4
TB LM (kg)	17.8±3.8	19.2±4.3	17.2±4.8	17.2±3.2	18.7±3.1	17.5±3.2
FA MCSA(mm^2)	1568±305	1707±364	1529±234	1522±305	1578±281	1481±192
LL MCSA(mm^2)	3218±465	3188±589	2797±542	2955±388	3146±500	2979±358
PA Score	27.1±4.0	26.0±3.5	26.0±4.0	26.4±3.6	25.3±3.7	24.3±3.4
VitD (IU)	297±227	266±174	199±109[a,b]	204±261	198±89	135±131[a,b]
Ca$^+$(mg)	1076±421	1285±534 [c]	1036±538	976±379	952±408	782±369[a,b]
Gym hrs/wk	2.0±2.3	1.0±0.2[c]	-	5.0±5.0	1.5±1.8[c]	-
Yrs of Gym	2.9±1.1	1.9±0.9[c]	-	3.2±0.9	2.1±0.9[c]	-

Variables mean ± SD. ♀= female, ♂=male, Gym = gymnast group, XGym = ex-gymnasts group, NGym = non-gymnast group, TB = total body, FM= fat mass, LM= lean mass, FA= forearm, LL= lower leg, MCSA = muscle cross-sectional area, PA score = Netherlands physical activity score, VitD= Vitamin D, Ca$^+$= calcium, Gym hrs/wk = hours per week engaged in gymnastics participation, Years of Gym = total number of years participated in gymnastics
[a]Gymnasts significantly different than non-gymnasts
[b]Ex-Gymnasts significantly different than non-gymnasts
[c]Gymnasts significantly different than ex-gymnasts

Comparison of unadjusted pQCT bone parameters for gymnasts, non-gymnasts

and ex-gymnasts (mean ± SD) are presented in Table 3.2.2. There were no interactions

between sex and gymnastics status for any of the bone variables (p>0.05); therefore, male

and female data were combined. Comparison of pQCT bone outcomes adjusted for sex,

age and height (mean ± SD) are presented in Table 3.2.3. Once adjusted gymnasts and ex-gymnasts had significantly greater ($p<0.05$) ToC, ToD and BSI at the distal radius compared to non-gymnasts (Figure 3.2.2). Ex-gymnasts also had greater adjusted ToC and BSI compared to non-gymnasts at the distal tibia ($p<0.05$) (Figure 3.2.2). Ex-gymnasts had greater CoC and CoA at the shaft of the radius compared to both gymnasts and non-gymnasts ($p<0.05$) (Figure 3.2.3). Ex-gymnasts had significantly greater CoC compared to gymnasts and non-gymnasts and significantly greater estimated strength (SSIp) than gymnasts at the tibial shaft (Figure 3.2.3). Since vitamin D and calcium were significantly different between groups the models were also run with those variables added as covariates along with sex, age and height (data not shown). The addition of these dietary variables did not alter any of the significant bone outcomes with the exception of estimated bone strength (SSIp) at the tibial shaft ($p>0.05$).

Table 3.2.2 – Unadjusted pQCT bone parameters of the radius and tibia for gymnasts, ex-gymnasts and non-gymnasts (mean±SD)

Site	Variable	Gymnasts	Ex-Gymnasts	Non-Gymnasts
4% Radius	ToC (g/cm)	59.6±17.0	60.6±17.8 [a]	51.7±12.6
	ToD(mg/cm^3)	303±34	307±28 [a]	284±32
	ToA(mm^2)	197±53	196±51	184±41
	BSI (mg^2/mm^4)	18.6±0.6	18.9±0.6 [a]	14.8±0.4
65% Radius	ToA (mm^2)	87±16	90±18	87±18
	CoC (g/cm)	49.5±9.6	55.0±8.1[a,b]	50.1±8.3
	CoD(mg/cm^3)	795±71	795±72	821±61
	CoA (mm^2)	62±10	69±10[a,b]	61±10
	SSIp (mm^3)	107±32	122±30	113±32
	CoThk (mm)	1.02±0.12	1.10±0.18	1.10±0.16
	MedA(mm^2)	25±10	25±10	26±10
4% Tibia	ToC (g/cm)	157±36	182±43[a,b]	156±37
	ToD(mg/cm^3)	289±34	302±34	285±71
	ToA(mm^2)	543±116	599±121	560±130
	BSI (mg^2/mm^4)	45.4±1.3	55.7±1.7[a,b]	44.3±1.4
66% Tibia	ToA (mm^2)	309±67	332±62	323±67
	CoC (g/cm)	137±28	156±28[b]	145±27
	CoD(mg/cm^3)	829±74	860±65	846±65
	CoA (mm^2)	164±31	181±30	171±30
	SSIp (mm^3)	651±160	777±190 [b]	702±170
	CoThk (mm)	2.19±0.19	2.35±0.16	2.44±0.15
	MedA(mm^2)	145±57	152±43	152±50

[a] Ex-gymnasts significant different than non-gymnasts

[b] Ex-gymnasts significantly different than gymnasts

Variable mean ± SD. Variable definitions: ToC = total bone content, ToD = total bone density, ToA = total bone area, BSI = bone strength index, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, SSIp = polar stress strain index, CoThk = cortical thickness, MedA = medullary area.

Table 3.2.3 – Results for peripheral quantitative computed tomography of the radius and tibia after adjustment for age, sex and height

Site	Variable		Gymnasts	Ex-Gymnasts	Non-Gymnasts	P	Interaction P
4% Radius	ToC (g/cm)	M + F	61.2±2.6	59.2±2.1	52.0±2.0[a,b]	0.013	0.97
	ToD(mg/cm^3)	M + F	301±6	308±5	284±5[a,b]	0.003	0.39
	ToA(mm^2)	M + F	204±7	191±6	184±6	0.10	0.55
	BSI (mg^2/mm^4)	M + F	18.6±1.0	18.5±0.8	14.9±0.8[a,b]	0.004	0.80
65% Radius	ToA (mm^2)	M + F	90±3	92±3	87±2	0.35	0.57
	CoC (g/cm)	M + F	50.7±1.3	54.0±1.0[c]	50.2±1.0[b]	0.02	0.64
	CoD(mg/cm^3)	M + F	799±12	793±9	820±10	0.09	0.25
	CoA (mm^2)	M + F	63±2	68±1[c]	61±1[b]	0.002	0.64
	SSIp (mm^3)	M + F	113±5	118±4	114±4	0.39	0.32
	CoThk (mm)	M + F	1.04±0.13	1.11±0.18	1.11±0.14	0.82	0.66
	MedA(mm^2)	M + F	27±2	24±2	26±2	0.62	0.55
4% Tibia	ToC (g/cm)	M + F	163±6	176±4	157±4[b]	0.009	0.08
	ToD(mg/cm^3)	M + F	290±10	303±8	283±8	0.20	0.92
	ToA(mm^2)	M + F	565±15	581±11	566±11	0.66	0.10
	BSI (mg^2/mm^4)	M + F	47.8±2.1	54.3±2.6	44.6±2.1[b]	0.007	0.29
66% Tibia	ToA (mm^2)	M + F	322±10	323±8	324±8	0.80	0.32
	CoC (mg)	M + F	142±3	152±2[c]	144±2[b]	0.02	0.14
	CoD(mg/cm^3)	M + F	833±12	859±10	845±10	0.29	0.97
	CoA (mm^2)	M + F	170±3	177±2.6	171±3	0.22	0.25
	SSIp (mm^3)	M + F	690±19	748±15[c]	705±16	0.04	0.17
	CoThk (mm)	M + F	2.25±0.15	2.34±0.15	2.40±0.15	0.81	0.07
	MedA(mm^2)	M + F	152±9	146±7	153±7	0.67	0.18

Variables mean ± SD. ToC = total bone content, ToD = total bone density, ToA = total bone area, BSI = bone strength index, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, SSIp = polar stress strain index, CoThk = cortical thickness, MedA = medullary area, P from ANCOVA, Interaction P – ANCOVA with sex*gymnastics status interaction P value
[a]Gymnasts significantly different than non-gymnasts
[b]Ex-Gymnasts significantly different than non-gymnasts
[c]Gymnasts significantly different than ex-gymnasts
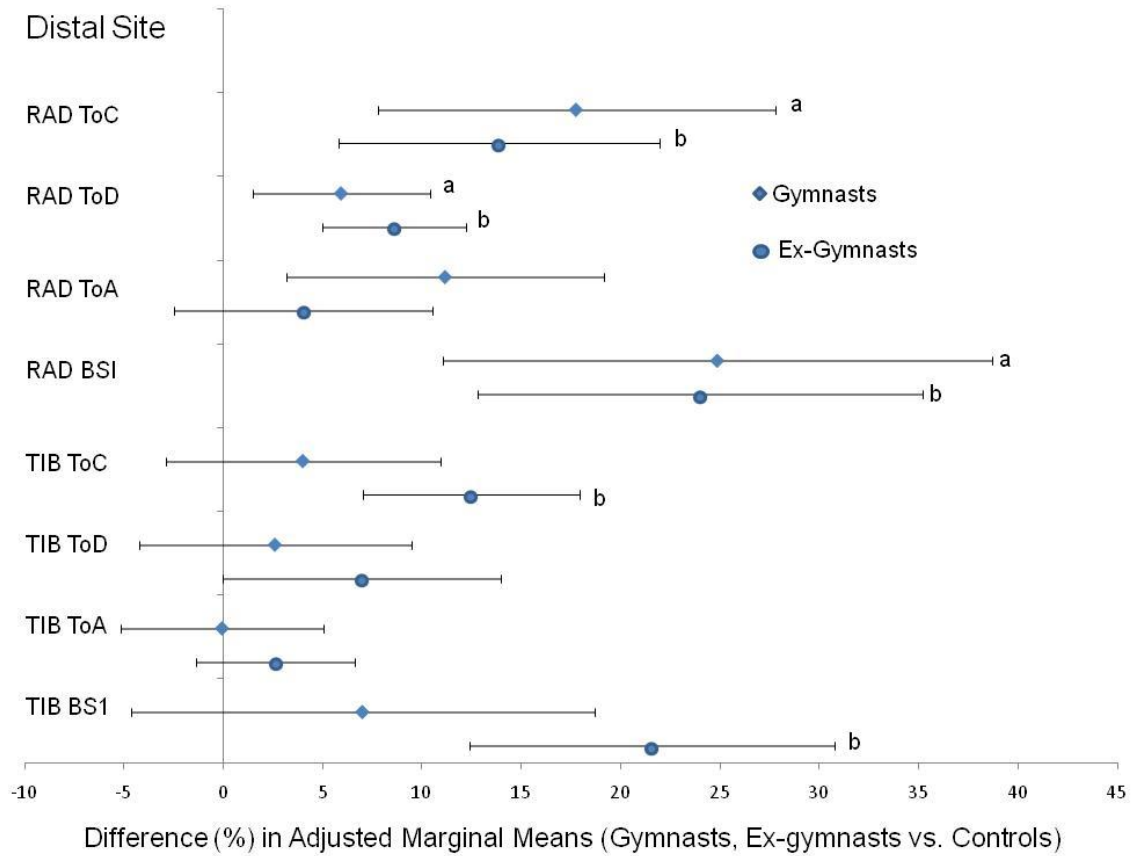
Figure 3.2.2 – Percent difference in adjusted marginal means for pQCT distal radius (4%) and distal tibia (4%) and 95% CI for gymnasts and ex-gymnasts compared to non-gymnasts. pQCT values were adjusted to control for sex, age, and height. The zero on the graph represents non-gymnasts, the diamond is gymnasts and the circle is ex-gymnasts.
RAD = Radius, TIB = Tibia, ToC = total bone content, ToD = total bone density, ToA = total bone area, BSI = bone strength index, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, SSIp = polar stress strain index, CoThk = cortical thickness, MedA = medullary area
[a]Gymnasts significantly different than non-gymnasts
[b]Ex-Gymnasts significantly different than non-gymnasts
[c]Gymnasts significantly different than ex-gymnasts
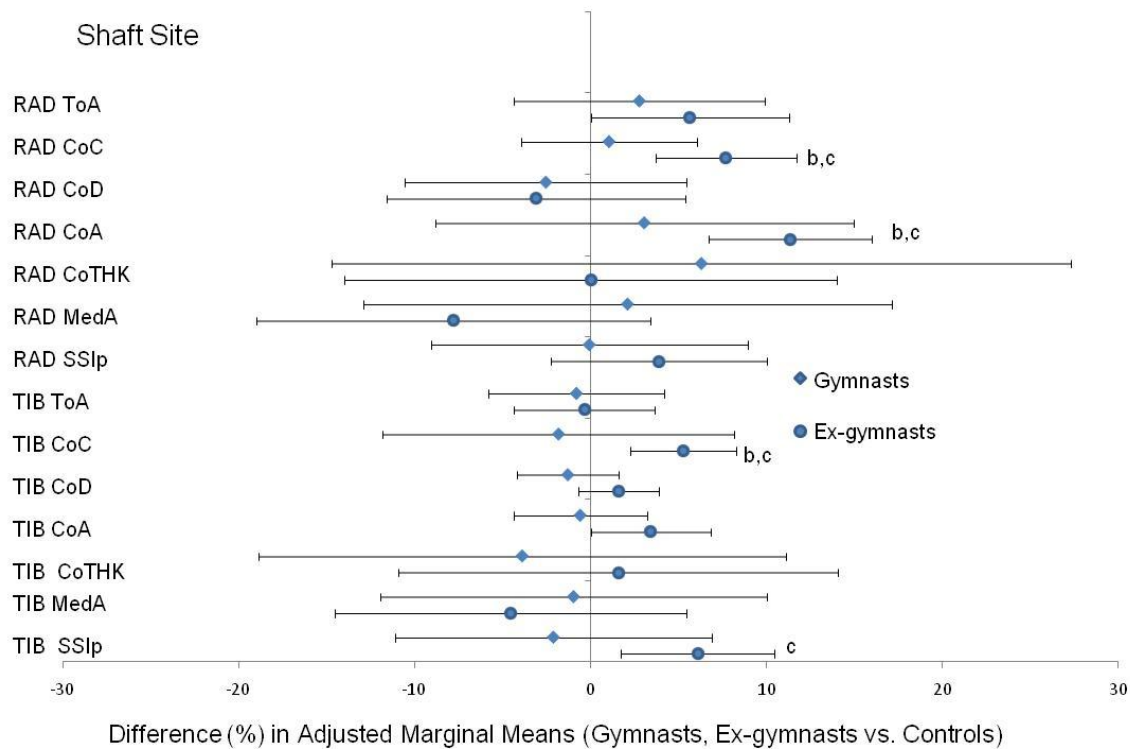
Figure 3.2.3 – Percent difference in adjusted marginal means for pQCT radial shaft (65%) and tibial shaft (66%) and 95% CI for gymnasts and ex-gymnasts compared to non-gymnasts. pQCT values were adjusted to control for sex, age, and height. The zero on the graph represents non-gymnasts, the diamond is gymnasts and circle ex-gymnasts. RAD = Radius, TIB = tibia, ToC = total bone content, ToD = total bone density, ToA = total bone area, BSI = bone strength index, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, SSIp = polar stress strain index, CoThk = cortical thickness, MedA = medullary area
[a]Gymnasts significantly different than non-gymnasts
[b]Ex-gymnasts significantly different than non-gymnasts
[c]Gymnasts significantly different than ex-gymnasts

Unadjusted total body, lumbar spine and femoral neck BMC is presented in Table 3.2.4. DXA bone outcomes adjusted for age, sex, height are presented in Table 3.2.5. Gymnasts and ex-gymnasts had 5% greater adjusted total body BMC compared to non-gymnasts (p<0.05). There were no significant differences (p>0.05) between groups for either spine or hip BMC. The addition of calcium and vitamin D as covariates to the analysis did not alter the outcomes. Pearson correlations revealed a significant positive

93

correlation between total body BMC and hours spent participating in gymnastics (r=0.38, p<0.05). The remaining DXA and all pQCT variables were positively but not significantly (r=0.05-0.28, p>0.05) correlated with current hours engaged in gymnastics training.

Table 3.2.4 Results for dual energy X-ray absorptiometry of total body, lumbar spine and femoral neck

Site	Variable	Gym	XGym	NGym
Total Body	BMC (g)	820±123	875±158[b]	799±129
Lumbar Spine	BMC (g)	18.0±3.8	19.4±3.7	18.1±3.2
Femoral Neck	BMC (g)	10.5±2.7	12.0±2.9	10.7±2.4

Variables mean ± SD. BMC= Bone Mineral Content, Gym = gymnast group, XGym = ex-gymnast group, NGym = non-gymnast group
[a]Gymnasts significant different than non-gymnasts
[b]Ex-gymnasts significant different than non-gymnasts

Table 3.2.5 Results for dual energy X-ray absorptiometry of total body, lumbar spine and femoral neck after adjustment for age, sex, and height

Site	Variable	Gym	XGym	NGym	P	Interaction P
Total Body	BMC (g)	853±14	854±11	811±11[a,b]	0.007	0.625
Lumbar Spine	BMC (g)	18.9±0.4	18.9±0.3	18.4±0.3	0.087	0.195
Femoral Neck	BMC (g)	11.0±0.4	11.5±0.3	10.7±0.3	0.445	0.301

Variables mean ± SD. BMC= Bone Mineral Content, Gym = gymnast group, XGym = ex-gymnast group, NGym = non-gymnast group, P from ANCOVA, Interaction P = ANCOVA with sex*gymnastics status interaction P value
[a]Gymnasts significant different than non-gymnasts
[b]Ex-gymnasts significant different than non-gymnasts

3.2.5 Discussion

The aim was to investigate the influence of low level gymnastics exposure on bone mass, size, volumetric density and estimated strength in young children with a current or past participation history in recreational and precompetitive gymnastics. The main finding was that gymnasts and ex-gymnasts had greater mass, density and estimated strength at the distal radius compared to non-gymnasts.

We found that recreational and precompetitive gymnasts had 18% greater total content, 6% greater total density and 25% greater estimated strength at the distal radius compared to non-gymnasts when sex, age and height were considered. Ex-gymnasts had 14% greater adjusted total content, 9% greater adjusted total density and 24% greater adjusted estimated strength at the same site compared to the non-gymnast group. These differences are of a much greater magnitude than the differences found in Section 3.1 using DXA, this highlights the ability of pQCT to detect differences not found using other less sensitive measures of bone parameters. The greater bone density observed in these young recreational and precompetitive gymnasts at the distal radius is consistent with the two previous studies examining the impact of competitive, high exposure gymnastics training on bone structure in childhood. Dyson et al. (1997) were the first to study gymnastics training and bone parameters using pQCT and found that competitive gymnasts had significantly greater total, cortical and trabecular density (20%, 16%, and 27%, respectively) at the distal radius when compared to non-gymnasts. Similarly, Ward et al. (2005) reported 17% greater total density and 21% greater trabecular density at the distal radius in young gymnasts. Both Ward et al. (2005) and Dyson et al. (1997) observed gymnasts who were engaged in competitive rather than recreational gymnastics

95

classes and who had high and extremely high levels rather than low levels of gymnastics exposure. The gymnasts in the Dyson et al. (1997) study trained a minimum of 15 hours per week and were an average of 9.8 years of age; the gymnasts in the Ward et al. (2005) study trained a minimum of 6 hours per week and were an average of 9 years of age at the time of measurement. The greater training volume, longer training history and older age of the gymnasts could explain the difference in the observed differences between gymnasts and non-gymnasts in these three cohorts. Despite the fact that the current cohort was younger and had a low level of gymnastics exposure they also had greater total density suggesting that recreational and precompetitive gymnastics participation is beneficial at this young age. The greater bone mass, density and estimated strength in the current cohort supports Laing et al.'s (2005) assertion that the mechanical stimuli received during introductory gymnastics classes is sufficient to increase bone mass compared to other recreational sports.

Dyson et al. (1997) and Ward et al. (2005) did not assess estimated strength (BSI) at the distal radius; however, since BSI is a product of squared total density and total area it is likely that the competitive gymnasts in these studies also had greater estimated strength at the distal radius. No significant differences in bone area at the distal radius were found in either the current or previous studies (Dyson et al., 1997; Ward et al., 2005). Dyson et al. (1997) concluded that these findings suggest the primary response to increased load at the distal wrist in young gymnasts is increased bone density without larger bone size. In contrast, in a study of retired competitive female gymnasts, 18-36 years of age, Eser et al. (2009) found significantly greater total bone area as well as total content at the distal radius when compared to non-gymnasts. These findings suggest

96

measureable changes in bone area may need more time or training, i.e. increased

gymnastics exposure, to be observed at the distal radius.

Ward et al. (2005) found that young male and female gymnasts had greater

cortical area and estimated strength at the radial shaft compared to non-gymnasts. Retired

female gymnasts have also been shown to have greater cortical area, BMC and estimated

strength at the radial shaft (Eser et al., 2009). In the present study there were no

significant differences between gymnasts and non-gymnasts at the radial shaft; however,

ex-gymnasts had significantly greater cortical content (~7%) and cortical area (~8%) at

this site. Although our group comparisons were adjusted for possible sex differences, the

greater number of males in the ex-gymnast group may be relevant to this finding. Ward et

al. (2005) reported a significant interaction between sex and gymnastics activity for

cortical thickness. Male gymnasts had significantly greater cortical thickness compared to

non-gymnasts while female gymnasts had a non-significant smaller cortical thickness

compared to non-gymnasts (Ward et al., 2005); however, there was no sex by gymnastic

status interaction in the study participants presented here. The lack of a difference

presented here between gymnasts and non-gymnasts in the shaft of the radius may also be

a reflection of training volume and/or age of the gymnasts. As previously stated the

gymnasts in the Ward et al. (2005) study were an average 9 years of age and were

considered to be competitive athletes, engaging in at least six hours per week of

competitive gymnastics training, i.e. high gymnastics exposure. In a group of competitive

gymnasts 8-12 years of age also training a minimum of 6 hours per week, Dowthwaite et

al. (2007) found training duration and maturity to be associated with BMC and aBMD at

the shaft of the forearm. This suggests that changes in the radial shaft may be a reflection of cumulative training or increased gymnastics exposure.

Ex-gymnasts had greater total content (12%) and estimated strength (22%) at the distal tibia compared to non-gymnasts. Ex-gymnasts also had greater cortical content (~6%) and estimated strength (8%) at the tibial shaft. However, when differences in dietary intakes between the groups were considered there was no difference in estimated strength at the tibial shaft. This suggests that nutrition differences may be influencing tibial bone strength and highlights the importance of calcium and vitamin D for bone health. When MCSA was considered along with the other covariates all significant differences in the tibial shaft disappear, suggesting that perhaps the differences in bone parameters in the tibial shaft are related to increased muscle mass in the ex-gymnasts. Lean mass was not significantly greater in ex-gymnasts; however, they did have approximately 2 kg more lean mass which was situated in the lower limbs. Although sex was controlled for in the model, the greater number of males in the ex-gymnast cohort may be influencing this result as males tend to have more lean mass. It is well established that muscle is a major correlate and determinant of bone. In the current study muscle cross sectional area and total body lean mass were highly and significantly correlated (r=0.709-0.257, p<0.05) with ToC, ToA and BSI at the distal sites and ToA, CoC, CoD, SSIp and Medullary area at the shaft sites. However, when MCSA was added to the model (data not shown) all bone parameters at the distal sites remained significantly greater in gymnasts and ex-gymnasts compared to non-gymnasts. This supports the assertion by Dowthwaite et al (2009) that non-muscular loading is a distinct and important determinant of human skeletal structure. There were no significant differences

between gymnasts and non-gymnasts at the tibia. Ward et al. (2005) also found no difference between gymnasts and non-gymnasts at the tibial shaft; however, they reported a greater total density at the distal tibia. In contrast, Eser et al. (2009) reported greater total content, area and estimated strength at the tibial shaft in retired female gymnasts when compared to non-gymnasts. These findings along with those at the radius, suggest that distal sites may be more sensitive to loading than shaft sites. Eser et al (2009) reported adaptations of both the radial and tibial shafts attributable to years of high gymnastics exposure. Ward et al (2005) also found higher BMD at the radial shaft in children exposed to high levels of gymnastics training; however, the effect size in these young gymnasts was 17-21% at the distal radius whereas it was only 5-6% at the shaft site. The gymnasts in the current study had greater bone strength at the distal site with low gymnastics exposure; however, it may be that more exposure, years of cumulative loading or higher levels of loading are required for adaptation at the shaft site.

The lack of a significant difference between gymnasts and non-gymnasts at both the distal and shaft sites in the tibia may be related to the fact that our non-gymnasts were participating in recreational sports (such as soccer, hockey and karate) which may load the tibia in a similar manner to recreational gymnastics. This is supported by the similar and high physical activity scores across the groups. It is also consistent with Ward et al. (2005) and Eser et al. (2009) who found the differences in bone geometry variables between gymnasts and non-gymnasts were greater at the distal radius than tibia. Ward et al. (2005) suggested that the relative difference in the loading patterns and intensity between gymnasts and non-gymnasts would be much greater at the radius compared to the tibia. Dowthwaite et al. (2007) stated that the weight-bearing pattern of the upper

99

extremity in gymnastics is unlike the loading patterns experienced in any other activities. Therefore, the unique loading patterns and intensity in the radius may explain why the differences between groups were greater at the distal radius than the non-significant distal tibia.

Studies of pre- and peri-pubertal as well as college-aged and retired gymnasts show greater total body and regional aBMD and BMC when compared to other athletic and non-athletic populations (Proctor et al., 2002; Robinson et al., 1995; Bass et al., 1998; Dowthwaite et al., 2007; Laing et al., 2005; Pollock et al., 2006). We did not present aBMD values as it is well documented that this measurement does not adequately adjust for bone size which is particularly problematic when examining children (Faulkner et al., 2003). Rather than using aBMD we applied a size correction directly to the DXA measured BMC by adjusting for participants' height. We also included age and sex in the corrected model as participants in the current study were not matched for these variables and both have been shown to impact bone development. Gymnasts and ex-gymnasts had 5% greater total body BMC which is consistent with, but lower than, the differences previously reported from high gymnastics exposure. It should be noted that when total body lean mass was entered as a covariate (data not shown) there was no longer a significant difference between groups suggesting that increased lean mass in the gymnasts and ex-gymnasts may be accounting for the greater total body BMC as measured by DXA. In contrast to the existing literature on competitive gymnasts, there were no significant differences between the recreational, precompetitive and ex-gymnasts for hip and spine BMC when compared to non-gymnasts.

The greater total body BMC observed in the current study is consistent with previous studies of competitive gymnasts. Faulkner et al. (2003) also found significant differences in total body BMC between gymnasts and non-gymnasts who were an average of 11.7 years of age. In contrast to the current findings, Faulkner et al. (2003) also reported greater hip and spine BMC in the gymnasts. Our spine results are consistent with Zanker and colleagues (2003) who found no significant difference in spine BMC when gymnasts were compared to age-, height- and weight-matched non-gymnasts. They used a similar study population to the current cohort, investigating both male and female gymnasts approximately 8 years of age. Competitive gymnasts are consistently found to have greater total body as well regional BMC; therefore, it is possible that the benefit of gymnastics participation on bone mineral content, as measured by DXA, will emerge as participants become more mature when their bone accrual accelerates and/or they advance to a more competitive training level, engaging in activities that promote loading on the skeleton (Laing et al., 2005; Zanker et al., 2003). This is supported by the positive correlation between hours engaged in training and total body BMC (r=0.38, $p<0.05$).

Our study has several strengths. To our knowledge, we are the first to use pQCT to compare gymnasts and ex-gymnasts of extremely low gymnastics exposure versus non-gymnasts, evaluating bone mass, density, size and estimated strength. This study is the first to show benefits in estimated strength at the distal radius that are likely related to recreational and precompetitive gymnastics training. For comparison with previous literature, bone parameters were adjusted for age, sex and height; however, lean mass and diet were also considered and carefully controlled for to account for any possible differences between groups other than gymnastics participation. These findings are

101

important as recreational gymnastics skills are attainable by most children and do not require a high level of training. Recreational gymnastics involves the development of spatial and body awareness, muscular strength and neuromuscular coordination. Low level gymnastics skills can easily be implemented into school physical education programs; thus, most children may benefit from this training, potentially developing greater BMC, BMD and estimated strength at the distal radius. The distal radius is an important clinical site as it is a common site of fracture in childhood as well as osteoporotic fracture later in life (Goulding et al., 2000; Rennie et al., 2007). It should also be noted that while elite gymnastics training has been associated with an increased risk of musculoskeletal injury the low level skills applied by participants in the current study are unlikely to confer undue injury risk.

There are a number of shortcomings to this study. The cross-sectional design does not allow for a cause-effect assessment of current or past gymnastics participation on bone parameters. We are not able to provide detailed information about the types of exercises undertaken by the gymnasts at the four different centers and therefore, unable to quantify the loading experienced by these young recreational and precompetitive gymnasts. The high activity level of our non-gymnasts may be reducing or even masking the positive impact of gymnastics participation at the tibia compared to a sedentary control group. The use and interpretation of cortical measures should be done with caution. The narrow cortical thickness observed at both the tibial and radial shafts (< 2.5mm) are subject to partial volume effects and may be adversely influencing estimates of cortical vBMD (Zemel et al., 2008). The placement of the pQCT reference line on the medial point of the distal endplate may influence the relative position of the

scans due to inter-individual variability in the distance between the articular surface and the proximal border of the physis. However, there were no differences in the distance between these two landmarks between groups and this distance did not correlate with metaphyseal bone outcomes. We may also be underpowered to compare differences at the shaft compared to distal sites.

In summary, when compared to other physically active children, recreational and precompetitive gymnasts had greater distal radius density, mass and estimated strength in young childhood. Greater differences in bone parameters between gymnasts, ex-gymnasts and non-gymnasts were observed in the distal radius compared to the distal tibia. Greater differences were also found at the distal compared to proximal radius, suggesting that changes in bone geometry at the distal site may precede adaptations at the proximal site. As recreational gymnastics can be implemented into school physical education programs, this training could have a potential impact in primary wrist fracture prevention. However, randomized controlled trials are required to tests our findings.

3.2.6 Acknowledgements

CHAPTER 4: *Retirement from Gymnastics and Bone Parameters*

4.1 *Elite premenarcheal gymnasts have higher bone mass in childhood and adolescence that is maintained after long-term retirement from sport: A 14-year follow-up*

4.1.1 Abstract

Systematic impact loading activity during childhood and adolescence has been shown to increase bone mineral content and density. However, it is unclear if this benefit is maintained after retirement from sport and removal of the osteogenic stimulus. The purpose of this study was to assess whether the previously reported greater bone mass in premenarcheal gymnasts was maintained 10 years after the cessation of gymnastics participation. In 1995, 22 elite premenarcheal gymnasts 8-15 years of age (mean=11.6) were measured and compared to 22 age-matched non-gymnasts. Gymnasts (n=22) and non-gymnasts (n=22) were measured again 14 years later (2009-2010). Gymnasts had been retired from gymnastics training and competition for an average of 10 years. Total body (TB), lumbar spine (LS), and femoral neck (FN) bone mineral content (BMC) was assessed at both measurement occasions by dual x-ray absorptiometry (DXA). ANCOVA was used to compare gymnasts' and non-gymnasts' BMC while controlling for differences in body size and maturation (covariates: age, height, weight, and years from menarche (1995) or age at menarche (2009/10)). Gymnasts were found to have significantly greater size adjusted TB, LS, and FN BMC (15, 17, and 12%, respectively) at 12 years of age (1995). Retired gymnasts were also found to have greater size adjusted

TB, LS, and FN BMC compared to non-gymnasts (13, 19 and 13%, respectively). Bone

mass benefits related to gymnastics training before menarche were still apparent even

after long-term removal of the gymnastics loading stimulus.

4.1.2 Introduction

It has been hypothesized that attaining a high peak bone mass early in life may prevent the risk of osteoporosis and related fracture risk later in life. Studies examining the role of physical activity during growth have shown that habitual physical activity increases bone mineral accrual (Bailey et al., 1999). Furthermore, there is recent evidence to support a continued benefit of childhood habitual physical activity on bone parameters in young adulthood (Baxter-Jones et al. 2008). The skeleton responds to systematic impact loading activity in childhood and adolescence by increased bone mineralization (Gunter et al., 2008; McKay et al., 2005); however, there is no clear evidence of a persisting benefit of systematic impact loading activity during growth on adult bone mass once the stimulus has been removed. Currently, the best evidence linking childhood exercise and bone health in adulthood arises from cross-sectional and short-term prospective studies in retired competitive athletes (Bass et al., 1998; Kontulainen et al., 1999; Kontulainen et al., 2001; Pollock et al., 2006; Uzunca et al., 2005; Zanker et al., 2004). Cross-sectional studies of retired athletes who started training in childhood suggest that bone gains achieved during the younger years may be maintained into adulthood; however, systematic impact loading activity during growth remains an unproven investment as an evidence-based means to prevent osteoporotic fracture (Pollock et al., 2006).

Retirement from artistic gymnastics provides a unique model to examine the impact of systematic childhood weight bearing training on adult bone health. Competitive female gymnasts have greater areal bone mineral density (aBMD, g/cm^2) and bone mineral content (BMC, g) when compared to other athletic and non-athletic populations

(Bass et al., 1998; Caswell et al., 1996; Laing et al., 2002; Nickols-Richardson 2000; Proctor et al., 2002; Robinson et al., 1995; Zanker et al., 2003). Furthermore, retired artistic female gymnasts have significantly higher aBMD values when compared to non-gymnasts, with differences ranging from 5-22% (Bass et al., 1998; Kirchner et al., 1996; Pollock et al., 2006; Zanker at al., 2004). This suggests that potential bone gains from participation in high impact sport in childhood and adolescence persist into adulthood after removal of the stimulus. However, to date, few studies have examined high impact or weight bearing training in childhood and followed the same individuals into adulthood after cessation of sport participation. The question that arises; therefore, is: how much of the increased bone mineral accrued during childhood and adolescence is maintained in young adulthood after the withdrawal of the ostoegenic stimulus? The purpose of the present study was to assess whether the previously reported benefit of premenarcheal gymnastics training on bone mass (Faulkner et al., 2003) was maintained 10 years after the cessation of participation and withdrawal of the gymnastics loading stimulus. We hypothesized that retired female gymnasts would have greater total body, lumbar spine, and femoral neck size-adjusted bone mineral content and areal bone mineral density compared to non-gymnasts.

4.1.3 Methods

4.1.3.1 Participants: In 1995, thirty elite premenarcheal female gymnasts were recruited into a study investigating the role of high impact physical activity on bone mass in childhood (Faulkner et al., 2003). Gymnasts were recruited from two nationally ranked gymnastics clubs in Saskatoon, Saskatchewan. Gymnasts were considered elite if they

were competing at the provincial level or higher and training a minimum of 15 hours per week. They also had to have been involved in competitive gymnastics training for at least 2 years prior to study initiation. In 1995, the gymnasts were 8-15 years of age (11.65±1.9yrs). Gymnasts were age, height, weight, and maturity matched to a non-gymnast premenarcheal female (n=30) drawn from the University of Saskatchewan's Pediatric Bone Mineral Accrual Study (PBMAS). PBMAS has been described in detail elsewhere (Bailey et al. 1997). In brief, the study utilized a mixed longitudinal design to examine bone development throughout childhood, adolescence, and into young adulthood. PBMAS children were aged 8-15 years at study entry and have been followed from 1991 to the present. All gymnasts and non-gymnasts were Caucasian.

In 2009-2010, the gymnasts and non-gymnasts (n=60) from the 1995 study (Faulkner et al., 2003) were re-contacted. Of the 30 gymnasts, 27 were traced and contacted; 25 agreed to participate in the present study (83%). One gymnast was pregnant and could not participate, one declined and three were untraceable (17%). All of the gymnasts had retired from gymnastics training and competition in the preceding years. Gymnasts had been retired, on average, for 10 years in 2009-2010. Of the 30 non-gymnasts 22 participated in the present study (73%). Three non-gymnasts had previously withdrawn from the PBMAS study, two were pregnant and three were untraceable (27%). To be included in the present investigation both the gymnast and their 1995 matched non-gymnast required follow-up measurements; therefore, data is presented for 22 gymnasts and their 1995 size matched control (n=22). Written informed consent was obtained from all participants and the study was approved by the University of Saskatchewan's Biomedical Research Ethics Board (Bio # 88-102) (Appendix D).

4.1.3.2 Chronological Age, Biological Age and Anthropometrics: The chronological age of each participant was recorded to the nearest 0.01 year by subtracting the decimal year of the participant's date of birth from the decimal year of the day of testing. Anthropometric measurements included standing height and weight. Height was recorded to the nearest millimeter using a wall mounted stadiometer (Holtain Limited, Britain) and body mass to the nearest 0.5 kilogram using a digital scale (Tanita Corporation, Model 1631, Japan). All measures were performed twice and if the difference was greater than 0.4 cm a third measure was recorded. The mean or median was then reported depending on whether two or three measures were recorded (ISAK, 2004). Age at menarche was retrospectively attained in the retired female gymnasts and prospectively attained in the PBMAS non-gymnasts. Retrospective recall of age at the occurrence of menarche has a high degree of accuracy within a 4-month window of the event (Damon and Bajema, 1974). Age at the attainment of menarche was then used to create a biological age. Chronological age was subtracted from age at menarche to create of years from menarche (such that -1 represents one year prior to age at menarche and +1 represents one year past the event).

4.1.3.3 Physical Activity, Dietary and Health Assessment: Physical activity was assessed in 1995 using the Physical Activity Questionnaire for Children (PAQ-C) (Appendix E) and in 2009-2010 using the Physical Activity Questionnaire for Adults (PAC-AD) (Appendix F). The PAQ-C/AD are self-administered seven-day recall questionnaires created to assess general levels of physical activity (Crocker et al., 1997, Kowalski et al., 1997, Copeland et al., 2003). The total activity score on the PAQ-C/AD is calculated as

the mean of seven items (each scored on a five-point scale) with five representing high activity and one representing low activity. Calcium and vitamin D intake were assessed through the use of a 24-hour recall questionnaire at both measurement points (Appendix C). Dietary data was analyzed using the Food Processor and Nutritional Software version 8.5 (ESHA research software, Salem, Oregon).

In 2009-2010 data on menstrual history, use of contraceptives, and fracture history were assessed by questionnaire (Appendix G). In gymnasts, further questions included age of onset of gymnastics activity, intensity and duration of training (number of sessions/hours of training per week, and level of competition), and age of retirement as well as reason for retirement from gymnastics activity (Appendix H).

4.1.3.4 Dual Energy X-ray Absorptiometry: Body composition measurements were performed in 1995 using a Hologic 2000 QDR dual energy X-ray absorptiometry scanner and in 2009-2010 using a Hologic Discovery Wi DXA scanner. A different scanner was utilized at baseline and follow-up; however, since data was not being compared between time points the authors did not adjust the values obtained. Three different scans were performed; total body, lumbar spine, and femoral neck. Bone mineral content (g), areal bone mineral density (g/cm^2), lean mass (kg) and fat mass (kg) were derived from the scans. All scans were administered and analyzed by a certified radiology technologist. Quality control phantom scans were performed daily. The coefficients of variation (CV%) for these measures from our laboratory, based on duplicate measures in young healthy female university students (20-30 yrs), are 0.5% for total body BMC, 0.7% for lumbar spine BMC and 1.0% for the proximal femur BMC. Fat and lean tissue mass were

assessed from the total body scans. Our laboratory has determined coefficients of variation for these measures to be 3.0% and 0.5% respectively.

4.1.3.5 Statistical Analysis: Variables are presented as means and standard deviation (SD). Group differences (gymnasts vs. non-gymnasts) for age, age at menarche, years from menarche, height, weight, lean mass, percent body fat, physical activity, vitamin D, calcium, and absolute bone values were assessed by independent sample T-Tests. Group differences in TB, LS, and FN T-scores were also compared using independent sample T-Tests. Analysis of covariance (ANCOVA) was used to assess differences between groups in TB, LS and FN BMC and aBMD while accounting for differences in body size, age and maturity, all of which have been shown to impact bone parameters (covariates: age, height, weight, and years from menarche or age at menarche). Correlations between years of retirement and bone parameters were assessed using Bivariate Pearson correlations. All analyses were performed using SPSS version 18.0. Alpha was set as $p < 0.05$.

4.1.4 Results

Anthropometric, body composition and life style characteristics as well as absolute bone parameters for gymnasts and non-gymnasts are presented in Tables 4.1.1 and 4.1.2. Table 4.1.1 contains the 1995 childhood data and Table 4.1.2 contains the adulthood data collected in 2009-2010. Retired gymnasts trained, on average, 20 hours per week at the peak of their training (range, 16-30hrs) and had been retired for approximately 10 years (range, 6-14 yrs) at follow-up. Gymnasts were significantly shorter and lighter in childhood ($p < 0.05$); however, there was no significant difference in

111

height in adulthood ($p>0.05$). Gymnasts also had a lower percentage body fat at both measurement occasions and an older age at menarche suggesting that they were maturing later than the non-gymnasts ($p<0.05$). Gymnasts were approximately 2 years from age at menarche when tested in childhood whereas non-gymnasts were 1 year premenarcheal; however, this difference was also non-significant ($p>0.05$), suggesting maturationally the groups were similar.

Table 4.1.1 – Childhood anthropometric, body composition and lifestyle data for gymnasts and non-gymnasts (mean±SD)

	Gymnasts (n=22)	Non-Gymnast (n=22)
Age (yrs)	11.6±1.9	11.9±1.7
Yrs from Men (yrs)	-2.0±1.9	-1.0±2.0
Height (cm)	144.2±12.5[a]	151.6±11.7
Weight (kg)	37.2±10.2[a]	44.3±11.9
TB Lean Mass (kg)	29.1±7.4	29.1±7.0
% Fat	15.8±4.2[a]	28.7±7.5
TB BMC (g)	1268.3±417.2	1303.8±453.9
TB aBMD (g/cm^2)	0.89±0.09	0.84±0.09
LS BMC (g)	33.6±10.7	33.6±14.7
LS aBMD (g/cm^2)	0.78±0.13	0.73±0.16
FN BMC (g)	3.2±0.7	3.2±0.8
FN aBMD (g/cm^2)	0.78±0.10[a]	0.69±0.10
PA Score	3.2±0.4	3.0±0.6
Calcium (mg)	1076±554	1148±459
Vitamin D (IU)	329±245	287±147
Gym hrs/wk	20.0±4.5	-

[a] Gymnasts significant different than non-gymnast ($p<0.05$)

Variable definitions: Yr from Men = years from age at menarche, % Fat = total body percent fat, TB = total body, BMC = bone mineral content, BMD = areal bone mineral density, LS = lumbar spine, FN = femoral neck, PA score = Physical Activity Questionnaire for Children score, Gym hrs/wk = hours per week engaged in gymnastics participation at peak of training

Table 4.1.2 – Adulthood anthropometric, body composition and lifestyle data for retired gymnasts and non-gymnasts (mean±SD)

	Gymnasts (n=22)	Non-Gymnast (n=22)
Age (yrs)	26.6±1.8	27.5±1.9
Age at Menarche (yrs)	13.7±1.6[a]	12.8±1.2
Yrs from Menarche	12.5±2.0	14.7±2.2
Height (cm)	162.9±6.6	165.8±7.4
Weight (kg)	60.0±7.9[a]	67.1±12.6
TB Lean Mass (kg)	42.7±4.9	42.3±6.0
% Fat	23.4±5.0[a]	32.1±5.4
TB BMC (g)	2330.7±286.2	2213.0±329.8
TB aBMD (g/cm^2)	1.18±0.08[a]	1.12±0.11
LS BMC (g)	65.4±9.1	59.3±12.8
LS aBMD (g/cm^2)	1.09±0.9[a]	1.02±0.12
FN BMC (g)	4.59±0.61[a]	4.14±0.68
FN aBMD (g/cm^2)	0.96±0.11	0.94±0.59
PA Score	2.4±0.62	2.1±0.41
Calcium (mg)	899±663	936±448
Vitamin D (IU)	265±203	168±200
Years of Retirement	9.6±2.7	-

[a] Gymnasts significant different than non-gymnast
Variable definitions: TB = total body, % Fat = total body percent fat, BMC = bone mineral content, BMD = areal bone mineral density, LS = lumbar spine, FN = femoral neck, PA score = Physical Activity Questionnaire for Adults score, Years of Retirement = total number of years since participation in gymnastics

While gymnasts had significantly greater unadjusted aBMD at the femoral neck in childhood, they had significantly greater unadjusted total body and lumbar spine aBMD as well as femoral neck BMC ($p<0.05$) 14 years later (Tables 4.1.1 and 4.1.2, respectively). As shown in Figure 4.1.1, gymnasts had significantly greater size-adjusted BMC and aBMD compared to non-gymnasts at all sites ($p<0.05$), with the exception of FN aBMD in adulthood ($p>0.05$). Retired gymnasts also had significantly greater T-scores at the TB, LS and FN compared to non-gymnasts (Table 4.1.3, $p<0.05$). There was no significant correlation between the number of years the gymnasts had been retired and any bone parameter measured ($p>0.05$).

Table 4.1.3 – T-score for total body, lumbar spine and femoral neck for retired gymnasts and non-gymnasts (means±SD)

	Gymnasts (n=22)	Non-Gymnast (n=22)
TB T-Score	0.94±0.95[a]	0.20±1.06
LS T-Score	0.90±0.74[a]	-0.16±0.78
FN T-Score	0.46±0.81[a]	-0.28±1.10

[a] Gymnasts significant different than non-gymnast

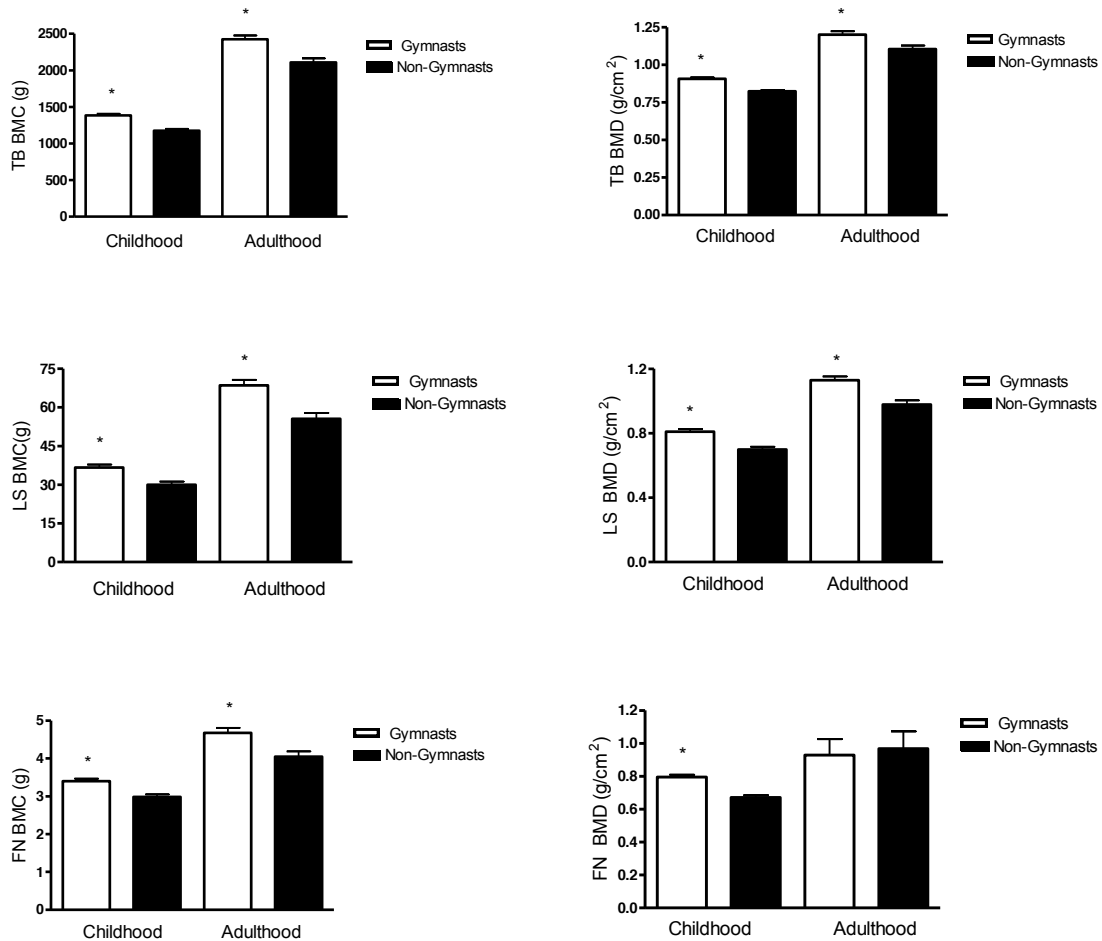Variable definitions: TB = total body, LS = lumbar spine, FN = femoral neck

Figure 4.1.1 Gymnasts' and non-gymnasts' adjusted mean and standard error of the mean (SEE) for total body, femoral neck and lumbar spine BMC and aBMD in childhood (1995) and adulthood (2009-10). Bone parameters were adjusted for age, height, weight, and years from menarche or age at menarche.
*Gymnasts significantly different than non-gymnasts

There was no significant difference between groups in history of oral contraceptive use ($p>0.05$). In adulthood the retired female gymnasts had been on oral contraceptives for 5.4±3.5 years while the non-gymnasts had been on for 4.7±4.4 years. Including history of oral contraceptive use as a covariate did not alter the significance of any bone parameter (data not shown). The most common reasons cited for retirement from gymnastics training and competition were social life and lack of interest followed by school demands, injury and the perception of being too old.

4.1.5 Discussion

This is one of the first studies to prospectively examine the influence of premenarcheal gymnastics training on bone mass and follow the same individuals into adulthood after retirement from sport and removal of the gymnastics loading stimulus. The aim was to assess whether the previously reported greater BMC in elite premenarcheal gymnasts when compared to non-gymnastic controls (Faulkner et al., 2003) was still apparent 10 years after the cessation of gymnastics participation. The main finding was that gymnasts had greater size-adjusted bone mineral content and areal bone mineral density both in childhood and adulthood after long-term retirement from gymnastics training and competition. This suggests that premenarcheal gymnastics training results in benefits that are maintained after long-term retirement, potentially impacting lifetime skeletal health.

The gymnasts in the present cohort were significantly shorter and lighter and had significantly greater bone mass in childhood and adolescence (Faulkner et al., 2003). However, the long-term impact of premenarcheal gymnastics participation on adult body

116

and bone composition are not well known. The high intensity training associated with competitive gymnastics participation during childhood and adolescence has been suggested to negatively impact growth and maturation resulting in compromised adult stature (Bass et al., 2000; Theintz et al., 1993). However, that was not the case in the current cohort. Retired gymnasts and non-gymnasts did not differ in adult height; this would suggest that premenarcheal gymnastics training did not compromise the attainment of adult stature in this group. Observed differences in stature at childhood (Faulkner et al., 2003) probably reflected the fact that the gymnasts were maturing at a later age. The current findings are consistent with the previous literature that gymnasts report an older age of attainment of menarche compared to the non-gymnasts (Beunen et al., 1999; Baxter-Jones et al., 1994; Claessens et al., 1992; Theintz et al., 1989). The attainment of menarche at an older age in the retired gymnasts is of interest as it has been suggested that late maturing individuals have lower bone mass in young adulthood (Chevalley et al., 2009a; Jackwoksi et al., 2010). However, retired female gymnasts had greater bone mineral content despite having a later age at the attainment of menarche than non-gymnasts.

Gymnasts had greater adjusted total body, lumbar spine, and femoral neck bone mineral content compared to non-gymnasts in childhood and adolescence (15%, 18%, and 12%, respectively). Bone parameters were adjusted for differences in body size and maturity, as these have been found to influence bone measures. It is well documented that aBMD does not adequately adjust for bone size which is particularly problematic when examining children (Faulkner et al., 2003); however, for comparison with previous research aBMD as well as BMC values are presented here. Gymnasts also had 9-16%

greater aBMD compared to non-gymnasts in childhood and adolescence. These values are consistent with previous studies examining the influence of premenarcheal gymnastics training on bone parameters (Laing et al., 2002; Nickols-Richardson et al., 2000; Scerpella et al., 2003; Zanker et al., 2003). Zanker et al. (2003) found that young female gymnasts 7-8 years of age had 8-10% greater total body and lumbar spine aBMD. Similarly, Nickols-Richardson et al. (2000) found that elite premenarcheal gymnasts had 13% greater lumbar spine aBMD and 12% greater FN aBMD. Furthermore, young competitive gymnasts have also been found to have greater increases in aBMD over time compared to non-gymnasts (Laing et al., 2002). These observed differences in aBMD between premenarcheal gymnasts and non-gymnasts approach the differences reported between collegiate gymnasts and non-gymnasts, suggesting that much of the enhancement in aBMD and BMC from gymnastics participation may occur before menarche.

Premenarcheal and collegiate-aged gymnasts have not only been found to exhibit greater aBMD and size-adjusted BMC compared to non-athletes but also compared to athletes involved in other sports (Cassell et al., 1996; Fehling et al., 1995; Robinson et al., 1995s). Therefore, gymnasts provide an interesting model to examine the impact of structured premenarcheal loading on adult bone parameters. If the higher bone measures observed from artistic gymnastic skills performed during growth are sustained into adulthood after retirement from sport, the residual benefits may delay or even prevent osteoporotic fractures. It has been suggested that a 10% increase in peak bone mass would delay the onset of osteoporosis by 13 years (World Health Organization, 1994). However, currently, systematic impact loading training during growth remains an

118

unproven investment as an evidence-based means to prevent osteoporotic fractures (Pollock et al., 2006). Prior to this study, there had been limited long-term prospective studies that tracked bone gains acquired from premenarcheal sport participation into adulthood after removal of stimulus.

The decreased mechanical loading experienced upon retirement from impact loading sports should, in theory, result in a decrease in BMC and aBMD (Kudlac et al., 2004). Kirchner et al (1995 & 1996) examined current and retired collegiate level gymnasts and found that both groups had significantly higher aBMD compared to non-gymnasts, but that the relationship was more pronounced in the active college level gymnasts compared to retired gymnasts. For example, lumbar spine aBMD was 18% greater in collegiate gymnasts and 16% in retired gymnasts and femoral neck aBMD was 22% greater in collegiate gymnasts compared to 18% greater in retired gymnasts (Kirchner et al., 1995; Kirchner et al., 1996). The authors speculated that while some advantages may be lost these findings suggest that there is a residual benefit of gymnastics participation on bone mass that carries on years after gymnastics participation of the retired gymnasts had ended (Kirchner et al., 1996). However, the active collegiate gymnasts and retired gymnasts in the previous studies were not the same individuals; therefore, the observed differences between groups could also be related to differences in genetics or gymnastics exposure (i.e., years or level of training).

Kudlac et al (2004) were the first to examine the impact of gymnastics detraining on aBMD; they measured collegiate female gymnasts at the beginning of their final competitive year and then again approximately four years later. They found gymnasts had significantly greater BMC and aBMD at the total body, femoral neck, trochanter and total

hip in their final year of gymnastics competition as well as 4 years after retirement compared to non-gymnasts (Kudlac et al., 2004). They also found that aBMD declined at a similar rate in both gymnasts and non-gymnasts at the hip (approximately 0.72-1.9% a year) (Kudlac et al., 2004). The similar rate of bone loss at the hip between gymnasts and non-gymnasts is promising; if the decline continues at the same rate retired gymnasts will always have greater aBMD compared to non-gymnasts which may reduce fracture risk at this site. However, it should be noted that the gymnasts in the Kudlac et al. (2004) study were approximately three years younger than non-gymnasts and they only measured 10 gymnasts and 9 non-gymnasts which may be influencing the findings.

In the current cohort retired gymnasts were found to have greater size-adjusted total body, lumbar spine, and femoral neck BMC compared to non-gymnasts (13%, 19%, and 13%, respectively). Retired gymnasts also had 8% greater TB and 13% greater LS aBMD. Furthermore, the observed difference between groups in adulthood, an average of 10 years after retirement from sport and removal of the gymnastics stimulus, was similar to the difference found between premenarcheal gymnasts and non-gymnasts. This finding would suggest that the benefit of premenarcheal gymnastics training relative to non-gymnasts was maintained 14 years later. Gymnastics training before menarche resulted in benefits that were still apparent even after long-term removal of the gymnastics loading stimulus.

After retirement from gymnastics, individuals participated in other competitive sports at the high school and collegiate level such as track and field, basketball, and soccer and were found to participate in average levels of physical activity in adulthood. There were no differences between groups in the reported levels of physical activity

either in childhood or as an adult; however, it may be that the average levels of activity that the retired gymnasts participated in was sufficient to maintain the benefits of previous gymnastics participation. It is unknown if the same retention would be observed if the retired gymnasts in the current study were sedentary. However, Zanker et al. (2004) examined sedentary retired gymnasts, defined as not meeting the UK requirement for participation in 30 minutes of physical activity on at least 5 days of the week, and found that they had 6-11% greater aBMD compared to non-gymnasts. Suggesting that a physically active lifestyle may not be required for the maintenance of premenarcheal skeletal benefits. Duration of retirement had no effect on bone parameters, further lending support to the suggestion that the positive effect of premenarcheal participation does not diminish over time. Pollock et al. (2006) found retired female gymnasts maintained higher aBMD values an average of 24 years after retirement and showed a similar pattern of bone loss as non-gymnasts.

This study has several strengths. To our knowledge this is first gymnastics study to have prospective childhood and adulthood data on the same individuals. This allows for a comparison of the observed difference between premenarcheal gymnasts and non-gymnasts and retired gymnasts and non-gymnasts. The previous studies examining retirement from sport and bone parameters in gymnasts have generally utilized former collegiate level gymnasts. A very small proportion of competitive female gymnasts continue to compete to the collegiate level; the majority retires in their teenage years. The gymnasts in the current study retired before the collegiate level, some as young as 12 years of age. Therefore, the current cohort may be a better representation of a composite group of former gymnasts than the studies utilizing solely collegiate level athletes.

A limitation of this study is that although gymnasts were measured in childhood and found to have significantly greater premenarcheal size-adjusted BMC and strength indices (Faulkner et al., 2003), there are no measures before the onset of gymnastics training. Therefore, it is possible that these observed benefits in bone mass were present before the onset of training and not the result of gymnastics participation. However, previous research has found that young competitive gymnasts not only have greater aBMD as assessed by cross-sectional comparison but also accrue more bone over time suggesting that is gymnastics training and not genetics which is resulting in the greater BMC and aBMD observed in gymnasts (Laing et al., 2005; Nickols-Richardson et al., 1999; Laing et al. 2002). Finally, assessment of bone mineral content with exercise studies is limited because important changes in the structural properties of bone may occur and go undetected. Therefore, the current investigation may be underestimating the impact of premenarcheal gymnastics training on adulthood bone health. Longitudinal investigations of bone structural adaptation are required to better understand the effect of premenarcheal gymnastics participation on future bone strength and subsequent fracture risk.

In summary, premenarcheal elite gymnasts had greater size-adjusted total body, lumbar spine, and femoral BMC and aBMD and these benefits were found to be maintained after long-term retirement, an average of 10 years, from gymnastics training. Similar differences between gymnasts and non-gymnasts were observed both in childhood, when gymnasts were actively training, and in adulthood after retirement. These findings suggest that premenarcheal gymnastics training results in benefits that are maintained after the removal of the gymnastics loading stimulus supporting the assertion

that structured physical activity during growth is an effective means to increase bone mass and potentially prevent or delay the risk of osteoporosis and related fracture. However, long-term studies are required which follow retired female gymnasts as they approach menopause and bone lose accelerates to better understand the impact of premenarcheal gymnastics participation on osteoporosis and related fracture risk.

4.1.6 Acknowledgements

4.2 - Former elite premenarcheal gymnasts exhibit site-specific skeletal benefits in adulthood after long-term retirement.

4.2.1 Abstract

Young female gymnasts have greater bone strength compared to non-gymnasts, suggesting that physical activity during growth increases bone mass. If high bone mass is maintained this may potentially decrease the risk of osteoporosis and related fracture later in life. However, there is no clear evidence of a persisting benefit of exercise during growth on adult bone parameters. Therefore, the purpose of this study was to determine whether adult bone geometry, volumetric density and estimated strength were greater in retired premenarcheal gymnasts compared to non-gymnasts, 10 years after retirement from gymnastics. Bone geometric and densitometric parameters, measured by peripheral quantitative tomography at the radius and tibia, were compared between 25 retired female gymnasts and 22 non-gymnasts by analysis of covariance (covariates: age, age at menarche, height, muscle cross-sectional area). Retired female gymnasts had significantly greater adjusted total and trabecular area, total and trabecular bone mineral content (BMC), and estimated strength at the distal radius ($p<0.05$). Adjusted total and cortical area and BMC, medullary area, and estimated strength were also significantly greater in retired gymnasts at the 30% and 65% radial shaft sites ($p<0.05$). At the distal tibia gymnasts had greater total and trabecular BMC and volumetric bone mineral density as well as estimated strength; total and cortical BMC and estimated strength were also greater at the tibial shaft ($p<0.05$). Female gymnasts have significantly better geometric

and densitometric properties, and estimated strength at the radius and tibia 10 years after

retirement from gymnastics compared to females who did not participate in gymnastics.

4.2.2 Introduction

Weight bearing physical activity during childhood and adolescence is associated with site-specific increases in bone mass (Bailey et al., 1999; Janz et al., 2006; Slemenda et al., 1991), which have been hypothesized to reduce the risk of osteoporosis and related fractures later in life. Gymnastics training, a weight bearing physical activity, generates high mechanical loading on the skeleton; young gymnasts experience forces 3-10 times that of body weight on both their hands and feet (Daly, Rich, Klien, & Bass, 1999). Thus, young gymnasts provide an excellent model for assessing impact loading and bone accrual. Adolescent female gymnasts have 8-23% greater areal bone mineral density (aBMD, cm/g^2) compared to non-gymnasts at the total body, lumbar spine and hip (Laing et al., 2002; Nickols-Richardson et al., 2000; Zanker et al., 2003). As such competitive gymnastics training may be an effective means to reduce the risk of low bone mass and potentially osteoporosis. However, only if skeletal benefits are maintained into adulthood, after removal of the oteogenic stimulus, can training during growth influence subsequent fracture risk.

A number of studies have examined retirement from sport and bone mineral parameters and have in general found that retired athletes have greater bone mass compared to sedentary controls (Bass et al., 1998; Kontulainen et al., 1999; Kontulainen et al., 2001; Pollock et al., 2006; Uzunca et al., 2005; Zanker et al., 2004). As described in section 4.1, the current cohort of retired gymnasts were found to have greater size-adjusted total body, lumbar spine, and femoral neck BMC compared to non-gymnasts (13%, 19%, and 13%, respectively). The observed difference between groups in adulthood, an average of 10 years after retirement from sport and removal of the

126

gymnastics stimulus, was similar to the difference found between premenarcheal gymnasts and non-gymnasts (Faulkner et al. 2003). However, the assessment of aBMD and BMC following exercise intervention has limitations because important changes in the structural properties of bone may occur that DXA is unable to detect. DXA provides a reasonable overall description of bone status, but overlooks structural alterations which can influence bone strength (Jarvinen et al., 1999). This is important as bone strength has been shown to significantly improve with exercise training independent of changes in aBMD (Adami et al., 1999; Robling et al., 2006).

There is limited information on gymnastics training and bone geometry, structure and estimated strength. Two studies have shown that young competitive gymnasts have greater total, trabecular and cortical vBMD compared to non-gymnasts at the distal radius (Dyson et al., 1997; Ward et al., 2005). In study one (section 3.1) it was found that young recreational and precompetitive gymnasts also had greater total vBMD and estimated strength at the distal radius compared to non-gymnasts. In the current cohort, using hip structural analysis (HSA), it was found that premenarcheal gymnasts had significantly greater strength at the proximal femur compared to age and size matched non-gymnasts (Faulkner et al., 2003). HSA is a software program that can applied to DXA scans which allows for an estimation of hip geometry and bending strength. However, this cross-sectional study during childhood gives no indication of the possible persisting benefit of exercise during growth on adult volumetric density, structure or estimated strength once the stimulus has been removed. Therefore, the aim of the present study was to determine whether adult bone geometry, volumetric density and estimated strength was greater in retired premenarcheal gymnasts compared to non-gymnasts, 10 years after retirement.

We hypothesized that retired gymnasts would have greater bone mass, volumetric density and estimated strength at the radius and tibia compared to non-gymnasts.

4.2.3 Methods

4.2.3.1 Participants: Participants are described in detail in section 4.1.3.1. In brief, in 2009-2010, 30 retired female gymnasts and 30 non-gymnasts who had participated in a study on impact loading physical activity in childhood and bone strength (Faulkner et al., 2003) were re-contacted. Of the 30 gymnasts, 27 were traced and contacted; 25 agreed to participate in the present study (83%). One gymnast was pregnant and could not participate, one declined and three were untraceable (17%). Of the 30 non-gymnasts 22 participated in the present study (73%). Three non-gymnasts had previously withdrawn from the PBMAS study, two were pregnant and three were untraceable (27%). Written informed consent was obtained from all participants and the study was approved by the University of Saskatchewan's Biomedical Research Ethics Board (Bio # 88-102) (Appendix D).

4.2.3.2 Age and Anthropometrics: The chronological age of each participant was recorded to the nearest 0.01 year by subtracting the decimal year of the participant's date of birth from the decimal year of the day of testing. Anthropometric measurements included standing height, weight and limb length. Height was recorded to the nearest millimeter using a wall mounted stadiometer (Holtain Limited, Britain) and body mass to the nearest 0.5 kilogram using a digital scale (Tanita Corporation, Model 1631, Japan). Participants were asked for hand and leg dominance. Non-dominant tibia length was

measured from base of the medial malleolus to the superior margin of the medial epicondyle. Non-dominant ulna length was measured from the distal tip of the styloid process to the proximal endplate using an anthropometric caliper (Rosscraft Lufkin, Canada). All measures were performed twice and if the difference was greater than 0.4 cm a third measure was recorded. The mean or median was then reported depending on whether two or three measures were recorded, respectively (ISKA, 2005). All measures were performed by the same Canadian Society for Exercise Physiology-Certified Exercise Physiologist.

4.2.3.3 Physical Activity, Dietary and Health Assessment: Physical activity was assessed using the Physical Activity Questionnaire for Adults (PAQ-AD) (Appendix F). The PAQ-AD is a seven day physical activity recall questionnaire created for use with participants once beyond the high school years (Copeland et al., 2003). The total activity score on the PAQ-AD is calculated as the mean of seven items (each scored on a five-point scale) with five representing high activity and one representing low activity. The PAQ-AD is a valid measure of current physical activity for an adult sample (Copeland et al., 2003). Calcium and vitamin D intake were assessed through the use of a 24-hour recall questionnaire (Appendix C). Dietary data were analyzed using the Food Processor and Nutritional Software version 8.5 (ESHA research software, Salem, Oregon).

Data on menstrual history including age at menarche and use of contraceptives were assessed by questionnaire (Appendix G). In gymnasts, further questions included age of onset of gymnastics activity, intensity and duration of training (number of

sessions/hours of training per week, and level of competition), and age of retirement as well as reason for retirement from gymnastics activity (Appendix H).

4.2.3.4 Peripheral Quantitative Computed Tomography (pQCT): Cross-sectional slices (2.4±1mm) of the non-dominant radius and tibia were measured by pQCT (XCT-2000; Stratec Medizintechnik GmbH, Pforzheim, Germany). A scout scan was performed and the reference line was placed according to manufacturer recommendation on the medial point of the distal endplate. The forearm was scanned at the distal and shaft sites, 4%, 30% and 65% of the limb length proximal to the reference line, respectively. The lower leg was scanned at the 4% and 66% sites. All measurements were performed by the same trained technician and a voxel size of 0.4 mm was used for all sites at a scan speed of 20 mm/s.

Analyses were performed with manufacturer provided software (XCT, version 5.4). Scans were analyzed using contour mode 1 with a threshold of 280 mg/cm^3 (to separate bone from soft tissue) at the distal site. Bone properties at the shaft sites were analyzed using separation mode 4 with a threshold of 280 mg/cm^3 and 540 mg/cm^3 (to separate cortical bone from marrow). Thresholds were selected based on line analysis. Muscle cross-sectional area (MCSA) was calculated by subtracting total bone area from total limb area. Limb area was analyzed using contour mode 1 and a threshold of 30 mg/cm^3 (to separate muscle from fat tissue) (XCT Manual, 2007). The laboratory coefficients of variation (CV%$_{RMS}$), based on duplicate measures in 65 healthy adult volunteers, for MCSA, bone density, content, area and strength indices at the radius and tibia ranged from 1.8-6.3%.

The distal epiphysis (4%) was used to determine total bone area (ToA), total volumetric bone density (ToD), total bone content (ToC), trabecular area (TrA), trabecular volumetric bone density (TrD), and trabecular bone content (TrC). ToA, ToC, ToD, cortical bone area (CoA), cortical volumetric density (CoD), cortical content (CoC), cortical wall thickness (CoTHK) and medullary area (MedA) were assessed at the shaft sites in the radius and tibia (30%, 65%, and 66% respectively). Medullary area was calculated by subtracting cortical area from total bone area. Bone strength index (BSI) was calculated (ToA x ToD^2) as a measure of estimated compressive strength at the distal site and polar stress-strain index (SSIp) was derived from the shaft measurements as a surrogate for bone torsional strength (XCT manual 2007; Lochmuller et al., 2002; Kontulainen et al., 2008). Measures of bone bending in the x and y axis were also derived from the shaft sites (SSIx and SSIy). Images found to contain movement artifacts were excluded from analysis if bone edge detection was impeded (n= 2). The 30% radius of one gymnast and 65% radius of one non-gymnast were excluded.

4.2.3.5 Statistical Analysis: Variables are presented as means and standard deviations (SD). Group differences (retired gymnasts vs. non-gymnasts) for age, age at menarche, height, weight, forearm and lower leg MCSA, physical activity, vitamin D, and calcium were assessed by independent sample T-Test. Mean differences (and their 95% Confidence Intervals) for pQCT bone parameters across groups were assessed by Analysis of Covariance (ANCOVA) (covariates: age, height, age at menarche and forearm or lower leg MCSA). Correlations between years of retirement and bone

parameters were assessed using Bivariate Pearson correlations. All analyses were

performed using SPSS version 18.0. Alpha was set as $p<0.05$.

4.2.4 Results

Retired gymnasts trained, on average, 20 hours per week during childhood and

adolescence (range, 16-30 hrs). By 2009/10 they had been retired for approximately 10

years (mean=9.6±2.7). Anthropometric, body composition and dietary data as well as

physical activity scores in young adulthood are presented in Table 4.2.1. Retired

gymnasts were significantly lighter and had more forearm muscle mass than non-

gymnasts ($p<0.05$). There was no difference in height between the two groups ($p>0.05$).

Gymnasts attained menarche at an older age ($p<0.05$). There were no differences in

lifestyle characteristics (current physical activity and diet) between the groups ($p>0.05$).

Table 4.2.1 – Anthropometric, body composition and lifestyle data for retired gymnasts and non-gymnasts (mean±SD)

	Retired Gymnasts (n=25)	Non-gymnasts (n=22)
Age (yrs)	26.6±1.8	27.5±1.9
Age at Menarche (yrs)	13.7±1.6[a]	12.8±1.2
Height (cm)	162.9±6.6	165.8±7.4
Weight (kg)	60.0±7.9[a]	67.1±12.6
Forearm MCSA (mm^2)	231±25[a]	202±30
Lower leg MCSA (mm^2)	489±74	461±64
PA Score	2.4±0.62	2.1±0.41
Vitamin D (IU)	265±203	167.9±199.5
Calcium (mg)	899±663	936±448

[a] Retired gymnasts significant different than controls, $p<0.05$
Variable definitions: TB = total body, MCSA = muscle cross-sectional area, PA score = Physical Activity Questionnaire for Adults score

Comparison of unadjusted pQCT bone outcomes (mean±SD) at the radius and tibia are presented in Tables 4.2.2 and 4.2.3, respectively. Retired gymnasts had significantly greater ToC, ToA, TrC, TrD, TrA and BSI at the distal radius ($p<0.05$) compared to non-gymnasts (Table 4.2.2). Retired gymnasts also had significantly greater ToC, ToA, CoC, CoA, MedA, and estimated strength at the 30% radial shaft ($p<0.05$) (Table 4.2.2). Retired gymnasts had significantly greater ToC, ToA, CoC, CoA, MedA and estimated strength at the 65% radial shaft ($p<0.05$) (Table 4.2.2). In contrast, non-gymnasts had significantly greater ToD at the 30% shaft site and greater CoD at the 65% shaft site in the radius ($p<0.05$) (Table 4.2.2). There were no differences between groups at the tibial shaft; however, retired gymnasts had significantly greater ToC, ToD, TrC, TrD and BSI at the distal tibia (Table 4.2.3).

Table 4.2.2 – Unadjusted pQCT bone parameters at the radius for retired gymnasts and non-gymnasts (mean±SD)

		Retired Gymnasts (n=25)	Non-Gymnasts (n=22)
Radius			
4%	ToC (g/cm)	127.6±18.7[a]	98.2±13.9
	ToD (mg/cm^3)	302±48	293±39
	ToA (mm^2)	426±57[a]	337±48
	TrC (g/cm)	87.3±16.1[a]	63.0±15.2
	TrD (mg/cm^3)	239±29[a]	218±25
	TrA (mm^2)	368±64[a]	288±55
	BSI (mg^2/mm^4)	39.1±10.9[a]	29.1±6.7
30%	ToC (g/cm)	117.0±14.9[a]	95.6±9.3
	ToD (mg/cm^3)	924±62[a]	989±45
	ToA (mm^2)	127±20[a]	97±10
	CoC (g/cm)	114.5±14.6[a]	94.0±9.2
	CoD (mg/cm^3)	1120±31	1134±30
	CoA (mm^2)	102±14[a]	83±8
	CoTHK (mm)	3.6±0.3	3.5±0.2
	MedA (mm^2)	25±9[a]	14±4
	SSIy (mm^3)	185.1±38.9[a]	126.3±20.3
	SSIx (mm^3)	163.3±34.8[a]	106.7±17.5
	SSIp (mm^3)	302.±66.6[a]	202.1±33.1
65%	ToC(g/cm)	113.2±12.0[a]	99.7±13.5
	ToD (mg/cm^3)	818±79	844±64
	ToA (mm^2)	140±21[a]	118±13
	CoC (g/cm)	109.7±11.7[a]	97.1±13.1
	CoD (mg/cm^3)	1050±36[a]	1072±26
	CoA (mm^2)	105±11[a]	91±12
	SSIy (mm^3)	185.3±35.9[a]	154.4±25.7
	SSIx (mm^3)	171.0±35.6[a]	129.7±22.5
	SSIp (mm^3)	320.2±62.8[a]	256.1±41.4
	CoTHK (mm)	3.4±0.3	3.2±0.4
	MedA (mm^2)	35±14[a]	27±7

[a]Retired gymnasts significant different than controls, $p<0.05$

Variable definitions: ToC = total bone content, ToD = total bone density, ToA = total bone area, TrC = trabecular content, TrD = trabecular density, TrA = trabecular area, BSI = bone strength index, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, CoThk = cortical thickness, MedA = medullary area, SSIp = polar stress strain index, SSIy = stress strain index on the y axis, SSIx = stress strain index on the x axis

Table 4.2.3 – Unadjusted pQCT bone parameters at the tibia for retired gymnasts and non-gymnast (mean±SD)

		Retired Gymnasts (n=25)	Non-gymnasts (n=22)
Tibia			
4%	ToC (g/cm)	330.3±48.9 [a]	290.4±39.0
	ToD (mg/cm^3)	305±41 [a]	281±32
	ToA (mm^2)	1088±145	1035±114
	TrC (g/cm)	263.1±39.5 [a]	228.1±31.5
	TrD (mg/cm^3)	268±35 [a]	242±22
	TrA (mm^2)	989±147	946±122
	BSI (mg^2/mm^4)	102.0±25.9 [a]	82.4±18.0
66%	ToC (g/cm)	407.7±58.0	383.1±46.8
	ToD (mg/cm^3)	709±46	691±60
	ToA (mm^2)	576±79	558±77
	CoC (g/cm)	383.4±56.2	362.1±45.6
	CoD (mg/cm^3)	1067±29	1062±14
	CoA (mm^2)	359±53	341±43
	SSIy (mm^3)	1186.4±298.2	1112.7±177.7
	SSIx (mm^3)	1717.0±338.9	1637.7±329.3
	SSIp (mm^3)	2491.7±501.9	2320.3±434.7
	CoTHK (mm)	5.3±0.6	5.0±0.5
	MedA (mm^2)	216±43	217±54

[a]Retired gymnasts significant Different than controls, $p<0.05$
Variable definitions: ToC = total bone content, ToD = total bone density, ToA = total bone area, TrC = trabecular content, TrD = trabecular density, TrA = trabecular area, BSI = bone strength index, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, CoThk = cortical thickness, MedA = medullary area, SSIp = polar stress strain index, SSIy = stress strain index on the y axis, SSIx = stress strain index on the x axis

When pQCT outcomes were adjusted for age, age at menarche, height and forearm muscle cross-sectional area (ANCOVA) retired gymnasts retained significantly greater adjusted ToC, ToA, TrC, TrA and BSI compared to non-gymnasts at the distal radius ($p<0.05$) (Figure 4.2.1). Retired gymnasts also had significantly greater adjusted ToC, ToA, CoC, CoA, MedA and estimated strength at the 30% and 65% radial shaft sites ($p<0.05$) (Figure 4.2.2). Non-gymnasts had significantly greater ToD at the 30% shaft site; however, CoD at the 65% site was no longer significantly greater in the non-

gymnasts (p>0.05). Retired gymnasts also had significantly greater adjusted (covariates: age, age at menarche, height, lower leg MSCA) ToC, ToD, TrC, TrD and BSI at the distal tibia (Figure 4.2.1) and ToC, CoC and SSIp at the 66% tibial shaft ($p<0.05$) (Figure 4.2.3).
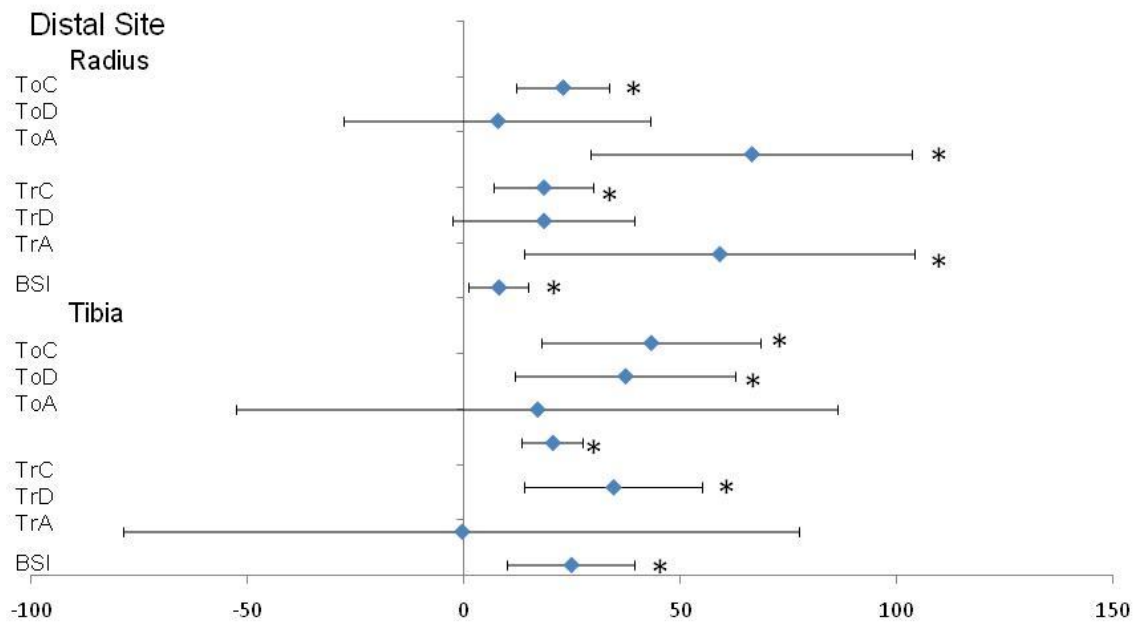

Figure 4.2.1 – Percent difference in adjusted marginal means for pQCT distal radius (4%) and distal tibia (4%) and 95% CI for retired gymnasts compared to non-gymnasts. pQCT values were adjusted for age, age at menarche, height and muscle cross-sectional area. The zero on the graph represents non-gymnasts, the diamond is the retired gymnasts. Retired gymnasts (n=25), non-gymnasts (n=22)
ToC = total bone content, ToD = total bone density, ToA = total bone area, BSI = bone strength index, TrC = trabecular content, TrD = trabecular density, TrA = trabecular area
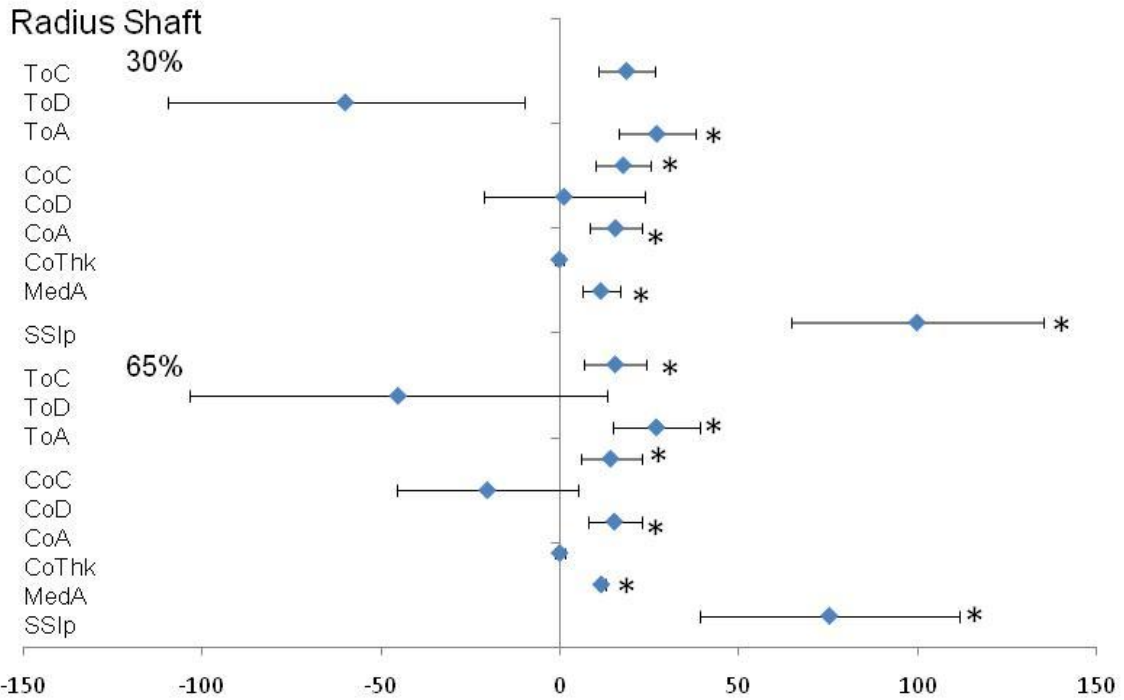*Retired gymnasts significantly different than non-gymnasts, $p<0.05$

Figure 4.2.2 – Percent difference in adjusted marginal means for pQCT 30% and 65% radial shaft and 95% CI for retired gymnasts compared to non-gymnasts. pQCT values were adjusted for age, age at menarche, height, and forearm muscle cross-sectional area. The zero on the graph represents non-gymnasts, the diamond is the retired gymnasts. Retired gymnasts (n=25), non-gymnasts (n=22)

ToC = total bone content, ToD = total bone density, ToA = total bone area, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, SSIp = polar stress strain index, CoThk = cortical thickness, MedA = medullary area
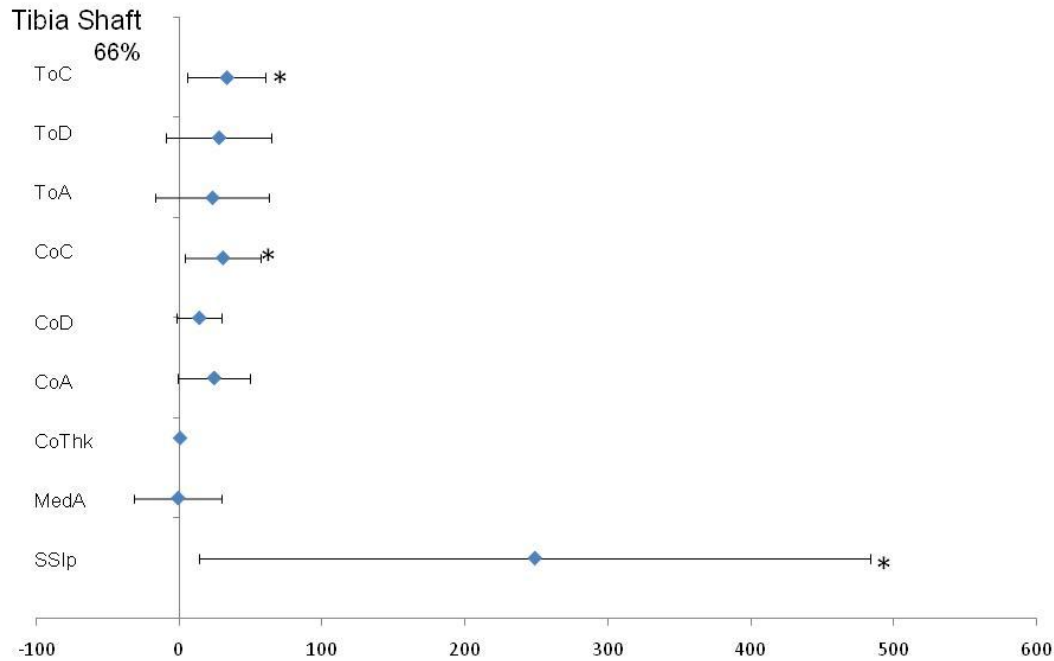*Retired gymnasts significantly different than non-gymnasts, $p<0.05$

Figure 4.2.3 - Percent difference in adjusted marginal means for pQCT 66% tibial shaft and 95% CI for retired gymnasts compared to non-gymnasts. pQCT values were adjusted for age, age at menarche, height, and forearm muscle cross-sectional area. The zero on the graph represents non-gymnasts, the diamond is the retired gymnasts.
Retired gymnasts (n=25), non-gymnasts (n=22)
ToC = total bone content, ToD = total bone density, ToA = total bone area, CoC = cortical bone content, CoD = cortical bone density, CoA = cortical bone area, SSIp = polar stress strain index, CoThk = cortical thickness, MedA = medullary area
[*]Retired gymnasts significantly different than non-gymnasts, $p<0.05$

4.2.5 Discussion

This is one of the first studies to prospectively examine gymnastics training in childhood and adolescence and follow the same individual into young adulthood after retirement from sport. Gymnasts had greater size adjusted total body, lumbar spine, and proximal femur BMC in childhood (section 4.1; Faulkner et al., 2005). Retired gymnasts also had greater BMC at all sites 14 years later (section 4.1). Furthermore, similar differences between gymnasts and non-gymnasts were observed both in childhood, when

gymnasts were actively training, and in adulthood after retirement. These findings suggest that premenarcheal gymnastics training results in benefits that are maintained after stimulus removal. However, as previously stated BMC and aBMD may underestimate the impact of gymnastics training on bone strength; therefore, the aim of this section was to determine adult bone geometry, volumetric density and estimated strength 10 years after retirement from gymnastics. The main finding was that retired female gymnasts had significantly better site-specific bone geometric and densitometric properties and estimated strength at the radius and tibia in young adulthood compared to females who had not participated in gymnastics.

Retired female gymnasts have greater aBMD, as measured by DXA, compared to non-gymnasts with differences ranging from 5-22% (Bass et al., 1998; Kirchner et al., Pollock et al., 2006; Zanker et al., 2004). We found retired gymnasts had greater size-adjusted total body, lumbar spine, and femoral neck BMC compared to non-gymnasts (13%, 19%, and 13%, respectively) (Section 4.1). However, the impact of previous gymnastics training on true volumetric density (gm/cm^3), as well as bone geometry, remain largely unknown. Modeling during growth can alter endosteal (inner) and periosteal (outer) dimensions (Petit et al., 2002). During childhood the most important adaptation to loading may be the change in bone geometry. Failure load of bone depends largely on bone size, so adaptations in bone geometry during growth, if permanent, could have a significant impact on bone strength later in life (Haapasalo et al., 2000). Therefore, the impact of previous gymnastics participation on adult bone parameters may be underestimated without measurements of bone structure. In the present pQCT study,

retired gymnasts were found to have adaptations that were geometric rather than densitometric in nature at the radius, supporting this assertion.

The present results are consistent with the findings of Eser et al. (2009) who observed geometric benefits of past gymnastics participation at the radius in young women. In the present study retired gymnasts had 16% greater total bone cross-sectional area (CSA) at the distal radius and 22% and 19% greater total CSA at the 30% and 65% radial shaft sites, respectively, when age, maturity, height and forearm MSCA were controlled. The adjusted trabecular area was 16% greater at the distal radius and cortical area was 15-16% greater at the radial shaft in the retired gymnasts compared to non-gymnasts. The adjusted medullary CSA was also greater at both the 30% and 65% radial shaft sites (45% and 32%, respectively). This is in line with the Eser et al. (2009) study that reported a 25-32% greater total CSA at the radius in females with a past history of gymnastics training. The higher reported values for total bone area may be related to the fact that Eser et al. (2009) did not adjust for the significantly greater forearm muscle CSA (15%) in their retired gymnasts. The retired gymnasts in the current study had 13% greater forearm muscle CSA; however, this was adjusted for when comparing bone parameters. Alternatively, it may be that the longer duration of retirement in the present cohort compared to the Eser et al (2009) cohort explains these differences. However, previous research has found no significant decline in bone parameters with increasing duration of retirement (Zanker et al., 2003, Bass et al., 1998; Eser et al., 2009).

In contrast to the current findings studies of young competitive and recreational gymnasts have found no significant differences in bone geometry at the distal radius (Ward et al. 2005; Dyson et al. 1997 and Erlandson et al. in press). However, the

gymnasts in the previous studies were between 4 and 12 years of age. The lack of a difference in bone area in the young gymnasts combined with the results from the present study and the Eser et al (2009) study, suggest that more time, or training (i.e. increased gymnastics exposure) may be needed to alter distal radius bone geometry. The result from this study and Eser et al. (2009) suggest that gymnasts have greater CSA at the distal radius by the end of their careers. This is supported by Dowthwaite et al. (2010) who found that postmenarcheal gymnasts and ex-gymnasts (13-20 years of age) had significantly greater total, trabecular and cortical CSA, resulting in at least 20% greater estimated bone strength at the distal radius. The gymnasts in the Dowthwaite et al. (2010) cohort were purposefully selected to ensure that all gymnasts were exposed to gymnastics loading during the perimenarcheal period when estrogen levels and bone mineral accrual increase. Therefore, it may be that increases in bone area occurred in this perimenarcheal period; as all gymnasts in the studies which reported no significant differences between gymnasts and non-gymnasts bone area were premenarcheal (Ward et al., 2005; Dyson et al., 1997; Erlandson et al., in press).

Similar to the present findings, though of a smaller magnitude, Ward et al. (2005) reported that young competitive male and female gymnasts had greater total and cortical CSA at the radial shaft (9% and 8%, respectively). The lower magnitude response in these young gymnasts is not unexpected as total and regional aBMD is greater in gymnasts with higher exposure to gymnastics (i.e. greater hours or years of training) suggesting a dose response relationship between loading and bone mass (Scerpella et al., 2003). Young premenarcheal gymnasts have also been found to have greater vBMD at both the distal radius and radial shaft (Ward et al. 2005; Dyson et al. 1997; Erlandson et

141

al. in press); therefore, we hypothesized that retired elite premenarcheal gymnasts would also have higher vBMD. However, retired gymnasts were found to have 6% lower vBMD than non-gymnasts at the 30% radial shaft. Eser et al. (1997) also found that retired gymnasts had lower vBMD at the radial shaft. It may be that detraining and removal of the gymnastics stimulus resulted in a decline in vBMD while bone geometry adaptations remained. However, Dowthwaite et al. (2010) reported that postmenarcheal non-gymnasts had 33% greater total vBMD than gymnasts. They hypothesized that the lower vBMD was a reflection of the increased cross-sectional area in the gymnasts. The geometric expansion in postmenarcheal gymnasts may limit any increase in vBMD. However, it should be noted that vBMD was only lower than non-gymnasts at the radial shaft in the current cohort of retired gymnasts. Additionally, the retired female gymnasts had 14-18% greater adjusted BMC and 22-33% greater estimated bone strength at the radius.

Our results are also consistent with studies using pQCT to examine other youth sport participation and adult bone parameters. Increased loading during adolescence has been found to stimulate geometric bone adaptation at the shaft of long bones, resulting in greater bone compressive, bending and torsional strength (Heinonen et al., 2001; Kontulanine et al., 2002; Haapasalo et al., 2000). vBMD, on the other hand, is unchanged or even slightly reduced (Heinonen et al., 2001; Kontulanine et al., 2002; Haapasalo et al., 2000). Kontulainen et al. (2002) and Haapasalo et al. (2000) found that male and female racquet sports players had greater total and cortical cross-sectional area (9-32%) in their dominant playing arm compared to non-playing arm; however, males had significantly less cortical and trabecular vBMD in their playing arm. The structural

142

adaptations were the result of periosteal enlargement of shaft in the loaded arm (Kontulainen et al., 2002; Haapasalo et al., 2000). These findings mirror the ones in retired female gymnasts suggesting that prepubertal sport participation results in forearm geometric bone adaptations without accompanying increases in volumetric bone mineral density.

In contrast to the radius, differences at the distal tibia were densitometric rather than geometric in nature. Retired gymnasts had 12-13% greater total and trabecular volumetric bone mineral density. Eser et al (2009) also found that the tibial epiphyseal cross-sectional area was not increased in retired gymnasts. Similarly, young competitive gymnasts have greater total and trabecular vBMD but not CSA at the distal tibia (Ward et al., 2005). It may be that the loading experienced by gymnasts at the tibial epiphysis versus the radial epiphysis is not of a great enough magnitude to increase bone area compared to normally active individuals. The retired gymnasts in both studies as well as the young female gymnasts in the Ward et al (2005) cohort had significantly greater muscle cross-sectional area at the forearm but not the lower leg. While the relative difference in bone area between the groups at the forearm was greater than the relative difference in MSCA, suggesting that non-muscular loading is a distinct and important determinant of human skeletal structure (Dowthwaite et al., 2009), it may be that the similar lower limb MSCA combined with the greater body weight of the non-gymnasts is influencing bone area in the lower limb. Retired gymnasts also had 8-13% greater total, trabecular and cortical BMC and greater estimated bone strength at both the distal and shaft sites (24% and 10%, respectively).

The relative differences between the two groups were smaller at the tibia compared to the radius at both the distal and shaft sites. This is consistent with findings of other pQCT studies of past or present gymnastics participation (Eser et al., 2009; Ward et al., 2005; Erlandson et al., in press). The smaller and sometimes lack of a difference between gymnasts and non-gymnasts at the lower leg may be related to the activities that the non-gymnast comparison groups participate in. Ward et al. (2005) suggested that the relative loading patterns and intensity between gymnasts and non-gymnasts would be much greater at the radius than tibia. Furthermore, the weight-bearing pattern of the upper-extremity in gymnastics has been suggested to be unlike the loading patterns experienced in any other activity (Dowthwaite et al., 2007). The non-gymnasts in the current cohort where involved in other sports such as dance, basketball and volleyball in childhood and adolescence which may load the tibia in a similar manner to gymnastics. This is also supported by the similar level of physical activity between the gymnast and non-gymnast groups both in childhood and adulthood (Faulkner et al., 2003). Therefore, the unique loading patterns and intensity in the radius may explain why the differences between groups were greater at the radius than tibia. Furthermore, a confounding factor may have been the lighter body weight of the gymnasts. Even if gymnasts are experiencing forces that are greater relative to their body weight it may still be less than the forces experienced by non-gymnasts with a significantly greater body weight.

A limitation of this study is that although gymnasts were measured in childhood and adolescence there was no pQCT measure of bone geometry and volumetric density; therefore, it is not possible to quantify the reduction in bone strength since retirement from gymnastics. Furthermore, while gymnasts were found to have significantly greater

144

premancheal size-adjusted BMC and strength indices, there are no measures before the onset of gymnastics training. Therefore, it is possible that these observed benefits in bone geometry, densitometry and estimated strength were present before the onset of training and not the result of gymnastics participation. However, it is unlikely as the benefits observed mirror the adaptations found in the dominant compared to non-dominant arm in racquet sport athletes. Some gymnasts participated in other competitive sports at the high school and collegiate level after retiring from gymnastics training, which may be influencing the results. However, they participated in sports such as track and field and basketball which while likely to load the lower extremity probably did not influence radial bone parameters where the greatest differences between groups were observed. Finally, Ducher et al (2009) recently reported greater skeletal benefits at the ulna compared to radial shaft in former gymnasts. Therefore, the use of the radius may be underestimating the impact of gymnastics training on bone parameters at the forearm shaft. However, radial measures are traditionally reported for both the distal and shaft of the forearm; therefore, it was reported for comparison with other studies.

In summary, 10 years after retirement premancheal female gymnasts had significant site-specific bone geometric, densitometric and estimated strength benefits at the radius and tibia compared to females who had not participated in gymnastics. Skeletal adaptations were geometric in nature at the radius resulting in 22-32% greater estimated bone strength in retired gymnasts compared to non-gymnasts. At the distal tibia greater volumetric bone mineral density was observed without a change in bone size resulting in 24% greater estimated bone strength at this site. The results from this study suggest that premancheal gymnastics training results in increased bone strength which is maintained

10 years after retirement and removal of the gymnastics loading stimulus. These findings provide evidence for the hypothesis that physical activity during growth may influence the risk of osteoporosis and subsequent fracture later in life. However, long-term prospective studies of retired female gymnasts, especially at the time of menopause when bone loss accelerates, are required to determine the impact on fracture risk.

4.2.6 Acknowledgements

CHAPTER 5 – Summary and Conclusions

The overall goal of this thesis was to examine low exposure impact loading activity and bone development and determine the influence of childhood and adolescent sport participation on adult bone health. A gymnastics model was used and two studies were required to address the objectives above. Study 1, was the first study to prospectively examine low-level gymnastics exposure and bone mineral accrual in young males and females (section 3.1). Bone mass, volumetric density, structure, and estimated strength in recreational and precompetitive gymnasts was also assessed (section 3.2). Study 2, was the first study to prospectively examine elite premenarcheal gymnasts and follow the same individuals into adulthood after retirement from sport and removal of the gymnastics loading stimulus (section 4.1). Adult bone mass, volumetric density, structure, and estimated strength in retired premenarcheal gymnasts was also assessed (section 4.2). Dual x-ray absorptiometry was used to assess bone development and maintenance and peripheral quantitative computed tomography was used to cross-sectional assess the structural properties of bone.

The primary finding from study 1 was that when compared to other physically active children young recreational and precompetitive gymnasts had 3 % greater total body and 7% femoral neck bone mineral content after 4 years of gymnastics participation. Furthermore, recreational and precompetitive gymnasts were found to have 18% greater total content, 6% greater total volumetric density, and 25% greater estimated strength at the distal radius compared to non-gymnasts when sex, age, and height were considered. These findings are consistent with, although on a smaller magnitude to, the findings previously reported in competitive female gymnasts (Bass et al., 1998; Nickols-

Richardson et al., 1999; Dowthwaite et al., 2007; Nickols-Richardson et al., 2000; Ward et al., 2005; Dyson et al., 1997). The lower magnitude response is not unexpected as total and regional aBMD has been shown to be greater in gymnasts with higher exposure to gymnastics (i.e., greater hours or years of training) suggesting a dose response relationship between loading and bone mass (Laing et al., 2005; Scerpella et al., 2003). However, despite the fact that the gymnasts in study one were young and had a low-level of gymnastics exposure they had greater bone parameters than children participating in other recreational sports. This would suggest that stimuli received during introductory gymnastics classes are sufficient to increase bone mass and estimated strength compared to other recreational sports.

These findings are important as recreational gymnastics skills are attainable by most children and do not require a high level of training. Therefore, low-level gymnastics skills can easily be integrated into school physical education programs and thus most children may benefit from this training, potentially developing greater bone mass and strenght. This training could have a potential impact in primary osteoporosis and fracture prevention. However, randomized control trials are required to substantiate our findings.

The primary finding from study 2 was that the previously reported benefits of premenarcheal gymnastics training (Faulkner et al., 2003) were still apparent after10 years of retirement from sport and removal of the gymnastics loading stimulus. Retired female gymnasts were found to have 13% greater size-adjusted total body, 19% greater lumbar spine, and 13% greater femoral neck bone mineral content. Furthermore, the observed difference between groups in adulthood was similar to the difference found between premenarcheal gymnasts and non-gymnasts. Retired female gymnasts were also

found to have site-specific bone geometric, densitometric, and estimated strength benefits after long-term retirement. Retired gymnasts had 16-22% greater size-adjusted bone area at the radius. The adjusted medullary area was also greater at the radial shaft (32-45%) in gymnasts. These geometric skeletal adaptations at the radius resulted in 22-32% greater estimated bone strength in retired gymnasts compared to non-gymnasts. Retired gymnasts were also found to have greater total and trabecular volumetric density at the distal tibia resulting in 24% greater estimated strength at this site.

These findings suggest that premenarcheal gymnastics training results in benefits that are maintained after gymnastics stimulus removal supporting the assertion that structured physical activity during growth is an effective means to increase bone mass and potentially prevent or delay the risk of osteoporosis and related fracture. This research aids in providing an evidence-base rationale for public health strategies aimed at optimizing lifestyle choices during childhood and adolescence as a preventative measure against the development of osteoporosis (Faulkner and Bailey, 2007). However, prospective long-term studies are required which follow retired female gymnasts as they reach menopause and bone loss accelerates to better understand the impact of childhood and adolescent physical activity on osteoporosis and related fracture risk.

The results presented here also highlight the importance of assessing not only bone mineral values as measured by DXA, but also bone geometric or structural properties. The adaptation of bone to gymnastics loading is site-specific with estimated strength benefits resulting from differences in density or area at different measurement sites. Furthermore, values obtained from the pQCT three-dimensional assessment of bone revealed greater between group differences compared to DXA derived values. Therefore,

149

assessment of the impact of structured physical activity during growth with DXA may underestimate the benefits.

Caution must be taken when interpreting these results, as there are no measures of bone parameters before the onset of training. Therefore, it is possible that these observed benefits in bone parameters were present before the onset of training and not the result of gymnastics participation. However, previous research has found that young gymnasts not only have greater bone parameters when measured in cross-section, but also accrue more bone over time suggesting that it is gymnastics training and not genetic predisposition which is resulting in the greater bone parameters observed.

In conclusion, recreational gymnastics participation, low-level gymnastics exposure, appears to be of a sufficient magnitude to result in bone benefits. Furthermore, the benefits of gymnastics participation during childhood and adolescence appear to be maintained after long-term retirement from training and competition. Future studies should recruit children before the onset of gymnastics training and prospectively follow them through childhood and adolescence into adulthood and retirement from sport to determine the effect of impact loading activity during growth on adult skeletal health.

CHAPTER 5: *References*

Ackerman, A., Thornton, J. C., Wang, J., Pierson, R. N., Horlick, M. (2006). Sex difference in the effect of puberty on the relationship between fat mass and bone mass in 926 healthy subjects, 6 to 18 years old. *Obesity, 14,* 819-825.

Adachi, J. D., Ioannidis, G., Berger, C., Joesph, L., Papioannour, A., Pickard, E., et al. (2001). The influence of osteoporotic fractures on health-related quality of life in community-dwelling mean and women across Canada. *Osteoporosis International, 12,* 903-908.

Adachi, J. D., Ioannidis, G., Pickard, L., Berger, C., Prior, J. C., Joseph L., et al. (2003). The association between osteoporotic fractures and health related quality of life as measured by the Health Utilities Index in the Canadian Multicenter Osteoporosis Study (CaMos). *Osteoporosis International, 14,* 895-904.

Adami, S., Gatti, D., Barga, V., Bainchini, D., Rossini, M. (1999). Site-specific effects of strength training on bone structure and geometry of ultradistal radius in postmenopausal women. *Journal of Bone and Mineral Research, 14,* 120-124.

Arden, N. K., Spector, T. D. (1997). Genetic influences on muscle strength, lean body mass and bone mineral density: A twin study. *Journal of Bone and Mineral Research, 12:* 2076-2081.

Ashe, M. C., Khan, K. M., Kontulainen, S. A., Guy, P., Liu, D., Beck, T. J, Mckay, H. A. (2006). Accuracy of pQCT for evaluating the aged human radius: an ashing, histomorphometry and failure load investigation. *Osteoporosis International, 17,* 124-151.

Bailey, D. (1997). The Saskatchewan pediatric bone mineral accrual study: Bone mineral acquisition during the growing years. *International Journal of Sports Medicine, 18,* S191-S194.

Bailey, D., Faulkner, R. McKay, H. (1996). Growth, physical activity, and bone mineral acquisition. In J.O. Holloszy (Ed.), *Exercise and Sports Sciences Reviews, Vol. 24 American College of Sports Medicine Series.* Baltimore, MR: Williams & Wilkins.

Bailey, D., McKay, H., Mirwald, R., Crocker, P., Faulkner, R. (1999). The university of Saskatchewan bone mineral accrual study: A six year longitudinal study of the relationship of physical activity to bone mineral accrual in growing children. *Journal of Bone and Mineral Research, 14,* 1672-1679.

Barbeau, P., Litaker, M. (2003). Effects of physical activity intervention on bone mineral density in black girls: Relative contribution of changes in fat mass and fat free soft tissue. *Medicine and Science in Sports and Exercise, 35,* S82.

Baron, J., Karagas, M., Barrett, J., Kniffin, W., Malenka, D., Mayor, M., Kellet, R. (1996). Basic epidemiology of fractures of the upper and lower limb in American over 65 years of age. *Epidemiology, 7,* 612-618.

Bass, S. L. (2000). The pre-pubertal years. A uniquely opportune stage of growth when the skeleton is most responsive to exercise? *Sports Medicine, 30,* 73-78.

Bass, S., M. Bradney, G. Pearce, E. Hendrich, K. Inge, S. Stuckey, S. K. Lo, E. Seeman. (2000). Short stature and delayed puberty in gymnasts: influence of selection bias on leg length and the duration of training on trunk length. *Journal of Pediatrics, 136,* 149-155.

Bass, S., Pearce, G., Bradney, M., Hendrich, E., Delmas, P. D., Harding, A., Seeman, E. (1998). Exercise before puberty may confer residual benefits in bone density in adulthood: Studies in active prepubertal and retired female gymnasts. *Journal of Bone Mineral Research, 13,* 500-507.

Bass, S., Pierre, D. D., Pearce, G., Hendrich, E., Taensky, A., Seeman, E. (1999). The differing tempo of growth in bone size, mass, and density in girls is region-specific. *Journal of Clinical Investigation, 104,* 795-804.

Baxter-Jones, A., Helms, P. (1996). Effects of training at a young age: A review of the training of young athletes (TOYA) study. *Pediatric Exercise Science, 8,* 310-317.

Baxter-Jones, A. D. G., Helms, P., Baines, J., Preece, M. (1994). Menarche in intensively trained gymnasts, swimmers, and tennis players. *Annuals of Human Biology, 21,* 407-415.

Baxter-Jones, A., P. Helms, N. Maffulli, J. Baines Preece, M. Preece. (1995). Growth and development of male gymnasts, swimmers, soccer and tennis players: A longitudinal study. *Annals of Human Biology 20,* 381-394.

Baxter-Jones, A. D. G., Kontulainen, S. A., Faulkner, R. A., Bailey, D. A. (2008). A longitudinal study of the relationship of physical activity to bone mineral accrual from adolescence to young adulthood. *Bone, 43,* 1101-1107.

Baxter-Jones, A. D. G., Maffulli, N. (2003). Parental influence on sport participation in elite young athletes. *The Journal of Sports Medicine and Physical Fitness, 43,* 250-255.

Baxter-Jones, A. D. G., Mirwald, R. Multilevel modeling. (2004) In: Hauspie, R. C., Cameron, N., Molinari, L. (eds). Methods in Human Growth Research. Cambridge University Press, Cambridge, UK, pp. 306-330.

Bessette, L., Ste-Maire, L. G., Jean, S., Davison, K. S., Beaulieu, M., Baranci, M., Bessant, J., Brown, J. P. (2008). The care gap in diagnosis and treatment of women with a fragility fracture. *Osteoporosis International, 19,* 79-86.

Beunen, G. P., Malina, R. M., Thomis, M. (1999). Physical growth and maturation of female gymnasts. In Johnston, F. E., Zemel, B., Eveleth, P. B. (eds). *Human Growth in Context.* London UK: Smith-Gordon. pp. 281-289.

Binkley, T. Specker, B. (2004) Increased periosteal circumference remains present 12 months after an exercise intervention in preschool children. *Bone, 35,* 1383-1388.

Bischoff-Ferrari, H. A., Willett, W. C., Wong, J. B. Givannucci, E., Dietrich, T., Dawson-Hughes, B. (2005). Fracture prevention with vitamin D supplementation: a meta-analysis of randomized control trails. *Journal of the American Medical Association, 293,* 2257-2264.

Bischoff-Ferrari, H. A., Rees, J. R., Grau, M. V., Barry, E., Bui, J., Baron, J. A. (2008). Effect of calcium supplementation on fracture risk: a double-blind randomized controlled trial. *American Journal of Clinical Nutrition, 87,* 1945-1951.

Blum, M., Harris, S. S., Must, A., Phillips, S. M., Rand, W. M., Dawson-Hughes, B. (2001). Weight and body mass index a menarche are associated with premenopausal bone mass. *Osteoporosis International, 12,* 588-594.

Bonjour, J. P., Carrie, A. L., Ferrari, S., Cavien, H., Slosman, D., Theintz, G., Rizzoli, R. (1997). Calcium enriched fodds and bone mass growth in pre-pubertal girls: a randomized double bind, placebo controlled trial. *The Journal of Clinical Investigation, 99,* 1287-1294.

Bonjour, J. P., Theintz, G., Law, F., Slosman, D., Rizzoli, R. (1994). Peak bone mass. *Osteoporosis International, 4,* 7-13.

Bradford, P.G., Gerace, K. V., Roland, R. L., Chrzan, B. G. (2010). Estrogen regulation of apoptosis in osteoblast. *Physiology and Behavior, 99,* 181-185.

Brook, C. G. D. (1978). *In Human Growth,* Eds. Falkner & Tanner. Plenum Press, New York and London.

Cale, L. (1998). Monitoring young people's physical activity. *The British Journal of Physical Education, 29,* 28-30.

Caine, D., T. Lewis, T. O'Connor, W. Howe, and S. Bass. (2001). Does gymnastics training inhibit growth of females? *Clinical Journal of Sports Medicine,* 293, 299-303.

Carter, L. M., Whiting, S. J., Drinkwater, D. T., Zello, G. A., Faulkner, R. A., Bailey, D. A. (2001). Self-reported calcium intake and bone mineral content in children and adolescents. *Journal of the American College of Nutrition, 20,* 502-509.

Cassell, C., Benedict, M., Specker B. (1996). Bone mineral density in elite 7- 9 year old female gymnasts and swimmers. *Medicine and Science in Sports and Exercise, 28,* 1243-1246.

Centers for disease control and prevention (CDC). (2000). *National Center for Health Statistics CDC growth charts:* United States. Retrieved: February 10, 2007, from www.dcd.goc/growthcharts.htm.

Chan, G. M. (1992). Performance of dual-energy x-ray absorptiometry in evaluating bone, lean body mass, and fat in pediatric subjects. *Journal of Bone and Mineral Research, 7,* 369-74.

Cheek, D. B. (1968). *Human Growth.* Philidephia: Lea & Febiger.

Chevalley, T., Bonjour, J. P., Ferrari, S., Rizzoli, R. (2008). Influence of age at menarche on forearm bone microstructure in health young women. *Journal of Clinical Endocrinology and Metabolism, 93,* 2594-2601.

Chevalley, T., Bonjour, J. P., Ferrari, S., Rizzoli, R. (2009a). The influence of pubertal timing on bone mass acquisition: a predetermined trajectory detectable five years before menarche. *J Clin Endocrinol Meta, 94,* 3424-31.

Chevalley, T., Bonjour, J. P., Ferrari, S., Rizzoli, R. (2009b). Deleterious effect of late menarche on distal tibia microstructure in health 20-year-old and premenopausal middle-aged women. *Journal of Bone and Mineral Research, 24,* 144-152.

Claessens, A. L., Malins, R. M., Lefevre, J. (1992). Growth and menarcheal status of elite female gymnasts. *Medicine and Science in Sports and Exercise, 24,* 755-763.

Compston, J. (1995). Bone density: BMC, BMD or corrected BMD? *Bone, 16,* 5-7.

Cooper C. (1999). Epidemiology of Osteoporosis. *Osteoporosis International,* 9, S2-S8.

Cooper, C., Atkinson, E. J., Jacobsen, S. J., Ofallon, W. M., Melton L. J. (1993). Population-based study of survival after osteoporotic factures. *American Journal of Epidemiology, 137,* 1001-1005.

Cooper, C., Cawely, M., Bhalla, A., Egger, P., Ring, F., Morton, L., Barker, D. (1995). Childhood growth, physical activity, and peak bone mass in women. *Journal of Bone and Mineral Research, 10,* 940-947.

Copeland, J. L., Kowalski, K. C., Tremblay, M. S. (2003). Validity of the Physical Activity Questionnaire for Adults: The new member of the PAQ family. Abstract – presented at the Canadian Society of Exercise Physiology Conference.

Courteix, B. P., Lespessailles, E., Jaffre, C., Obert, P., Benhamou, C. L. (1999). Bone mineral acqusotion and somatic development in highly trained girl gymnasts. *Acta Paediatrica, 88,* 803-808.

Courteix, B. P., Lespessailles, E., Peres, S. L., Obert, P., Germain, P., Benhamou, C. L. (1998). Effect of physical training on bone mineral density in prepubertal girls: A comparative study between impact-loading and non-impact-loading sports. *Osteoporosis International, 8,* 152-158.

Cranney, A., Weiler, H. A., O'Donnell, S., Puil, L. (2008). Summary of evidence-based review on vitamin D efficacy and safety in relation to bone health. *American Journal of Clinical Nutrition, 88,* S513-S519. s

Crocker, P. R., Bailey, D. A., Faulkner, R. A., Kowalski, K. C., McGrath, R. (1997). Measuring general levels of physical activity: Preliminary evidence for the Physical Activity Questionnaire for Older Children. *Medicine and Science in Sports and Exercise, 29,* 1344-1349.

Cummings, R. G. (1990). Calcium intake and bone mass: A quantitative review of the evidence. *Calcified Tissue International, 47,* 194-201.

Cumming, S. R., Black, D., Nevitt, M., Browner, W., Cauley, J., Ensrud, K., Genant, H., Palermo, l., Scott, J., Vogot, T. (1993). Bone density at various sites for prediction of hip fractures. *Lancet, 341,* 72-75.

Cummings, S. R., Browner W. S., Bauer, D., Stone, K., Ensurd, K., Janal, S., Ettinger, B. (1998). Endogenous hormones and the risk of hip and vertebral fractures among older women. *New England Journal of Medicine, 339,* 733-738.

Daly, R. M., Caine, D., Bass, S. L., Pieter, W., Broekhoff, J. (2005). Growth of highly vs moderately trained competitive female artistic gymnasts. *Medicine and Science in Sports and Exercise, 37,* 1053-1060.

Daly, R., Rich, P., & Klein, R. (1998). Hormonal responses to physical training in high-level peripubertal male gymnasts. *European Journal of Applied Physiology and Occupational Physiology, 79,* 74-81.

Daly, R., Rich, P., Klein, R., & Bass, S. (1999). Effects of high-impact exercise on ultrasonic and biochemical indices of skeletal status: A prospective study in young male gymnasts. *Journal of Bone and Mineral Research, 14,* 1222-1230.

Daly, R., Rich, P., Klein, R., & Bass, S. (2000). Short stature in competitive prepubertal and early pubertal male gymnasts: The result of selection bias or intense training? *Journal of Pediatrics, 137,* 510-516.

Damon, A., Bajema, C. J. (1974). Age at menarche: Accuracy of recall after thirty-nine years. *Human Biology, 46,* 381-384.

Damsgaard, R., Bencke, J., Matthiesen, G., Petersen, H., Muller, J. (2000). Is prepubertal growth adversely affected by sport? *Medicine and Science in Sport and Exercise,* 32(10): 1698-1703.

de Kam, D., Smulders, E., Weerdesteyn, V., Smits-Engelsman, B. C. (2009). Exercise interventions to reduce fall-related fractures and their risk factors in individuals with low bone density: a systematic review of randomized controlled trials. *Osteoporosis International, 20,* 2111-2125.

Demissie, S., Dupuis, J., Cupples, L. A., Beck, T. J., Kiel, D. P., Karasik, D. (2007). Proximal hip geometry is linked to several chromosomal regions: genome-wide linkage results from the Framingham osteoporosis study. *Bone, 40,* 743-750.

Di, D. N., Carbonelli, M. G., Candeloro, N., Iacopino, L., De Loranzo, A., Andreoli, A. Effect of supplementation of calcium and vitamin D on bone mineral density and bone mineral content in peri- and post- menopausal women; a double-blind, randomized, controlled trail. *Pharmacological Research, 50,* 637-641.

Dimitri, P., Wales, J. K., Bishop, N. (2010). Fat and bone in children: the differential effects of obesity on bone size and mass according to fracture history. *Journal of Bone and Mineral Research, 25,* 257-536.

Dowthwaire, J. N., Flowers, P. P., Spadaro, J. A., Scerpella, T. A. (2006). Maturity and activity-related differences in bone mineral density: Tanner I vs. II and gymnasts vs non-gymnasts. *Bone, 39,* 895-900.

Dowthwaite, J. N., Flowers, P. P., Spadaro, J. A., Scerpella, T. A. (2007). Bone geometry, density, and strength indices of the distal radius reflect loading via childhood gymnastics activity. *Journal of Clinical Densitometry, 10,* 65-75.

Dowthwaite, J. N., Kanaley, J. A., Spardaro, J. A., Hickman, R. M., Scerpella, T. A. (2009). Muscle indices do not fully account for enhanced upper extremity bone mass and strength in gymnasts. *Journal of Musculoskeletal Neuroanl Interaction, 9,* 2-14.

Dowthwaite, J. N., Scerpella, T. A. (2009) Skeletal geometry and indices of bone strength in artistic gymnasts. *Journal of Musculoskeletal Neuroanl Interaction, 9,* 198-214.

Dowthwaite, J. N., Scerpella, T. A. (2010). Distal radius geometry and skeletal indices after peripubertal artistic gymnastics. *Osteoporosis International, in press.*

Duke, P. M., Litt, I. F., Gross, R. T. (1980). Adolescents' self-assessment of sexual maturation. *Pediatrics, 66,* 918-920.

Dyson, K., Blimkie, C. J., Davidson, S. K., Webber, C. E., Adachi, J. D. (1997). Gymnastics training and bone density in pre-adolescent females. *Medicine and Science in Sport and Exercise, 29,* 443-450.

Einhorn, T. A. (1996). The bone organ system: Form and function. In: Marcus, R., Feldman, D., Kelsey, J. (eds). Osteoporosis. San Diego, CA., USA: Academic Press, 3-22.

El-Hajj Fuleihan, G., Nabulsi, M., Tamim, H., Maalouf, J., Salamoun, M., Khalife, H., Choucair, M., Arabi, A., Vieth, R. (2006). Effect of vitamin D replacement on musculoskeletal parameters in school children: A randomized control trail. *The Journal of Clinical Endocrinology and Metabolism, 91,* 405-412.

Elowsson, P., Forslund, A. H., Mallmin, H., Feuk, U., Hansson, I. Carlsten, J. (1998). An evaluation of dual x-ray absorptiometry and underwater weighing to estimate body composition by means of carcass analysis in piglets. *The Journal of Nutrition, 128,* 1543-1549.

Erlandson, M. C., Kontulainen, S. A., Baxter-Jones, A. D. G. (2010). Precompetitive and recreational gymnasts have greater bone density, mass, and estimated strength at the distal radius in young childhood. *Osteoporosis International, in press.*

Erlandson, M. C., Sherar, L. B., Mirwald, R. L., Maffulli, N., Baxter-Jones, A. D. G. (2008). Growth and maturation of adolescent female gymnasts, swimmers and tennis players. *Medicine and Science in Sports and Exercise, 40,* 34-42.

Eser, P., Hill, B., Ducher, G., Bass, S. L. (2009). Skeletal benefits after long term retirement in former elite female gymnasts. *Journal of Bone and Mineral Research, 12,* 1981-1988.

Faulkner, R., Bailey, D. (2007). Osteoporosis: A pediatric concern? *Medicine and Sport Science, 51,* 1-12.

Faulkner, R., Bailey, D., Drinkwater, D., McKay, H., Arnold, C., Wilkinson, A. (1996). Bone densitometry in Canadian children 8-17 years of age. *Calcified Tissue International, 59,* 344-351.

Faulkner, R. A., Forwood, N. R., Beck, T. J., Mafukidze, J. C., Russell, K., Wallace, W. (2003). Strength indices of the proximal femur and shaft in prepubertal females gymnasts. *Medicine and Science in Sports and Exercise, 35,* 513-518.

Fehling, P. C., Alekel, L., Clasey, J., Rector, A., Stillman, R. J. (1995). A comparison of bone mineral densities among female athletes in impact loading and active loading sports. *Bone, 17,* 205-210.

Filaire, E., Lac, G. (2002). Nutritional status and body composition of juvenile elite female gymnasts. *Journal of Sports Medicine and Physical Fitness, 42,* 65-70.

Forwood, M. R., Burr, D. B. (1993). Physical activity and bone mass: Exercise in futility? *Bone Mineral Research, 21,* 89-112.

Frasen, M., Woodward, M., Norton, R., Robinson, E., Bulter, M., Campbell, A. (2002). Excess mortality or institutionalization after hip fracture: men are at greater risk then women. *J Am Geriatr Soc, 50,* 685-690.

Fricke, O., Semier, O., Stabrey, A., Tutlewski, B., Remer, T., Herkenrath, P., Schoenau, E. (2009). High and low birth weight and its implication for growth and bone development in childhood and adolescence. *Journal of Pediatric Endocrinology and Metabolism, 22,* 19-30.

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

Frost, H. M. (1989). Some effects of the basic multicellular unit-based remodeling on photon absorptiometry of trabecular bone. *Bone Mineral Reserach, 7,* 47-65.

Frost, H. M. (1990). Skeletal structural adaptations to mechanical usage (SATMU): 1. redefining Wolff's Law: The bone modeling problem. *The Anatomical Record, 226,* 403-413.

Genant, H. K., Engelke, K., Fuerst, T., et al. (1996). Noninvasive assessment of bone mineral and structure. *Journal of Bone and Mineral Research, 11,* 707-730.

Gilsanz, V., Chalfant, J., Kalkwarf, H., Zemel, B., Lappe, J., Oberfield, S., Shepard, J., Wren, T., Winer, K. (2010). Age at onset of puberty predicts bone mass in young adulthood. *The Journal of Pediatrics, in press.*

Griffith, J. F., Engelke, K., Ganant, H. K. (2010). Looking beyond bone mineral density. *Annals of the New York Academy of Science, 1192,* 45-56.

Grimston, S. K., Willows, N. D., Hanley, D. A. (1993). Mechanical loading regime and its relationship to bone mineral density in children. *Medicine and Science in Sports and Exercise, 25,* 249-255.

Gordon, C. M., Bachrach, L. K., Carpenter, T. O., Crabtree, N., El-Hajii Fuleihan, G., Kutilek, S., Lorenc, R. S., Tosi, L. L., Ward, K. A., Ward, L. M., Kalkwarf, H. J. (2008). Dual energy x-ray absorptiometry interpretation and reporting in children and adolescents: the 2007 ISCD Pediatric Official Positions. (2008). *Journal of Clinical Densitometry,*11, 43-58.

Goulding, A., Jones, I. E., Taylor, R. W., Manning, P. J., Williams, S. M. (2000). More broken bones: a 4 year double cohort study of young girls with and without distal forearm fractures. *Journal of Bone and Mineral Research, 15,* 2001-2018.

Gunter, K., Baxter-Jones, A. D. G., Mirwald, R. L., Almstedt, H., Fuchs, R. K., Durski, S., Snow, C. (2003). Impact exercise increases BMC during growth: a 8-year longitudinal study. *Journal of Bone and Mineral Research, 23,* 986-993.

Gurd, B., Klentrou, P. (2003). Physical and pubertal development in young male gymnasts. *Journal of Applied Physiology, 95,* 1011-1015.

Haapasalo, H., Kannus, H., Sievane, H., Heinonem, A., Oja, P., Vuori, I. (1994). Long-term unilateral loading and bone mineral density and content in female squash player. *Calcified Tissue International, 54,* 249-255.

Haapasalo, H., Kontulainen, S. A., Sievanen, H., Kannus, P., Jarvinen, M., Vuori, I. (2000). Exercise-induced gain is due to enlargement in bone size without a change in volumetric density: a peripheral quantitative computed tomography study of the upper arms of male tennis players. *Bone, 27,* 351-357.

Hage, R., Courteix, D., Benhamou, C. L., Jacob, C., Jaffre, C. (2009). Relative importance of lean and fat mass on bone mineral density in a group of adolescent girls and boys. *European Journal of Applied Physiology, 105,* 759-764.

Hage, R., Jacob, C., Moussa, E., Benhamou, C. L., Jaffre, C. (2009). Total body, lumbar spine and hip bone mineral density in overweight adolescent girls: decreased or increased? *Journal of Bone and Mineral Metabolism, 27,* 629-633.

Hage, R., Moussa, E., Jacob, C. (2010). Femoral neck geometry in overweight and normal weight adolescent girls. *Journal of Bone and Mineral Metabolism, 28,* 595-600.

Hannan, M. T., Felson, D. T., Anderson, J. J. (1992). Bone mineral density in elderly men and women: results from the Framingham osteoporosis study. *Jounral of Bone and Mineral Research, 7,* 547-553.

Heinonen, A., Sievanen, H., Kyrolainen, H., Pertunen, J., Kannus, P. (2001). Mineral mass, size, and estimated mechanical strength of triple jumpers' lower limb. *Bone, 29,* 219-224.

Hologic. (1992). Hologic QDR 2000 supine lateral bone densitometer; Operator's Manual. Waltham MA: Hologic Inc.

Hopper, J. L., Green, R. M., Nowson, C. A., et al. (1998). Genetic, common environment, and individual specific components of variance for bone mineral density in 10- to 26-year old females: A twin study. *American Journal of Epidemiology, 147:* 17-29.

Ho-Pham, L., Nguygen, N., Lai, T. Q., Nguygen, T. (2010). Contributions of lean mass and fat mass to bone mineral density: a study of postmenopausal women. *BMC Musculoskeletal Disorders, 11,* 59.

Huang, A. J., Ettinger, B., Wittinghoff, E., Ensurd, K. E., Johnson, K. C., Cummings, S. R. (2007). Endogenous estrogen levels and the effects of ultra-low-dose transdermal estradiol therapy on bone turnover and BMC in postmenopausal women. *Journal of Bone and Mineral Research, 22,* 1791-1797.

Huang, C., Ross, P. D., Wasnich, R. D. (1996). Vertebral fracture and other predictors of physical impairment and health care utilization. *Archives of Internal Medicine, 15,* 2469-2475.

International standards for anthropometric assessment. (2001). International Society for the Advancement of Kinanthropmetry, Australia.

Ito, M., Yamada, M., Hayashi, K., Ohki, M., Uetani, M., Nakamura, T. (1995). Relation of early menarche to high bone mineral density. *Calcified Tissue International, 57,* 11-14.

Jackowski, S., Erlandson, M. C., Mirwald, R. L., Faulkner, R. A., Bailey, D. A., Baxter-Jones, A. D. G. (2010). Effects of maturational timing on the accrual of adult bone mineral content. *Journal of Bone and Mineral Research, 25(S1),* S365.

Janz, K., Boffitt, B., Levy, S. (2005). Validation evidence for the Netherlands physical activity questionnaire for young children: The Iowa bone development study. *Research Quarterly for Exercise and Sport, 76,* 363-369.

Janz, K. F., Gilmore, J. M., Burns, T. L., Levy, S. M., Torner, J. C., Willing, M. C. et al. (2006). Physical activity augments bone mineral accrual in young children. The Iowa Bone Development Study. *Journal of Pediatrics, 148,* 793-799.

Janz, K., Gilmore, J. M., Levy, S. M., Letuchy, E. M., Burns, T. L., Beck, T. J. (2007). Phsyical activity and femoral neck bone strength during childhood: the Iowa Bone Development Study. *Bone, 4,* 216-222.

Janz, K. F., Latuchy, E. M., Eichenberger-Gilmore, J. M., Burns, T. L., Torner, J. C., Willing, M. C., Levy, S. M. (2010). Early physical activity provides sustained bone health benefits later in childhood. *Medicine and Science in Sports and Exercise, 42,* 1072-1078.

Janz, K. F., Levy, S. M., Burns, T. L., Torner, J. C., Willing, M. C., & Warren, J. J. (2002). Fatness, physical activity, and television viewing in children during the adiposity rebound period: The Iowa bone development study. *Preventive Medicine, 35,* 563-571.

Jarvinen, T. L., Kannus, P., Sievanen, H. (1999). Have the DXA-based exercise studies seriously underestimated the effects of mechanical loading on bone? *Journal of Bone and Mineral Research, 14,* 1634-1635.

Jarvinen, T. L., Kannus, P., Sievanen, H. (2003). Estrogen and bone - a reproductive and locomotive perspective. *Journal of Bone and Mineral Research, 18,* 1921-1931.

Johnell, O., Kanis, J. A. (2006). An estimate of the worldwide prevalence and disability associated with osteoporotic fractures. *Osteoporosis International, 17,* 1726-1733.

Johnston, C. C., Miller, J. Z., Slemenda, C. W., Reister, T. K., Hui, S., Chrsitian, J. C., Peacock, M. (1992). Calcium supplementation and increases in bone mineral density in children. *New England Journal of Medicine, 327,* 82-87.

Kanis, J. A., Ode, A., Johnell, O., Johnsson, B., de Laet, C., Dawson, A. (2001). The burden of osteoporotic fractures: a method for setting intervention thresholds. *Osteoporosis International, 12*, 417–427.

Kannus, P., Haapasalo, H., Sankelo, M., Sievanen, H., Pasanen, M., Heinonen, A., Oja, P., & Vuori, I. (1995) Effect of starting age of physical activity on bone mass in the dominant arm of tennis and squash players. *Annuals of Internal Medicine, 123,* 27-31.

Karkkainen, M., Tupperalnen, M., Salovaara, K., Sandini, L., Rikkonen, T., Sirola, J., Honkanen, R., Jurvelin, J., Alhava, E., Kroger, H. (2010). Effect of calcium and vitamin D supplementation on bone mineral density in women aged 65-71 years: a 3-year randomized population-based trial (OSTPRE-FPS). *Osteoporosis International, 21,* 2047-2055.

Kemper, H. C. G. (1985). *Growth, Health, and Fitness of Teenagers.* Basel: Karger.

Khan, K., Mckay, H., Kannus, P., Bailey, D., Wark, J., Bennell, K. (2001). Physical activity and bone health. Human Kinetics. USA.

Kiel, D. P., Demissie, S., Dupuis, J., Lunetta, K. L., Murabito, J. M., Karasik, D. (2007). Genome-wide association with bone mass and geometry in the Framingham Heart Study. *BMC Medical Genetics, 8 (Suppl 1),* S14.

Kindblom, J. M., Lorentzon, M., Norjavaara, E., Hellqvist, A., Nilsson, S., Mellstrom, D., Ohlsson, C. (2006). Pubertal timing predicts previous fractures and BMD in young adult men: the GOOD study. *Journal of Bone and Mineral Research, 21,* 790-795.

Kirchner, E., Lewis, R. O'Conner, P. (1995). Bone mineral density and dietary intake of female college gymnasts. *Medicine and Science in Sports and Exercise,* 24, 543-549.

Kirchner, E. M., Lewis, R. D., O'Conner, J. P. (1996). Effect of past gymnastics participation on adult bone mass. *Journal of Applied Physiology, 80,* 226-232.

Klein, G., Fitzpatrick, L., Langman, C., Beck, T., Carpenter, T., Gilsanz, V., Holm, I., Leonard, M., & Specker, B. (2005). The state of pediatric bone: Summary of the ASBMR pediatric bone initiative. *Journal of Bone Mineral Research, 20,* 207-2081.

Kontulainen, S. A., Johnston, J. D., Liu, D., Leung, C., Oxland, T. R., McKay, H. A. (2008). Strength indices from pQCT imaging predict up to 85% of variation in bone failure properties at tibial epiphysis and diaphysis. *Journal of Musculoskeletal Neuroanal Interaction, 8,* 401-409.

Kontulainen, S. A., Kannus, P., Haapasalo, H., Heinonen, A., Sievanen, H., Oja, P., Vuori, I. (1999). Changes in bone mineral content with decreased training in competitive young adult tennis players and controls: A prospective 4-yr follow-up. *Medicine and Science in Sport and Exercise, 5,* 646-652.

Kontulainen, S. A., Kannus, P., Haapasalo, H., Sievanen, H., Pasanen, M., Heinonen, A., Oja, P., Vuori, I. (2001). Good maintennce of exercise-induced bone gain with decreased training of female tennis and squash players: A prospective 5-year follow-up of young and old starters and controls. *Journal of Bone and Mineral Research, 16,* 195-201.

Kontulainen, S. A., Macdonald, H. M., Khan, K. M., McKay, H. A. (2005). Examining bone surfaces across puberty: A 20-month pQCT trial. *Journal of Bone and Mineral Research, 20:* 1202-1207.

Kontulainen, S. A., Sievanen, H., Kannus, P., Pasanen, M. Vuori, I. (2002). Effect of long-term impact-loading on mass, size and estimated strength of humerus and radius of female racquet sports players: a peripheral quantitative computed tomography study between young and old starters and controls. *Journal of Bone and Mineral Research, 17,* 2281-2289.

Kowalski, K. C., Crocker, P. R., Faulkner, R. A. (1997). Validation of the Physical Activity Questionnaire for Older Children. *Pediatric Exercise Science, 9,* 174-186.

Krall, E., Dawson-Hughes, B., Hirst, K. et al. (1997). Bone mineral density and biochemical markers of bone turnover in healthy elderly men and women. *J Gerontol A Biol Sci Med Sci, 52,* M61-67.

Kudlac, J., Nicols, D. L., Sanborn, C. F., DiMarco, N. M. (2004). Impact of detraining on bone loss in former collegiate female gymnasts. *Calcified Tissue International, 75,* 482-487.

Lai, K. C., Goodsitt, M. M., Murano, R., Chesnut, C. H. d. (1992). A comparison of two dual-energy X-ray absorptiometry systems for spinal bone mineral measurement. *Calcified Tissue International, 50,* 203-8.

Laing, E. M., Massoni, J. A., Nickols-Richardson, S. M., Modlesky, C. M., O'Conner, P. J., Lewis, R. D. (2002). A prospective study of bone mass and body composition in female adolescent gymnasts. *Journal of Pediatrics, 141,* 211-216.

Laing, E. M., Wilson, A. R., Modlesky, C. M., O'Conner, P. J., Hall, D. B., Lewis, R. D. (2005). Initial years of recreational gymnastics training improves lumbar spine bone mineral accrual in 4- to 8- year old gymnasts. *Journal of Bone and Mineral Research, 20,* 509-519.

Langsetmo, L., Poliquin, S., Hanley, D. A., Prior, J. C., Barr, S., Anatassiades, T., Towheed, T., Goltzman, D., Kreiger, N. CaMos Research Group. (2010). Dietary patterns in Canadian men and women ages 25 and older: relationship to demographics, body mass index, and bone mineral density. *BMC Musculoskeletal Disorders, 11,* 20.

Lappe, J., Cullen, D., Haynatzki, G., Recker, R., Ahlf, R., Thompson, K. (2008). Calcium and vitamin D supplementation decreases incidence of stress fractures in female navy recruits. *Journal of Bone and Mineral Research, 23,* 741-749.

Lanyon, L. E., Rubin, C. T. (1984). Static vs dynamic loads as an influence on bone remodelling. *Journal of Biomechanics, 17,* 897-905.

Lee, W. T. K., Leung, S. S. F., Leung, D. M., Cheng, J. C. (1997). A follow-up study on the effects of calcium supplement withdrawal and puberty on bone acquisition of children. *American Journal of Clinical Nutrition, 64,* 71-77.

Linneman, C., Hessler, K., Nanney, S., Steger-May, K., Huynh, A., & Haire-Joshu, D. (2004). Parents are accurate reporters of their preschoolers' fruit and vegetable consumption under limited conditions. *Journal of Nutrition Education and Behavior, 36,* 305-308.

Liu, S., Li, J., Sheng, Z., Wu, X., Liao, E. (2010). Relationship between body composition and age, menopause and its effects on bone mineral density at segmental regions in Central Southern Chinese postmenopausal elderly women with and without osteoporosis. *Archives of Gerontology and Geriatrics, in press.*

Llyod, T., Andon, M. B., Rollings, N., Martel, J. K., Landis, J. R., Demars, L. M., Eggli, D . F., Kieselhorst, K., Kulin, H. E. (1993). Calcium supplementation and bone mineral density in adolescent girls. *Journal of the American Medical Assoication, 270,* 841-844.

Lochmuller, E. M., Lill, C. A., Kuhn, V., Schneider, E., Eckstein, F. (2002). Radius bone strength in bending, compression and falling and its correlation with clinical densitometry at multiple sites. *Journal of Bone and Mineral Research, 17,* 1629-1683.

Looker, A. C., Beck, T. J. (2002). Maternal history of osteoporosis is related to femur bone density and geometry in men and women. *Journal of Bone and Mineral Research, 17,* S200-S200.

Lorrain, J., Paiement, G., Chevrier, N., Lalumiere, G., Laflamme, G., Caron, P., Fillion, A. (2003). Population and demographics and socioeconomic impact of osteoporotic fractures in Canada. *Menopause: The Journal of The North American Menopause Society, 10,* 228-234.

Mafukidze, J. C. (2000). A comparison of bone mineral content between premenarcheal elite gymnasts and normally active girls. Unpublished masters thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Magaziner, J., Simonsick, E. M., Kashner, T. M., Hebel, J. R., Kenzora, J. E. (1990). Predictors of functional recovery one year following hospital discharge for hip fracture: a prospective study. *Journal of Gerontology, 45,* M101-M107.

McKay, H. A., MacLean, L., Petit, M., Mackelvie-O'Brien, K., Janssen P., Beck, T., Khan, K. M. (2005). "Bounce at the Bell": a novel program of short bouts of exercise improves proximal femur bone mass in early pubertal children. *British Journal of Sports Medicine, 39,* 521-526.

Malina, R. M. Physical growth and biological maturation of young athletes. (1994). *Exercise and Sport Science Review* 22: 389-434.

Malina, R. M. (1998). Growth and maturation of young athletes: Is training for sport a factor? In Chan & Mucheli, eds., Sports and Children. Hong Kong, Williams and Wilkins Asia-Pacific, 133-138.

Malina, R. M., Bouchard, C., bar-Or, O. (2004). *Growth, Maturation, and Physical Activity.* (2nd ed.). Windsor, Ont: Human Kinetics.

Mazess, R., Collick, B., Trempe, J., Barden, H., Hanson, J. (1989). Performance evaluation of a dual-energy x-ray bone densitometer. *Calcified Tissue International, 44,* 228-32.

Mazess, R. B., Barden, H. S., Bisek, J. P., Hanson, J. (1990). Dual-energy x-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. *American Journal of Clinical Nutrition, 51,* 1106-1112.

Mazess, R., Wahner, H. (1988). Nuclear medicine and densitometry. In L. Riggs & L. Melton (Eds.), *Osteoporosis: Etiology, Diagnosis, and Management.* pp.251-295. New York: Raven Press.

McClung, J. P., Karl, J. P. (2010). Vitamin D and stress fracture: the contribution of vitamin D receptor gene polymorphism. *Nutrition Reviews, 68,* 365-369.

Melton, E. L., Chrischilles E. A., Cooper, C., Lane, A. W., Riggs, B. L. (1992). How many women have osteoporosis? *Journal of Bone and Mineral Research, 7,* 1005-1010.

Miller, P. D., Bonncik, S., Rosen, C. (1995). Guidelines for the clinical utilization of bone mass measurement in the adult population. *Calcified Tissue International, 57,* 251-252.

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

Moayyeri, A., Besson, H. Luben, R. N., Wareham, N. J., Khaw, K. T. (2010). The association between physical activity in different domains of life and risk of osteoporotic fracture. *Bone, 47,* 693-700.

Molgaard, C., Larnkjaer, A., Cashman, K. D., Lamberg-Allardt, C., Jakobsen, J., Michaelsen, K. F. (2010). Does vitamin D supplementation of healthy Danish Caucasian girls affect bone turnover and bone mineralization? *Bone, 46,* 432-439.

Monotoye, H. J., Kemper, H. C. G., Saria, W. H. M., Washburn, R. A. (1996). Measuring physical activity and energy expenditure. Human Kinetics, Champagin IL.

Nguyen, T. V., Center, J. R., Eisman, J. A. (2000). Osteoporosis in elderly men and women: effects of dietary calcium, physical activity, and body mass index. *Journal of Bone and Mineral Research, 15,* 322-331.

Nickols-Richardson, S. M., Modelsky, C. M., O'Conner, P. J., Lewis, R. D. (2000). Premenarcheal gymnasts possess higher bone mineral density than controls. *Medicine and Science in Sport and Exercise, 32,* 63-69.

Nickols-Richardson, S. M., O'Conner, P. J., Shapses, S. A., Lewis, R. D. (1999). Longitudinal bone mineral density changes in female child artistic gymnasts. *Journal of Bone Mineral Research, 14,* 994-1002.

Nordin, B. E. C., Heany, R. P. (1990). Calcium supplementation of the diet: Justified by evidence. *The British Medical Journal,* 300, 1056-1060.

Ohlsson, C., Isgaard, J., Tornell, J., Nilsson, A., Isaksson, O., Lindahl, A. (1993). Endocrine regulation of longitudinal bone growth. *Acta Pediatrica, S391,* 119-125.

Parfitt, A. M. (1994). The two faces of growth: benefits and risks to bone integrity. *Osteoporosis International, 4,* 382-398.

Parfitt, A. M. (1996). *Skeletal heterogeneity and the purpose of bone remodeling.* In: Marcus, R., Feldman, D., Kelsey, J. (eds). Osteoporosis. San Diego, CA: Academic Press. pg 315-329.

Papadimitropoulos, E. A., Coyte, P., Josse, R., Greenwood, C. (1997). Current and projected rates of hip fracture in Canada. *The Journal of the Canadian Medical Association, 157,* 1357-1363.

Papaioannou, A., Kennedy, C. C., Ioannidis, G., et al., for the CaMos Study Group. (2008). The impact of incident fractures on health-related quality of life: 5 years of data from the Canadian Multicenter Osteoporosis Study. *Osteoporosis International, 20,* 703-714.

Petit, M. A., McKay, H. A., Mackelvie, K. J., Heinonen, A., Khan, K. M., Beck, T. J. (2002). A randomized school-based jumping intervention confers site and maturity-specific benefits on bone structural properties in girls: A hip structural analysis study. *Journal of Bone and Mineral Research, 17,* 363-372.

Plowman, S. A., Smith, D. L. (1997). *Exercise Physiology: For Health, Fitness and Performance* (1st ed.). Toronto, ON: Allyn & Bacon.

Pollock, N. K., Laing, E.M., Modlesky, C. M., O'Conner, P. J., Lewis, R. D. (2006). Former college artistic gymnasts maintain higher BMD: A nine-year follow-up. *Osteoporosis International, 17,* 1691-1697.

Prentice, A., Parson, T. J., Cole, T. J. (1994). Uncritical use of bone mineral density in absorptiometry may lead to size-related artifacts in the identification of bone mineral determinants. *American Journal of Clinical Nutrition, 60,* 837-842.

Proctor, K. L., Adams, W. C., Shaffrath, J.D., Van Loan, M. D. (2002). Upper-limb bone mineral density of female collegiate gymnasts versus controls. *Medicine and Science in Sport and Exercise, 34,* 1830-1835.

Reid, I. R. (2008). Relationships between fat and bone. *Osteoporosis International, 19,* 595-606.

Rencken, M. L., Murano, R., Drinkwater, B. L., Chesnut, C. H., III. (1991). In vitro comparability of dual energy X-ray absorptiometry (DEXA) bone densitometers. *Calcified Tissue International, 48,* 245-248.

Rennie, L., Court-Brown, C. M., Mok. J. Y. Q., Beattie, T. F. (2007). The epidemiology of fractures in children. *Injury: International Journal of the Care of the Injured, 38,* 913-922.

Ribot, C., Tremollieres, F., Pouilles, J. M., Bonneu, M., Germain, F., Louvet, J. P. (1987). Obesity and postmenopausal bone loss: the influence of obesity on vertebral density and bone turnover in postmenopausal women. *Bone, 8,* 327-331.

Riggs, B. L. (2000). The mechanisms of estrogen regulation and bone resorption. *Journal of Clinical Investigation, 106,* 1203-1204.

Riggs, B. L., Melton, L. J., (1995). The worldwide problem of osteoporosis: Insights afforded by epidemiology. *Bone, 17,* 505S-511S.

Riggs, B. L., Khosla, S., Melton, L. J., III (2002). Sex steroids and the construction and conservation of the adult skeleton. *Endocrinology Reviews, 23,* 279-302.

Rizer, M. K. (2006). Osteoporosis. *Primary Care: Clinics in Office Practice, 33,* 943-951.

Robinson, T. L., Snow-Harter, C., Taaffee, D. R., Gillis, D., Shaw, J., Marcus, R. (1995). Gymnasts exhibit higher bone mass than runners despite similar prevalence of amenorrhea and oligmenorrhea. *Journal of Bone and Mineral Research, 10,* 26-35.

Robling, A. G., Castillo, A. B., Turner, C. H. (2006). Biomechanical and molecular regulation of bone remodeling. *Annual Review of Biomedical Engineering, 8,* 455-498.

Rosen, C. J., Klibanski, A. (2009). Bone, fat and body composition: evolving concepts in the pathogenesis of osteoporosis. *The American Journal of Medicine, 122,* 409-414.

Rosenthal, D. I., Mayo-Smith, W., Hayes, C. W., Khurana, J. A., Biller, B. M., Neer, R. M. Klibanski, A. (1989). Age and bone mass in premenopausal women. *Journals of Bone and Mineral Research, 4,* 533-538.

Sacco, M., Ward, W. E. (2010). Revisiting estrogen: efficacy and safety for postmenopausal bone health. *Journal of Osteoporosis, in press.*

Saito, T., Nakamura, K., Okuda, Y, Nashimoto, M., Yamamoto, M. (2009). Weight gain in childhood and bone mass in female college students. *Journal of Bone and Mineral Metabolism, 23,* 69-75.

Salkeld, G., Cameron, I. D., Cumming, R. G., Easter, S., Seymour, G., Kurrle, S., Quinn, S. (2000). Quality of life related to fear of falling and hip fracture in older women: A time trade-off study. *British Medical Journal, 320,* 241-246.

Saris, W. H. M., Binkhorst, R. A. (1977). The use of pedometry and actometer in studying daily physical activity in man. Part 2: Validity measuring the daily physical activity. *European Journal of Applied Physiology, 37,* 229-235.

Saris, W. H. M., Binkhorst, R. A., Cramwinckle, A. B., van Waesberghe, F., Vander Veen-Hezenmans, A. M. (1980). The relationship between working performance, daily activity, fatness, blood lipids, and nutrition in school children. In K. Berg & B. O. Eriksson (eds), Children and Exercise 9 (pp. 166-173). Baltimore: University Park Press.

Scerpella, T. A., Davenport, M., Morganti, C. M., Kannaley, J. A., Jonhson, L. M. (2003). Does related association of impact activity and bone mineral density in pre-pubertal girls. *Calcified Tissue International, 72,* 24-31.

Scerpella, T. A., Dowthwaite, J. N., Rosenbaum, P. F. (2010). Sustained skeletal benefit from childhood mechanical loading. *Osteoporosis International, in press.*

Schoenau, E., Neu, C. M., Rauch, F., Manz, F. (2001). The development of bone strength at the proximal radius during childhood and adolescence. *Journal Clinical Endocrinology and Metabolism, 86:* 614-618.

Slemenda, C. W., Miller, J. Z., Hui, S. L., Reister, T. K., Johnson, C. C. Jr. (1991). Role of physical activity in the development of skeletal mass in children. *Journal of Bone and Mineral Research, 6,* 1227-1233.

Slemenda, C. W., Reister T. K., Miller, J. Z., Christian, J C., Johnson, C. C. Jr. (1994). Influences on skeletal mineralization in children and adolescents: Evidence for varying effects of sexual maturation and physical activity. *Journal of Pediatrics, 125,* 201-207.

Specker, B., Binkley, T. (2003). Randomized trail of physical activity and calcium supplementation on bone mineral content in 3- to 5-year-old children. *Journal of Bone and Mineral Research, 18,* 885-892.

Szulc, P., Delmas, P. (2007). Bone loss in elderly men: increased edosteal bone loss and stable periosteal position. The prospective MINOS study. *Osteoporosis International, 18,* 45-503.

Taaffe, D., Snow-Harter, C., Connolly, D., Robinson, T., Brown, M., Marcus, R. (1995). Differential effects of swimming versus weight-bearing activity on bone mineral status of eumenorrheic athletes. *Journal of Bone and Mineral Research, 10,* 586-593.

Taaffe, D., Robinson, T., Snow, C., Marcus, R. (1997). High-impact exercise promotes bone gain in well-trained athletes. *Journal of Bone and Mineral Research, 12,* 255-260.

Taes, Y. E., Lapauw, B., Vanbillemont, G., Bogaert, V., De Bacquer, D., Zmierczak, H., Goemaere, S., Kaufman, J. M. (2009). Fat mass is negatively associated with cortical bone size in young healthy male subjects. *Journal of Clinical Endocrinology and Metabolism, 94,* 2325-2331.

Tanner, J. M. (1978). *Foetus into Man* (1st ed.). London, U.K.: Open Books Publishing Ldt.

The Consensus of Development Conference: Diagnosis, Profilaxus, and Treatment of Osteoporosis. (1993). *American Journal of Medicine, 94,* 646-650.

The ESHRE Capri Working Group: Bone fractures after menopause. (2010). *Human Reproduction Update,* 1-13.

Theintz, G. E., H. Howald, U. Allemann, P. C. Sizonenko. (1989). Growth and pubertal development of young female gymnasts and swimmers: a correlation with parental data. *International Journal of Sports Medicine, 10*, 87-91.

Theintz, G. E., H. Howald, U. Weiss, P. C. Sizonenko. (1993).Evidence for a reduction of potential in adolescent female gymnasts. *Journal of Pediatrics 122*, 306-313.

Tranquill, A. L., Lucino, E., Garzetti, G. G., Romanini, C. (1994). Calcium, phosphorous, and magnesium intake correlated with bone mineral content in postmenopausal women. *Gynecological Endocrinology, 8*, 55-58.

Tremollieres, F. A., Pouilles, J. M., Robot, C. (1993). Vertebral postmenopausal bone loss is reduced in overweight women: a longitudinal study in 155 early postmenopausal women. *Journal of Clinical Endocrinology and Metabolism, 77*, 683-686.

US Department of Health and Human Services: Bone Health and Osteoporosis. (2004). A report of the surgeon general. Rockville, US Department of Health and Human Sevices, Office of the Surgeon General.

Uzunca, K., Birtane, M., Durmus-Altun, G., Ustun, F. (2005). High bone mineral density in loaded skeletal regions of former professional football (soccer) players: What is the effect of time after active career? *British Journal of Sports Medicine, 39*, 154-15.

Viljakainen, H. T., Natri, A. M., Karkkainen, M., Huttunen, M. H., Palssa, A., Jakobsen, J., Cashman, K. D., Molgaard, C., Lamberg-Allardt, C. (2006). A positive does-response effect of vitamin D supplementation on site-specific bone mineral augmentation in adolescent girls: A double-blinded randomized placebo-controlled 1-year intervention. *Journal of Bone and Mineral Research, 21*, 836-844.

Vincent, W. J. (EdD). (2005). *Statistics in Kinesiology.* Human Kinetics: Brigham Young University.

Ward, K. A., Das, G., Roberts, S. A., Berry, L. J., Adams, J. E., Rawer, R., Mughal, M. Z. (2010). A randomized, controlled trial of vitamin D supplementation upon musculoskeletal health in postmenarcheal females. *Journal of Clinical Endocrinology and Metabolism, 95*, 4643-4651.

Ward, K. A., Roberts, S. A., Adams, J. E., Mughal, M. Z. (2005). Bone geometry and density in the skeleton of pre-pubertal gymnasts and school children. *Bone, 36*, 1012-1018.

Warner, J., Cowan, F., Dunstan, F., Evans, W., Webb, D., & Gregory, J. (1998). Measured and predicted bone mineral content in health boys and girls aged 6-18 year: Adjusted for body size and puberty. *Acta Paediatrica, 87*, 244-249.

Weimann, E. (2002). Gender-related differences in elite gymnasts: The female athlete triad. *Journal of Applied Physiology, 92,* 2146-2152.

Weimann, E., W. F. Blum, C. Witzel, S. Schwidergall, and H. J. Bohles. (1999). Hypoleptinemia in female and male elite gymnasts. *European Journal of Clinical Investigation,* 29, 853-860.

Whiting, S. J., Shrestha, R. K. (1993). Dietary assessment of elementary school-aged children and adolescents. *Journal of Canadian Dietetic Association, 54,* 193-196.

Wiktorowicz, M. E., Goeree, R., Papaioannou, A., Adachi, J. D., Papadimitropoulos, E. (2001). Economic implications of hip fractures: Health service use, institutional care and cost in Canada. *Osteoporosis International, 12,* 271-278.

World Health Organization: Assessment of fracture risk and its application to screening for post-menopausal osteoporosis. (1994). Report of a WHO study group. WHO Tech Rep Ser 843. Geneva, World Heath Organization.

World Health Organization: Prevention and management of osteoporosis. (2003). Report of a WHO scientific group. WHO Technical Report Series 921. Geneva, World Health Organization.

XCT 2000 Manual. (2007). Stratec Medizintechnik GmbH, Pforzhemin, Germany.

Zanker, C. L., Gannon, L., Cooke, C. B., Gee, K. L., Oldroyd, B., Truscott, J. (2003). Differences in bone density, body composition, physical activity and diet between child gymnasts and untrained children 7-8 years of age. *Journal of Bone and Mineral Research, 18,* 1043-1050.

Zanker, C. L., Osborne, C., Cooke, C. B., Oldroyd, B., Truscott, J. G. (2004). Bone density, body composition and menstrual history of sedentary female former gymnasts, aged 20-32 years. *Osteoporosis International, 15,* 145-154.

Zemel, B., Bass, S., Binkley, T., Ducher, G., Macdonald, H., McKay, H., Moyer-Mileur, L., Shepherd, J., Specker, B., Ward, K., Hans, D. (2008). Peripheral quantitative computed tomography in children and adolescents: the 2007 ISCD official positions. *Journal of Clinical Densitometry: Assessment of Skeletal Health, 11,* 59-74.

APPENDIX A: Ethics for Study One

University of Saskatchewan
Biomedical Research Ethics Board (Bio-REB)   12-Jul-2006

Certificate of Approval

PRINCIPAL INVESTIGATOR	DEPARTMENT	Bio #
Adam Baxter-Jones	Kinesiology	06-111

INSTITUTION (S) WHERE RESEARCH WILL BE CARRIED OUT

College of Kinesiology
105 Gymnasium Place
Saskatoon SK S7N 5C2

STUDENT RESEARCHER(S)
Marta Erlandson
SPONSORING AGENCIES
UNIVERSITY OF SASKATCHEWAN

TITLE:
The Effects of Structured Early Childhood Physical Activity of Childhood Body Composition

ORIGINAL APPROVAL DATE	CURRENT EXPIRY DATE	APPROVAL OF
12-Jul-2006	01-Jul-2007	Revised Researcher's Summary Form
		Appendix A -- Revised Research Participant Information and Consent Form
		Appendix B -- Recruitment Advertisement/Poster
		Appendix C -- Food Frequency Questionnaire
		Appendix D -- Parent Survey, Parts I and II

CERTIFICATION

The University of Saskatchewan Biomedical Research Ethics Board has reviewed the above-named research project at a full-board meeting (any research classified as minimal risk is reviewed through the expedited review process). The proposal was found to be acceptable on ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research project, and for ensuring that the authorized research is carried out according to governing law. This Approval is valid for the above time period provided there is no change in experimental protocol or in the consent process.

ONGOING REVIEW REQUIREMENTS/REB ATTESTATION

In order to receive annual renewal, a status report must be submitted to the Chair for Committee consideration within one month of the current expiry date each year the study remains open, and upon study completion. Please refer to the following website for further instructions: http://www.usask.ca/research/ethics.shtml. In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. This approval and the views of this REB have been documented in writing.

APPROVED.

Michel Desautels, Ph.D./Chair
University of Saskatchewan
Biomedical Research Ethics Board

APPENDIX B: The Netherlands Physical Activity Questionnaire

Instructions: Please circle the number that **best describes your child during the past six months**. For example, if in the past six months, your child preferred to play alone as often as he/she preferred to play with other children, circle the number three for the first question. On the other hand, if he or she almost always preferred playing with other children, rather than alone, circle the number five.

		Almost Always ↙		About Equal ↓		Almost Always ↘	
1.	Prefers to play alone	1	2	3	4	5	Prefers to play with other children
2.	Prefers vigorous games (e.g., tag, kickball)	1	2	3	4	5	Prefers quiet games (e.g., board games)
3.	Dislikes playing sports (e.g., soccer, basketball)	1	2	3	4	5	Likes playing sports
4.	Is more introverted (e.g., quiet, reserved)	1	2	3	4	5	Is more extroverted (e.g., outgoing)
5.	Likes to read	1	2	3	4	5	Dislikes to read
6.	Likes to play outside	1	2	3	4	5	Likes to play inside (home/school)
7.	Less physically active compared to other children of same age	1	2	3	4	5	More physically active compared to other children of same age

Instructions: Please answer the following questions as they relate to your child's **usual daily routine during the past six months**. Estimate the time to the nearest 1/4 hour (15 minutes) per day.

8. On average, how many hours per day does your child spend watching any type of television including video movies?

_____hours per day

9. On average, how may hours per day does your child spend playing video games (such as Nintendo®) and/or computer games?

_____hours per day

10. On average, how many hours per night does your child spend sleeping? (Do not include naps.)

_____ hours per night

11. On average, how many hours per day does your child sleep during naps?

_____ hours per day

Please list the two play- or sport-related physical activities which your child did most often during the past six months (e.g., kickball, board games, biking, soccer, puzzles, playing on playground equipment, roller blading, swimming, rope jumping):

12. _____   13. _____

14. During the past six months, did your child participate in or take lessons in any of the following organized sports? (Check all that apply.)

_____ Swim lessons/swim club   _____ Youth soccer

_____ Basketball league/camp   _____ T-ball/baseball/softball

_____ Gymnastics/tumbling   _____ Dance/ballet/jazz/aerobic

_____ Hockey/ice/roller/indoor   _____ Tennis/racquetball

_____ Track & field/running   _____ Football league/camp

_____ Horseback riding   _____ Volleyball league/camp

_____ None

Others (Please list.)   _____ .

15. When in school, how often does your child participate in physical education (PE)?

____daily   ____2-4 times/week   ____once/week   ____does not participate   ____don't know

16. What arm does your child prefer to throw with?

____right   ____left   ____no preference   ____don't know

17. What leg does your child prefer to kick with?

____right   ____left   ____no preference   ____don't know

Thank you for taking the time to complete this physical activity questionnaire.

APPENDIX C: 24 Hour Dietary Recall

UNIVERSITY OF SASKATCHEWAN
24-HOUR RECALL

Please list every food and drink your child had yesterday

Name:_____   Age:_____   Date: _____

Time	Food Item	Type & Preparation	Amount	Brand Name or Where Bough
Morning				
Mid-morning				
Noon Meal				
Midday				
Evening Meal				
Before Bed				
Example	Cereal	Corn Flakes	1 cup	Kellogs
	Milk	1%	½ cup	Dairy Land

Was this intake usual? Please circle one: Yes   No (if no please explain:_____)

APPENDIX D: Ethics for Study Two

UNIVERSITY OF SASKATCHEWAN

Biomedical Research Ethics Board (Bio-REB)

Certificate of Re-Approval

PRINCIPAL INVESTIGATOR	DEPARTMENT	Bio #
Adam Baxter-Jones	Kinesiology	88-102

INSTITUTION (S) WHERE RESEARCH WILL BE CARRIED OUT

College of Kinesiology
87 Campus Drive
Saskatoon SK S7N 5B2

SPONSORING AGENCIES
CANADIAN INSTITUTES OF HEALTH RESEARCH (CIHR)

TITLE:
Protocol NHRDP #6608-126-OS:: Relationship of Growth and Lifestyle to Peak Bone Mass
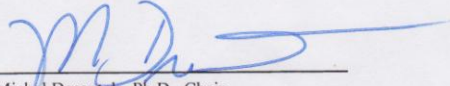
RE-APPROVED ON	EXPIRY DATE
21-Oct-2009	20-Oct-2010

Full Board Meeting ☐
Delegated Review ☑

CERTIFICATION
The study is acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This re-approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face meeting. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://www.usask.ca/research/ethics_review/.

REB ATTESTATION
In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. This re-approval and the views of this REB have been documented in writing.

Michel Desautels, Ph.D., Chair
University of Saskatchewan
Biomedical Research Ethics Board

Please send all correspondence to:

Ethics Office
University of Saskatchewan
Room 302 Kirk Hall, 117 Science Place
Saskatoon, SK S7N 5C8
Phone: (306) 966-2975 Fax: (306) 966-2069

Physical Activity Questionnaire (Elementary School)

Name:_____   Age:_____

Sex: M_____   F_____   Grade:_____

We are trying to find out about your level of physical activity from *the last 7 days* (in the last week). This includes sports or dance that make you sweat or make your legs feel tired, or games that make you breathe hard, like tag, skipping, running, climbing, and others.
Remember:
1. There are no right and wrong answers — this is not a test.
2. Please answer all the questions as honestly and accurately as you can — this is very important.

---

1. Physical activity in your spare time: Have you done any of the following activities in the past 7 days (last week)? If yes, how many times? (Mark only one circle per row.)

	No	1-2	3-4	5-6	7 times or more
Skipping	○	○	○	○	○
Rowing/canoeing	○	○	○	○	○
In-line skating	○	○	○	○	○
Tag ○	○	○	○	○	
Walking for exercise	○	○	○	○	○
Bicycling	○	○	○	○	○
Jogging or running	○	○	○	○	○
Aerobics	○	○	○	○	○
Swimming	○	○	○	○	○
Baseball, softball	○	○	○	○	○
Dance ○	○	○	○	○	
Football	○	○	○	○	○
Badminton	○	○	○	○	○
Skateboarding	○	○	○	○	○
Soccer	○	○	○	○	○
Street hockey	○	○	○	○	○
Volleyball	○	○	○	○	○
Floor hockey	○	○	○	○	○
Basketball	○	○	○	○	○
Ice skating	○	○	○	○	○
Cross-country skiing	○	○	○	○	○
Ice hockey/ringette	○	○	○	○	○
Other:					
_____....	○	○	○	○	○
_____....	○	○	○	○	○

2. In the last 7 days, during your physical education (PE) classes, how often were you very active (playing hard, running, jumping, throwing)? (Check one only.)

I don't do PE ....………○
Hardly ever .... ○
Sometimes .... ○
Quite often .... ○
Always .... ○

3. In the last 7 days, what did you do most of the time *at recess*? (Check one only.)

Sat down (talking, reading, doing schoolwork)… ○
Stood around or walked around .... ○
Ran or played a little bit .... ○
Ran around and played quite a bit .... ○
Ran and played hard most of the time .... ○

4. In the last 7 days, what did you normally do *at lunch* (besides eating lunch)? (Check one only.)

Sat down (talking, reading, doing schoolwork).… ○
Stood around or walked around .... ○
Ran or played a little bit .... ○
Ran around and played quite a bit .... ○
Ran and played hard most of the time .... ○

5. In the last 7 days, on how many days *right after school*, did you do sports, dance, or play games in which you were very active? (Check one only.)

None ....……○
1 time last week .... ○
2 or 3 times last week .... ○
4 times last week .... ○
5 times last week .... ○

6. In the last 7 days, on how many *evenings* did you do sports, dance, or play games in which you were very active? (Check one only.)

None .... ○
1 time last week .... ○
2 or 3 times last week .... ○
4 or 5 last week .... ○
6 or 7 times last week .... ○

7. *On the last weekend*, how many times did you do sports, dance, or play games in which you were very active? (Check one only.)

None .... ○
1 time .... ○
2 — 3 times .... ○
4 — 5 times .... ○
6 or more times .... ○

8. Which *one* of the following describes you best for the last 7 days? Read *all five* statements before deciding on the *one* answer that describes you.

A. All or most of my free time was spent doing things that involve little physical effort .... ○

B. I sometimes (1 — 2 times last week) did physical things in my free time (e.g. played sports, went running, swimming, bike riding, did aerobics) .... ○

C. I often (3 — 4 times last week) did physical things in my free time .... ○

D. I quite often (5 — 6 times last week) did physical things in my free time ○

E. I very often (7 or more times last week) did physical things in my free time ○

9. Mark how often you did physical activity (like playing sports, games, doing dance, or any other physical activity) for each day last week.

	None	Little bit	Medium	Often	Very often
Monday	○	○	○	○	○
Tuesday	○	○	○	○	○
Wednesday	○	○	○	○	○
Thursday	○	○	○	○	○
Friday	○	○	○	○	○
Saturday	○	○	○	○	○
Sunday	○	○	○	○	○

10. Were you sick last week, or did anything prevent you from doing your normal physical activities? (Check one.)

Yes ....………….. ○
No .... ○

If Yes, what prevented you? _____

Bone Mineral Accrual Study
Physical Activity Questionnaire (Adults)

We are trying to find out about your level of physical activity from *the last 7 days* (in the last week). This includes activities that make you sweat, make your legs feel tired, or make you breathe hard, such as team sports, running, strenuous occupational activities, and others.

Remember:
There are no right and wrong answers — this is not a test.
Please answer all the questions as honestly and accurately as you can — this is very important.

Physical activity in your spare time: Have you done any of the following activities in the past 7 days (last week)? If yes, how many times? (Mark only one circle per row.)

	No	1-2	3-4	5-6	7 times or more
Rock climbing	○	○	○	○	○
Rowing/canoeing	○	○	○	○	○
Tennis/squash	○	○	○	○	○
Stair climber (or other similar equipment)	○	○	○	○	○
Walking for exercise	○	○	○	○	○
Heavy yard work	○	○	○	○	○
Jogging or running	○	○	○	○	○
Bicycling	○	○	○	○	○
Aerobics (or other exercise class)	○	○	○	○	○
Swimming	○	○	○	○	○
Baseball, softball	○	○	○	○	○
Dance	○	○	○	○	○
Football	○	○	○	○	○
Badminton	○	○	○	○	○
Soccer	○	○	○	○	○
Street/floor hockey	○	○	○	○	○
Volleyball	○	○	○	○	○
Basketball	○	○	○	○	○
Skating (in-line/ice)	○	○	○	○	○
Cross-country skiing	○	○	○	○	○
Ice hockey/ringette	○	○	○	○	○
Martial arts	○	○	○	○	○
Weight training	○	○	○	○	○
Other:					
_____	○	○	○	○	○
_____	○	○	○	○	○

179

In the last 7 days, *during the morning*, how often were you very active (for example: playing sports, exercise classes, strenuous occupational activity)? (Check one only.)

None .....……………………………………...…… ❍
1 time last week .... ❍
2 or 3 times last week .... ❍
4 or 5 times last week.. ❍
6 or 7 times last week .... ❍

In the last 7 days, *after lunch and before supper*, how often were you very active (for example: playing sports, exercise classes, strenuous occupational activity)? (Check one only.)

None ....……. ❍
1 time last week .... ❍
2 or 3 times last week .... ❍
4 or 5 times last week.. ❍
6 or 7 times last week.. ❍

4. In the last 7 days, *during the evening*, how often were you very active (for example: playing   sports, exercise classes, strenuous occupational activity)? (Check one only.)

None .... ❍
1 time last week .... ❍
2 or 3 times last week .... ❍
4 or 5 last week .... ❍
6 or 7 times last week .... ❍

5. On the last weekend, how often were you very active (for example: playing sports, exercise   classes, strenuous occupational activity)? (Check one only.)
None ....…… ❍
1 time .... ❍
2 — 3 times .... ❍
4 — 5 times .... ❍
6 or more times .... ❍

180

6. Which *one* of the following describes you best for the **last 7 days**? Read *all five* statements before deciding on the *one* answer that describes you.

    F. All or most of my free time was spent doing things that involve little physical effort .... ○

    G. I sometimes (1 — 2 times last week) did physical things in my free time (e.g. played sports, went running, swimming, bike riding, did aerobics) ...... ○

    H. I often (3 — 4 times last week) did physical things in my free time .... ○

    I. I quite often (5 — 6 times last week) did physical things in my free time ○

    J. I very often (7 or more times last week) did physical things in my free time ○

7. Mark how often you did physical activity (for example: playing sports, exercise classes, strenuous occupational activity).

	None	Little bit	Medium	Often	Very often
Monday	○	○	○	○	○
Tuesday	○	○	○	○	○
Wednesday	○	○	○	○	○
Thursday	○	○	○	○	○
Friday	○	○	○	○	○
Saturday	○	○	○	○	○
Sunday	○	○	○	○	○

8. Were you sick last week, or did anything prevent you from doing your normal physical activities? (Check one.)

    Yes ....……………   ○
    No .... ○

    If Yes, what prevented you? _____

Bone Mineral Accrual Study
Females Only Questionnaire

1. How old were you when you started to have menstrual cycles?_____ years old

   Did it occur in:
   ❑ Spring
   ❑ Summer
   ❑ Fall
   ❑ Winter

2. Are you currently using oral contraceptives?
   ❑ No
   ❑ Yes

   If yes, for how long have you used them? _____ Years   _____ Months

   What is the brand name of the oral contraceptives that you use? _____

   If no, have you used them in the past?

   ❑ No
   ❑ Yes

   If yes, for how long had you used them? _____ Years   _____ Months

   What brand name of oral contraceptives did you use? _____

3. How many periods do you have in a year?
   ❑ Over 13 periods
   ❑ 9 to 13 periods
   ❑ 3 to 8 periods
   ❑ less than 3 periods

4. Have you had a period in the past three months?
   ❑ No
   ❑ Yes

5. What is the date of the first day of your last period? _____

6. Have you ever had an absence or loss of periods (pregnancy and lactation not included)?
   - ❑ No
   - ❑ Yes

   If yes, at what age(s) did you miss a period(s)?
   _____ years old
   _____ years old

   For how long did your periods stop?
   _____mos.   _____ yrs
   _____mos.   _____ yrs

Legally, you cannot be scanned if you are pregnant.

7. Are you pregnant?
   - ❑ No
   - ❑ Yes
   - ❑ I don't know

8. How many children have you given birth to? _____ If none, go to next page

   List their birthdates:

   Child 1: _____   Did you breastfeed?   ❑ No   ❑ Yes
                                     If yes, how many months? _____

   Child 2: _____   Did you breastfeed?   ❑ No   ❑ Yes
                                     If yes, how many months? _____

   Child 3: _____   Did you breastfeed?   ❑ No   ❑ Yes
                                     If yes, how many months? _____

   Child 4: _____   Did you breastfeed?   ❑ No   ❑ Yes
                                     If yes, how many months? _____

183

APPENDIX H: Retired Gymnast Questionnaire

Current Sport Involvement

1. Are you still involved in gymnastics?   Yes / No

   If no go to question 5

2. At what level?
   - International
   - National
   - Provincial
   - Recreational
   - Other (please specify) _____

3. Do you still actively train for gymnastics?   Yes / No

   If no go to question 5

4. How many hours per week do you train? _____

5. Have you retired from gymnastics?   Yes / No

6. How would you describe your involvement now?
   - No Involvement
   - Recreational involvement
   - Training at same level, stopped competition
   - Competing only
   - Reduced training time
   - Other (please specify) _____

7. Can you remember exactly when you retired from gymnastics?
   _____/_____/_____

8. What was your main reason for retiring?
   - School/ university / work
   - Lack of interest
   - Disappointing results
   - Injury
   - Pressure of sport
   - Social life

- Illness
- Problems with coach
- Parental pressure
- Funding / Financial restraints
- Start a family
- Other (please specify) _____

9. Have you been involved in any other competitive sports since finishing gymnastics?   Yes / No

If so what activities / how many hours per week / how many years

_____
_____
_____
_____
_____
_____
_____
_____
_____

10. Compared to others your same age would you describe yourself as more active , average or less active than your peers
    a. During Childhood (6-12) _____
    b. During Adolescence (12-18)_____
    c. Young Adulthood (18+)_____