UPPER BODY BONE STRENGTH AND MUSCLE FUNCTION IN NON-ELITE ARTISTIC GYMNASTS

Submitted by

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STATEMENT OF SOURCES

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ABSTRACT

Introduction: Musculoskeletal development in the upper limbs of non-elite female gymnasts during pre and early pubescent growth is under researched. Most studies have focussed on elite rather than non-elite gymnasts, via dual-energy X-ray absorptiometry (DXA). The purpose of this thesis was to longitudinally characterise the effects of non-elite female artistic gymnastics participation on upper limb musculoskeletal parameters using peripheral Quantitative Computed Tomography (pQCT), DXA and muscle function assessments.

Three major studies were designed. Study one compared the upper limb of two groups of gymnasts (high-training gymnasts (HGYM), participating in 6-16 hr/wk, low-training gymnasts (LGYM), participating in 1-5 hr/wk) and an age matched control group (NONGYM) for differences in bone mass, size and strength. Difference in upper limb muscle size, structure and function were also compared. Study two pooled both HGYM and LGYM to compare traditional pQCT skeletal parameters at the radius (4% and 66% sites) with NONGYM. To advance the understanding of site and bone specificity in young gymnastics, similar measures were also undertaken at the ulna. Study three combined variables in studies one and two in a longitudinal (6-month) comparison of the upper limb musculoskeletal changes in two groups of gymnasts (HGYM, LGYM) and a NONGYM group. Benefits beyond growth associated with gymnastics participation during pre- and early pubertal years were examined.

Methods: Ninety-one girls (age 6 to 12 years, Tanner stage 1 to 3) participated in the study. Total body DXA scans assessed body composition (lean mass and fat mass) as well as the skeletal parameters of total body and arms, bone mineral content (BMC) and bone mineral density (BMD). Peripheral QCT was used to assess BMC, total and trabecular density (ToD, TrD), bone strength (BSI, SSI), total and cortical area (ToA, CoA) of the non-dominant radius and ulna at the 4% and 66% sites. Muscle cross sectional area (MCSA) was also obtained from pQCT. Muscle function was assessed with generic tests for strength, explosive power and endurance.

Results: At baseline, results from weight adjusted ANCOVA showed HGYM had greater radial bone strength than NONGYM as well as greater arm lean mass, BMC and muscle function (+5 to +103%, $p<0.05$). LGYM displayed greater arm lean mass, BMC (DXA), explosive power and endurance than NONGYM (+4% to +46%, $p<0.05$). Differences in bone strength between LGYM and NONGYM did not reach significance. HGYM showed larger skeletal differences with NONGYM than LGYM, yet differences between the two groups of gymnasts were not significant. At the 4% forearm, the gymnastics-induced skeletal benefits were greater at the radius than ulna (Z-scores for BMC, TrD and BSI +0.40 to +0.61 SD, $p<0.05$ vs. +0.15 to +0.48 SD, NS). At the 66% forearm, skeletal benefits were greater at the ulna than the radius (Z-scores for BMC, ToA, CoA, SSI +0.59 to +0.82 SD, $p<0.01$ vs. +0.35 (ToA) and +0.43 SD (SSI), $p<0.01$).

Longitudinal results showed both groups of gymnasts had increased ToD at the 4% radius as well as bone mass, area and strength at the 66% forearm compared with NONGYM (LGYM +6 to +18%, HGYM +6 to +25%, $p<0.05$). HGYM had increased BMC and BSI (4% radius) as well as CoA and ToD (66% ulna) and MCSA compared with LGYM (+7 to +28%, $p<0.05$). HGYM had the greatest skeletal gains over the six month period at the 4% radius. Despite NONGYM showing the greatest improvement in most muscle function tests after the six months, gymnasts' muscle function remained superior.

Conclusion: At baseline, non-elite gymnastics participation was associated with musculoskeletal benefits in upper limb bone geometry, strength and muscle function. However, differences between the two gymnastics groups did not emerge. Positive skeletal associations for gymnasts compared with NONGYM were greater when the radius and ulna were combined. Following six months of growth and non-elite gymnastics participation HGYM showed greatest increases at the 4% radius. While differences between LGYM and NONGYM emerged, HGYM clearly had the greatest skeletal benefits, irrespective of bone and site. Unlike baseline results, pQCT differences in upper limb skeletal parameters between HGYM and LGYM, and LGYM and NONGYM were apparent following longitudinal analysis. Gymnasts, independent of training hours, consistently displayed superior muscle function although, with growth, non-gymnasts' muscle function improved. Musculoskeletal benefits beyond growth exist following non-elite gymnastics participation during early puberty.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Sports participation may positively influence children's growth and development. Regular physical activity is an important health maintenance strategy for children with potential links to weight management, skeletal and cardiovascular parameters, and mental health benefits (Ganley & Sherman, 2000). However, the literature reports conflicting views on the overall health and wellbeing of young children participating in gymnastics. Concerns for young gymnasts focus around growth and maturation, pressure, injury and inadequate nutrition (Caine, Bass, & Daly, 2003; Caine & Nassar, 2005; Weimann, Witzel, Schwidergall, & Bohles, 2000). Conversely, gymnastics participation resulting in musculoskeletal health benefits are frequently reported (Vicente-Rodriguez et al., 2007). These musculoskeletal benefits can be maintained into retirement (Eser, Hill, Ducher, & Bass, 2009) and may possibly decrease fracture risk later in life. Potential benefits and detriments associated with gymnastics participation may be dose-responsive (Scerpella, Davenport, Morganti, Kanaley, & Johnson, 2003) but the evidence base is under-researched.

Several studies suggest intensive training in artistic gymnastics has detrimental effects on an individual's growth and development (Caine et al., 2003; Daly, Caine, Bass, Pieter, & Broekhoff, 2005; Theintz, Howald, Weiss, & Sizonenko, 1993). In particular, concerns focus on delayed growth and maturation, "catch-up" growth and the possibly of reduction in final adult stature. Often, young elite gymnasts are also under enormous pressure from coaches, parents and themselves. Gymnasts continually worry and fear being viewed as incompetent, unable to perform skills, body size and shape changes and injury (Martin, Polster, Jackson, Greenleaf, & Jones, 2008). In addition, the high aesthetic nature of the sport is associated with young gymnasts consuming less energy than is required to meet their energy expenditure (Nova, Montero, López-Varela, & Marcos, 2001). Furthermore, gymnastics participation involving intensive training is associated with serious consequences such as overuse, stress fracture and growth plate injuries (Caine & Nassar, 2005; DiFiori, Puffer, Aish, & Dorey, 2002). This negativity surrounding gymnastics participation focuses on elite participation in the sport rather than non-elite or recreational involvement. Proportionally, there are many more non-elite level gymnasts participating in the sport, yet the literature does not reflect this.

On a more positive note, participation in artistic gymnastics is associated with musculoskeletal health benefits. Specifically, gymnastics participation has been linked with greater bone density and muscle strength (Scerpella et al., 2003; Vicente-Rodriguez et al., 2007). The majority of sports and physical activities load the lower body. However, artistic gymnastics is a unique sport as it bilaterally loads the upper body. Therefore, the benefits are generally greater in the upper than lower body (Ward, Roberts, Adams, & Mughal, 2005).

Furthermore, most studies investigating skeletal benefits associated with gymnastics participation have used dual-energy X-ray absorptiometry (DXA). However, concerns with reporting DXA-derived bone mineral density (BMD) in paediatric populations are well recognised (Prentice, Parsons, & Cole, 1994). More recently, both DXA and peripheral quantitative computed tomography (pQCT) have been used to assess skeletal health in gymnasts (Erlandson, Kontulainen, & Baxter-Jones, 2011; Ward, et al., 2005).

Investigations into the muscle-bone relationship have increased. Muscle cross sectional area (MCSA) derived from pQCT and lean mass derived from DXA are often used as surrogate measures of muscle force. However, few studies assess actual measures of muscle function in combination with bone in describing musculoskeletal parameters

(Gero, Cole, Kanaley, van der Meulen, & Scerpella, 2005; Scerpella, et al., 2003). Gymnastics is a sport that requires great strength and a high power to weight ratio as well as exposing limbs to high ground reaction forces. Detailed assessment of muscle function in combination with skeletal changes may add insight to the vital components driving skeletal adaptations, muscle or impact forces.

Peripheral QCT also allows individual bones to be analysed. To date, one study has compared the radius and ulna in retired gymnasts, finding site and bone specific adaptations (Ducher, Hill, Angeli, Bass, & Eser, 2009). Interestingly, skeletal adaptations may be under reported if only the radius is included in analyses.

Gymnastics based literature tends to be cross-sectional with few longitudinal study designs. Of the longitudinal literature, there is yet again, a focus on elite level participation. Elite gymnastics is associated with extraordinary hours of participation from a very young age, high ground reaction forces (Brown et al., 1996) and copious muscle strength (Bencke, Damsgaard, Saekmose, Jorgensen, & Klausen, 2002); all of which are known to affect skeletal development. Therefore, it is not surprising elite gymnasts are commonly assessed and reported to have skeletal benefits, compared with non-gymnasts.

The benefits of high impact physical activity on bone health before puberty are well established (Bass, 2000; Kontulainen, Sievänen, Kannus, Pasanen, & Vuori, 2003; Sanchis-Moysi, Dorado, Olmedillas, Serrano-Sanchez, & Calbet, 2010). However, there are more studies on pubertal, adult and retired gymnasts than pre-pubertal gymnasts. Nevertheless, gymnastics participation is most popular during childhood (Australian Bureau of Statistics, 2011; Gymnastics Australia, 2009) and involves more participants at a non-elite or recreational level than elite level. Although literature exists, additional research is required on the potential benefits associated with non-elite gymnastics participation during pre-pubertal growth.

While most childhood gymnastics studies have assessed gymnasts with non-gymnasts, two studies have further divided non-elite gymnasts into high and low training groups (Laing et al., 2005; Scerpella, et al., 2003). A trend towards a dose-response relationship emerged (Scerpella, et al., 2003). No studies have followed a similar study design, in young non-elite gymnasts exposed to different hours of participation, using pQCT technology.

Longitudinal monitoring of young, pre-pubertal non-elite gymnasts is required to determine skeletal changes over time. In order to compare with previous literature, DXA analysis should be conducted. In addition, pQCT should be included to determine volumetric bone density and geometric changes during growth. Furthermore, analyses should include different groups of gymnasts to explore the possibility of a dose-response relationship between training and musculoskeletal increases. Given the unique loading of the upper limb, both the radius and ulna should be analysed to avoid underreporting upper limb skeletal advantages. To improve the understanding of musculoskeletal health and to more accurately describe the muscle-bone relationship, actual measures of muscle function should be included.

1.2 Purpose

The purpose of this thesis was to longitudinally examine the effects of non-elite female artistic gymnastics participation on upper limb musculoskeletal parameters using pQCT, DXA and muscle function assessments. A schematic overview of the thesis is outlined in Figure 1.1.

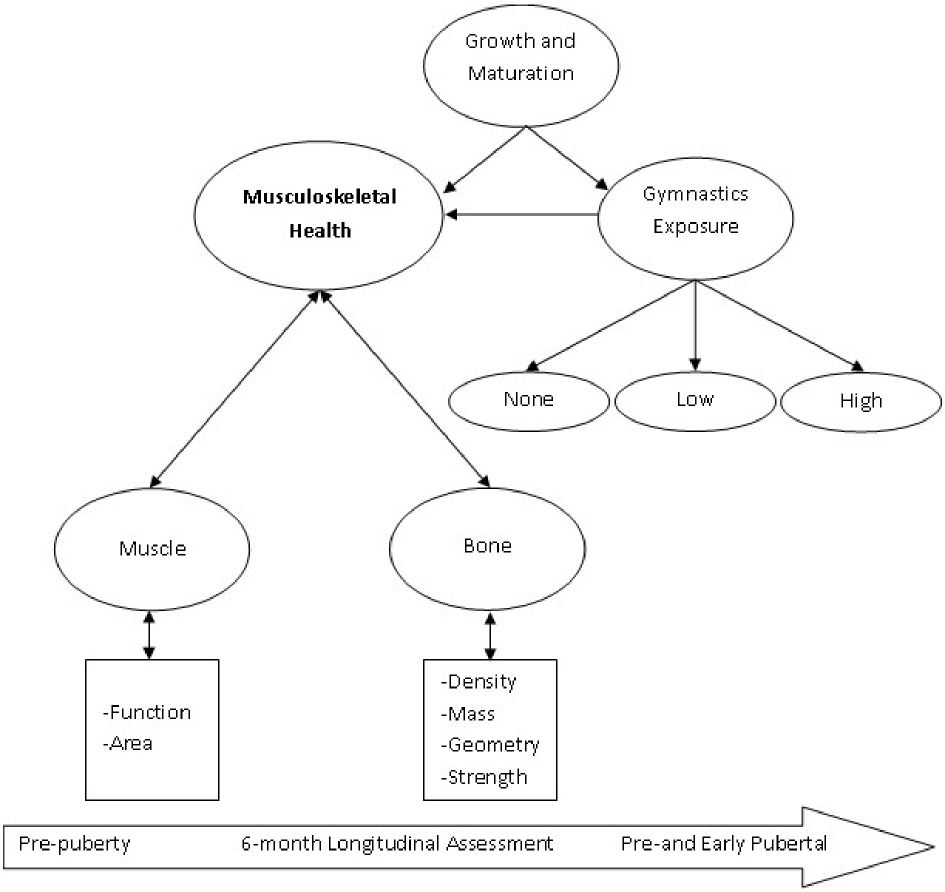

Figure 1.1. Schematic overview of the thesis

1.3 Thesis Overview

Three studies were conducted to examine the upper limb musculoskeletal effects that may differentiate young non-elite gymnasts from their non-gymnastic peers.

1.3.1 Study One

Non-elite gymnastics participation is associated with greater bone strength, muscle size and function in pre-and early pubertal girls.

1.3.1.1 Aim

To determine the association between non-elite gymnastics participation and upper limb bone mass, geometry, strength and muscle function in young girls.

1.3.1.2 Hypotheses

1. Gymnasts would have greater bone mass, size and strength compared with non-gymnasts.
2. Gymnasts were expected to have greater lean mass and improved muscle function than non-gymnasts.
3. Musculoskeletal benefits of gymnasts with high-training commitments would be larger than those with low-training commitments.

1.3.2 Study Two

Skeletal differences of the ulna and radius in pre-pubertal non-elite female gymnasts

1.3.2.1 Aim

To investigate pQCT-derived structural properties of bone at the distal and proximal radius and ulna in a group of pre-pubertal non-elite gymnasts and age-matched non-gymnasts.

1.3.2.2 Hypothesis

1. Gymnasts will display greater structural properties of bone at the radius and the ulna compared with non-gymnasts.

1.3.3 Study Three

Non-elite gymnastics induces musculoskeletal benefits in the upper limbs of early pubertal girls: A 6-month study using pQCT

1.3.3.1 Aim

To compare changes in musculoskeletal parameters over six months in pre- and early pubertal females involved in different quantities of artistic gymnastics (high- 10.5 hr/wk and low- 3 hr/wk training gymnasts) with a group of age and gender matched non-gymnasts.

1.3.3.2 Hypotheses

1. Sports participation, specifically in artistic gymnastics, in the early stages of puberty would favour upper body musculoskeletal development. Furthermore, gymnasts were expected to have greater increases in upper limb skeletal and muscle function parameters than non-gymnasts.
2. A dose-response would emerge between musculoskeletal parameters and weekly gymnastics exposure.

1.4 Limitations

The following limitations are acknowledged:

1. Data collection outlining the specific details of the type of activities, loading on bones and skills undertaken at all the different gymnastics centres was not feasible. Therefore, it was not possible to estimate the exact loading of the gymnasts.
2. The phase of periodised training that gymnasts were experiencing at the time of testing may have altered results. If gymnasts performed their follow up assessment during the summer holidays they may have had one month away from gymnastics training prior to testing. Non-elite gymnasts usually train during school terms and break over the holidays. Furthermore, if non-gymnasts baseline testing was conducted during pre or off season for their chosen sport, and follow up testing at the end of a season, results particularly for muscle function may have improved due to training rather than growth. A limitation therefore was the inability to collect data at the same phase of competition/training in all participants.

3. Injury or illness that altered usual training for gymnasts may have decreased actual weekly exposure to training. While injuries were recorded and there were no serious injuries forcing prolonged breaks from training; some gymnasts may have modified training (and altered loading to the musculoskeletal system) due to injury. Furthermore, it was up to parents to inform the primary investigator of such circumstances upon follow up assessment. Therefore, some incidences may not have been reported.
4. Motivation of the participants may have affected the results of the study. Participants were required to complete challenging muscle function tasks until fatigue. Most participants arrived for testing in groups and were very competitive either towards beating other girls or the task record. However, the level of motivation was not assessed and may be a limitation of the study.
5. Pubertal status was determined via proxy report of Tanner's five stage model for pubertal maturation (Duke, Litt, & Gross, 1980; Tanner, 1978). Biochemical analysis of pubertal maturation was outside the scope of the study.
6. Nutritional practices fell outside the scope of this study. While an estimate of total energy, calcium and protein intake was observed during the study through dietary intake records completed by participants and parents, whether or not participants habitually consumed adequate nutrients or met their daily requirements was out of our control.
7. All questionnaires physical activity, general health and injury were completed by parents and daughters together. These questionnaires may be limited by recall accuracy.
8. Genetic predisposition to strong bones and muscles and the genetic basis of participants' response to training also fell outside the scope of the study.

1.5 Delimitations

The following delimitations were implemented for all participants:

1. The study was delimited by the recruitment of female, Caucasian, pre-and early pubertal participants. Pubertal status was identified by Tanner (Tanner, 1978).
2. The study was restricted to participants who: were injury free at commencement of the study, had no recent (12-months) broken/fractured bones in the upper body, had no history of medical conditions and were not taking any medication or supplementation known to affect bone metabolism.
3. Data collection was delimited to a total of two testing sessions, six months apart.
4. Musculoskeletal assessment was restricted to the use of bone imaging technique of DXA (Norland, XR-36 System, Fort Atkinson, Wisconsin) and a newer technique commonly used among pediatric populations, pQCT (XCT 2000, Stratec Medizintechnik, Pforzheim, Germany).
5. Muscle function assessments of muscle strength and power were restricted to grip strength and a medicine ball throw, which have previously been used in pediatric populations. Two original muscle endurance tasks were devised to assess muscle endurance. All muscle function tasks were pilot tested and deemed reliable.

The following delimitations were implemented for all gymnasts:

1. Gymnasts were delimited to those training at a non-elite level of participation, with a weekly exposure of equal to or less than 16 hr/wk and a minimum training history of six months.
2. Gymnasts also needed to have a current Gymnastics Australia membership and not be participating in more than one hour of additional upper body loading outside gymnastics training.

The following delimitation applied to all non-gymnasts:

1. Non-gymnasts were delimited to participating in equal to or less than 4 hr/wk of organised physical activity outside school and with no previous participation in artistic gymnastics.

1.6 Assumptions

1. Participants and parents completed questionnaires accurately and in full detail.
2. Any previous injuries or medical conditions did not affect the results of the study.
3. Gymnasts who were injured and participated in modified training programs at anytime over the duration of the study did not affect the outcome of the results.
4. Non-gymnasts did not perform any gymnastic-based skills during free play or as a prolonged component of the school physical education curriculum.
5. Participants performed all muscle endurance tasks with maximal effort.

1.7 Definitions

Artistic gymnast: A female gymnast participating in four primary apparatus including the vault, uneven bars, balance beam and floor exercise. Artistic gymnastics may also involve training on trampolines as well development of general strength and flexibility.

Bone mineral content (BMC): The amount of bone mineral per anatomical region (g).

Bone mineral density (BMD): An areal density measurement derived by dividing bone mineral content by the bone area (g/cm^2).

Bone strength index (BSI): Total area multiplied by total density^2 (mg^2/mm^4) (Kontulainen, et al., 2003).

Cortical area (CoA): Cross sectional area of the cortical portion of the total bone area (mm^2).

Cortical density (CoD): Volumetric bone mineral density of the cortical bone (mg/cm^3).

Cortical thickness (CoTh): The average thickness of the cortical shell (mm).

Dual-energy X-ray absorptiometry (DXA): A two dimensional bone and soft tissue imaging procedure that transmits X-rays with high- and low-photon energies (Genton, Hans, Kyle, & Pichard, 2002).

Early pubertal: A total Tanner score of four. Young girls who were classified as pre-pubertal at baseline however, increased in maturation over the six months of the study. Early pubertal girls were not menstruating.

High-training gymnast (HGYM): A female artistic gymnast participating in more than one gymnastics class per week, training between 6 and 16 hr/wk.

Low-training gymnast (LGYM): A female artistic gymnast participating in one gymnastics class per week, training between 1 and 5 hr/wk.

Medullary area (MedA): Total bone area minus cortical area (mm^2).

Muscle cross sectional area (MCSA): The amount of muscle remaining once bone area, fat area and medullary area have been subtracted from the total cross sectional pQCT slice taken at the bone shaft.

Muscle Function: The combined effect of muscle strength, explosive power and endurance.

Non-elite gymnast: A gymnast who is not aiming for international competition. For the purpose of this study, the non-elite status applied to gymnasts participating in a weekly training duration of equal to or less than 16 hr/wk and who may or may not be participating in small regional competitions.

Non-gymnast (NONGYM): A young female not participating in and having no previous experience in any gymnastics discipline. Non-gymnasts may participate in other forms of sport or physical activity up to 4 hr/wk.

Peripheral quantitative computed tomography (pQCT): A three dimensional musculoskeletal imaging procedure that uses X-rays to produce digital images by transmitting a beam through the peripheral skeleton (Johnson & Steinbach, 2004).

Pre-pubertal: A combined Tanner score (breast and pubic hair) of three or less. Tanner stage was identified by proxy report (Duke, et al., 1980; Tanner, 1978).

Strength strain index (SSI): Density weighted polar moment of inertia (mm^3). The polar moment of inertia is defined as $\pi/2({R_o}^4 - {R_i}^4)$, where R_o = the outer radius and R_i = the inner radius, indicative of strength in torsion (Zemel et al., 2008).

Total area (ToA): Total cross sectional area of the bone (mm^2).

Total density (ToD): Total volumetric bone mineral density (mg/cm^3).

Trabecular density (TrD): The volumetric bone mineral density of trabecular bone (metaphyseal sites only) (mg/cm^3). This includes the bone marrow fat that is interspersed within the trabecular bone.

1.8 Thesis Presentation

This thesis includes eight chapters. Chapter one is completed above. Chapter two presents a narrative review of the literature while chapter three consists of a systematic review of the literature, including a meta-analysis. Generic methods are described in chapter four. Chapters five, six and seven have been presented as stand-alone chapters and have/will be submitted for publication. The final chapter summarises the major findings of the thesis.

CHAPTER TWO

NARRATIVE REVIEW OF THE LITERATURE

2.1 Musculoskeletal Health During Growth

2.1.1 Skeletal Acquisition During Growth

Bone growth and development are products of complex interactions between genetic, environmental and behavioural factors. The skeleton grows in length, breadth and mass as the body develops (Heaney et al., 2000). Long bones comprise of an epiphysis which consists of two wider portions/ends, a diaphysis also known as the bone shaft and a metaphysis where remodelling takes place during growth and development (Figure 2.1) (Khan et al., 2001). Long bones contain both cortical and trabecular bone. Cortical bone constitutes approximately 80% of the skeleton and forms the external part of long bones at the diaphysis, whereas trabecular bone is found towards the metaphysis and epiphysis (Brandi, 2009). A thin layer of cortical bone is also found at the metaphysis of long bones. Cortical bone has two surfaces known as the endosteum and periosteum. The endosteum is the inner surface of long bones and comprises of a thin layer of cells lining the medullary cavity. The periosteum forms the outside surface of the bone and consists of two layers: an outer layer, which is rich in blood vessels and nerves and an inner layer, the cambium, which contributes to appositional bone growth during bone development (Khan, et al., 2001).

Elongation of long bones continues through childhood and into late adolescence, as new bone is continuously added via osteoblast activity between the epiphyseal plate and the metaphysis. At the other end of the metaphysis (near the diaphysis), inwaisting occurs. The process of inwaisting involves trabeculae being removed and the bone continuing to decrease in diameter via periosteal resorption, until the width of this end of the metaphysis matches the cross-sectional size of the diaphysis (Rauch, Neu, Manz, & Schoenau, 2001). Bone formation also occurs beneath the periosteal envelope resulting in the widening of the bone shaft (Seeman, 2003). Periosteal apposition accounts for the majority of the increase in cortical area observed before puberty (Bass, 2003). The thickening of the bone cortex occurs because endocortical resorption proceeds slower than the periosteal apposition at this time (Seeman, 2007). There are few differences in bone growth between boys and girls before puberty. The extent of periosteal apposition and endocortical remodelling are similar until sexual dimorphism appears (Seeman, 2003). As girls enter puberty, estrogen in girls inhibits periosteal bone formation and promotes bone growth on the endocortical surface (Seeman, 2003). During late and post puberty, boys exhibit greater periosteal expansion than girls (Bass, 2003).

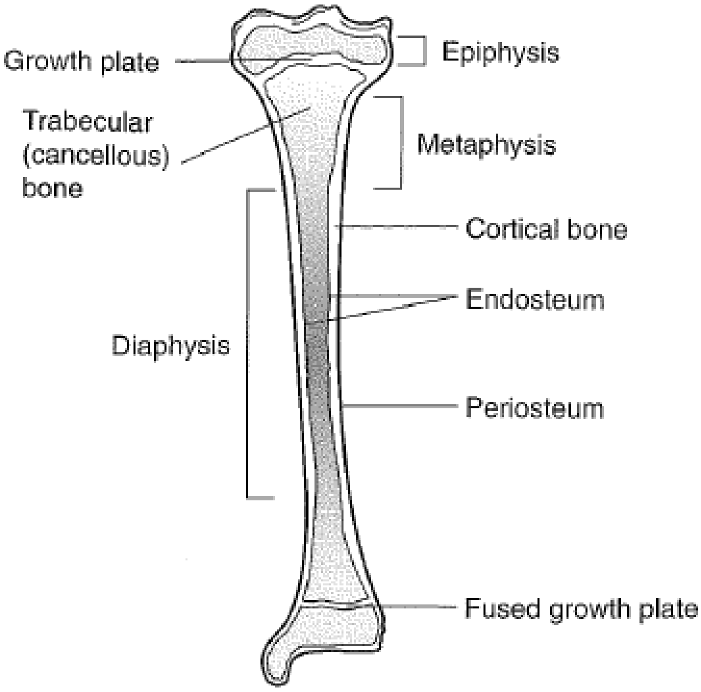

Figure 2.1. Schematic view of a growing long bone (Khan, et al., 2001)

2.1.2 Bone Strength During Growth

The strength of a bone is directly related to its ability to resist fracture in a given environment. Bone strength is dependent on a number of factors including material and geometric properties. Throughout life, bones modify their material properties and geometric characteristics as a means of sustaining the demands placed upon them from their genetic blueprint and mechanical usage. The material properties of bone consist of mass, density, stiffness and strength. Geometric characteristics of bone include size, shape, cortical thickness, cross-sectional area and trabecular architecture (Khan, et al., 2001).

2.1.2.1 Material properties of bone

Material properties of bone depend on the quality and quantity of the bone mineral mass. A key material property in bone strength is the elastic modulus or stiffness (Turner & Burr, 1993), which is the slope of the stress-strain curve (Khan, et al., 2001). The stress-strain curve is comprised of an elastic, yielding and plastic region (Figure 2.2). When a force is applied to a bone within the elastic region (E), the bone regains its original shape upon the cessation of the force. Hence, bone deformation is temporary and reversible. However, if a force is applied to a bone beyond its yielding point, the bone enters a plastic region and permanent deformation occurs. Assuming the force increases in magnitude, beyond the plastic region, the bone begins to crack reaching breaking point (Wendlova, 2008). The elastic modulus cannot be measured directly in vivo, but it is closely related to the volumetric density of cortical bone (Schiessl, Ferretti, Tysarczky-Niemeyer, & Willencker, 1996).

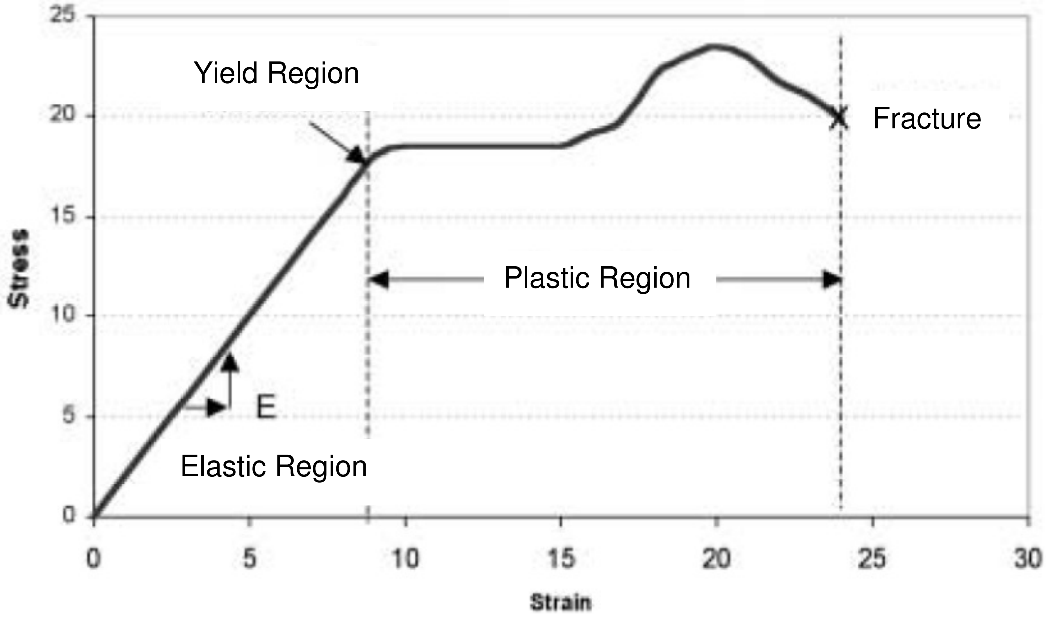

Figure 2.2. Stress-strain curve, modified from (Petit, Beck, & Kontulainen, 2005)

Volumetric bone mineral density (BMD) depends on the amount of cortical and trabecular bone contained within the periosteal surface of the bone during growth as well as the external size of the bone, relative to bone accrual (Seeman, 1998). If size is constant, increasing bone density may be the result of increasing cortical thickness, trabecular number or thickness, or increasing true (material) density of these structures (Seeman, 1998). The ability to determine the mechanisms contributing to bone density is often limited by the inability of some equipment to distinguish between cortical and trabecular bone.

2.1.2.2 Geometric characteristics of bone

The resistance of bone to bending and torsion depends on elastic modulus and bone geometry (Forwood, 2001). Growth results in an increase in the external size of long bones. Bone shape occurs through modelling and remodelling on the periosteal and endosteal surfaces of cortical bone, resulting in adaptations in bone geometry (Figure 2.3). During growth, new bone formation occurs on the periosteal surface at which a relatively small increase in bone apposition provides a disproportionate mechanical advantage at the locations of greatest strain. This bone formation results in a small amount of bone strategically placed away from the bone's axis of bending, where it has an exponential capacity to resist bending loads (Forwood, 2008). This distribution of bone mass away from the neutral axis is known as cross-sectional moment of inertia (CSMI). Maximal CSMI is identified and a stronger bone is achieved when a cross-sectional bone area is measured at the furthest distance from the neutral axis (Khan, et al., 2001).

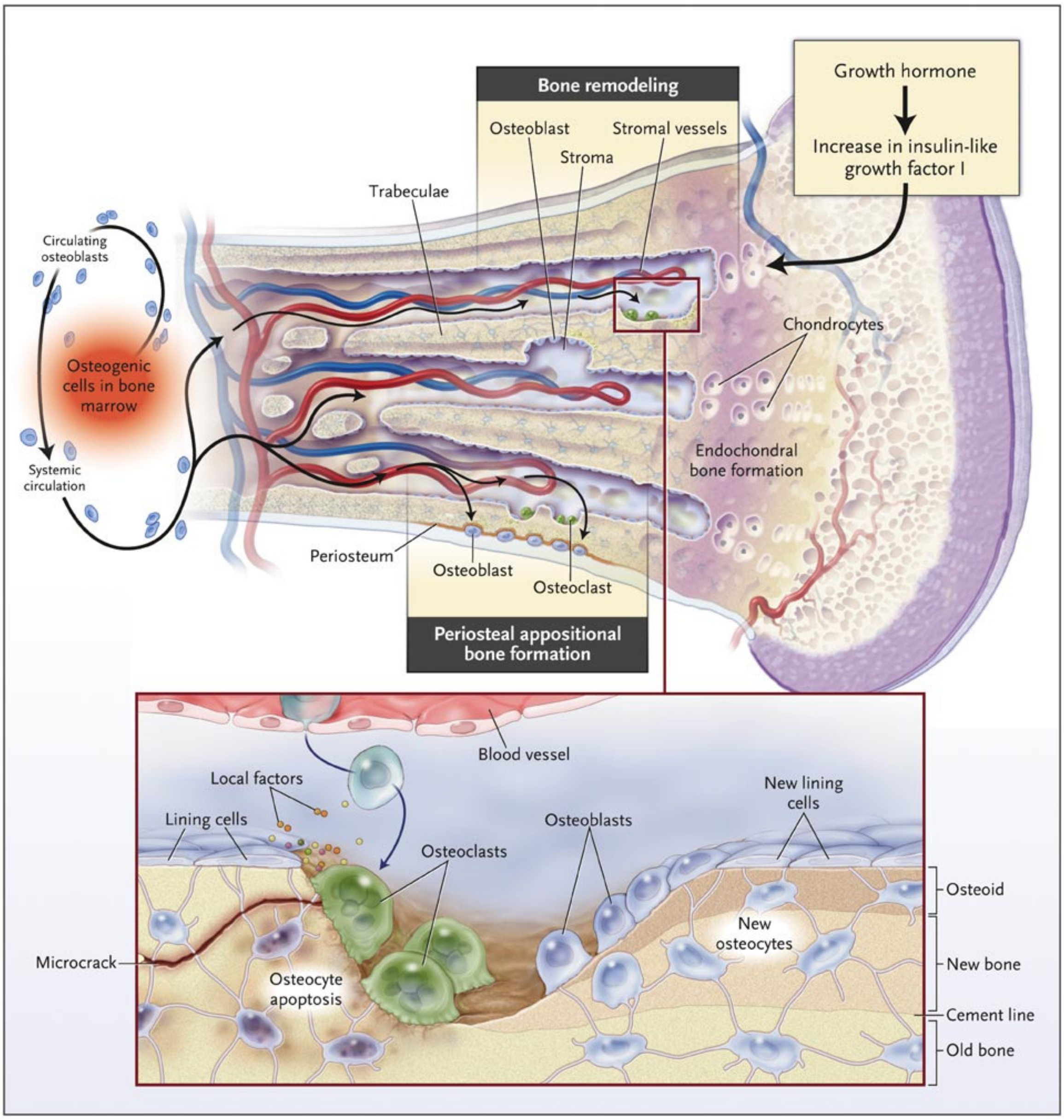

Figure 2.3. Bone remodelling and modeling (Canalis, Giustina, & Bilezikian, 2007)

2.1.2.3 Assessment of bone strength

Previously, bone strength was estimated in human studies from measurements of bone density, focusing more on the material composition of bone. However, bone strength is known to increase in proportion of the bone's radius to the power of four (Seeman, 2003). Therefore, bone strength and resistance to fracture strongly depend on geometric characteristics, specifically the distribution of bone around the medullary cavity.

There are several different techniques used to assess the material properties and geometric characteristics of bone. The most frequently used non-invasive paediatric techniques include dual-energy X-ray absorptiometry (DXA) and peripheral quantitative computed tomography (pQCT). Occasionally magnetic resonance imaging (MRI) is used to assess skeletal properties in children. In addition to bone, these techniques have the ability to measure soft tissue such as lean and fat mass as well as muscle and fat cross-sectional area. Before deciding which machine to use, specific advantages and disadvantages should be considered.

2.1.2.3.1 Dual-energy X-ray absorptiometry (DXA)

The DXA device was introduced commercially as the direct successor to dual photon absorptiometry in 1987 (Njeh, Fuerst, Hans, Blake, & Genant, 1999). A DXA machine can measure different body tissues through the transmission of X-rays with high- and low-photon energies (Genton, et al., 2002). At low energy bone attenuation is greater than soft tissue attenuation, whereas at high-energy bone attenuation is similar to soft tissue. As a result, the machines are able to identify three types of tissue: bone mineral, lean tissue and adipose tissue (El Maghraoui & Roux, 2008). However, DXA devices provide only a two dimensional view of bone and are therefore unable to evaluate true density or describe bone geometric properties. Most commonly, DXA reports areal BMD. Other variables frequently reported include BMC and BA. Bone mineral content is derived by multiplying BMD by projected area (Njeh, et al., 1999; Prentice, et al., 1994). The most universally reported regions of interest scanned via DXA include the total body, lumbar spine, hip, and forearm. Other scan functions include the lateral spine and body composition. Separate DXA devices are available for human and animal research (El Maghraoui & Roux, 2008).

Dual-energy X-ray absorptiometry is safely and effectively used in paediatric populations because it is non-invasive, exposes children to low ionizing radiation, scans the selected region fairly quickly and offers paediatric reference data (Ward, Mughal, & Adams, 2007). However, a large limitation associated with DXA stems from the two dimensional design and the inability of the machine to accurately determine and adjust results for bone depth (Ward, Mughal, et al., 2007). For example, two bones can have an identical volumetric BMD, yet one is smaller than the other. The results from DXA analysis show the smaller bone has a lower areal BMD than the larger one. Therefore, areal BMD in a small child would be lower than areal BMD in a taller child even if they had identical volumetric bone densities (Crabtree, Leonard, & Zemel, 2007). For this reason, assessment of bone density in paediatric populations, using DXA, has been cautioned. Studies may have under- or overestimated bone density if bone size was not taken into account when reporting results. Furthermore, discontinued used of bone density in population based studies was suggested some time ago (Prentice, et al., 1994).

Effective ionizing radiation dose for a total body scan varies depending on the type of machine (fan beam, narrow fan beam and pencil beam). However, exposure is generally less than both the naturally occurring background radiation (8.6 μSv/day) and a round transatlantic flight (80 μSv) (Njeh, et al., 1999). Despite the increase in radiation dose associated with the development of fan beam technology, patient dose remains relatively small (Njeh, et al., 1999). The time it takes to scan the total body is also dependent on the type of machine, but usually takes less than ten minutes (Genton, et al., 2002). The latest technology is able to complete scans in 10 to 30 seconds (Njeh, et al., 1999).

Precision for DXA total body analysis is approximately 1% for measures of total body BMD (Genton, et al., 2002). Error measurements for BMD have been reported at 5–8% (El Maghraoui & Roux, 2008). Specifically, anteroposterior images at the spine report CV values of 1–2% and a little higher 2–3% at the proximal femur in individuals with normal BMD values (El Maghraoui & Roux, 2008). Although not relevant in paediatric populations, the size of participants may also affect the accuracy of the machine. Obese or extremely tall people may not fit on the scanner. Furthermore, hyperhydration affects the analysis of soft tissue and may result in an inaccurate assessment of percent body fat (Jebb, 1997).

2.1.2.3.2 Magnetic resonance imaging (MRI)

Magnetic resonance imaging was initially introduced in the early 1980's and uses magnetic fields and radio frequency signals to acquire images (Grey & Ailinani, 2003). Specifically, the technique is based on the resonance and relaxation of protons in lipids and water. Different tissues in the body have varying quantities of water and lipids, thus allowing imaging and differentiation of various anatomical structures (Ward, Mughal, et al., 2007).

Several advantages are associated with MRI. This technique does not use ionizing radiation; produces excellent soft tissue contrast; has the ability to acquire true volumetric images in a variety of anatomical planes for the entire body without repositioning and can determine different bone tissue such as trabecular and cortical bone (Grey & Ailinani, 2003; Ward, Mughal, et al., 2007). The disadvantages associated with MRI include the high cost; loud noise of the machine, potential for claustrophobia and the long scan time that requires complete stillness which can be difficult in young populations (Grey & Ailinani, 2003; Ward, Mughal, et al., 2007).

2.1.2.3.3 Peripheral quantitative computed tomography (pQCT)

Peripheral QCT first became commercially available in the early 1990's (Ruegsegger, Durand, & Dambacher, 1991; Rüegsegger, Durand, & Dambacher, 1991). Peripheral QCT uses a series of X-rays to produce digital images by transmitting a beam through the patient (Johnson & Steinbach, 2004). X-ray attenuation data is acquired at multiple angles around the gantry to reconstruct a three dimensional representation of the patient's limb. Although the pQCT exposes patients to radiation, it is a low dose (Australian Radiation Protection and Nuclear Safety Agency, 2005). For example, a scan of the distal radius results in 0.22 μSv of radiation exposure (Stratec, 2005). As the name suggests this device is used to scan the peripheral skeleton. Measurement sections are taken at 4, 14, 20, 38, and 66% of the leg length and, at 4, 33, 50, and 65% of the forearm length (Ward, Mughal, et al., 2007).

A major advantage of pQCT is its ability to calculate true volumetric density measurement of appendicular bone without superimposition of other tissues (Njeh, et al., 1999). Furthermore, pQCT is a relatively portable device that measures bone geometry related to bone strength; can determine muscle cross-sectional area and differentiates cortical from trabecular bone (Ashe et al., 2006). Peripheral QCT image acquisition is based on a number of factors including: the number of blocks, field of view, scan speed and voxel size (Ashe, et al., 2006). Voxel size is particularly important when scanning children as it may influence the partial volume effect. The partial volume effect occurs when more than one tissue composed of different densities is present in a single voxel (Gonzalez Ballester, Zisserman, & Brady, 2002) and may cause inacruacies in density measurements. However, adjustment for the partial volume effect may not always be necessary (Rittweger, Michaeli, Giehl, Wusecke, & Felsenberg, 2004).

Accuracy of the pQCT depends on the selected analysis mode, resolution, contour mode and threshold (Ashe, et al., 2006). It is important to ascertain the appropriate analysis mode based on the bone compartment of interest. Unfortunately, due to the partial volume effect and potential movement artifacts the resolution of the pQCT is usually too low to ensure perfect definition of trabecular elements such as trabecular number, thickness and spacing (Lespessailles, Chappard, Bonnet, & Benhamou, 2006). As a result the trabecular BMD reported by pQCT contains trabeculae and bone marrow.

When scanning children, caution should be taken not to scan the section of bone including the growth plate. The reference line should be positioned at the most distal portion of the open growth plate (Neu, Manz, Rauch, Merkel, & Schoenau, 2001; Rauch & Schoenau, 2005). Scanning through or too close to the growth plate will result in falsely high measures as a result of the zone of provisional calcification (Ward, Mughal, et al., 2007). Upon closure of the growth plate, a line is drawn through the middle of the ulnar border of the articular cartilage (Rauch & Schoenau, 2005).

More recently, high resolution peripheral Quantitative Computed Tomography (HR pQCT) has been introduced. High resolution pQCT is based on the same techniques as QCT and exposes patients to ionizing radiation (Kazakia & Majumdar, 2006). This newer technology has an isotropic voxel size 82 µm and permits direct and reliable imaging of bone microstructure in vivo to assess key structural elements (Burrows, Liu, Moore, & McKay, 2010). The HR pQCT enables trabecular microarchitecture and individual trabeculae (although only the large trabeculae, not all) to be analysed (Kazakia & Majumdar, 2006; Lespessailles, et al., 2006). Specifically, measures of trabecular bone volume fraction, trabecular thickness, trabecular spacing and trabecular number can be determined at the distal radius and tibia (Boutroy, Bouxsein, Munoz, & Delmas, 2005; Laib & Ruegsegger, 1999). As with any technology, there are limitations associated with the HR pQCT. At this stage, the greatest limitations associated with HR pQCT lie in the cost and access, because it is a relatively new technology. Furthermore, HR pQCT is similar to pQCT and therefore only scans the peripheral skeleton, administers a low dose of radiation and the scans are susceptible to movement artifacts.

By evaluating bone microstructure in the developing skeleton, we are able to get a better understanding of trabecular and cortical bone compartments (Burrows, et al., 2010). The recent HR-pQCT technology and MRI, share the attraction of easier and non-invasive assessment of bone microstructure. However, little is known about the development and advantages of microstructural properties in the growing skeleton. Comparatively, few studies have used HR-pQCT in children compared with DXA (Burrows, et al., 2010). The majority of literature focuses on microstructure in older populations (Boutroy et al., 2008; Nishiyama, Macdonald, Buie, Hanley, & Boyd, 2010; Vico et al., 2008) and more recently adolescents (Burrows, et al., 2010; Kirmani et al., 2009). Recent research using HR-pQCT in young populations reported differences in trabecular bone microstructure across age categories in males and females (Burrows, et al., 2010). At the tibia, males had a higher trabecular number however; trabecular thickness was the same between males and females (Burrows, et al., 2010). This finding is inconsistent with previous literature. For example an increase in trabecular thickness not number was reported in adolescents, although different methodology was used (Parfitt, Travers, Rauch, & Glorieux, 2000). During childhood development and puberty, the trabecular parameters of girls remain relatively stable (Kirmani, et al., 2009; Rauch, et al., 2001). These findings suggest that in girls, trabecular bone volume and structure at the radius may be programmed early in life and do not change significantly through growth (Kirmani, et al., 2009).

In summary, each method has its advantages and disadvantages (Table 2.1). Accessibility, funding and location of data collection are likely to determine the selection of the device for musculoskeletal analysis. However, combining DXA-derived data with pQCT-derived data is likely to be routine over the next few years (Bishop, Sawyer, & Leonard, 2007).

Table 2.1

Advantages and Disadvantages of Musculoskeletal Imaging Techniques

	Advantages	Disadvantages
DXA	1. Rapid scan times 2. Relatively low cost 3. High precision 4. Availability of paediatric reference data 5. Low ionizing radiation dose 6. Clinical applications have been established 7. Can assess body composition 8. Can be used to assess hip region	1. Size-dependent measurements 2. Sensitive to body composition changes 3. Software and reference data changes 4. Integral measurement of trabecular and cortical bone
MRI	1. Non- ionizing 2. Noninvasive 3. Size-independent 4. Can image in multiple planes without moving the patient 5. Applicable to axial and peripheral sites 6. Measures muscle and fat	1. Noisy 2. Long scan time 3. Claustrophobia in some individuals 4. Parents cannot be in room with children
pQCT	1. Size-independent 2. Separate measure of cortical and trabecular bone 3. Measures bone geometry 4. Imaging of trabecular bone structure feasible 5. Measures muscle and fat 6. Low radiation dose 7. Assessment of cortical bone at the metaphysis	1. Only applicable to peripheral sites

Modified from (Ward, Mughal, et al., 2007)

2.1.2.4 Assessment of fracture risk

There has been an increase in the incidence of distal forearm fractures in young children however; the reasoning is unclear (Khosla et al., 2003). The literature suggests children who fracture have lower areal (Goulding et al., 1998; Goulding, Jones, Taylor, Manning, & Williams, 2000) and volumetric (Clark, Ness, Bishop, & Tobias, 2006) BMD, lower bone mass (Manias, McCabe, & Bishop, 2006) and a smaller cross sectional area (Skaggs, Loro, Pitukcheewanont, Tolo, & Gilsanz, 2001) than those who do not fracture.

Bone strength measures have been used in combination with a moment arm (limb length) and body weight to assess fracture risk in the forearm during growth, known as strength/weight index (Dowthwaite, Flowers, Spadaro, & Scerpella, 2007; Rauch, et al., 2001). Fracture risk is a concern during growth because the timing in bone mineral accrual and longitudinal growth differs (Blimkie et al., 1993). For example, in children, development of bone mass and strength at the distal radius lag behind the increase in the mechanical factors that challenge bone stability in the event of a fall (Rauch, et al., 2001).

The reason for this lag in bone development at the distal radius may be due to a relatively static expansion of cortical thickness which remains unchanged from 6 to 13 years in girls and from 6 to 15 years in boys (Rauch, et al., 2001). However, accurate assessment and reporting of cortical thickness in paediatric populations are difficult due to the small size of the bones, cross sectional nature of the literature, limitations linked to resolution and voxel size of devices such as pQCT that in turn lead to a partial volume effect (Hangartner & Gilsanz, 1996; Prevrhal, Engelke, & Kalender, 1999).

2.1.2.5 Long-term fracture risk: The importance of peak bone mass

Pre-pubertal growth accounts for 40% of peak BMC accrual (Bass et al., 1999). At this time hormonal and growth activity is important for skeletal acquisition. Therefore, these pre-pubertal years are a critical time for bone accrual. Any negative or positive influence during this period could dramatically influence peak bone mass. By the end of puberty, boys and girls have accrued approximately 85 to 90% of their peak BMC (Bailey, Faulkner, & McKay, 1996; Bailey, McKay, Mirwald, Crocker, & Faulkner, 1999; Heaney, et al., 2000; Nattiv & Armsey, 1997). Furthermore, genetic factors account for an estimated 60–80% of the variability in peak bone mass, with diet and nutrition, physical activity and hormonal status serving as important modifiers of bone accrual (Bachrach, 2001). The attainment of a higher peak bone mass during childhood and adolescence will ideally help prevent fractures later in life (Heaney et al., 2000). However, a recent trend away from peak bone mass, to be more inclusive of the role of muscle function and for a sufficiently developed muscular system has emerged (Fricke, Beccard, Semler, & Schoenau, 2010).

2.1.2.6 Additional considerations of bone acquisition

Bone acquisition may be influenced by genetic factors as well as other adjustable factors such as individual nutrition and physical activity (discussed later). Furthermore, as children enter puberty hormonal activity will also influence skeletal development.

Genetic predisposition towards bone size, mineral accrual and resorption can be adjusted, within reason, by modifiable environmental factors (Sawyer & Bachrach, 2007). Modifiable factors include physical activity and nutrition, particularly calcium and vitamin D.

Calcium is a key nutrient in skeletal development during growth as it allows for optimal gains in bone mass (Heaney, et al., 2000). In order to achieve optimal skeletal development calcium intake must meet the demands required for bone mineral accrual allowing for losses through urine, feces and sweat (Sawyer & Bachrach, 2007).

Supplementation has had positive results on skeletal gains in children (Bonjour et al., 1997; Greene & Naughton, 2011; Ianc et al., 2006). However, calcium supplementation may not have an effect when children are meeting their recommended intake (Ward, Roberts, Adams, Lanham-New, & Mughal, 2007). The daily recommended calcium intake may vary depending on the amount of physical activity undertaken by children (Specker & Binkley, 2003). Children not consuming recommended amounts of calcium may be compensated by regular involvement in sport or physical activity (Anderson, 2001). Calcium supplementation among pre-pubertal children in addition to physical activity and exercise has positively influenced skeletal properties (Ianc, et al., 2006; Iuliano-Burns, Saxon, Naughton, Gibbons, & Bass, 2003). The National Health and Medical Research Council recommend young girls nine to 11 years consume 1000 mg/day of calcium (National Health and Medical Research Council, 2009). In addition to a healthy and adequate nutrition consumption, girls (five to 18 years of age) should participate in at least 60 minutes of moderate to vigorous physical activity daily (Department of Health and Ageing, 2010).

In addition to calcium, Vitamin D must be considered as it is required for the absorption of calcium. Vitamin D plays a critically important role in the development, growth and mineralization of the skeleton during its formative years (Holick, 1996). Furthermore, protein, total energy and nutritional intake must also be adequate for optimal bone development (Alexy, Remer, Manz, Neu, & Schoenau, 2005).

2.1.3 Muscle-Bone Relationship

According to the mechanostat theory, bone mass and strength increase via modelling and remodelling if the peak strains exerted on the bone exceed a modelling threshold (Schoenau, 2005). However, when the amount of loading is not producing sufficient strain, the bone is unable to maintain its current state, resulting in bone tissue being lost

(Davison, Blimkie, Faulkner, & Giangregorio, 2005). Furthermore, the theory states the largest physiological loads placed on the skeleton result from muscle contraction. Mechanostat theory therefore, predicts that the increasing muscle mass and therefore muscle force during development creates the stimulus for the increase in bone mass and strength (Rauch, Bailey, Baxter-Jones, Mirwald, & Faulkner, 2004).

Animal research supports the notion that muscle contraction and loading have the ability to cause an osteogenic response, independent of impact forces (Nagasawa, Honda, Sogo, & Umemura, 2008; Umemura, Ishiko, Yamauchi, Kurono, & Mashiko, 1997). These findings are not totally supported in human studies. Weight supported sports such as swimming and cycling in which muscle requirements are high and impact with the ground does not occur, reveal mixed results and often report no osteogenic effects (Duncan et al., 2002; Fehling, Alekel, Clasey, Rector, & Stillman, 1995; Nikander, Sievänen, Uusi-Rasi, Heinonen, & Kannus, 2006). On the other hand, resistance training has previously produced bone benefits (Heinonen, Sievänen, Kannus, Oja, & Vuori, 2002; Virvidakis, Georgiou, Korkotsidis, Ntalles, & Proukakis, 1990). However, greatest benefits come from sports involving impacts as well as muscle forces. Therefore, both muscle strain and ground reaction forces play a role in skeletal stimulus. Currently researchers are unable to agree on the precise mechanisms of response (Judex & Carlson, 2009; Kohrt, Barry, & Schwartz, 2009).

Confounding factors such as body size, genetics, and self-selection in physical activity influence the results of the muscle-bone relationship outlined in the literature. Tennis participation may provide an example in which possible confounders are avoided as the loaded (playing) arm can be directly compared to the non-loaded (non-playing) arm. When determining the effects of tennis participation, the playing arm had more muscle and bone mass than the non-playing arm (Bass et al., 2002; Daly, Saxon, Turner, Robling, & Bass, 2004; Ducher, Jaffré, Arlettaz, Benhamou, & Courteix, 2005; Kannus, Haapasalo, Sievänen, Oja, & Vuori, 1994).

Childhood growth and development support the muscle-bone relationship as some bone variables, mainly bone strength and mass show a linear relationship with muscle development (Schoenau, 2005). Muscle development may play a causal role in the accrual of bone strength during growth and development as muscle development seems to occur ahead of bone development by a few months (Rauch, et al., 2004). However, this view may not hold true among pubertal girls (Xu, Nicholson, Wang, Alén, & Cheng, 2009). Nevertheless, the muscle-bone relationship is widely accepted and measures of muscle force and size are now used in combination with bone parameters to clinically assess children at risk of potential bone disease (Schoenau, Neu, Beck, Manz, & Rauch, 2002).

If muscle forces influence bone development, then muscle function should be assessed in combination with bone parameters. However, the literature usually reports surrogate measures of muscle force such lean tissue mass and muscle cross sectional area (Daly, Stenevi-Lundgren, Linden, & Karlsson, 2008). The best approach to represent the functional muscle–bone unit may be to incorporate surrogate measures of muscle force, bone strength, and moment arm length (Petit, et al., 2005).

2.1.4 Muscle Function During Growth

Muscle function including strength, power and endurance are important fitness components essential for the execution of a variety of daily and sport-specific activities throughout the life span. Various indicators of muscle strength have been used in epidemiological studies of growth and development within the literature and include assessment of static or isometric strength, explosive strength or power, and dynamic or functional strength (Beunen & Thomis, 2000). Assessment of muscle function should take into account the many confounders known to influence muscle development such as age, sex, stature and mass related changes, hormonal influences, biomechanical considerations, neuromuscular factors and where possible, genetics (De Ste Croix, 2007).

2.1.4.1 Assessment of muscle function

Common measures of paediatric muscle function outlined in the literature include one repetition maximums (Faigenbaum, Milliken, & Westcott, 2003; Milliken, Faigenbaum, Loud, & Westcott, 2008; Robertson et al., 2008; Scerpella, et al., 2003), isokinetic or isotonic contractions (Bencke, et al., 2002; Grund et al., 2000; Holm, Fredriksen, Fosdahl, & Vøllestad, 2008; Robertson, et al., 2008; Stenevi-Lundgren, Daly, Lindén, Gärdsell, & Karlsson, 2009), grip strength (Milliken, et al., 2008; Molenaar, Zuidam, Selles, Stam, & Hovius, 2008; Neu, Rauch, Rittweger, Manz, & Schoenau, 2002; Okumus et al., 2006), jumping tasks (Bencke, et al., 2002; Holm, et al., 2008; Milliken, et al., 2008; Stenevi-Lundgren, et al., 2009), ball throws (Davis et al., 2008; Salonia, Chu, Cheifetz, & Freidhoff, 2004), static holds (Prista, Maia, Damasceno, & Beunen, 2003) and number of repetitions successfully performed in a given time (Holm, et al., 2008; Prista, et al., 2003; Scerpella, et al., 2003). Assessments are commonly performed in a laboratory or out in the field.

Muscle function testing in young children has multiple challenges including the size of equipment, previous experience, technique, the testing environment and motivation of the young participants. There is also a lack of valid and reliable field based tests available for assessing muscle function in the upper body (Pate, Burgess, Woods, Ross, & Baumgartner, 1993). One of the most frequently cited upper body tests in young populations is the pull-up test, or modified pull-up test. Results often show approximately 80% of participants scoring less than four pull-ups of whom 20% unable to complete one (Davis, et al., 2008). Furthermore, tests that do not take participants' body size or at least some index of body size into account may be inaccurately reporting muscle function results (De Ste Croix, 2007; De Ste Croix, Deighan, & Armstrong, 2003).

The increases in both muscle size and strength associated with growth and maturation are well documented. Improvements in strength increase linearly with age until 12 or 13 years in boys and 15 years in girls. Similarly, improvements in explosive power increase fairly linearly in both genders (Malina, Bouchard, & Bar-Or, 2004).

2.2 Physical Activity and Musculoskeletal Health During Growth

2.2.1 Physical Activity and Bone Acquisition

Sports participation during growth has been shown to increase bone mineral density (Bass et al., 1998; Karlsson, Magnusson, Karlsson, & Seeman, 2001), bone strength (Erlandson, et al., 2011; Ward, et al., 2005) and may be site or region specific (Laing, et al., 2005; Ward, et al., 2005). These benefits are greater if the exercise precedes pubertal growth (Bradney et al., 1998; Vicente-Rodriguez et al., 2003). Furthermore, several cross-sectional studies have shown bone benefits can be maintained into adulthood following discontinued sporting participation (Dowthwaite & Scerpella, 2011; Eser, Hill, Ducher, & Bass, 2009).

The potential for rigorous forms of physical activity to produce an osteogenic response in the pre-pubertal skeleton is well supported in the literature (Bass, 2000; Dowthwaite & Scerpella, 2011; Ducher, et al., 2005; Erlandson, et al., 2011; Ward, et al., 2005). However, some high impact jumping interventions have failed to report changes in bone health among pre-pubertal participants (Greene, Wiebe, & Naughton, 2009; MacKelvie, McKay, Khan, & Crocker, 2001; Petit et al., 2002). Despite overall loading (number of jumps, jump height and therefore ground reaction forces) progressively increasing through the intervention, loading remained constant for three months at a time before increasing (MacKelvie, et al., 2001; Petit, et al., 2002). As bone adaptation depends on strain size, distribution and type, as well as duration, frequency and previous history (Bubanj & Obradovi 2002), perhaps there was insufficient variation in the jumping interventions to cause bone adaptations. Participants may have learnt how to absorb the impact force involved in landing or used eccentric muscle contractions therefore reducing and modifying the strain applied to the bone (Bauer, Fuchs, Smith, & Snow, 2001; Greene, et al., 2009). In addition, if a strain magnitude is held constant for a period of time or the load is applied gently the osteogenic effects will be minimal or nonexistent (Forwood, 2008).

Animal-based research shows the frequency and timing of exercise bouts in addition to the magnitude of the strains, produced in a dynamic environment optimises skeletal adaptation (Davison, et al., 2005). Participating in shorter diverse bouts of exercise including rest periods is more beneficial than one longer session (Rubin & Lanyon, 1984, 1987; Turner & Robling, 2005) furthermore these gains may location dependent (Rubin & Lanyon, 1985). These findings may be supported by the diminishing returns or lack of bone adaptations found in long distance runners (Iwamoto, Sato, Takeda, & Matsumoto, 2009), although other factors may also contribute.

2.2.2 Physical Activity and Muscle Function

A strong evidence base supports gains in muscle strength as a result of resistance training in children, although to a lesser extent than adults (Faigenbaum, Westcott, Loud, & Long, 1999). The term 'resistance training' involves using body weight, machines, free-weights, elastic bands, medicine balls or plyometrics to progressively increase the number of repetitions performed or the load applied (Faigenbaum & Myer, 2010). Resistance training during childhood is now viewed as a safe and effective method for increasing muscle strength, providing adequate supervision is available and the correct technique is reinforced (Behm, Faigenbaum, Falk, & Klentrou, 2008; Phillips, 2008). Children may also report a desirable change in body composition and an improvement in motor skills and sports performance following resistance training (Behm, et al., 2008).

Furthermore, resistance training used to increase sports-specific muscle strength may even result in decreased risk of sports-related injuries (Faigenbaum & Myer, 2010).

Assessment of muscle strength has also focused around sports participation. Involvement in numerous sports has been associated with increased muscle strength and endurance (Scerpella, et al., 2003) as well as muscle power (Sanchis-Moysi, et al., 2010). However, limited research has investigated muscle power and endurance in children (Behm, et al., 2008).

The amount of force or power a muscle can produce depends partially on the size of the muscle which is a well recognised relationship (De Ste Croix, 2007; De Ste Croix, et al., 2003). Previously it was thought that pre-pubertal children could not attain muscle hypertrophy (Ozmun, Mikesky, & Surburg, 1991). However, recent studies challenge this notion. Pre-pubertal children participating in a variety of sports can show muscle hypertrophy via an increase in muscle cross-sectional area using pQCT (Sanchis-Moysi, et al., 2010; Ward, et al., 2005).

2.3 Effects of Gymnastics Participation on Musculoskeletal Health During Growth

2.3.1 Muscle Function Profiles of Gymnasts

2.3.1.1 Muscle function and elite gymnastics participation

Gymnastics is a sport requiring the involvement of maximal and sub-maximal muscle contractions. The speed and coordination of contractions are important in the composition of the many diverse sport-specific skills. If the speed of the contraction is not well coordinated, the movement or skill execution is unsuccessful. Therefore, the succeeding movement or skill is unlikely to be effective. Within skill levels of gymnastics, gains in strength and power increase proportionately. Elite pre- and peri-pubertal gymnasts have greater explosive power as measured by squat jumps and counter movement jumps, than non-elite gymnasts (Bencke, et al., 2002).

Elite pre- and peri-pubertal gymnasts showed better explosive power measured via jump height and drop jump ratios than swimmers, tennis and handball players (Bencke, et al., 2002). Gains in explosive power observed in pre- and peri-pubertal elite gymnasts continue through puberty and concur with strength based differences. Elite adolescent gymnasts had better maximal trunk and knee extension strength than non-gymnasts as well as better knee extension in one leg than rhythmic gymnasts (Helge & Kanstrup, 2002). Differences in strength do not stop at adolescence. Elite collegiate gymnasts had better elbow flexor strength than elite synchronised swimmers (Liang, Arnaud, Steele, Hatch, & Moreno, 2005). Collegiate gymnasts also showed greater muscle strength than non-gymnasts (Taaffe & Marcus, 2004). Specifically, the gymnasts had better upper body strength identified by a bench press as well as lower body strength assessed with a leg press and knee extension. Therefore, elite gymnasts have better strength and power than non-elite gymnasts, rhythmic gymnasts, participants in other sports and non-gymnasts (Bencke, et al., 2002; Helge & Kanstrup, 2002; Laing, et al., 2005; Taaffe & Marcus, 2004). When strength scores were adjusted for differences in body weight, gymnasts' advantages in strength increased (Helge & Kanstrup, 2002).

2.3.1.2 Muscle function and non-elite gymnastics participation

Although most of the literature on artistic gymnastics tends to focus on elite level gymnasts, some investigations have included muscle parameters of non-elite gymnasts. Lower body strength and power has been assessed through one repetition maximum knee extensions and counter movement jumps. In agreement with elite level gymnasts, non-elite artistic gymnasts demonstrated greater dynamic strength and power than rhythmic gymnasts and controls. This was reflected by 30 to 39% greater vertical jump height compared with rhythmic gymnasts and controls, respectively (Vicente-Rodriguez, et al., 2007). Non-elite gymnasts also displayed better explosive power than endurance trained girls and controls (Jurimae & Jurimae, 2005). Furthermore, the leg strength of artistic gymnasts was greater among high (11.6 hr/wk) level gymnasts than controls and low (4.7 hr/wk) level gymnasts (Scerpella, et al., 2003).

In agreement with trends in results from muscle function in the lower body, muscle function gains in pre-pubertal non-elite gymnasts have been reported at the upper body. High level artistic gymnasts, had significantly greater elbow extension strength, determined by one repetition maximum, than controls and low level gymnasts (Scerpella, et al., 2003). Grip strength and elbow flexion were also assessed among high and low level gymnasts and controls. Between group differences among the two gymnastic groups were not observed for these measures however, both elbow flexion and grip strength were significantly higher for gymnasts than controls (Scerpella, et al., 2003). However, differences in strength between non-elite gymnasts and non-gymnasts are not guaranteed. Strength gains observed between pre-pubertal non-elite gymnasts and controls at baseline decreased over time (two years) and at study completion, no significant strength differences existed between groups (Gero, et al., 2005).

In addition to strength, upper body explosive power is vital to success in artistic gymnastics. Upper body power has been measured by medicine ball throws among gymnasts of varying ability and ages (Salonia, et al., 2004). No differences between the type of throw (overhead forwards, backwards and chest pass), throw distance and age or participation level occurred. Indices of upper body strength and power generally favoured gymnasts. However, upper body protocols and group characteristics lack consistencies between studies and compromise external validity.

Literature reporting muscle function in young gymnasts may be under reporting muscle advantages. Although gymnasts are characterised by small stature and light body weight, only one study reported muscle function parameters relative to body weight (Helge & Kanstrup, 2002). Furthermore, bias may be evident in the literature as gymnasts typically strength train in many of the tasks or movements used for assessment. Future muscle function assessment between gymnasts and non-gymnasts should involve non gymnastic-specific movements and be normalised for body weight.

CHAPTER THREE

SKELETAL ADAPTATIONS ASSOCATED WITH PRE-PUBERTAL GYMNASTICS PARTICIPATION: A META-ANALYSIS

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3.1 Abstract

The objective of this meta-analysis was to determine the magnitude of difference in bone mineral density and content between pre-pubertal girls participating in artistic gymnastics, compared with non-gymnasts. Previous reviews on gymnastics participation and bone health were broad; not limited to a particular maturation period, such as pre-puberty, and lacked methodological rigor. Following a systematic search strategy, 17 studies were included in this review and meta-analysis; 6 were longitudinal, one was a randomised control trial and the remaining were cross-sectional studies. All studies used dual-energy X-ray absorptiometry (DXA) to assess skeletal health. In addition, two studies included peripheral quantitative computed tomography (pQCT) to assess the forearm and lower leg. Following the implementation of a random effects model within the meta-analysis, bone-related properties as measured by both DXA and pQCT, showed gymnasts had greater bone properties than non-gymnasts. The largest positive effect on bone health was observed in pQCT-derived bone density between gymnasts and non-gymnasts, at the distal radius (d = 1.06). Upper body DXA results also favoured gymnastics participation revealing gymnasts had more bone mass than non-gymnasts (d = 0.84). In conclusion, participation in artistic gymnastics during pre-pubertal growth was associated with positive skeletal health benefits, particularly to the upper body.

3.2 Introduction

In that last decade, general involvement in childhood physical activity has increased (Australian Bureau of Statistics, 2010). Gender-specific statistics show, participation has increased more for girls than boys (Australian Bureau of Statistics, 2010). Strategies to increase physical activity in girls may include the promotion of participation in sports or physical activities that are predominantly dominated by females, for example gymnastics and ballet. Over the past decade, participation rates in gymnastics have continually increased and now involve over 121,000 participants within Australia; 80% of whom are female (Australian Bureau of Statistics, 2011; Gymnastics Australia, 2009). Furthermore, gymnastics popularity is nationwide, for example in the USA there are over five million participants, again the majority being female under 18 years old (USA Gymnastics, n.d.).

Physical activity and skeletal health benefits are particularly important for young girls as later in life; osteoporosis and osteoporosis-related fractures are known to affect more women than men. Participation in sport and physical activity during growth increases bone mineral density (Bass, et al., 1998; Karlsson, et al., 2001), bone mass (Ducher, et al., 2009; Matthews et al., 2006; Vicente-Rodriguez, et al., 2003; Zouch et al., 2008) and bone strength (Erlandson, et al., 2011; Ward, et al., 2005). Generally, high impact sports are associated with greater osteogenic benefits than low impact or weight supported sports (Ferry et al., 2011; Nikander, et al., 2006; Silva, Goldberg, Teixeira, & Dalmas, 2011). Furthermore, some studies suggest skeletal benefits may be greater if sports participation precedes pubertal growth (Bradney, et al., 1998; Kontulainen, et al., 2003; Vicente-Rodriguez, et al., 2003). It has also been speculated that skeletal benefits acquired during growth may help prevent fractures later in life however, additional research is required (Bass, 2000).

Gymnastics offers a unique sport-related model. On one hand, the young age and extraordinary training duration of gymnasts, continued for many years (Caine, Cochrane, Caine, & Zemper, 1989), in addition to the high impact and muscular loading offer skeletal adaptations. However, on the other hand, poor nutrition practices (Jonnalagadda, Benardot, & Nelson, 1998; Nova, et al., 2001), injuries (Caine, et al., 1989; Kirialanis et al., 2002) and delayed maturation (Caine, et al., 2003) are a concern for young gymnasts. The combination of these characteristics provides an exceptional model worth investigating.

The osteogenic effects of gymnastics participation have previously been investigated at different stages of maturation. Other than pre-pubertal maturation, pubertal (Dowthwaite, Kanaley, Spadaro, Hickman, & Scerpella, 2009; Dowthwaite & Scerpella, 2011; Gero, et al., 2005; Pikkarainen et al., 2009; Scerpella, Dowthwaite, Gero, Kanaley, & Ploutz-Snyder, 2010), collegiate (Modlesky, Majumdar, & Dudley, 2008; Mudd, Fornetti, & Pivarnik, 2007; Taaffe & Marcus, 2004) and retired (Ducher, et al., 2009; Eser, et al., 2009; Kudlac, Nichols, Sanborn, & DiMarco, 2004; Pollock, Laing, Modlesky, O'Connor, & Lewis, 2006) artistic gymnasts have been examined. The majority of previous studies addressed female artistic gymnasts, although males have been investigated individually (Daly, Rich, Klein, & Bass, 1999) and combined with females (Erlandson, et al., 2011; Ward, et al., 2005). Furthermore, previous research in young female gymnasts has also relied on dual-energy X-ray absorptiometry (DXA) to explore skeletal parameters. Three-dimensional imaging techniques such as peripheral quantitative computed tomography (pQCT) are now combined with DXA to better assess bone health, particularly in pediatric populations (Bishop, et al., 2007).

The objective of this meta-analysis was to determine the magnitude of differences in bone mineral density and content between pre-pubertal girls participating in artistic gymnastics, compared with non-gymnasts.

3.3 Methods

3.3.1 Search Strategy

The search strategy consisted of four online databases: Pubmed, Ovid Medline, Web of Science and Sports Discus. Data bases accessed were limited to literature between 1996 to June 2010. This period was chosen because of the dynamic and ongoing changes to gymnastics following 1996. In 1996, the way team competitions were performed changed. Compulsory routines were eliminated from competition. In 1997 the minimum age for international elite competition became sixteen years of age. In addition a new ‘code of points’ which regulates all gymnastics competition and changes every four years would have been implemented in 1997, following the 1996 Olympics.

General search strategies can be seen in Table 3.1. Individual databases were adapted based on specific options such as MeSH terms (PubMed) and subject headings (Ovid Medline). Specific terms were not used in the remaining databases however, limits were set. Reference lists of included studies were manually searched for additional manuscripts.

Table 3.1

Outline of General and Specific Search Terms

General Terms	Specific Terms	Limits
1. Gymnastics 2. Gymnast* 3. Bone 4. 2 and 3 5. Bone Strength 6. Bone Density 7. 1 and 5 8. 1 and 6	PubMed MeSH Major Topic • Bone Density Ovid Medline Subject Heading • Bones and Bones [physiology] • Gymnastics	1. Humans 2. English 3. Child

3.3.2 Inclusion and Exclusion Criteria

Studies involving pre-pubescent girls were selected for inclusion. Pre-pubertal maturation classification required participants to have a Tanner score of stage one for breast and pubic hair development or a serum estradiol level at or below the diction limit of 55 pmol/l (Bass, et al., 1998). If stage of pubertal maturation was not reported, a conservative estimate was made. Specifically, girls aged ten years and under (identified from a range rather than mean score) were classified as pre-pubertal. Although this may also include early pubertal girls, it is expected that the large majority of the sample would be pre-pubertal.

Studies of gymnasts were included independent of level of participation (elite, non-elite or recreational). Elite gymnasts are those training at an international level. These gymnasts often train in excess of 25 hours per week, up to six days a week for 12 months of the year. Furthermore, these young gymnasts typically begin training at the age of five or six years old (Caine, et al., 1989). Highly competitive gymnasts also participate seriously, often 12 months of the year however, this group of gymnasts may not be at an international level. Non-elite gymnasts, for the purpose of this review, were classified as those gymnasts who may or may not have competed at a low level and who participated in gymnastics for less than 15 hours per week. Recreational gymnasts were non-competitive gymnasts participating in the sport for fun, health, and social benefits. While gymnasts were not excluded based on level of participation, they had to be involved in artistic gymnastics. Hence, studies in which gymnasts were participating in rhythmic or other gymnastic disciplines were excluded. If the study combined gymnasts with another sporting activity, or combined male and female gymnasts and only reported collective data, the study was excluded.

Studies identifying bone density and or bone content and area as primary outcome variables were included in this review. However, studies were only included if they used either DXA or pQCT to quantify bone outcome variables. Studies using MRI, radiographs or ultrasound were excluded. Furthermore, studies assessing bone health were excluded when related to injury or nutritional practices (e.g. adequate caloric/nutritional intake).

3.3.3 Study Selection

One author (L.B.) conducted all literature searches and collated the abstracts. Two authors (L.B and G.N.) then separately reviewed the abstracts and based on the selected criteria, determined if the studies were suitable for inclusion. If the abstract did not give a clear indication of eligibility the full text article was obtained and reviewed. If the two authors disagreed a discussion took place. A third author (D.G.) was asked to review the study, if the previous two authors could not resolve the issue.

Authors of several studies (four) were sent emails requesting data necessary for inclusion as their research could potentially be included. Correspondence was initiated if data were combined for sporting involvement (one author), maturation Tanner stage 1 and 2 (one author) or gender (two authors) and met all other criteria. Two authors replied to emailed requests and one provided data that were included in this review.

Quality assessment of all studies included in the review (Table 3.2) was categorised via the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) criteria (Vandenbroucke et al., 2007; Von Elm et al., 2007).

3.3.4 Data Extraction

One author (L.B.) independently extracted bone density, content and area data from the included studies, creating a database of study details. Additional data from personal communication (K.A. Ward, personal correspondence, February 25, 2011) were compiled, added to the database and included in the results.

Estimates of volumetric bone density calculated by DXA (bone mineral apparent density or volumetric BMD), reported by several studies was not extracted for this review. Volumetric density by DXA is an empirical method of attempting to adjust for differences in the third dimension that BMD does not capture (Heaney, 2003). Furthermore, calculation/inferred bone data such as geometric properties generated from DXA, were not included in this review.

3.3.5 Meta-Analysis

Data from studies included in this review were able to be pooled on the basis of the similar methods selected for bone assessment. Studies using DXA for estimation of BMD were assembled and visually displayed in a forest plot. MetaEasy was used to perform the meta-analysis component of this systematic review (Kontopantelis & Reeves, 2009). Similar processes were conducted for DXA studies assessing BMC and bone area (BA). In addition to the two dimensional DXA reports, studies using pQCT to assess bone density were also combined using meta-analysis techniques.

Standardized mean differences, also known as Cohen's *d*, were used to explore the magnitude and direction of the extracted data. Specifically, small ($d = 0.2$), medium ($d = 0.5$) and large ($d = 0.8$) effects were identified.

Heterogeneity was used to assess the variability of the studies included in the review. The statistic I^2 was the selected measure of heterogeneity as it does not depend on the number or size of studies, nor the type of data included in the meta-analysis (Higgins, Thompson, Deeks, & Altman, 2003). As studies within the meta-analysis vary in level (elite, non-elite or recreational) and therefore hours of gymnastics participation, as well as training history, not all factors influencing the effect size were equal between studies. We therefore assume heterogeneity between studies and implemented a random effects model accordingly.

3.4 Results

The initial search strategy identified 143 potentially eligible studies. Of these, 55 were excluded on the basis of age or maturation status of participants. A further 18 were excluded as they were not focusing on artistic gymnastics, 17 were injury-based studies and 10 were review papers. Another 26 studies were excluded for numerous reasons such as full text not being in English, raw bone data not presented, and data being combined for sporting groups, maturation and/or gender. The remaining 17 studies are outlined in Table 3.2. Of the 17 studies, six were longitudinal (although at times only baseline data was included in the review due to follow up measures failing to meet the inclusion criteria i.e. pubertal maturation), one was a randomised controlled trial and the remaining were cross-sectional studies. All included studies used dual-energy X-ray absorptiometry (DXA) for whole body and or regional bone analyses. In addition, two of the studies extended analysis to include peripheral quantitative computed tomography (pQCT) of the radius and (in one case) tibia.

3.4.1 Participant Characteristics

A total of 370 young girls with a mean age of 9.9 years, training 13.5 hr/wk with a training history of 3.6 years were included in this review. No single country predominated the research on pre-pubertal gymnasts. Studies were from several different countries including: Australia, Canada, England, Finland, France, and the USA. Most studies had similar exclusion criteria, excluding participants who were not in good health, had recent fracture, were taking medication/supplementation or had a medical condition known to affect bone metabolism.

The involvement in physical activity of the control/non-gymnasts groups differed between studies and contributed to heterogeneity. Few had sedentary controls while others used active girls participating in a variety of sports such as soccer, basketball, dancing and swimming. Sporting participation of the controls varied from recreational to competitive involvement. Few studies included controls who had experience in or who were participating in recreational gymnastics (Bass, et al., 1998; Courteix, Lespessailles, Loiseau-Peres, Obert, Germain, et al., 1998).

Table 3.2

Specific Descriptive Characteristics of Studies Included in the Meta-Analysis

Title	Design	Participants	DXA ROI	DXA Variables	pQCT ROI	pQCT Variables	STROBE Score(%)
Ward et al., 2007 *	RCT	Gymnasts n = 20 **placebo**, age 9.8(±1.6) yrs, 13.2(±4.4) hr/wk PA & **calcium** n = 19, age 10.8(±1.4) yrs, 15.6(±4.3) hr/wk PA Controls n = 18 **placebo**, age 10.5(±1.1) yrs, 7.3(±3.6) hr/wk PA & **calcium** n = 18, age 9.8(±1.6) yrs; 6.9(±4.1) hr/wk PA Tanner 1 data only	Total body, Lumbar spine	BMC, BA, BMAD	4% & 50% radius 10mm & 65% Tibia	ToD, TrD, CoD ToD, TrD, CoD	90%
Dowthwaite et al., 2007	Cross-sectional	Gymnasts n = 12, min 6hr/wk, min 2 yrs training history Non-gymnasts n =10, >5hr/wk PA Age 7-12 yrs, Tanner 1 data only	Ultradistal, 1/3 Distal Radius	BMC, aBMD, BMAD	-	-	68%
Dowthwaite et al., 2006	Cross-sectional	Gymnasts n = 12, age 10.0 (±1.0) yrs, 10.3(±2.4) hr/wk, min 2yrs training history Non-gymnasts n =10, age 10.4(0.9) yrs, 4.6(±5.5) hr/wk PA Tanner 1 data only	Forearm, Lumbar Spine, Femoral Neck	aBMD, BMC, BA	-	-	81%
Laing et al., 2005	Longitudinal (2 years)	Gymnasts n = 65, age 6.0(±1.5) yrs at BL, low level 1.24(0.63) hr/wk, high level = 7.89(3.05) hr/wk, no training history at BL Controls n = 78, age 6.3(±1.6) yrs	Total Body, Lumbar Spine, Total Proximal Femur, Forearm	BA, BMC, aBMD	-	-	81%
Zanker et al., 2003	Cross-sectional	Gymnasts n = 10, age 8.0(±0.1) yrs, 8-10 hr/wk, 3-4 yrs training history Controls n = 10, age 7.6(±0.1) yrs Female data only	Total Body, Lumbar Spine, Total Body Regions	BMD, BMC, BA	-	-	86%

Title	Design	Participants	DXA ROI	DXA Variables	pQCT ROI	pQCT Variables	STROBE Score(%)
Jaffré et al., 2003	Cross-sectional	Gymnasts n = 56, age 10.8(±1.7) yrs, 12.4(±2.2) hr/wk Controls n = 64, age 10.7(±1.7) yrs, <3 hr/wk PA	Total Body, Lumbar Spine, Femoral Neck, Mid Radius	BMD	-	-	28%
Laing et al., 2002	Longitudinal (BL data only)	Gymnasts n = 7, age 10.7(±1.58) yrs, 11.7(±2.4) hr/wk, 5.9(±1.6) yrs training history Controls n = 10, age 10.7(±1.26) yrs, 3-5 hr/wk PA	Total Body, Lumbar Spine, Femoral Neck, Trochanter, Total Proximal Femur	aBMD, BMC, BA	-	-	74%
Lehtonen-Veromaa, Mottonen, Irjala et al., 2000a	Longitudinal (BL data only)	Gymnasts n = 12, age 11.4(±1.1) yrs, 64.3(±29.8) MET hr/wk, 5.4(±1.6) yrs training history Runners n = 8, age 10.1(±0.8) yrs, 37.7(±26.3) MET hr/wk, 3.2(±1.1) yrs training history Controls n = 9, age 11.1(±1.4) yrs, 8.4(±8.9) MET hr/wk Tanner 1 data only	Lumbar Spine, Trochanter, Femoral Neck	BMD	-	-	71%
Lehtonen-Veromaa, Mottonen, Svedstrom et al., 2000b	Cross-sectional	Gymnasts n = 16,age 11.2(±0.7) yrs, 63.3 MET hr/wk, >1yr training history Runners n = 15, age 10.5(±1.2) yrs, 20.0 MET hr/wk, >1yr training history Controls n = 14, age 10.9(±0.9) yrs, 7.8 MET hr/wk Tanner 1 data only	Femoral Neck, Lumbar Spine, Distal Radius, Distal Ulna	BMD	-	-	76%
Courteix, Lespessailles, Jaffre et al., 1999a	Longitudinal (1 year)	Gymnasts n = 14, age 11.6(±1.3) yrs at study completion, 12-15 hr/wk, 3 yrs training history Controls n = 21, age 11.8(±1.1) yrs at study completion, <3 hr/wk PA	Total Body, Lumbar Spine, Femoral Neck, Trochanter, Wards Triangle, Overall/Mid & Ultra-Distal Radius	BMD, BMC	-	-	67%

Title	Design	Participants	DXA ROI	DXA Variables	pQCT ROI	pQCT Variables	STROBE Score(%)
Courteix, Lespessailles, Obert et al., 1999b	Cross-sectional	Gymnasts n = 27, age 10.2(±1.4) yrs, 10-15 hr/wk, 3 yrs training history Swimmers n = 11, age 10.6(±1.1) yrs, 8-12 hr/wk, 3 yrs training history Controls n = 16, age 10.5(±1.1) yrs, 2 hr/wk PA	Total Body, Lumbar Spine, Femoral Neck, Trochanter, Wards Triangle, Mid & Ultra-Distal Radius, Head, Ribs	BMD, BMC	-	-	63%
Nickols-Richardson et al., 1999	Longitudinal (BL data only)	Gymnasts n = 9, age 10.0(±0.3) yrs at BL, 15.7(±1.6) hr/wk, 7.1(±0.6) yrs training history Controls n = 9, age 10.1(±0.3) yrs	Total Body, Lumbar Spine, Femoral Neck, Trochanter, Total Proximal Femur, Wards Triangle	BMD	-	-	77%
Courteix, Lespessailles, Loiseau-Peres, Obert, Ferry et al., 1998a	Cross-sectional	Gymnasts n = 18, age 10.4(±1.3) yrs, 3 yrs training history Swimmers n = 10, age 10.5(±1.4) yrs, 3 yrs training history Controls n = 13, age 10.7(±1.0) yrs	Total Body, Lumbar Spine, Femoral Neck, Trochanter, Wards Triangle, Overall Radius	BMD, BMC	-	-	54%
Courteix, Lespessailles, Loiseau-Peres, Obert, Germain et al., 1998b	Cross-sectional	Gymnasts n =18, age 10.4(±1.3) yrs, 10-15 hr/wk, 3 yrs training history Swimmers n = 10, age 10.5(±1.4) yrs, 8-12hr/wk, 3 yrs trainings history Controls n = 13, age 10.7(±1.0) yrs, 2 hr/wk PA	Total Body, Mid-Radius, Distal Radius, Lumbar Spine, Femoral Neck, Trochanter, Ward's Triangle	BMD, BMC	-	-	65%
Bass et al., 1998	Longitudinal (BL data only)	Gymnasts n = 45, age 10.4(±0.3) yrs, 15-36 hr/wk Controls n = 35, age 9.3(±0.2) yrs, 1.7(±0.3) hr/wk PA	Total Body, Lumbar Spine, Femoral Mid-shaft, Total Body Regions	aBMD, vBMD	-	-	68%
Dyson et al., 1997	Cross-sectional	Gymnast n = 16, age 9.8(±0.9) yrs, 16-23 hr/wk, 3-7 yrs training history Controls n = 16, age 9.9(±0.8) yrs, ≤1 PA session.wk^{-1}	Total Body, Femoral Neck, Trochanter, Lumbar Spine	BMD, BMAD	6% forearm	ToD, TrD, CoD	65%

Title	Design	Participants	DXA ROI	DXA Variables	pQCT ROI	pQCT Variables	STROBE Score(%)
Cassell et al., 1996	Cross-sectional	Gymnasts n = 14, age 8.8 (±0.2) yrs, 13.9 hr/wk; >1yr training history Swimmers n = 14, age 9.0 (±0.2) yrs, 4.7 hr/wk; >1yr training history Controls n = 17, age 8.3 yrs (±0.2) yrs	Total Body	BMD	-	-	63%

Where available, details given as mean (±SD). BL: Baseline; BMD: Bone Mineral Density; BMC: Bone Mineral Content; aBMD: Areal Bone Mineral Density; vBMD: Volumetric Bone Mineral Density; BMAD: Bone Mineral Apparent Density; BA: Bone Area; ToC: Total Content; ToD: Total Density; ToA: Total Area; TrD: Trabecular Density; BSI: Bone Strength Index; CoC: Cortical Content; CoD: Cortical Density; CoA: Cortical Area; SSIp: Polar Strength Strain Index; CoThk: Cortical Thickness; MedA: Medullary Area

* denotes data (bone not descriptive) modified (male participants removed from the study) as a result of personal correspondence with the authors.

3.4.2 Quality Assessment

Quality assessment of the 17 included studies, as outlined by the STROBE criteria, varied from 28 to 90% (Thesis Appendix A). Overall, the studies performed best in the methods section and worst in the discussion section. Declarations of study limitations and generalisability were the specific areas within the discussion that were poorly written. Additional components generally lacking within the literature included specific descriptions of: study design, sample size and power, number of participants at each stage of the study and how data were checked and treated for normal distribution. According to the STROBE criteria, the rationale, study setting, description of outcome variables, descriptive data, key findings and interpretation were reported well.

3.4.3 Bone Mineral Density

3.4.3.1 Dual-energy X-ray absorptiometry (DXA)

Areal bone mineral density (BMD) data were analysed both as a whole (total of all reported regions) and sub-divided into total body, upper body, lower body and axial skeletal regions. When all studies and body regions were analysed simultaneously, the overall effect of gymnastics participation on areal BMD was moderately positive ($d = 0.70$) (Figure 3.1). Fourteen studies reported lower body areal BMD measures, which for the purpose of this review consisted of legs, total proximal femur, femoral neck, trochanter and Ward's triangle. Compared with the upper body, the lower body region had a higher positive effect ($d = 0.75$) for bone density between gymnasts and non-gymnasts. In addition, the axial skeleton displayed a medium positive effect ($d = 0.56$), although to a lesser extent than the lower body. The meta-analysis revealed a positive trend towards total ($d = 0.22$) and upper body ($d = 2.22$) areal BMD benefits however, results were not significant due to large heterogeneity between studies.

Following separation for level of participation, elite and highly competitive gymnasts had greater areal bone density than non-gymnasts (*d* = 0.75) whereas non-elite and recreational gymnasts were not different from non-gymnasts (*d* = 0.54). The studies included in this analysis showed most of the variability was due to heterogeneity among studies, rather than chance (I^2 57 to 99%).

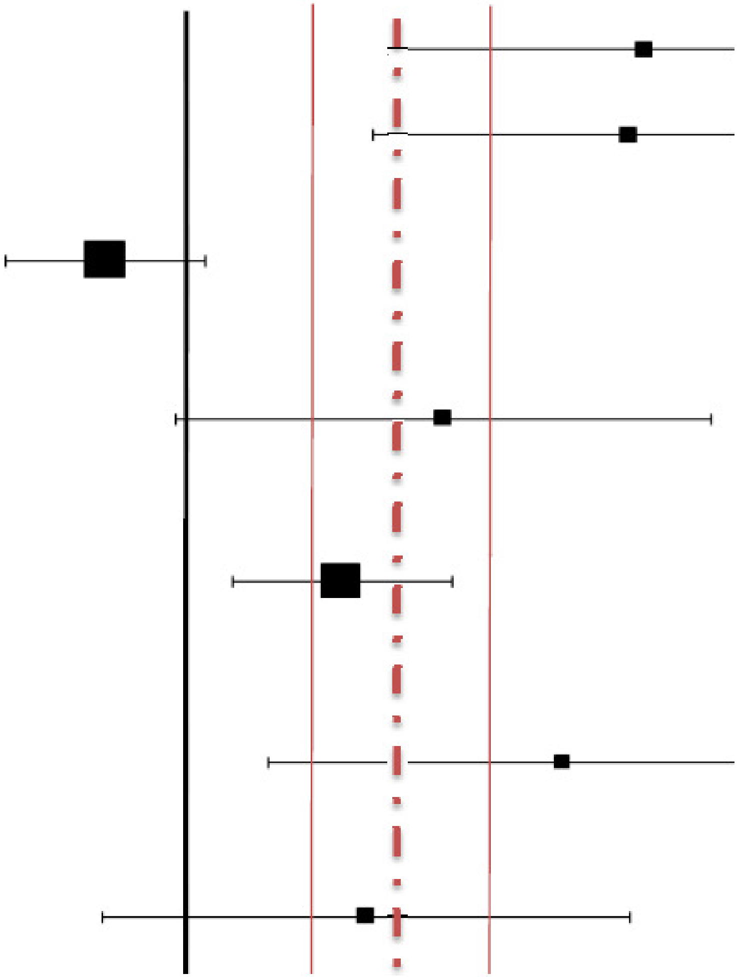
3.4.3.2 Peripheral quantitative computed tomography (pQCT)

Two studies reported volumetric bone density using pQCT. When data were interpreted as a whole (total of all radial and tibia regions and all measures of density; cortical, trabecular and total), the overall effect of gymnastics participation on bone density as determined by three dimensional pQCT analysis was largely positive (*d* = 0.83). Furthermore, a large positive effect (*d* = 1.06) was observed between the gymnasts and non-gymnasts for distal radial volumetric bone density (total of both trabecular and total). Only one study reported pQCT tibia volumetric bone density and as a result, no additional analyses were performed. The studies included in this analysis revealed moderate heterogeneity (I^2 64%).

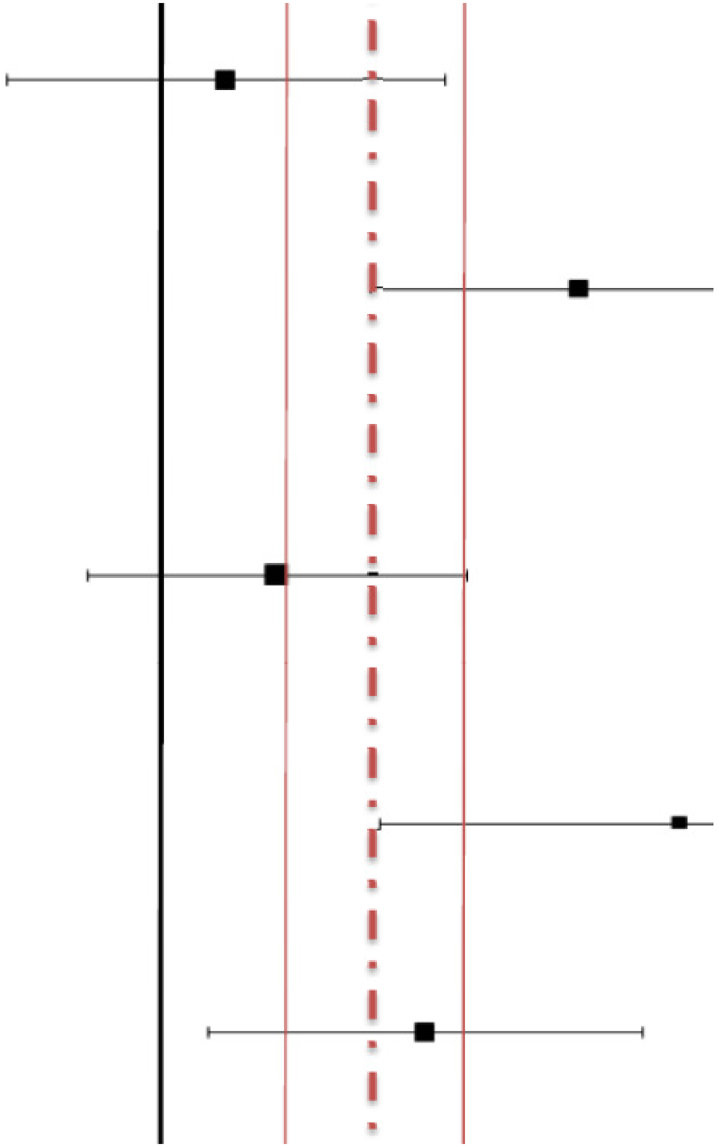
3.4.4 Bone Mineral Content Obtained by DXA

Ten of the included studies reported BMC. However, one study reported mean scores without the deviation around the mean. As a result, nine studies were entered into the BMC meta-analysis. Once again, studies and body regions were combined for analysis. The overall effect of gymnastics participation on BMC was moderate but positive (*d* = 0.46) (Thesis Appendix B). The only specific region to show significant differences between gymnasts and non-gymnasts was the upper body which consisted of forearm, ultra distal, mid and total radius (*d* = 0.84). As a marker of quality, the meta-analysis model rated heterogeneity (I^2) of the studies reporting bone mineral content from 69 to 82%.

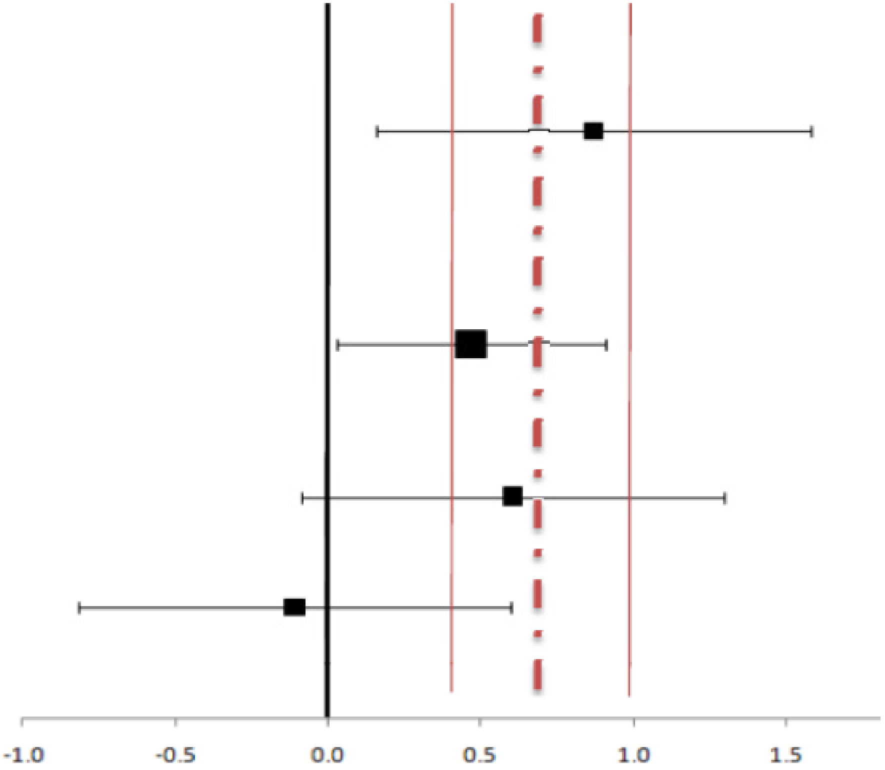
Author	Design	n	Region	Individual Variables			Overall		
				ES	**95% CI**	**95% CI**	**ES**	**95% CI**	**95% CI**
Dowthwaite et al., 2007	CS	12	ultradistal R	2.036	1.197	2.876	1.503	0.664	2.342
			1/3 distal R	0.970	0.130	1.809			
Dowthwaite et al., 2006	CS	12	LS	1.529	0.690	2.369	1.445	0.606	2.285
			F	1.445	0.606	2.285			
			FN	1.115	0.276	1.955			
Laing et al., 2005	LT	65	TB	-0.427	-0.756	-0.097	-0.271	-0.600	0.058
			LS	-0.237	-0.567	0.092			
			TPF	-0.292	-0.621	0.037			
			F	-0.250	-0.579	0.079			
Zanker et al., 2003	CS	10	TB	0.681	-0.195	1.558	0.833	-0.043	1.710
			Arms	1.624	0.748	2.501			
			Legs	0.592	-0.285	1.468			
			Spine	0.870	-0.007	1.746			
			LS	0.833	-0.043	1.710			
Jaffre et al., 2003	CS	56	TB	-0.076	-0.435	0.282	0.503	0.144	0.862
			LS	0.420	0.061	0.779			
			FN	0.586	0.227	0.945			
			Mid R	10.800	10.441	11.159			
Laing et al., 2002	CS	7	TB	0.922	-0.044	1.888	1.227	0.261	2.193
			LS	1.129	0.163	2.095			
			FN	1.294	0.328	2.260			
			T	1.161	0.195	2.127			
			TPF	1.391	0.425	2.357			
			R	3.028	2.062	3.994			
Lehtonen-Veromaa et al., 2000a	CS	12	LS	0.072	-0.792	0.936	0.581	-0.283	1.445
			FN	0.966	0.101	1.830			
			T	0.581	-0.283	1.445			



Lehtonen-Veromaa et al., 2000b	CS	16	LS	0.209	-0.508	0.927	0.209	-0.508	0.927
			FN	0.743	0.026	1.460			
			Distal R	0.209	-0.508	0.926			
			Distal U	0.183	-0.535	0.900			
Courteix et al., 1999a	LT	14	TB	0.598	-0.078	1.274	1.368	0.692	2.044
			LS	1.043	0.367	1.720			
			FN	1.554	0.878	2.231			
			T	1.075	0.399	1.752			
			WT	1.182	0.505	1.858			
			R	1.855	1.179	2.531			
			Distal R	1.862	1.185	2.538			
			Mid R	1.675	0.999	2.351			
Courteix et al., 1999b	CS	27	TB	-0.150	-0.768	0.468	0.379	-0.239	0.998
			LS	0.386	-0.232	1.005			
			FN	0.721	0.102	1.339			
			T	0.372	-0.246	0.991			
			WT	0.336	-0.282	0.954			
			Head	-0.984	-1.602	-0.366			
			Mid R	1.234	0.616	1.852			
			Distal R	1.740	1.122	2.358			
Nickols-Richardson et al., 1999	CS	9	TB	1.408	0.428	2.388	1.697	0.717	2.677
			LS	1.693	0.713	2.673			
			FN	1.701	0.721	2.681			
			T	2.166	1.186	3.146			
			WT	1.645	0.665	2.625			
			TPF	2.014	1.034	2.994			
Courteix et al., 1998a	CS	18	TB	0.173	-0.540	0.887	0.863	0.150	1.577
			LS	0.856	0.142	1.569			
			FN	1.276	0.562	1.989			
			T	0.777	0.064	1.491			
			WT	0.871	0.158	1.584			
			R	1.823	1.110	2.537			



Courteix et al., 1998b	CS	18	TB	0.173	-0.540	0.887	0.871	0.158	1.584
			LS	0.856	0.142	1.569			
			FN	1.276	0.562	1.989			
			T	0.777	0.064	1.491			
			WT	0.871	0.158	1.584			
			Mid R	1.740	1.027	2.454			
			Distal R	2.356	1.643	3.069			
Bass et al., 1998	CS	45	TB	0.471	0.912	0.442	0.471	0.912	0.442
			Spine	0.784	1.226	0.442			
			Legs	0.370	0.812	0.442			
			Arms	1.098	1.540	0.442			
			Skull	0.078	0.520	0.442			
Dyson et al., 1997	CS	16	TB	0.248	-0.445	0.941	0.610	-0.083	1.303
			LS	0.401	-0.292	1.094			
			FN	0.819	0.126	1.512			
			T	1.132	0.439	1.825			
Cassell et al., 1996	CS	14	TB	-0.102	-0.810	0.6051	-0.102	-0.810	0.6051
				Overall model			0.695	0.397	0.994
				I^2				71%	



Between group differences reported in effect size (ES) and 95% confidence intervals (95% CI). A positive ES (Cohen's *d*) indicates gymnasts > non-gymnasts. CS: cross-sectional; LT: Longitudinal; Ultra distal R: ultra distal radius; 1/3 distal R: 1/3 distal radius; R: radius; Distal R: distal radius; Distal U: distal ulna; Mid R: mid radius; F: forearm; LS: lumbar spine; TB: total body; FN: femoral neck; TPF: total proximal femur; T: trochanter; WT: Ward's triangle. Longitudinal studies from which only baseline data were extracted for inclusion have been identified as cross-sectional as one data point was included. The solid black line represents zero or no difference between gymnasts and non-gymnasts. Mean effects (black squares) to the right of the line indicated gymnasts had greater bone density than the non-gymnasts whereas mean effects to the left of the line indicated non-gymnasts had greater bone density than gymnasts. When the mean effect or error bars (predetermined by MetaEasy) crossed the 'zero line' there was no significant difference between groups. Red lines represent the mean (dashed line) and 95% CI (solid line) for the model.

Figure 3.1. Forest plot of bone mineral density identified by dual-energy X-ray absorptiometry

3.4.5 Bone Area Obtained by DXA

Four studies reporting BA were included in the meta-analysis, although not all studies reported the same regions (Thesis Appendix C). Gymnasts had a smaller BA than controls at the lower body (*d* = -0.32). Although insignificant, a trend towards a smaller bone area was evident for the total body (*d* = -0.32). Overall, heterogeneity of the studies ranged from low (I^2 = 25%) to high (I^2 = 82%).

3.5 Discussion

Following the implementation of a random effects model, bone-related properties as measured by both two (DXA) and three (pQCT) dimensional devices, revealed gymnasts had greater bone properties (BMD and BMC) than non-gymnasts. The positive magnitude of these differences was largest for pQCT-derived distal radial volumetric bone density followed by DXA upper body bone mass and lower body bone density. However, the increased DXA-derived bone density reported in the gymnasts' lower body may have been underestimated because gymnasts had smaller bones than non-gymnasts at this region. This meta-analysis on the effects of artistic gymnasts on pre-pubertal girls' bone health demonstrated considerable heterogeneity among studies. Specifically, studies varied in level and hours of participation, training history, selected equipment and regions of interest.

3.5.1 Site-Specific Effects of Gymnastics Participation

Bone density results favour gymnastics participation when all skeletal regions were analysed simultaneously. Following separation for specific skeletal regions, results from DXA and pQCT differed. From pQCT data, gymnasts had a denser distal radius compared with non-gymnasts. While the overall effect size for upper body bone density was large for DXA studies, it failed to reach significance. This non-significant result may have emerged as fewer studies reported upper body than lower body areal bone density. Perhaps with the inclusion of additional studies with less variable results, significance would have been attained. In addition, the inter-study variability identified by the upper body DXA meta-analysis may have resulted from differences between the distal and proximal regions of long bones, as well as the type of bone (cortical and trabecular), all of which the pQCT is able to analyse separately. Results from DXA were collated for regions of interest in the meta-analysis. Differences in findings regarding trabecular, cortical and total bone density have previously been identified in pre-pubertal gymnasts using pQCT (Erlandson, et al., 2011; Ward, et al., 2005).

Using DXA, results indicated pre-pubertal gymnasts had denser bones at the lower body and axial skeletal regions, compared with non-gymnasts. Direct comparisons with the three dimensional meta-analysis were not possible as the pQCT is unable to scan the axial skeleton and only one study reported bone density at the lower limb (K.A. Ward, personal correspondence, February 25, 2011). While a small to medium positive trend emerged for pQCT based tibia density among pre-pubertal female gymnasts, size-related DXA discrepancies in areal BMD cannot be confirmed due to the single study included in this review (K.A. Ward, personal correspondence, February 25, 2011). Additional pre-pubertal research using three dimensional techniques are required to determine if the gains in bone density within young girls outlined with two dimensional techniques are in fact present.

3.5.2 Bone Mineral Density vs. Bone Mineral Content

Within the literature, bone density was most commonly assessed with DXA. Therefore, conclusions relating to children investigated longitudinally should be cautioned. Bone geometry, which changes dramatically during growth, introduces bias in basic DXA analyses. Bone density calculated by DXA is the result of BMC divided by bone area, not bone volume (Prentice, et al., 1994). This is an inadequate surrogate for bone density during growth and limits the use of BMD as a reliable estimate of bone density in children (Nelson & Koo, 1999). As the gymnasts within this review displayed a trend towards increased BMC and had a smaller bone area than non-gymnasts at the lower body, the areal BMD of gymnasts may have been underestimated.

Bone mineral content identified by DXA was reported less frequently than density among these pre-pubertal gymnasts. In light of previous concerns about areal bone density (Heaney, 2003), longitudinal studies more appropriately report bone mass. When all studies and regions of interest were combined together, bone mass differences between gymnasts and non-gymnasts favoured the gymnasts. The upper body, when analysed independently was the only additional region of interest that followed this trend. Assessment of bone mass was not reported in the pQCT studies included in this review (K.A. Ward, personal correspondence, February 25, 2011; Dyson, et al., 1997). Even when the scope of the literature was widened to include male and female pre-pubertal gymnasts, results remained inconclusive. Pre-pubertal male and female gymnasts and ex-gymnasts have previously shown greater radial and tibial total and cortical bone mass (Erlandson, et al., 2011). In contrast, no differences in cortical bone mass at the radius and tibia were observed between male and female pre pubertal gymnasts and non-gymnasts, in another study (Ward, et al., 2005).

Bone benefits observed in young gymnasts when compared to non-gymnasts may have been masked by the sporting involvement of the non-gymnasts who remain relatively active during the first decade of life. Generally, the non-gymnasts were actively involved in organised physical activity outside school (Bass, et al., 1998; Courteix, Lespessailles, Loiseau-Peres, Obert, Ferry, et al., 1998; Courteix, Lespessailles, Loiseau-Peres, Obert, Germain, et al., 1998; Dowthwaite, et al., 2006; Dowthwaite, et al., 2007; Jaffre, et al., 2003; Laing, et al., 2002; Ward, Roberts, et al., 2007). Participation in such activities, in addition to childhood free play and school-based physical education programs which predominantly load the lower limbs, may have influenced the bone properties of the non-gymnasts within this review. Gains in lower body bone density from pre-pubertal involvement in soccer and dance (Matthews, et al., 2006; Vicente-Rodriguez, et al., 2003) in which some of the non-gymnasts were involved, have previously been reported. Nevertheless, some between-group differences for the lower body emerged. Gymnastics participation is associated with higher ground reaction forces at the lower body compared with the upper body (Burt, Naughton, Higham, & Landeo, 2010; Daly, et al., 1999) furthermore gymnasts have greater lower body explosive power (Bencke, et al., 2002) and strength (Helge & Kanstrup, 2002) than non-gymnasts. Therefore, the varied and habitual loading synonymous with gymnastics participation, even from an early age, is likely to contribute to bone development, and may have influenced the between group differences.

3.5.3 Study Design

Following separation of studies based on study design (longitudinal vs. cross-sectional), the results generally concur. Based on longitudinal BMC, one study reported gymnasts had less BMC (Laing, et al., 2005) whereas another study found gymnasts to have more BMC, at both the lower and upper body (Courteix, Lespessailles, Jaffre, et al., 1999). However, when adjustments were made for baseline differences, the gymnasts in both studies displayed greater BMC gains than non-gymnasts over the duration of the study. Longitudinal literature on pre-pubertal gymnasts suggests that irrespective of training history and participation level (beginner, recreational gymnasts or highly competitive gymnasts), involvement in gymnastics tends to favour bone acquisition among gymnasts (Courteix, Lespessailles, Jaffre, et al., 1999; Laing, et al., 2005). The bone benefits displayed through the cross-sectional studies included in this review are supported by the findings of the longitudinal literature.

One randomised control trial on calcium supplementation and elite gymnastics participation was included in this review (K.A. Ward, personal correspondence, February 25, 2011). Calcium supplementation has previously been associated with positive effects on bone density (Bonjour, et al., 1997; Greene & Naughton, 2011; Ianc, et al., 2006) and area (Greene & Naughton, 2011) in children. Furthermore, an increase in calcium intake positively affected pubertal bone mass accrual in girls who initially had a calcium intake lower than the recommended nutrient intake (Zhang et al., 2010). However, when an adequate dietary intake was consumed, exercise may have a greater osteogenic effect than calcium alone (Iuliano-Burns, Stone, Hopper, & Seeman, 2005). Relating to gymnastics specifically, these results have been supported. No additional gains in skeletal adaptations following calcium supplementation were observed among pre-pubertal gymnasts who consumed their recommended nutrient intake (Ward, Roberts, et al., 2007). It was postulated, the bones of these elite gymnasts had already adapted from the high mechanical loading associated with the sport (Ward, Roberts, et al., 2007).

3.5.4 Participation Level

Sub-analysis of studies included in this review based on participation level (elite and highly competitive vs. non-elite and recreational) may support the notion that elite gymnasts have greater bone properties than non-elite and recreational gymnasts when compared with non-gymnasts. Following separation for participation level, elite and highly competitive gymnasts (Bass, et al., 1998; Courteix, Lespessailles, Jaffre, et al., 1999; Courteix, Lespessailles, Loiseau-Peres, Obert, Ferry, et al., 1998; Courteix, Lespessailles, Loiseau-Peres, Obert, Germain, et al., 1998; Courteix, Lespessailles, Obert, et al., 1999; Dyson, et al., 1997; Jaffre, et al., 2003; Nickols-Richardson, et al., 1999; Zanker, et al., 2003) had greater overall areal bone density than non-gymnasts. In contrast, non-elite and recreational gymnasts were not significantly different from the non-gymnasts (Cassell, et al., 1996; Dowthwaite, et al., 2006; Dowthwaite, et al., 2007; Laing, et al., 2002; Laing, et al., 2005; Lehtonen-Veromaa, Mottonen, Irjala, et al., 2000; Lehtonen-Veromaa, Mottonen, Svedstrom, et al., 2000). At the upper body, these differences appeared to be more pronounced with reported benefits for elite gymnasts more than three times greater than the mean effect of other studies (Jaffre, et al., 2003). Differences between participation level and bone density were not surprising given that elite gymnasts not only train significantly more hours than their non-elite counterparts, they also have a longer training history, larger muscle cross sectional area (Ducher, et al., 2009; Ward, et al., 2005) and are exposed to higher impact forces (Brown, et al., 1996; Panzer, Wood, Bates, & Mason, 1988), all of which play a role in bone health.

One longitudinal study assessing recreational gymnasts from their first gymnastics lesson compared girls remaining in a one hour per week class to those who increased participation to approximately eight hours per week (Laing, et al., 2005). The higher training gymnasts gained more bone area at the forearm than the girls who remained in the low training group. Similarly, a high group of peri-pubertal gymnasts (excluded from this review) training 11.6

hours per week had higher total body, forearm and hip bone density than gymnasts training 4.76 hours per week (Scerpella, et al., 2003). These findings suggest a dose-response relationship exists between hours of participation and bone development. Additional longitudinal research using three dimensional technologies is required to verify this association and to determine if the does-response relationship is similar in different bones and at different skeletal regions.

3.5.5 Quality Assessment

Quality of the included studies averaged 70% (range 28 to 90%). However, STROBE scores may not reflect the statistical power of individual studies. For example, one study scored 86% on the STROBE but had a total of 20 participants (n =10 gymnasts and n = 10 non-gymnasts) (Zanker, et al., 2003). Alternatively, another study with a total of 120 participants (56 gymnasts and 64 non-gymnasts) had a STROBE score of 28% (Jaffre, et al., 2003). Based on the results of this meta-analysis and the moderate overall effect size of the model (d = 0.695), it is recommended that future cross-sectional DXA studies looking to identify differences between two independent groups have a minimal sample size of 90 participants in order to maintain statistical power (90%) and to detect potential differences in areal BMD between gymnasts and non-gymnasts (Erdfelder, Faul, & Buchner, 1996).

3.5.6 Strengths and Limitations

Interpretation of the data was difficult at times. Despite using similar two and three dimensional technology, not all studies reported the same primary variables. While areal BMD from DXA-derived bone results were commonly reported, few studies reported BMC and BA. Furthermore, the regions of interest varied across the literature. Specifically, pQCT studies report different density, content and area measures of different types of bone (cortical and trabecular) at varying sites of long bones including distal (4%, 6% and 10 mm) and proximal (50% and 65%). While some common distal (metaphyseal) and proximal bone outcomes were reported, measurement sites varied across studies. Such heterogeneity could cause substantial differences in outcomes at such a young age and during growth. Therefore, a collective agreement is needed for pQCT research, including the optimal reference line placement, measurement sites and scan analysis parameters for assessment of bone density and geometry in children (Zemel, et al., 2008).

Data within this meta-analysis were raw data and at times did not take into account anthropometric differences between gymnasts and non-gymnasts. As gymnasts were not always matched with non-gymnasts, they were often smaller and lighter (Laing, et al., 2005; Zanker, et al., 2003). If these differences were taken into account within this review, the authors believe greater benefits in pre-pubertal gymnasts would be apparent. In addition to potential anthropometric differences between gymnasts and non-gymnasts, this review did not consider nutritional, genetic or racial outcomes known to influence bone acquisition. Furthermore, potential confounders such as injury history, training demands and quality, muscle size, strength and function as well as lean tissue mass fell outside the scope of this review.

Research on pre-pubertal gymnasts using pQCT is limited. More studies, particularly adopting a prospective longitudinal design are required. This review confirms skeletal benefits from participation in gymnastics before puberty over and above a variety of non-gymnastic sports (reported in the control groups). Specifically, pre-pubertal gymnasts had greater BMD and BMC than young girls not participating in gymnastics. These benefits may be largest at the upper body as gymnastics offers direct loading, of a substantial force, to the upper limbs which exceed the requirements of other sports and usual free play. These findings prevail even though some studies included non-gymnasts who were in fact participating in a minimal quantity of gymnastics. Due to the limited number of studies using three dimensional technologies within the review, we were unable to confidently conclude if the skeletal benefits observed in the gymnasts were more pronounced with three dimensional technology than the more commonly selected two dimensional scanning technologies.

3.5.7 Conclusions

In conclusion, participation in artistic gymnastics during pre-pubertal growth is associated with positive skeletal health benefits. Specifically, three dimensional pQCT results revealed gymnasts had increased distal radial bone density. Additional pQCT research is required to determine if pre-pubertal gymnasts have greater bone density at the lower body, and to determine potential differences in bone size, mass and strength. Two dimensional DXA results showed gymnasts had greater upper body bone mass and lower body areal bone density than non-gymnasts, despite smaller bones. The results of the studies to date provide favourable trends for musculoskeletal health in gymnasts however, the research remains incomplete.

3.5.8 Acknowledgements

Thank you too to fellow researchers who generously replied to our emails. In particular, the authors would like to thank Dr Kate Ward for providing data to be included the meta-analysis.

CHAPTER FOUR

METHODOLOGY

This methodology chapter describes procedures and protocols generic to the three results chapters within the thesis.

4.1 Study Design

The purpose of this prospective cohort study with repeated measures on two occasions (baseline and six months) was to compare upper body musculoskeletal health and function between non-elite gymnasts and age-and gender-matched non-gymnasts.

4.2 Ethical Approval

Ethical approval was obtained from the Australian Catholic University's Human Research Ethics Committee prior to the commencement of the study (Appendix D). Parental consent and child assent were obtained from participants prior to participation in the study (Appendix E).

4.3 Participants

Participants in this study were female pre-pubertal girls, aged 6 to 12 years. This stage of development was selected in order to understand more about the potential bone benefits of upper body activity prior to menarche specifically, in non-elite artistic gymnastics. Gymnastics was chosen due to the high impact, upper limb weight bearing loading of the sport, over and above everyday activity. Furthermore, non-elite level gymnasts represent the majority of participants in this sport.

This study recruited female artistic gymnasts, involved in non-elite artistic gymnastics and a non-gymnastic control group. The gymnasts were involved in 1 to 16 hr/wk of training and the non-gymnasts participated in 4 hr/wk or less of organised physical activity, outside school hours. The hours of participation selected for inclusion represented the usual training exposure of non-elite level gymnasts. The hours may appear high for non-elite athletes however, within the sport of artistic gymnastics it is not uncommon for non-elite girls to train in excess of 16 hr/wk. When comparing the gymnasts with non-gymnasts for musculoskeletal differences at baseline (chapter five) and changes over a six month period (chapter seven), the group was categorised based on hours of participation: high weekly gymnastics participation (HGYM), 6 to 16 hr/wk, low weekly gymnastics participation (LGYM), 1 to 5 hr/wk. The cut-off point of 5 hr/wk, used to discriminate HGYM and LGYM, was based on the number of training sessions per week: LGYM participated in one gymnastics class per week (never exceeding 5 hr/wk), whereas HGYM participated in more than one class per week (always exceeding 5 hr/wk). In order to directly compare the results of this group of gymnasts and non-gymnasts, with a previous study (Ducher, et al., 2009), gymnasts were analysed together (chapter six).

4.4 Power Analysis

To allow for the detection of significant differences in musculoskeletal characteristics a small estimated effect size (*d* = 0.20), with a statistical power of 90% and a significance level of 0.05 (assuming the gymnasts are split into two groups), the minimum total sample size was calculated to be 84 participants (Erdfelder, et al., 1996). Anticipating approximately 20% participant attrition, a minimum of 100 participants were invited to participate in the study. Volunteers who agreed to participate were assigned to one of three groups of approximately 33 participants, based on hours of gymnastics participation (HGYM, LGYM and NONGYM).

4.5 Recruitment of Participants

Following approval from ACU Human Research Ethics Committee, gymnasts were recruited from several large clubs in Sydney. Participants involved in the non-gymnastics group volunteered via a peer recruitment system. Therefore, the non-gymnastic group comprised of friends or siblings the same ages as the gymnasts.

Gymnasts were recruited from information letters (Appendix F) sent home to parents via coaches. A general information flier (Appendix G) was also posted on notice boards at gymnasiums. As an additional source of recruitment, gymnastics venues were visited with an information board including pictures and details of the specific tasks involved. Figure 4.1 outlines the total number of participants involved in the study at each time point, from recruitment through to follow up assessments. Six gymnasts were excluded following baseline assessment as they were not pre-pubertal. However, six months later three of these girls remained early pubertal and were included back into the study.

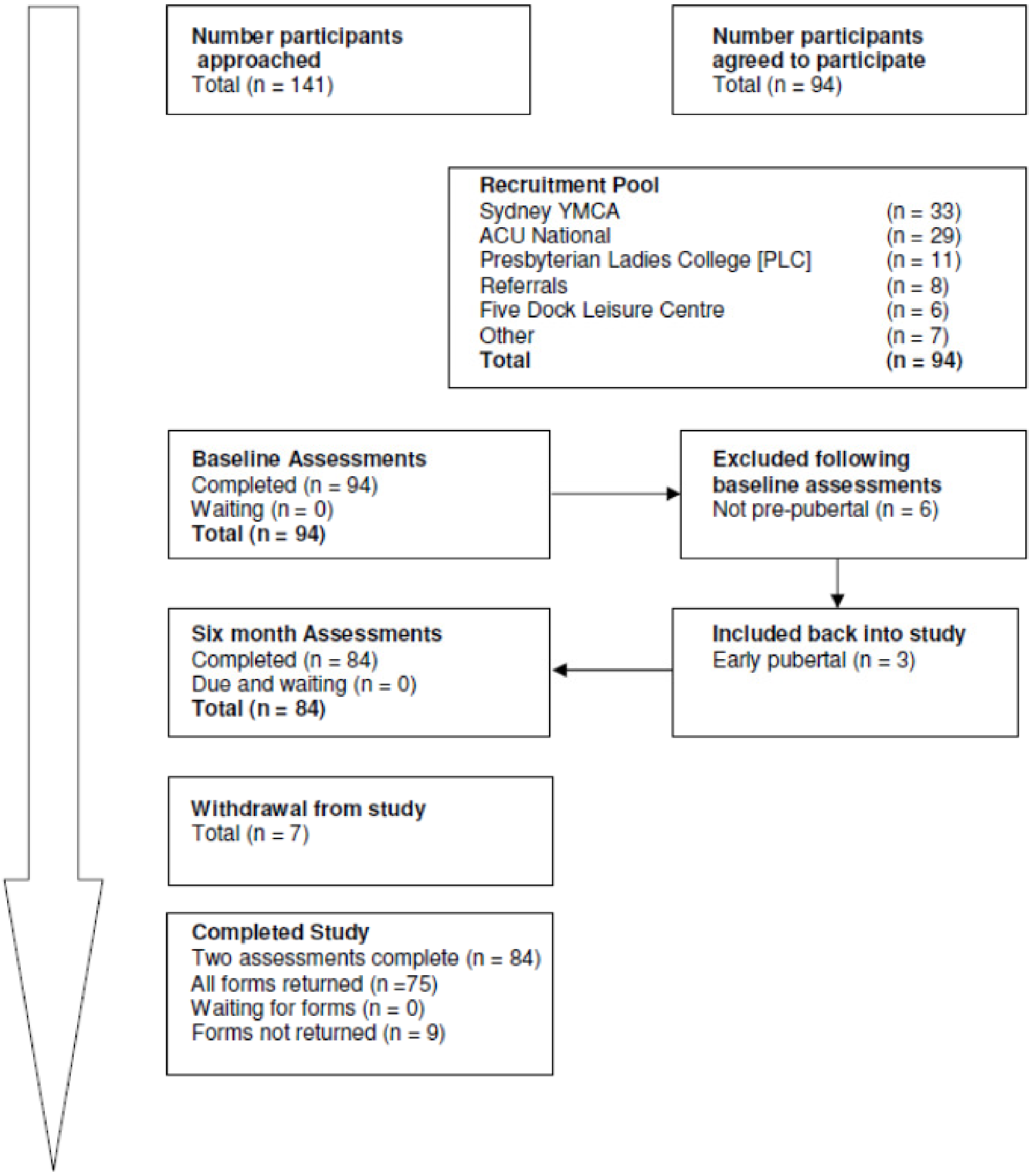


Figure 4.1. Number of participants involved in each stage of the study: recruitment, baseline and longitudinal time points

4.6 Data Collection Overview

The data collection procedure is outlined in Figure 4.2.

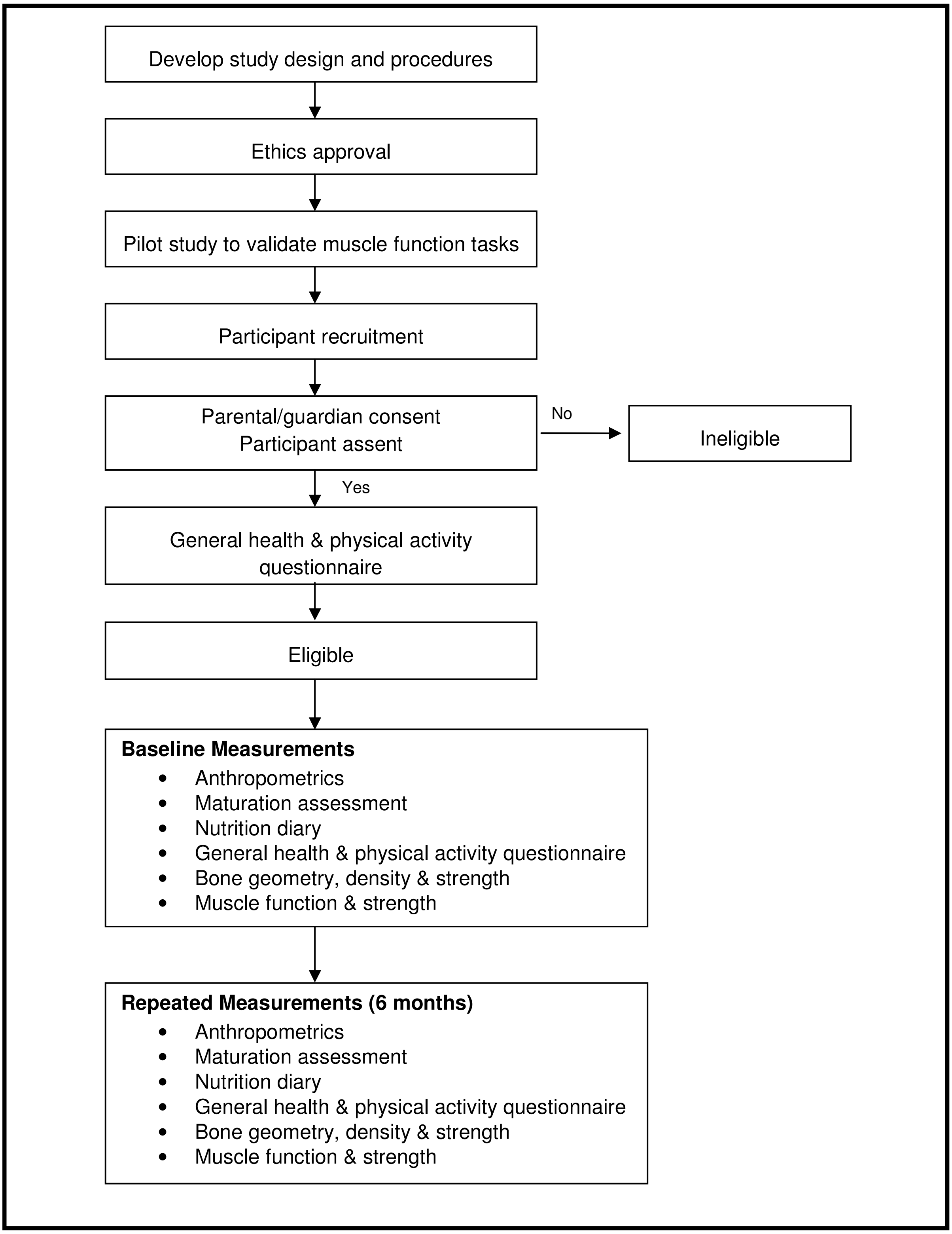


Figure 4.2. Data collection overview

4.7 Selection Criteria

Specifically, inclusion of gymnasts and controls was based on the following criteria:

- female
- 6 to 11 years of age
- pre-pubertal - total Tanner Pubertal Stage (score of 1 to 5) for breast + pubic hair development not exceeding three (see section below on maturation)
- good health and free from injury (i.e. no missed training sessions two weeks prior to the commencement of the study)
- no recent (12 months) broken/fractured bones in the upper body
- no history of medical conditions or medication or supplementation usage known to affect bone metabolism in the past six months

In addition to the above criteria, gymnasts must

- have had a current registration with Gymnastics Australia
- have a minimum training age in the sport of women's artistic gymnastics of six months
- not participate in more than one hour of additional upper limb weight bearing sport or recreational activities, in addition to gymnastics

Controls, in addition to less than 4 hours of organised physical activity outside of school must

- have had no training history in artistic gymnastics

4.8 General Health and Injury Questionnaire

Parents who provided consent for their daughter's participation were asked to, with the help of their daughter complete the general health and injury questionnaire (Appendix H). The questionnaire collected information on training background, physical activity/exercise routines, medication, injury and health status. This questionnaire was adapted from the NSW Child Health Survey (2001) and used to verify eligibility for participation in the study.

4.9 Maturation

Maturation was assessed using a proxy report of Tanner’s five stage model for pubertal maturation (Appendix I). Parents and daughters were asked to complete this questionnaire together via a series of diagrams depicting the five stages of puberty for breast and pubic hair development (Tanner, 1978). The validity and reliability for use of illustrations to represent stage of puberty has previously been reported (Duke, et al., 1980; Schmitz et al., 2004).

4.10 Nutrition and Physical Activity Questionnaire

Nutritional intake is an important determinant for optimal growth, maturation and bone development. It is therefore imperative to assess macro- and micro-nutrients within this study. Due to daily variability of food consumption, single measures of energy intake may not be accurate (Black et al., 1993). This study used a three day diet recall, which has been commonly used in other paediatric gymnastics studies (Laing, et al., 2005; Nickols-Richardson, et al., 1999). Furthermore, nutritional intakes via a three day diet recall correlate highly with observation for 9 and 10 year old females (Crawford, Obarzanek, Morrison, & Sabry, 1994).

For the purpose of this study, the three day diet recall took place over two weekdays and one weekend day. During these three days children and parents/carers completed the questionnaire together. Having both children and parents/carers complete the questionnaire together has been moderately successful in the past with children aged four to eight years (Bowman, Gortmaker, Ebbeling, Pereira, & Ludwig, 2004; Johnson, Driscoll, & Goran, 1996; Laing, et al., 2005; Zanker, et al., 2003), perhaps because it is largely the parents/careers who provide the recall.

Following the three day recall, nutrition data were entered into FoodWorks (dietary-analysis software Xyris Software Pty. Ltd., Highgate Hill, QLD, Australia) and average intakes were derived. For the purpose of this study, nutrition was a descriptor and a secondary explanatory variable, used to help explain the primary outcome variables (musculoskeletal). Therefore, calcium, protein and total energy intake were extracted for analysis. These nutrients have previously differed between gymnasts and non-gymnasts (Bass, et al., 1998; Nova, et al., 2001; Soric, Misigoj-Durakovic, & Pedisic, 2008). It was beyond the scope of this study to report other macro and micronutrients.

Assessment of physical activity consisted of both organised physical activities and additional sports or activities children participated in socially as part of free play. The information provided on organised physical was used to calculate the average yearly sports participation of all participants. A copy of the food and activity diary can be found in Appendix J.

4.11 Anthropometric Measurements

A selection of anthropometric measures were recorded to assist in the description of participants. Sensitive measures such as body mass were taken out of the view of other participants. The gymnasts wore their training attire during the collection of anthropometric measures. Controls wore a leotard, swimming costume or similar attire.

4.11.1 Body Mass and Stature

Body mass was recorded using digital scales (A&D Company Ltd., Tokyo, Japan) with an accuracy of 0.05 kg. A stadiometer (SECA height rod model 220, Hamburg, Germany) with an accuracy of 0.01 cm was used to measure standing and sitting height. Standing height was measured as the maximum distance from the floor to the vertex of the skull when the head was in the frankfort plane (Norton et al., 1996). Participants were required to stand in the anatomical position, keep their feet flat on the floor, place their back against the wall and take a deep breath. Sitting height was recorded as the distance from the bench on which the gymnast was seated to the vertex of the skull. The gymnast's head was again positioned in the frankfort plane and participants were directed to sit 'straight and tall'. During this measure, participants' feet were hanging freely and the thigh was in a horizontal position, parallel to the ground.

4.11.2 Limb Length

The length of the non-dominant forearm was measured as the distance between the olecranon process and the ulnar styloid process. A flexible steel tape with accuracy of 0.01 cm was be used to conduct the measurement.

Anthropometric measurements were taken twice. If measurements differed by more than 5% a third was recorded.

4.11.3 Body Composition, Areal Bone Mineral Density and Content

Whole body bone mineral density (BMD), bone mineral content (BMC), bone area, lean and fat mass were measured by dual-energy X-ray absorptiometry (DXA, Norland, XR-36 System, Fort Atkinson, Wisconsin). Body composition and bone parameters in the upper limb (including the humerus, ulna, radius, carpals, metacarpals and phalanges) were derived from the whole body scan. This method was previously used and showed good reproducibility with a CV below 1% (Ducher, et al., 2005). Measurements were performed at the predetermined scan mode (speed 180 mm/s, resolution 6.5 x 13.0 mm, source collimation 1.68 mm) with analysis software (2.5.3a). Participants were positioned on the bed in a supine position and instructed to remain as still as possible. The total scan time was approximately 15 minutes per scan. The coefficient of variation (CV) in our laboratory was calculated using duplicate scans of nine healthy university students, following repositioning. Specifically, CVs were: lean mass 1.3%, fat mass 3.5%, BMD 0.9%, BMC 1.1% and bone area 1.0%. Young children were not used to determine precision in our laboratory due to the ethical consideration of exposing children to additional repeated radiation exposure. All DXA scans were conducted by the same technician and quality assurance checks were regularly performed.

Figure 4.3. A dual-energy X-ray absorptiometry scan of the total body

4.12 Bone Analysis - Peripheral Quantitative Computed Tomography (pQCT)

Volumetric bone mineral density and bone geometry were measured by peripheral quantitative computed tomography (pQCT) in participants' non-dominant forearm (XCT 2000, Stratec Medizintechnik, Pforzheim, Germany). Given participants had an open growth plate at the distal radius, the reference line was positioned at the most distal portion of the growth plate, according to standard procedures (Figure 4.4) (Neu, et al., 2001; Rauch & Schoenau, 2005). Two tomographic slices of 2.3 mm thickness were obtained at the 4% and 66% forearm measured distally, with a voxel size of 0.4 mm and scan speed of 15 mm/s. Image processing and the calculation of bone parameters were conducted using the manufacturer's software package (version 6.00). Precision was obtained by scanning eight healthy adults twice, following repositioning. Once again, young children were not used for precision calculations due to the ethical considerations linked to repeated radiation exposure. The CVs in our laboratory ranged from 0.7 to 1.4% for pQCT-derived bone parameters at the radius. All bone analyses were conducted by the same technician and quality assurance checks of the pQCT device were regularly performed.

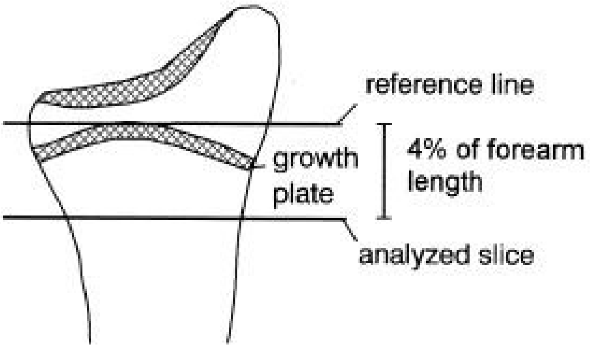


Figure 4.4. Location of the peripheral quantitative computed tomography reference line

(Neu, et al., 2001; Rauch & Schoenau, 2005)

At the 4% distal forearm, total bone mineral content (BMC), trabecular density (TrD), total bone area (ToA) density (ToD) and bone strength index (BSI) were determined. The BSI was calculated as an assessment of bone strength and was determined using the following formula (Kontulainen, et al., 2003). At this site, variables were calculated using contour and peel mode 1 with a threshold of 180 mg/cm^3.

$$Bone\ Strength\ Index = ToA * ToD^2$$

At the 66% site total BMC, cortical density (CoD), cortical area (CoA), cortical thickness (CoTh), ToA, ToD, medullary area (MedA) and the polar strength strain index (SSIp) were calculated. Cort mode 1 with a threshold of 711 mg/cm^3 was used for cortical bone and 280 mg/cm^3 for SSIp, ToA and ToD calculations. Keeping the same mode, an additional threshold (40 mg/cm^3) was applied to remove fat area from the total cross-sectional slice at the 66% site. What remains, denotes the muscle-bone area. Muscle cross sectional area (MCSA) was calculated by subtracting the bone area from the muscle-bone area.

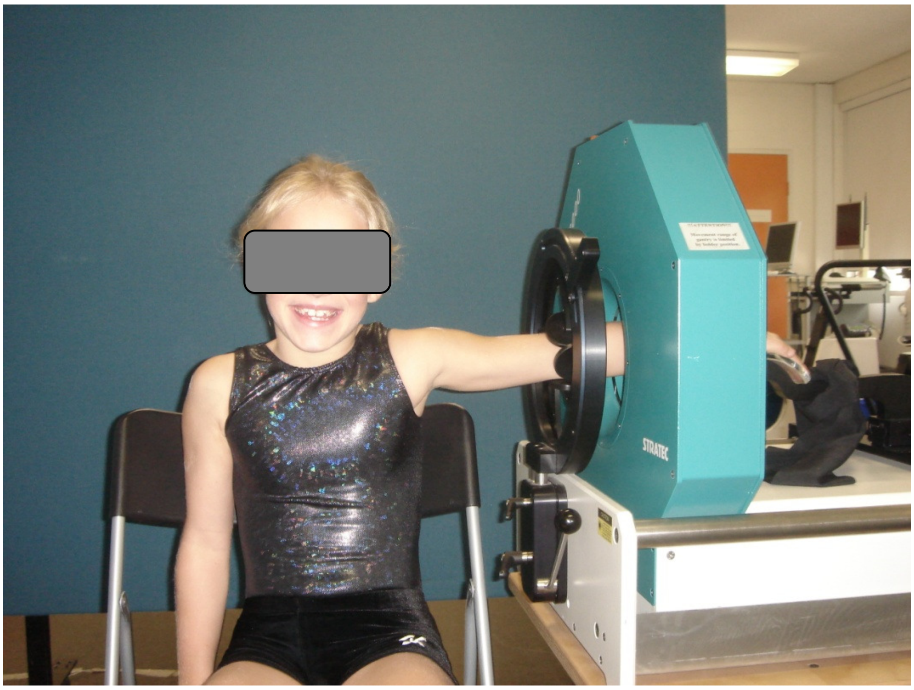

[redacted]

Figure 4.5. A peripheral quantitative computed tomography scan of the non-dominant forearm

4.13 Radiation

Although both DXA and pQCT provide measures of body composition and bone properties, they expose participants to low level radiation: 0.004 mSv from a total body DXA scan and 0.0002 mSv from the pQCT scan (Norland Medical System's Inc., 1997; Stratec, 2005). Over the duration of this study a dose of 0.0042 mSv was administered twice, six months apart.

4.14 Strength/Weight Index

Estimates of bone strength (BSI and SSIp at the 4% and 66% site, respectively) were used in combination with participant's body mass and forearm length as an indicator of fracture risk. The following formula was used to assess fracture risk (Rauch, et al., 2001)

$$Strength\,Weight\,Index = Bone\,strength \div Body\,Weight\,(kg) \times Moment\,Arm\,(cm)$$

4.15 Muscle Analyses

Subsequent to skeletal measurements and assessment of lean mass and MCSA, participants completed muscle strength, power, and endurance tasks as a way of practically observing the interaction of the muscle-bone unit.

4.15.1 Muscle Strength

A hand grip dynamometer is an appropriate and reliable way of analysing the strength of the forearm muscles in children less than 12 years (Molenaar, et al., 2008). To assess the muscle strength of the non-dominant arm, a hand grip dynamometer (Smedley's dynamometer TTM, Tokyo) was used. The dynamometer was individually adjusted for each participant. Participants were instructed to hold the dynamometer with their arm extending downwards, away from the body, and told to squeeze maximally for three seconds. This method has been used previously (Orjan, Kristjan, & Bjorn, 2005). All participants received two familiarisation trials prior to performing the actual assessment. Grip strength was repeated three times with the best trial used as the measure of muscle strength. Following each trial, participants were given two minutes rest. The best of three trials was used as it is more reliable than the mean of three trials when determining peak grip strength in children (Svensson, Waling, & Hager-Ross, 2008). An inter-day CV of 4.5% was obtained for this grip strength methodology following testing of a subsample of 21 girls, one week apart.


[redacted]

Figure 4.6. Assessment of grip strength

4.15.2 Muscle Power

Medicine ball throws have previously been used to assess upper body power in various levels of gymnastics participation (Salonia, et al., 2004). The medicine ball throw is a valid and reliable test for measuring upper body strength and power in kindergarten age children (Davis et al., 2008).

The protocol used for this study was similar to another published methodology (Davis, et al., 2008). Participants sat on the floor with their back against the wall. When ready to throw participants lifted the medicine ball to their chest and threw it as far forward as they could, keeping their back in contact with the wall. To add consistency, upon release of the ball, participants aimed their throw towards a target located 3.5 m away. As with the grip strength test, throws were repeated in triplicate and the best trial recorded. All participants received two familiarisation trials. An inter-day CV of 3.3% was obtained following testing of a subsample of 10 girls, one week apart. The weight of the medicine ball was relative to each individual participant. Balls were equal to 10% of the participant's body weight (range: 2 to 5 kg).

Figure 4.7. Medicine ball throw

4.15.3 Muscle Endurance

Measures of upper body function are required to assist in understanding the effects of recreational gymnastics participation. As many routines in artistic gymnastics last between 90 and 120 seconds muscle endurance was explored. In the absence of a definitive measure of upper body muscle endurance, two tasks have been devised for use in this study. During the first task, participants were seated on a chair and required to perform a maximum number of weighted arm sequences during 30 seconds. The arm sequence involved touching the shoulders, reaching for a rod positioned above participants and laterally returning the arms to the sides. The overhead rod was individually positioned to ensure participants completed each sequence accurately. Participants completed the weighted arm sequence three times with a work to rest ratio of 1:1; 30 seconds of activity followed by 30 seconds of rest. The number of successful arm sequences, recorded to the nearest half or full cycle, during the third trial was used for analysis. The weight applied to the arms (wrists) was relative to the participant's body weight. Through the use of velcro adjustable wrist weights, a total of 5% of the participant's body weight (range: 1 to 2.5 kg) was added to each arm. An inter-day CV of 2.5% was obtained for the arm sequence following testing of a subsample of eight girls, one week apart.

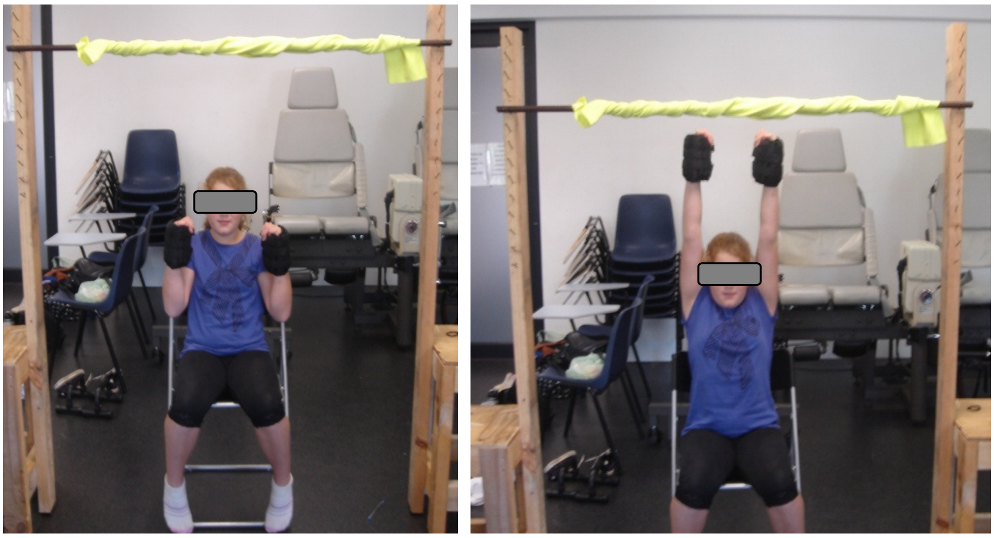


Figure 4.8. Weighted arm sequence

The second task required participants to support their own body weight to fatigue between two stabilised benches. The distance between these benches was relative to the individual (measured distance from the elbow joint to the most distal digit of the phalanges). For safety, benches were fixed at a height from which participants could reach the floor upon straightening their legs. During this task, participants had their arms slightly bent to ensure participants did not lock their elbow joints, keeping the focus on the muscles. Once again, three trials were performed; in the first two trials participants continued for 30 seconds (if successful), the final attempt was continued to volitional failure. Successful time on the third attempt was recorded for analysis. An inter-day CV of 3.6% was obtained for the static hold following testing of a subsample of eight girls, one week apart. All muscle function tasks obtained acceptable reliability as they had a CV percentage less than 9% (Fricke, Weidler, Tutlewski, & Schoenau, 2006).

Figure 4.9. Static hold assessment

4.16 Statistical Analyses

The data were checked for normal distribution based on a set of seven criteria. Variables were considered normally distributed if: there was a less than 10% difference between the mean and median values, the doubled standard deviation was less than the mean, skewness and kurtosis scores were within the range of -1.000 to 1.000, skewness and kurtosis scores divided by their corresponding standard error had values less than 1.96 and *p* values greater than 0.05 from the Kolmogorov-Smirnov test for normal distribution (Peat & Barton, 2005). Variables failing to meet the criteria for normal distribution were transformed using a log10 function prior to treatment with parametric statistical analyses.

Data were presented as mean ± 95% confidence intervals (CI) or standard deviation (SD). Proportional differences in non-parametric statistics were calculated using chi-square to test for differences in frequency/percentages between groups. Musculoskeletal parameters were compared between groups using independent sample t –tests (chapter six), body mass-adjusted ANCOVA (chapter five), or a body mass-adjusted repeated measures ANCOVA (chapter seven). Post hoc Bonferroni analyses were used to determine between group differences when mean differences were apparent among the three groups (HGYM, LGYM and NONGYM). Following univariate analyses, relationships between variables were explored with Pearson's and partial correlation analyses as well as MCSA-adjusted ANCOVA.

At completion of the longitudinal data collection, a stepwise multiple linear regression was conducted to determine the best predictors of changes in musculoskeletal parameters. Grouping and maturation factors were entered into the model as dummy variables to help understand the role of categories in observed variability among dependent variables.

The magnitude of between-group differences for muscle and bone parameters was quantified using population specific Z-scores. Population-specific Z-scores were calculated with EZAnalyze (Poynton, 2007) and used the control group as a reference. The use of Z-scores allowed between group differences of bone and muscle variables (with different units) to be compared in unison. Statistical significance of the unadjusted Z-scores was evaluated with a one-sample t-test, $p < 0.05$.

Data were analysed using SPSS for Windows, version 18 (SPSS Inc, Chicago, IL). Statistical significance was set at an alpha level of 0.05 for all tests with the exception of correlation analyses, for which 0.01 was set (Peat & Barton, 2005).

CHAPTER FIVE

NON-ELITE GYMNASTICS PARTICIPATION IS ASSOCIATED WITH GREATER BONE STRENGTH, MUSCLE SIZE AND FUNCTION IN PRE- AND EARLY PUBERTAL GIRLS

Submitted to Osteoporosis International (accepted for publication, May, 2011)

5.1 Abstract

Introduction: The primary aim of this study was to determine the association between non-elite gymnastics participation and upper limb bone mass, geometry and strength in addition to muscle size and function in young girls.

Methods: Eighty-eight pre- and early pubertal girls (30 high-training gymnasts [HGYM, 6-16 hr/wk], 29 low-training gymnasts [LGYM, 1-5 hr/wk] and 29 non-gymnasts [NONGYM]), aged 6-11 years were recruited. Upper limb lean mass, BMD and BMC were derived from a whole body DXA scan. Forearm volumetric BMD, bone geometry, estimated strength and MCSA were determined using peripheral QCT. Upper body muscle function was investigated with muscle strength, explosive power and muscle endurance tasks.

Results: HGYM showed greater forearm bone strength compared with NGYM, as well as greater arm lean mass, BMC and muscle function (+5 to +103%, $p<0.05$). LGYM displayed greater arm lean mass, BMC, muscle power and endurance than NGYM (+4 to +46%, $p<0.05$) however, the difference in bone strength did not reach significance. Estimated fracture risk at the distal radius, which accounted for body weight, was lower in both groups of gymnasts. Compared with NONGYM, HGYM tended to show larger skeletal differences than LGYM, yet the two groups of gymnasts only differed for arm lean mass and MCSA.

Conclusion: Non-elite gymnastics participation was associated with musculoskeletal benefits in upper limb bone geometry, strength and muscle function. Differences between the two gymnastic groups emerged for arm lean mass and MCSA, but not for bone strength.

5.2 Introduction

Elite gymnastics is associated with marked improvements in bone density (Bass, et al., 1998) and bone strength (Liang, et al., 2005; Ward, et al., 2005) that may be retained at least partly later in life (Bass, et al., 1998; Eser, et al., 2009; Pollock, et al., 2006). The skeletal gains tend to be larger in the upper body (Ward, et al., 2005) due to the unique pattern of loading induced by gymnastic manoeuvres on the upper limbs, including weight-bearing and large muscular forces. However, adaptations may come at a cost. Elite gymnasts typically engage in a high intensity and high volume of training, and often present with an elevated rate of injury, particularly at the wrist (DiFiori, Puffer, Mandelbaum, & Dorey, 1997). Non-elite gymnasts may have an advantage over elite gymnasts due to a decreased training load, less competitive pressure and potentially, a decreased risk of injury. Despite a greater number of participants involved in non-elite than elite gymnastics, the musculoskeletal advantages of non-elite participation are less known.

The majority of gymnastics-based literature focuses on elite gymnasts. Few studies have assessed the effects of non-elite gymnastics on bone mineral density (Laing, et al., 2005; Scerpella, et al., 2003; Vicente-Rodriguez, et al., 2007; Zanker, et al., 2003). Despite reports of significant skeletal benefits, there was a reliance on dual-energy X-ray absorptiometry (DXA) to assess areal bone density. The use of DXA in pediatric populations has been criticized because it is a two dimensional projectional technique which does not measure volumetric density. Furthermore, DXA derived areal BMD does not adequately correct for body and bone size (Lu, Cowell, Lloyd-Jones, Briody, & Howman-Giles, 1996; Prentice, et al., 1994).

Recent investigations using three-dimensional peripheral quantitative computed tomography (pQCT) technology showed low-moderate gymnastics training volume is associated with greater bone strength in young gymnasts (Erlandson, et al., 2011). Importantly, children who injured their forearm and sustained a fracture were found to have a lower volumetric density and cortical area than children who injured their forearm but did not fracture (Kalkwarf, Laor, & Bean, 2011). Forearm fractures may account for over 20% of all pediatric fractures and are increasing in incidence (Khosla et al., 2003; Mäyränpää, Mäkitie, & Kallio, 2010). The non-elite gymnastics-specific association between bone health and fracture risk warrants further investigation.

Varying levels of gymnastics participation improve performances of lower limb explosive power (Bencke, et al., 2002; Vicente-Rodriguez, et al., 2007). Moreover, a relationship between greater muscle power and higher bone density in adolescent gymnasts has been described (Jürimäe & Jürimäe, 2005). Few studies have directly assessed true measures of muscle function in combination with bone strength in young non-elite gymnasts (Scerpella, et al., 2003; Vicente-Rodriguez, et al., 2007). The extent to which non-elite level participation in gymnastics influences upper body musculoskeletal health is under researched.

The primary aim of this cross-sectional study was to determine the association between non-elite gymnastics participation and upper limb bone mass, geometry, strength and muscle function in young girls. We hypothesized gymnasts would have greater bone mass, size and strength compared with non-gymnasts. Furthermore, gymnasts were expected to have greater lean mass and improved muscle function than non-gymnasts. Specifically, we hypothesized musculoskeletal benefits of gymnasts with high-training commitments would be larger than those with low-training commitments.

5.3 Methods

5.3.1 Study Participants

Eighty-eight pre-pubertal girls aged 6-11 years were recruited. Participants were healthy pre-pubertal girls, not taking any medication known to affect bone or muscle metabolism, and without fracture to the upper limb within the previous 12 months. Non-gymnasts were involved in less than 4 hr/wk of organised physical activity outside school and were recruited via the “bring a friend” recruitment strategy. Gymnasts were recruited from local gymnastics centres and were training between 1 and 16 hr/wk. Gymnasts had trained for at least six months in the sport and were participating at a recreational or non-elite level, rather than the elite level. Elite gymnasts typically train in excess of 25 hr/wk, up to six days a week for 12 months of the year from a very young age (Caine, et al., 1989). Furthermore, elite level gymnasts are those training at or aiming towards international level competition. After obtaining parental consent and child assent, participants were assigned into one of three groups based on their gymnastics participation: high-training gymnasts (HGYM), 6 to 16 hr/wk, low-training gymnasts (LGYM), 1 to 5 hr/wk and non-gymnasts (NONGYM). The cut-off point of 5 hr/wk used to discriminate HGYM and LGYM, was chosen based on the number of training sessions per week: LGYM participated in one gymnastics class per week (never exceeding 5 hr/wk), whereas HGYM participated in more than one class per week (always exceeding 5 hr/wk). HGYM involved in the study were training 16 hr/wk or less, which is considerable however, still considered a non-elite level and is associated with normal growth and maturation (Theintz, et al., 1993). Compared with elite gymnasts, non-elite gymnasts have lower weekly training commitments, and are not aiming for international competition. However, these gymnasts may participate in small regional competitions. The study was approved by the University's ethics committee.

5.3.2 Anthropometric Assessment

A stadiometer (SECA height rod model 220, Hamburg, Germany) with an accuracy of 0.01 cm was used to measure standing and sitting height. Body mass was recorded using digital scales (A&D Company Ltd., Tokyo, Japan) with an accuracy of 0.05 kg. Forearm length was measured from the olecranon process to the ulna styloid process using a metal measuring tape with an accuracy of 0.01 cm.

5.3.3 Body Composition and Bone Mineral Density

Whole body bone mineral density (BMD), bone mineral content (BMC), bone area, lean and fat mass were measured by dual-energy X-ray absorptiometry (DXA, Norland, XR-36 System, Fort Atkinson, Wisconsin). Body composition and bone parameters in the upper limb (including the humerus, ulna, radius, carpals, metacarpals and phalanges) were derived from the whole body scan. This method was previously used and showed good reproducibility with a CV below 1% (Ducher, et al., 2005). Measurements were performed at the predetermined scan mode (speed 180 mm/s, resolution 6.5 x 13.0 mm, source collimation 1.68 mm) with analysis software (2.5.3a). The CV in our laboratory was calculated using duplicate scans of nine healthy university students, following repositioning. Specifically, CVs were: lean mass

1.3%, fat mass 3.5%, BMD 0.9%, BMC 1.1% and bone area 1.0%. All DXA scans were conducted by the same technician.

5.3.4 Volumetric Bone Mineral Density, Bone Geometry and Bone Strength

Volumetric bone mineral density and bone geometry were measured by peripheral quantitative computed tomography (pQCT) in participants' non-dominant forearm (XCT 2000, Stratec Medizintechnik, Pforzheim, Germany). Given participants had an open growth plate at the distal radius, the reference line was positioned at the most distal portion of the growth plate, according to standard procedures (Neu, et al., 2001; Rauch & Schoenau, 2005). Two 2-mm tomographic slices of 2.3 mm thickness were obtained at the 4% and 66% radius sites measured distally, with a voxel size of 0.4 mm and scan speed of 15 mm/s. Image processing and the calculation of bone parameters were conducted using the manufacturer's software package (version 6.00). Precision was obtained by scanning eight healthy adults twice following repositioning. Young children were not used to determine precision in our laboratory due to the ethical considerations linked to repeated radiation exposure. The CVs in our laboratory ranged from 0.7 to 1.4% for pQCT-derived bone parameters at the radius. All bone analyses were conducted by the same technician and quality assurance checks of the pQCT device were regularly performed.

At the 4% distal radial site, total bone mineral content (BMC), trabecular density (TrD), total bone area (ToA) density (ToD) and bone strength index (BSI) were determined. The BSI was calculated as an assessment of bone strength and was determined using the following formula: BSI= total area (ToA) * total density $(\text{ToD})^2$ (Kontulainen, et al., 2003). At this site, variables were calculated using contour and peel mode 1 with a threshold of 180 mg/cm^3.

At the 66% site BMC, cortical density (CoD), cortical area (CoA), cortical thickness (CoTh), ToA, ToD, medullary area (MedA) and the polar strength strain index (SSIp) were calculated.

Cort mode 1 with a threshold of 711 mg/cm^3 was used for cortical bone and 280 mg/cm^3 for SSIp, ToA and ToD calculations. Keeping the same mode, an additional threshold (40 mg/cm^3) was applied to remove fat area from the total cross-sectional slice. What remains denotes the muscle-bone area. Muscle cross-sectional area (MCSA) was calculated by subtracting the bone area from the muscle-bone area.

5.3.5 Strength/Weight Index

Estimates of bone strength (BSI and SSIp at the 4% and 66% site, respectively) were used in combination with participant's mass and forearm length as an indicator of fracture risk. The following formula was used: Strength to Weight Index = Bone Strength / (Mass * Forearm Length) (Rauch, et al., 2001).

5.3.6 Muscle Function

5.3.6.1 Muscle strength

A hand grip dynamometer (Smedley's dynamometer TTM, Tokyo) was individually adjusted for participants. Participants held the dynamometer with their non-dominant arm extending downwards, away from the body (Orjan, et al., 2005), squeezing the device maximally for three seconds. Participants had two familiarisation trials. The best of the three trials was recorded. An inter-day CV of 4.5% was obtained following testing of a subsample of 21 girls, one week apart.

5.3.6.2 Explosive power

The seated ball throw was adapted from a previous study (Davis, et al., 2008). However, participants aimed their throw towards a target located three meters away. Throws were repeated three times and the best trial recorded. The weight of the medicine ball was relative to 10% of the participant's body weight (range 2 to 5 kg). An inter-day CV of 3.3% was obtained following testing of a subsample of 10 girls, one week apart.

5.3.6.3 Muscle endurance

In the absence of valid paediatric muscle endurance tasks (Pate, et al., 1993) and to remove gymnastics-specific bias, two novel tasks were devised. During the first task, participants were seated and performed a maximum number of weighted arm sequences during a 30 second time period. The arm sequence involved touching the shoulders, reaching for a rod positioned above participants and laterally returning the arms to the sides. The overhead rod was individually positioned to ensure participants completed each sequence accurately. The weight applied to the arms (wrists) was relative to the participant's body weight. Weight was applied through the use of velcro adjustable wrist weights. A total of 5% of the participant's body weight was added to each arm (range 1 to 2.5 kg). The number of successful sequences performed during the 30 seconds was recorded to the nearest half or full cycle. An inter-day CV of 2.5% was obtained for the arm sequence following testing of a subsample of eight girls, one week apart.

The second task required participants to hold an upright static position (arms slightly bent and feet raised from the floor) using their arms to support their own body weight between two stabilised benches. Three trials were performed; the first two trials participants continued for 30 seconds (if successful), the final attempt was continued to volitional failure. Successful time on the third attempt was recorded. An inter-day CV of 3.6% was obtained for the static hold following testing of a subsample of eight girls, one week apart. All muscle function tasks obtained acceptable reliability as they had a CV percentage less than nine (Fricke, et al., 2006).

5.3.7 Pubertal Stage

Maturation was assessed using a proxy report of Tanner’s five stage model for pubertal maturation (Duke, et al., 1980). Parents and daughters were asked to complete this questionnaire together. Participants with a combined Tanner score (breast + pubic hair) of three or less were included in this study.

5.3.8 Calcium, Protein and Total Caloric Intakes

Calcium, protein and total caloric intake were quantified with a 3-day diet recall over two school days and one weekend day. During these three days, parents and daughters completed the questionnaire together. Data were then entered into FoodWorks (dietary-analysis software Xyris Software Pty. Ltd., Highgate Hill, QLD, Australia) and average intakes were derived.

5.3.9 Questionnaires

Parents completed questionnaires about their daughter’s training background, physical activity/exercise history, injury and health status. These answers were used to verify eligibility for participation in the study, participant grouping and provide descriptive profiles of groups.

5.3.10 Statistical Analyses

Statistical analyses were performed with SPSS for windows (version 18.0, SPSS Inc., Chicago, IL). Differences in mean and median in addition to Kolmogorov-Smirnov values were used to assess normal distribution (Peat & Barton, 2005). Data were presented as mean ± 95% confidence intervals (CI). Proportional differences in non-parametric statistics were calculated using chi-square to test for differences in percentages between groups. Strength/weight index at the 4% site and static hold variables were log10 transformed as they failed to meet criteria for normal distribution. Bone and muscle parameters were compared between groups using body mass-adjusted ANCOVA. Post hoc Bonferroni analyses were used to determine between-group differences and were reported as a percentage. Following univariate analyses, relationships between variables were explored with Pearson's and partial correlation analyses as well as MCSA-adjusted ANCOVA. Statistical significance was set at an alpha level of 0.05 for all tests with the exception of correlation analyses, for which 0.01 was set.

The magnitude of between-group differences for muscle and bone parameters was quantified using population specific Z-scores. Population-specific Z-scores were calculated with EZAnalyze (Poynton, 2007) and used the control group as a reference. The use of Z-scores allowed between group differences of bone and muscle variables (with different units) to be compared in unison. Statistical significance of the unadjusted Z-scores was evaluated with a one-sample t-test, $p < 0.05$.

5.4 Results

Descriptive characteristics for the three groups are presented in Table 5.1. Groups were not different for age, stature, body mass, and training age. Chi-square showed no associations between groups and the proportion of participants in each maturation stage was equal. Training for the LGYM ranged between 1-5 hr/wk, whereas HGYM trained between 6-16 hr/wk. Duration of training history was not different between gymnastic groups. Post hoc analyses showed differences between all groups for hours of weekly gymnastics participation (p <0.001). Non-gymnasts commonly participated in dancing, netball, soccer and swimming (range: 0-4 hr/wk). No differences were found among all three groups for forearm length, calcium, protein or total caloric intake.

Participants consenting to bone scans had a whole body DXA scan and two pQCT scans of the non-dominant forearm. Two participants, one NONGYM and one LGYM did not consent to bone scans. In addition, the pQCT scans of one HGYM and three NONGYM participants were removed due to movement artifacts. Four pQCT scans (one HGYM, one LGYM and two NONGYM) were excluded at the 4% site as TrD values were higher than 320 mg/cm^3. Such values for TrD suggest scans were conducted too close to the growth plate, considering the 95th percentile for TrD is 260 mg/cm^3, based on reference data (Rauch & Schoenau, 2005).

5.4.1 Upper Body Bone Parameters

Upper limb bone parameters are presented in Table 5.2. Statistical analyses were performed on parameters adjusted for body mass (except strength/weight index). Adjustment was deemed necessary, despite the absence of statistical differences in mass between groups, because HGYM were 7% lighter than NONGYM.

Compared with NONGYM, LGYM had 4% greater total arms BMC as derived by DXA (*p*=0.023). At the 4% site, pQCT results showed LGYM had an 8% larger ToD than NONGYM (*p*=0.042). At the 66% site, LGYM had an 8% greater ToA and 18% greater MedA than NONGYM (*p*<0.010). At this site, bone density was up to 9% lower for LGYM than NONGYM (p<0.050). Bone strength, while not significantly different, was +12% and +6% higher for LGYM than NONGYM at the distal radius and shaft, respectfully. The strength/weight index at the 4% site was higher for LGYM than NONGYM (*p*<0.050).

Table 5.1

Descriptive Characteristics and Body Composition of Pre-Pubertal Female Gymnasts with High- (HGYM) and Low- (LGYM) Training Commitments and Age-Matched Non-Gymnasts (NONGYM)

	NONGYM (n = 29)		**LGYM (n = 29)**		**HGYM (n = 30)**		
Variable	**Mean (95% CI)**	**Range**	**Mean (95% CI)**	**Range**	**Mean 95% CI**	**Range**	**P Value**
Age (yrs)	8.6 (8.1–9.0)	6-11	8.3 (7.8-8.8)	6-11	8.9 (8.4-9.4)	6-11	0.183
Standing Height (cm)	136.1 (133.5-138.6)	126.8-157.0	134.6 (132.2-137.0)	119.2-147.6	135.1 (132.3-137.8)	116.0-147.5	0.731
Sitting Height (cm)	67.7 (65.8-69.5)	59.0-79.5	67.1 (65.5-68.7)	57.5-75.0	67.3 (65.6-69.0)	56.3-75.0	0.883
Forearm Length (cm)	18.9 (18.5-19.5)	17.0-22.0	19.3 (18.7-19.9)	16.0-23.0	18.9 (18.2-19.5)	15.5-22.0	0.622
Body Mass (kg)	32.0 (29.7-34.4)	23.3-50.2	30.6 (28.3-32.8)	21.1-47.6	29.9 (27.9-31.9)	19.2-41.6	0.350
Tanner Stage 1 Breast (%)	83	1-2	86	1-2	87	1-2	0.901
Tanner Stage 1 Pubic Hair (%)	100	1-2	100	1-2	97	1-2	0.380

	NONGYM (n = 29)		LGYM (n = 29)		HGYM (n = 30)		
Variable	**Mean (95% CI)**	**Range**	**Mean (95% CI)**	**Range**	**Mean 95% CI**	**Range**	**P Value**
Whole body Lean Mass (kg)	19.0 (17.7-20.3)	13.2-27.7	19.1 (17.7-20.4)	12.8-28.1	20.0[a] (18.7-21.1)	13.6-25.2	0.001
Whole body Fat Mass (kg)	11.6 (9.9-13.4)	6.5-22.3	9.8 (8.6-11.0)	5.7-18.0	8.4[a] (7.4-9.5)	4.3-16.3	0.001
Percent Body Fat (%)	35.6 (32.3-38.8)	23.2-48.2	32.2 (30.0-34.3)	20.8-46.7	28.0[ab] (25.9-30.1)	18.2-39.5	<0.0001
Gymnastics Training History (yrs)	-	-	2.7 (2.2-3.3)	1.0-6.0	3.1 (2.6-3.5)	1.0-5.5	0.137
Gymnastics Training Volume (hr/wk)	-	-	3.0[a] (2.5-3.5)	1-5	10.6[ab] (9.2-12.0)	6-16	<0.0001
Total Physical Activity (hr/wk)	2.2 (1.5-2.6)	0-4.0	4.7[a] (3.8-5.5)	2.1-9.2	11.9[ab] (10.6-13.2)	6.3-18.5	<0.0001
Total Caloric Intake (KJ/day)	7128 (6279-7976)	4548-12420	7173 (6594-7751)	4723-9996	7551 (6923-8180)	4569-10132	0.613
Calcium Intake (mg/day)	932 (722-1141)	220-2345	1123 (846-1340)	436-2044	981 (839-1124)	430-1650	0.425
Protein Intake (g/day)	69.6 (62.7-76.5)	48.1-106.0	69.8 (62.7-76.8)	41.2-102.8	70.9 (66.0-75.9)	47.8-94.1	0.946

Mean score ± 95%CI and range for raw data are presented

[a] different from NONGYM (p< 0.05) [b] different from LGYM (p< 0.05) P value represents significance from ANOVA

Table 5.2

Upper Limb Bone Parameters in Three Groups of Pre-Pubertal Girls

Variable	**NONGYM**		**LGYM**		**HGYM**		**P Value**
	Mean	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**	
DXA Arms	**(n = 28)**		**(n = 28)**		**(n = 30)**		
BMD (g/cm^2)	0.450	(0.430-0.471)	0.445	(0.422-0.467)	0.430	(0.41-0.44)	0.392
BMC (g)	142.13	(132.06-152.20)	147.67[a]	(135.01-160.34)	148.77[a]	(136.83-160.00)	0.023
pQCT 4% Distal Radius	**(n = 23)**		**(n = 27)**		**(n = 28)**		
BMC (g/cm)	0.66	(0.60-0.71)	0.67	(0.62-0.73)	0.71[a]	(0.66-0.75)	0.049
TrD (mg/cm^3)	220.8	(200.3-241.4)	223.8	(210.6-247.9)	226.5.8	(216.9-236.2)	0.131
ToA (mm^2)	244.0	(222.1-265.9)	227.6	(212.0-243.3)	234.2	(216.2-252-1)	0.679
ToD (mg/cm^3)	275.3	(262.0-288.6)	297.3[a]	(284.2-310.5)	303.7[a]	(294.0-313.4)	<0.0001
BSI (mg/mm^4)	17.8	(15.8-19.7)	19.9	(17.8-22.1)	21.5[a]	(19.9-23.1)	0.002
Strength/Weight Index	0.22	(0.18-0.26)	0.27[a]	(0.24-0.31)	0.31[a]	(0.28-0.33)	0.002

Variable	**NONGYM**		**LGYM**		**HGYM**		**P Value**
	Mean	**95%CI**	**Mean**	**95%CI**	**Mean**	**95%CI**	
pQCT 66% Proximal Radius	**(n = 25)**		**(n = 28)**		**(n = 29)**		
BMC (g/cm)	0.61	(0.57-0.64)	0.59	(0.55-0.64)	0.62	(0.58-0.65)	0.108
CoD (mg/cm^3)	1049.0	(1029.6-1068.4)	1015.2^a	(1002.4-1028.0)	1035.7	(1017.5-1053.9)	0.034
CoA (mm^2)	45.3	(42.4-48.1)	44.7	(41.3-48.0)	46.0	(43.0-48.8)	0.238
CoTh	1.61	(1.50-1.72)	1.48	(1.39-1.57)	1.56	(1.47-1.65)	0.332
MedA	43.8	(39.0-48.6)	51.9^a	(45.1-58.7)	48.7	(44.4-53.0)	0.020
ToA (mm^2)	89.1	(84.1-94.1)	95.8^a	(87.8-103.9)	94.7^a	(89.0-100.3)	0.005
ToD (mg/cm^3)	684.0	(647.8-720.1)	625.1^a	(594.9-655.2)	657.6	(630.9-684.3)	0.023
SSIp (mm^3)	124.9	(115.4-134.3)	131.9	(119.1-144.7)	137.3^a	(124.5-150.2)	0.005
Strength/Weight Index	0.21	(0.19-0.22)	0.23	(0.21-0.24)	0.25^a	(0.23-0.26)	0.002

Unadjusted data are presented as means ± 95% CI.

Bone Mineral Density: BMD; Total Bone Mineral Content: BMC; Trabecular Density: TrD; Total Bone Area: ToA; Total Bone Density: ToD; Bone Strength Index: BSI; Cortical Density: CoD; Cortical Area: CoA; Cortical Thickness: CoTh; Medullary Area: MedA; Polar Strength Strain Index: SSIp; Non-Gymnast: NONGYM; Low-training volume gymnast: LGYM; High-training volume gymnast: HGYM. [a] different from NONGYM ($p < 0.05$) after adjustment for body mass. P value represents significance from a body mass adjusted ANCOVA

Similarly, compared with NONGYM, HGYM had a 5% greater upper limbs BMC as derived by DXA (*p*=0.002). At the 4% site, pQCT results showed HGYM had an 8% greater BMC and a 10% greater ToD than NONGYM (*p*<0.050). At the 66% site, HGYM had a 6% larger ToA than NONGYM (*p*=0.006). Bone strength was higher for HGYM than NONGYM at both the 4% and 66% sites. These bone strength benefits were greater for HGYM than NONGYM at the distal radius (BSI +21%, *p*=0.002) than the shaft (SSIp +10%, *p*=0.002). The strength/weight index was also higher for HGYM than NONGYM at the 4% and 66% sites (*p*<0.001). Differences between gymnastics groups and NONGYM were larger for HGYM than LGYM however, differences between the two groups of gymnasts regarding bone parameters were not significant (p>0.050). After adjusting for MCSA, all the aforementioned bone differences failed to reach significance with the exception of strength/weight index at the 4% site between HGYM and NONGYM.

5.4.2 Muscle Size and Function

Differences in muscle size and function between groups are outlined in Table 5.3. Compared with NONGYM, LGYM had higher upper limbs lean mass, explosive power and muscle endurance, as identified by both max arm sequence and static hold time (*p*<0.050). The LGYM group threw the ball an average 14 cm (+8%) further, performed three additional arm sequences (+16%) and remained static for 26 seconds (+46%) longer than NONGYM.

Compared with NONGYM, HGYM had more lean mass and MCSA, greater grip strength, explosive power and muscle endurance (max arm sequence and static hold time) (*p* <0.010). The HGYM group threw the ball on average 27 cm (+16%) further, completed six additional arm sequences (+31%) and held the static position on average 40 seconds (+103%) longer than NONGYM.

Table 5.3

Muscle Size, Structure and Function in Three Groups of Pre-Pubertal Gymnasts and Non-Gymnasts

Variable	NONGYM		LGYM		HGYM		P Value
	Mean	95% CI	Mean	95% CI	Mean	95% CI	
DXA Arms	**(n = 28)**		**(n = 28)**		**(n = 30)**		
Lean Mass (g)	1531	(1404-1658)	1614[a]	(1478-1749)	1767[ab]	(1645-1889)	<0.0001
pQCT 66% Distal Radius	**(n = 25)**		**(n = 28)**		**(n = 29)**		
MCSA (mm^2)	1565	(1484-1646)	1598	(1487-1710)	1718[ab]	(1630-1807)	<0.0001
Muscle Function	**(n = 29)**		**(n = 29)**		**(n = 30)**		
Grip Strength	13.9	(12.8-15.1)	14.6	(12.9-16.2)	15.1[a]	(13.9-16.3)	0.016
Ball Throw (m)	1.70	(1.60-1.81)	1.84[a]	(1.73-1.96)	1.97[a]	(1.87-2.07)	<0.0001
Max Arm Sequence	18.2	(16.4-19.9)	21.2[a]	(19.5-22.9)	23.8[a]	(22.0-25.5)	<0.0001
Static Hold Time (s)	34.7	(25.2-44.2)	52.3[a]	(40.3-64.3)	72.6[a]	(56.9-85.2)	<0.0001

Mean score ± 95% CI of raw data are outlined for the NONGYM, LGYM and HGYM.

Muscle cross-sectional area: MCSA; Non-gymnast: NONGYM; Low-training gymnast: LGYM; High-training gymnast: HGYM

[a] different from NONGYM ($p < 0.05$) following adjustment for body mass; [b] different from LGYM ($p < 0.05$) following adjustment for body mass. P value represents significance from a body mass adjusted ANCOVA

The HGYM group also had more arm lean mass and MCSA than LGYM *(p*<0.050). No differences were found in measures of muscle function between HGYM and LGYM (p>0.050).

5.4.3 Magnitude of the Musculoskeletal Benefits

Population-specific Z-scores confirmed LGYM and HGYM differed from NONGYM in bone and muscle parameters. Figure 5.1 displays the magnitude and direction in Z-scores between the LGYM and HGYM compared with NONGYM, who were used as the reference group. Z-scores for muscle function ranged from +0.48 to +0.63 SD in LGYM and +0.93 to +1.30 SD in HGYM. Z-scores for muscle endurance tasks showed the greatest differences between gymnasts and NONGYM participants.

5.4.4 Gymnastics Participation Correlations

Hours of weekly gymnastics participation positively correlated with bone strength at the 4% site (r =0.30, *p*=0.008) and strength/weight index at both the 4% and 66% sites (r =0.30 to 0.43, *p*=0.001). In addition, gymnastics training hours were also correlated with MCSA (r =0.34; *p*=0.001) and muscle function parameters of power and endurance (r =0.40 to 0.50; *p*=0.001).

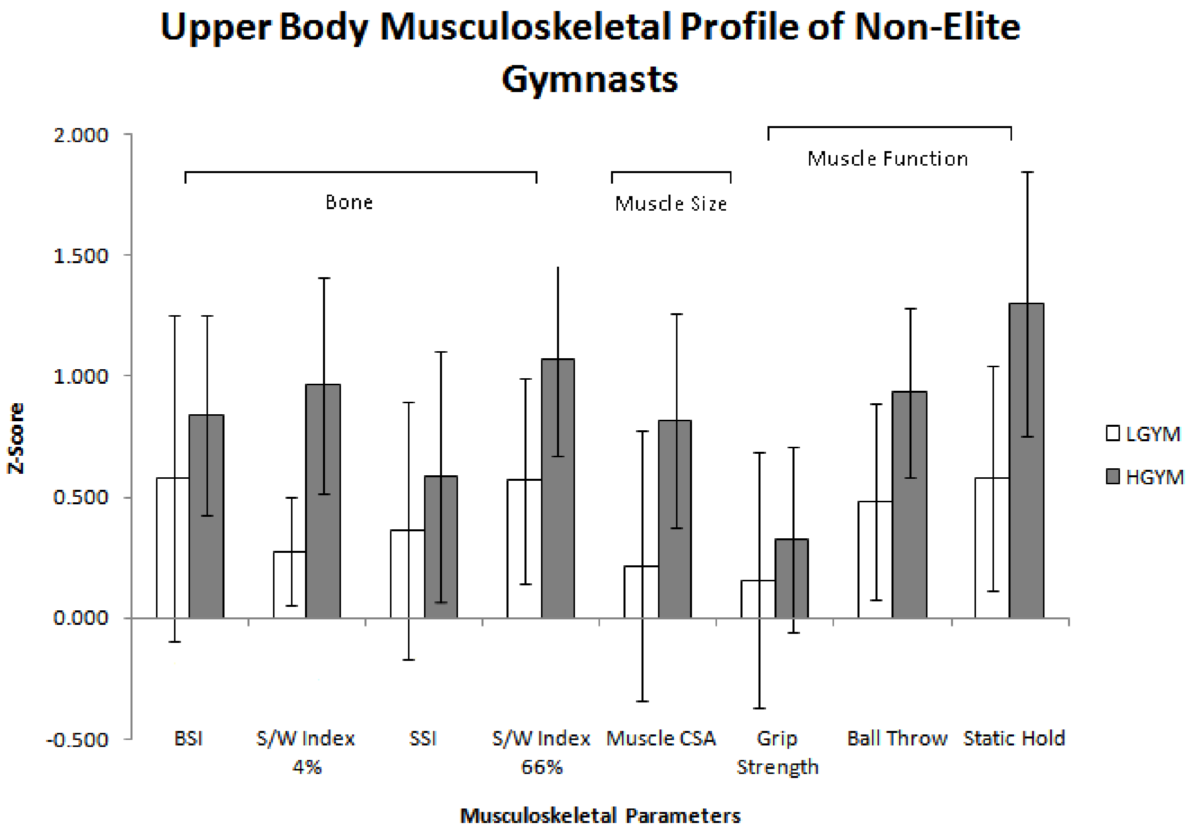


Figure 5.1. Z-scores for muscle function and pQCT-derived bone and muscle parameters in high- (HGYM) and low- (LGYM) training gymnasts

Bars indicate 95% CI for population-specific Z-scores in low-training gymnasts (LGYM) and high-training gymnasts (HGYM). Unadjusted Z-scores were calculated using the non-gymnasts as a reference. Bone Strength Index: BSI; Strength to Weight Index: S/W Index; Polar Strength Strain Index: SSIp; and Muscle Cross Sectional Area: Muscle CSA.

5.5 Discussion

Upper body musculoskeletal health was greater in non-elite artistic gymnasts compared with non-gymnasts. Specifically, gymnasts who were training from one to five hours per week had higher BMC and lean mass in the upper limb, higher forearm cross sectional bone area (66% site), bone density (4% site), medullary area, explosive strength and muscle endurance, than non-gymnasts. The benefits in bone strength did not reach significance. Gymnasts training six to sixteen hours per week had higher BMC, bone strength, bone area (66% site), bone density (4% site) as well as greater lean mass, muscle size and function than girls the same age not participating in gymnastics. Our findings suggest that gymnasts, even if participating at a non-elite level, have stronger and larger bones and muscles than non-gymnasts, which may decrease their risk of forearm fracture.

Higher bone strength has been consistently reported among actively training (Dyson, et al., 1997; Ward, et al., 2005) and retired (Ducher, et al., 2009; Eser, et al., 2009) elite gymnasts. Reports of enhanced bone strength are not surprising given the association of gymnastics training with greater muscle strength (Scerpella, et al., 2003; Vicente-Rodriguez, et al., 2007) and high mechanical loading (Panzer, et al., 1988), both of which influence bone development. Gymnasts within the current study were recreational and competitive non-elite gymnasts. Therefore, results suggest training at a non-elite intensity (max: 16 hr/wk) and being exposed to a smaller volume of mechanical loading than their elite counterparts, provided sufficient loading to induce bone strengthening mechanisms in pre-pubertal girls. At the 4% site, the high-training gymnasts had 21% greater bone strength than non-gymnasts. This is similar to the 25% greater bone strength at the distal radius recently reported in pre-pubertal recreational gymnasts (Erlandson, et al., 2011). Altogether, the findings demonstrate substantial benefits are achievable at the distal radius within a range of hours of non-elite gymnastics participation.

Within the current study, higher radial bone strength was observed not only at the 4% site but also further up the radial shaft at the 66% site, for the high-training gymnasts only. At the shaft, gains in bone strength in this group of non-elite gymnasts were due to larger bone area as a result of periosteal apposition. These findings are consistent with other pre-pubertal elite gymnasts (Ward, et al., 2005). At the bone shaft, increases in bone strength may be the result of bending forces created by muscle activity as a means of generating and absorbing forces of the moving skeleton. In contrast, axial compressive impact loading of the distal radius may be a greater contributor at the 4% site. At the distal radius, a greater bone density and to a lesser extent bone area seemed to be associated with the higher bone strength displayed by the gymnasts with high weekly training commitments. Despite higher bone strength failing to reach significance in the low-training gymnasts, a trend towards stronger bones at both the shaft and distal radius was evident (+6% and +12%, respectively). In agreement with other recreational gymnastics studies (Erlandson, et al., 2011), our low-training group did not report higher bone strength at the shaft.

In addition to the positive association with bone strength, previous studies of artistic gymnasts training for six or more hours per week also show benefits associated with a higher strength/weight index (Dowthwaite, et al., 2007; Dowthwaite, et al., 2009; Dowthwaite & Scerpella, 2011). This index estimates the risk of fracture from a low trauma fall based on bone strength relative to body weight and limb length (Rauch, et al., 2001). Both gymnastics groups in the present study demonstrated higher strength/weight index than non-gymnasts at the 4% site. The high-training gymnasts also demonstrated benefits at the 66% site.

While sports participation may enhance bone density and strength, it may not provide adequate site-specific bone adaptations able to increase the bones' capacity to withstand forces sustained during a fall. Peak wrist forces during falls, which are the most common cause of fracture in pre-pubertal children (Ma & Jones, 2002; Mäyränpää, et al., 2010), vary from 0.65 to 1.70 times body weight, from a one meter height (DeGoede & Ashton-Miller, 2002). Female fundamental gymnastics skills apply ground reaction forces up to four times body weight to the wrist. Furthermore, these impact forces are coupled with 38 to 58 wrist impacts on the beam and 30 to 35 wrist impacts on the floor at different phases of the training cycle within a 30 minute period (Burt, et al., 2010). The gymnastics-specific nature of impact loading directly to the distal radius may provide additional gains in bone strength and total density which, as a result may improve fracture resistance in pre-pubertal female gymnasts.

In addition to skeletal benefits, gymnasts had greater lean mass as measured by DXA and greater MCSA as measured by pQCT compared with non-gymnasts. Although longitudinal studies are necessary to confirm exercise-induced muscle hypertrophy, the larger MCSA identified in the high-training gymnastics group supports previously published data on elite pre-pubertal gymnasts (Ward, et al., 2005) and tennis players (Daly, et al., 2004; Sanchis-Moysi, et al., 2010). In the current study, bone benefits reported between gymnasts and non-gymnasts disappeared when differences in MCSA were accounted for. This suggests that at least part of the skeletal benefits seen in the gymnasts may be explained by larger MCSA. However, additional factors such as growth, genetics, nutritional, hormonal and impact forces associated with gymnastics participation may have influenced this increase (Dowthwaite, et al., 2009; Taaffe & Marcus, 2004).

Despite the known effect of muscle forces on bone tissue, few studies have directly assessed muscle strength or function in combination with bone strength in gymnasts (Scerpella, et al., 2003; Taaffe & Marcus, 2004). Contrary to previous findings (Scerpella, et al., 2003), our assessment of muscle function did not show a linear response between measures of muscle strength, endurance and hours of participation. The discrepancies may be due to the fact that we designed general muscle function tasks rather than gymnastics-specific strength based skills.

Importantly, the gymnasts with low-training commitments had better muscle function and more lean mass compared with non-gymnasts, although it was not associated with stronger bones. What is not known, is whether gymnasts training an average of 3 hr/wk catch up to gymnasts training an average of 10 hr/wk, and whether gymnasts with a high-training volume continue to gain additional bone strength.

5.5.1 Limitations

The cross-sectional nature of the study design did not allow for growth-related musculoskeletal alterations to be reported. Therefore, changes over time in association with gymnastics participation cannot be provided. Although difficult to quantify, the characteristics of self-selection and individual genetic makeup of the young girls within the current study restrict the strong musculoskeletal conclusions. Girls with greater mesomorphic somatotypes may experience greater success within many athletic activities and as a result, choose to participate in gymnastics (Caine, et al., 1989). Another limitation was the partial volume effect associated with the pQCT. This effect is known to reduce measurements of cortical density in the midshaft of bones with cortices thinner than 2.5 mm (Hangartner & Gilsanz, 1996). Finally, we may have been underpowered to compare differences between the two gymnastics groups.

5.5.2 Conclusions

Non-elite gymnastics participation is associated with musculoskeletal benefits to the upper limbs such as greater bone mass, estimated strength and muscle function in young girls. Longitudinal studies are needed to determine if further exposure to fundamental gymnastics skills performed less than 5 hr/wk can significantly enhance bone strength and decrease fracture incidence.

CHAPTER SIX

SKELETAL DIFFERENCES OF THE ULNA AND RADIUS IN PRE-PUBERTAL NON-ELITE FEMALE GYMNASTS

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6.1 Abstract

Objective: To compare skeletal differences between the ulna and radius associated with pre-pubertal non-elite gymnastics participation.

Methods: Fifty-eight non-elite artistic gymnasts, aged 6-11 years, were compared with 28 non-gymnasts for bone mineral content (BMC), total and cortical bone area (ToA, CoA), trabecular and cortical volumetric density (TrD, CoD) and estimated bone strength (BSI and SSIp), obtained by pQCT at the distal and proximal forearm.

Results: Gymnasts had greater estimated bone strength than non-gymnasts at both sites of the forearm. At the distal forearm, the gymnastics-induced skeletal benefits were greater at the radius than ulna (Z-scores for BMC, TrD and BSI +0.40 to +0.61 SD, $p<0.05$ vs. +0.15 to +0.48 SD, NS). At the proximal forearm, the skeletal benefits were greater at the ulna than the radius (Z-scores for BMC, ToA, CoA and SSIp +0.59 to +0.82 SD, $p<0.01$ vs. +0.35 (ToA) and +0.43 SD (SSIp), $p<0.01$).

Conclusion: Skeletal benefits at the distal and proximal forearm emerged in young non-elite gymnasts. Benefits were larger when considering skeletal differences at both the ulna and radius, than the radius alone as traditionally performed with pQCT. These

findings suggest the ulna is worth investigating in future studies that aim to accurately quantify the variation in skeletal parameters induced by exercise.

6.2 Introduction

Gymnastics participation provides a unique model for assessing skeletal adaptations due to high impact loading and muscle strength requirements, particularly in the upper limbs. Elite gymnastics participation prior to puberty is associated with greater bone strength at the radius as measured by peripheral quantitative computed tomography (pQCT) (Ward, et al., 2005). Skeletal benefits appear to be maintained among elite gymnasts after retirement (Eser, et al., 2009).

Previous investigations using pQCT on the upper limbs of pre-and early pubertal gymnasts (Dyson, et al., 1997; Erlandson, et al., 2011; Ward, et al., 2005) as well as retired or ex-gymnasts (Dowthwaite & Scerpella, 2011; Erlandson, et al., 2011; Eser, et al., 2009) have focused on the radius alone. Interestingly, although the radius is more than two times bigger, stronger and has more bone mass than the ulna at the distal forearm, the ulna has almost twice as much bone mass, cortical area and strength than the radius at the shaft, as demonstrated in former elite gymnasts and age-matched non-gymnasts (Ducher, et al., 2009). Skeletal benefits associated with approximately ten years of high-level gymnastics participation were shown to be greater at the radius than the ulna at the distal forearm (4% site) whereas the opposite was found at the proximal forearm (66% site) (Ducher, et al., 2009). Therefore, it is quite plausible that any future analysis of the radius without the inclusion of the ulna may result in underestimating skeletal benefits associated with gymnastics participation.

More recently, skeletal differences induced by recreational gymnastics participation have been explored since this mode of exercise is a more realistic approach to promote children's bone health than high-intensity elite gymnastics. Pre-pubertal gymnasts and ex-gymnasts, who have previously completed 1.5 hr/wk of gymnastic training over a two year period, displayed greater volumetric bone mineral density, bone mass and bone strength at the distal radius than controls (Erlandson, et al., 2011). No differences in bone size were evident for the radius between these gymnasts and controls (Erlandson, et al., 2011). However, skeletal differences of the ulna in pre-pubertal non-elite gymnasts remain unexplored. Therefore, similarly to what was found in retired elite gymnasts, assessing the radius alone may have underestimated skeletal benefits among pre-pubertal gymnasts.

The primary purpose of this study was to investigate pQCT-derived structural properties of bone at the distal and proximal radius and ulna in a group of pre-pubertal non-elite gymnasts and age-matched non-gymnasts. We hypothesize that gymnasts will display greater structural properties of bone at the radius and the ulna compared with non-gymnasts.

6.3 Materials and Methods

A total of 86 pre-pubertal girls aged 6 to11 years were recruited for this study. Gymnasts were training between 1 and 16 hr/wk and had trained for at least six months in the sport. All gymnasts were recruited from local gymnastics facilities and were participating at a recreational or non-elite level, rather than participating at an elite level. Non-gymnasts were recruited via the 'bring a friend' recruitment strategy as well as referral. Non-gymnasts were involved in equal to or less than 4 hr.wk of organised physical activity outside school. All participants were healthy pre-pubertal girls, not taking any medication known to affect bone or muscle metabolism, and without fracture to the upper limb within the previous 12 months. The study was approved by the University's ethics committees. Parental consent and child assent was obtained for all participants.

6.3.1 Anthropometric Assessment

A stadiometer (SECA height rod model 220, Hamburg, Germany) with an accuracy of 0.01 cm was used to measure standing height. Mass was recorded using digital scales (A&D Company Ltd., Tokyo, Japan) with an accuracy of 0.05 kg. Participants were asked about hand dominance and consequently the limb to be measured was determined as the non-dominant arm (except if a fracture had occurred, in which case the other limb was used). Forearm length was measured from the olecranon process to the ulnar styloid process using a metal measuring tape with an accuracy of 0.01 cm.

6.3.2 Body Composition

Body composition (lean and fat mass) was measured by dual-energy X-ray absorptiometry (DXA, Norland, XR-36 System, Fort Atkinson, Wisconsin). Measurements were performed at the predetermined scan mode (speed 180 mm/s, resolution 6.5 x 13.0 mm, source collimation 1.68 mm) with analysis software provided by the manufacturer (2.5.3a). Coefficients of variation in our laboratory were 1.3% for lean mass and 3.5% for fat mass.

6.3.3 Bone Mineral Density, Bone Geometry and Bone Strength

Bone parameters of the non-dominant forearm were measured by peripheral quantitative computed tomography (pQCT) (XCT 2000, Stratec Medizintechnik, Pforzheim, Germany). Given participants had an open growth plate at the distal radius, the reference line was positioned at the most distal portion of the growth plate, according to standard procedures (Neu, et al., 2001; Rauch & Schoenau, 2005). Two tomographic slices of 2.3 mm thickness were obtained at the 4% and 66% ulna and radius sites measured distally, with a voxel size of 0.4 mm and scan speed of 15 mm/s. Image processing and the calculation of bone parameters were conducted using the manufacturer's software package (version 6.00). The coefficients of variation in our laboratory ranged from 0.7 to 1.4% for pQCT-derived bone parameters at the forearm. All bone analyses were conducted by the same technician and quality assurance checks of the pQCT device were regularly performed.

At the 4% distal site, bone mineral content (BMC), total bone area (ToA), cortical thickness (CoTh), trabecular density (TrD) and bone strength index (BSI) were determined for both the ulna and radius. Cortical thickness was obtained using the method described by (Rauch, et al., 2001). The BSI was calculated as an assessment of bone strength and was determined using the following formula: BSI= total area (ToA) * total density $(ToD)^2$ (Kontulainen, et al., 2003). At this site, variables were calculated using contour and peel mode 1 with a threshold of 180 mg/cm^3.

At the 66% site, BMC, ToA, cortical area (CoA), medullary area (MedA), cortical density (CoD), CoTh, and the polar strength strain index (SSIp) were calculated. Cort mode 1 with a threshold of 711 mg/cm^3 was used for cortical bone and 280 mg/cm^3 for SSIp and ToA calculations.

Cortical thickness was calculated based on the assumption that all compartments of the bone shaft are cylindrical. To assess the influence of partial volume effect (Hangartner & Gilsanz, 1996), CoD was linearly correlated with CoTh. Partial volume effect is when voxels at the bone edges are incompletely filled, which can lead to an underestimation of cortical density in cortices that are thinner than 2.5 mm (Augat, Gordon, Lang, Iida, & Genant, 1998; Hangartner & Gilsanz, 1996; Prevrhal, et al., 1999). Medullary area was calculated by subtracting CoA from ToA. Bone strength (SSIp) was obtained using the manufacturer's software package.

6.3.4 Pubertal Stage

Maturation was assessed using a proxy report of Tanner's five stage model for pubertal maturation (Duke, et al., 1980; Tanner, 1978). Parents and daughters were asked to complete this questionnaire together. Participants with a combined Tanner score (breast + pubic hair) of three or less were included in this study.

6.3.5 Data Analysis

Data were presented as mean ± standard deviation (SD). The Gaussian distribution of the parameters was tested by the Kolmogorov–Smirnov test. Alpha level for statistical significance was set at 0.05. Baseline characteristics were compared between non-elite gymnasts and non-gymnasts using t-tests for independent samples. Bone parameters of the radius and ulna, as well as body composition, were compared between these two groups after adjustment for body weight using a one-way ANCOVA. Fisher's exact test was used to compare the incidence of fracture between the two groups. The effect size between the non-elite gymnasts and the non-gymnasts was evaluated using Z-scores. This allows comparing two groups with different distributions and parameters with different units. Individual Z-scores, expressed in standard deviations (SD), were calculated for the non-elite gymnasts using the following formula:

$$\text{Z-score} = (\text{Gymnast's Result} - \text{Mean}_{\text{Non-gymnast group}}) / \text{Standard Deviation}_{\text{Non-gymnast group}}$$

Significance of the Z-score was tested against zero using a one-sample t-test. All statistical procedures were performed with the software SPSS for Windows, version 18 (SPSS Inc., Chicago, IL).

6.4 Results

The pQCT scans of one gymnast (distal site) and three non-gymnasts (one distal and two proximal sites) were removed due to movement artifacts. In addition, four pQCT scans (two gymnasts and two non-gymnasts) were excluded at the distal site as radial TrD scores were higher than 320 mg/cm^3. Such values for TrD suggest scans were conducted too close to the growth plate, considering the 95th percentile for TrD is 260 mg/cm^3, based on reference data (Rauch & Schoenau, 2005).

Descriptive variables are shown in Table 6.1. The gymnasts had an average training history of 2.8 years (range: 0.5 to 6.0 years) and typically trained 7 hr/wk (range: 1 to 16 hr/wk). Non-gymnasts participated in 2 hr/wk of organised physical activity (range: 0 to 4 hr/wk). Organised physical activities among non-gymnasts included dancing, netball, soccer and swimming. Reports of previous fracture (>12 months prior) were not different between groups. All but one fracture occurred during free play rather than organised physical activity including gymnastics training.

Table 6.1

Anthropometric Data and Bone Mineral Density as Measured by DXA in Non-Elite Artistic Gymnasts and Age-Matched Non-Gymnasts (mean ± SD)

	Non-Elite Gymnasts (n=58)	Non-Gymnasts (n=28)
Age (yrs)	8.6 ± 1.3	8.5 ± 1.3
Tanner stage 1 breast (n=, %)	51 (88%)	23 (82%)
Tanner stage 1 pubic hair (n=, %)	57 (98%)	28 (100%)
Height (cm)	134.6 ± 6.6	135.9 ± 6.8
Weight (kg)	30.1 ± 5.6	32.1 ± 6.2
Forearm length (cm)	19.0 ± 1.6	19.0 ± 1.4
Lean body mass (kg)	19.48 ± 3.3	18.98 ± 3.3
Fat body mass (kg)	9.11 ± 3.0 [b]	11.63 ± 4.5
Gymnastics training hours (hr/wk)	6.9 ± 4.7 [a]	-
Total physical activity (hr/wk)	8.5 ± 4.6 [a]	2.0 ± 1.4

[a] $p<0.0001$, [b] $p<0.05$: Differences between gymnasts and non-gymnasts

6.4.1 Comparison of the pQCT-Derived Bone Parameters Between Non-Elite Gymnasts and Non-Gymnasts

Bone parameters obtained by pQCT in the two groups are shown for the radius and ulna in Table 6.2. The differences between the gymnasts and non-gymnasts are provided in Table 6.3, after adjusting for body weight. Adjustment for body weight was deemed necessary, despite the absence of statistical differences between groups, because gymnasts were 6% lighter than non-gymnasts. All parameters were greater in the gymnasts than the non-gymnasts at the distal radius (except ToA), proximal radius (except BMC, CoA, CoD and CoTh) and proximal ulna (except MedA and CoD). At the distal ulna, no differences were found between groups. Skeletal benefits at the distal forearm were characterized by greater trabecular volumetric BMD without differences in bone geometry however, the proximal forearm showed greater cross-sectional bone size.

6.4.2 Comparison of the pQCT-Derived Bone Parameters Between Radius and Ulna

Table 6.2 shows the relative differences in bone parameters between the radius and ulna. At the distal site, BMC, ToA, CoTh and BSI were more than twofold greater at the radius than the ulna in both groups ($p<0.0001$). The opposite was found at the proximal site, with BMC, ToA, CoA, MedA, and SSIp being greater at the ulna than the radius in both groups ($p<0.0001$). At the proximal forearm, bone parameters (with the exception of CoD and CoTh in the non-gymnasts) were 20 to 43% and 16 to 33% greater at the ulna than the radius in gymnasts and non-gymnasts, respectively.

Table 6.2

Comparison of the Ulna vs. Radius for Peripheral Quantitative Computed Tomography-Derived Bone Parameters at the 4% and 66% Sites in Non-Elite Gymnasts and Non-Gymnasts

	Ulna		Radius		% Differences Ulna vs. Radius[2]	
	Mean ± SD	**% Forearm[1]**	**Mean ± SD**	**% Forearm[1]**	**Mean difference**	**95% C.I.**
Non-Elite Gymnasts						
4% site (n= 55)						
BMC (g/cm)	0.33 ± 0.10	32	0.71 ± 0.18	68	-51.9% ‡‡	(-57.1 ; -46.8)
ToA (cm^2)	103.2 ± 16.6	30	236.5 ± 49.0	70	-55.8% ‡‡	(-57.1 ; -54.5)
CoTh (mm)	0.11 ± 0.13		0.38 ± 0.13		-69.1% ‡‡	(-91.3 ; -46.9)
TrD (mg/cm^3)	272.8 ± 37.8		229.3 ± 39.1		+20.1% ‡‡	(16.0 ; 24.2)
BSI (mg^2/mm^4)	9.5 ± 2.1		21.3 ± 6.6		-54.0% ‡‡	(-56.3 ; -51.7)

	Ulna		**Radius**		**% Differences Ulna vs. Radius**[2]	
	Mean ± SD	**% Forearm**[1]	**Mean ± SD**	**% Forearm**[1]	**Mean difference**	**95% C.I.**
66% site (n= 58)						
BMC (g/cm)	0.78 ± 0.12	56	0.61 ± 0.10	44	+30.2% ‡‡	(26.7 ; 33.8)
ToA (cm^2)	119.7 ± 22.1	56	95.7 ± 17.8	44	+26.1% ‡‡	(22.0 ; 30.2)
CoA (mm^2)	58.8 ± 9.4	57	44.8 ± 8.0	43	+32.5% ‡‡	(27.8 ; 37.3)
MedA (mm^2)	60.9 ± 17.5	54	51.7 ± 16.3	46	21.7% ‡‡	(14.4 ; 29.1)
CoD (mg/cm^3)	1012.4 ± 43.7		1023.7 ± 44.1		-1.1% ‡	(-2.0 ; -0.3)
CoTh (mm)	1.79 ± 0.26		1.51 ± 0.26		+19.5% ‡‡	(14.9 ; 24.0)
SSIp (mm^3)	189.8 ± 48.8		135.0 ± 32.4		+43.2% ‡‡	(35.9 ; 50.6)

	Ulna		Radius		% Differences Ulna vs. Radius[2]	
	Mean ± SD	**% Forearm[1]**	**Mean ± SD**	**% Forearm[1]**	**Mean difference**	**95% C.I.**
Non-gymnasts						
4% site (n=25)						
BMC (g/cm)	0.30 ± 0.06	31	0.66 ± 0.13	69	-53.1% ‡‡	(-56.8 ; -49.5)
ToA (cm^2)	109.2 ± 20.0	31	241.2 ± 46.6	69	-54.2% ‡‡	(-57.0 ; -51.4)
CoTh (mm)	0.06 ± 0.12		0.28 ± 0.16		-89.9% ‡‡	(-113.0 ; -67.0)
TrD (mg/cm^3)	266.2 ± 44.0		211.9 ± 32.5		+24.3% ‡‡	(17.8 ; 30.9)
BSI (mg^2/mm^4)	8.8 ± 2.4		18.3 ± 4.9		-51.0% ‡‡	(-55.6 ; -46.4)

	Ulna		**Radius**		**% Differences Ulna vs. Radius**[2]	
	Mean ± SD	**% Forearm**[1]	**Mean ± SD**	**% Forearm**[1]	**Mean difference**	**95% C.I.**
66% site (n=26)						
BMC (g/cm)	0.71 ± 0.11	54	0.61 ± 0.09	46	+20.0% ‡‡	(15.1 ; 24.9)
ToA (cm^2)	109.6 ± 17.2	55	90.8 ± 14.0	45	+21.16% ‡‡	(16.4 ; 26.0)
CoA (mm^2)	50.6 ± 10.7	54	43.9 ± 9.0	46	+16.04% ‡‡	(10.3 ; 21.8)
MedA (mm^2)	59.0 ± 18.8	56	46.9 ± 15.0	44	+28.7% ‡‡	(17.6 ; 39.7)
CoD (mg/cm^3)	1028.3 ± 59.6		1041.8 ± 51.5		-1.3% ‡	(-2.5 ; -0.1)
CoTh (mm)	1.60 ± 0.38		1.54 ± 0.35		+5.1%	(-1.2 ; 11.4)
SSIp (mm^3)	163.1 ± 32.4		123.8 ± 25.9		+33.3% ‡‡	(25.9 ; 40.7)

Values are given as mean ± standard deviation of the mean (SD). BMC: bone mineral content; ToA: total cross-sectional area; CoA: cortical cross-sectional area; MedA: medullary cross-sectional area; TrD: trabecular volumetric bone mineral density; CoD: cortical volumetric bone mineral density; CoTh: cortical thickness; BSI: bone strength index; SSIp: polar strength strain index.

[1] Values in each bone (ulna and radius) are also expressed as a percentage of the values in forearm bones, i.e. ulna + radius ('% Forearm').

For the ulna: Value Ulna * 100 / Value Ulna+Radius For the radius: Value Radius * 100 / Value Ulna+Radius

Masses and areas are additive, but characteristics such as densities and thicknesses are not. Therefore % Forearm values were not calculated for CoD, TrD, CoTh, BSI and SSIp. [2] The relative differences in bone parameters between the ulna and radius are indicated, with 95% confidence intervals.

% Difference Ulna vs. Radius: (Value Ulna – Value Radius) / Value Radius *100 Ulna ≠ Radius: ‡ $p<0.05$; ‡‡ $p<0.001$

Table 6.3

Body Weight-Adjusted Differences Between Non-Elite Artistic Gymnasts and Non-Gymnasts for Peripheral Quantitative Computed Tomography-Derived Bone Parameters at the Radius, Ulna and Ulna + Radius

	Ulna			**Radius**			**Ulna + Radius**[1]		
	Mean difference	**95% C.I.**	**Z-scores**	**Mean difference**	**95% C.I.**	**Z-scores**	**Mean difference**	**95% C.I.**	**Z-scores**
4% site									
BMC (g/cm)	+0.03	(-0.02 ; 0.07)	+0.48 SD	+0.08 [a]	(0.00 ; 0.15)	+0.40 SD	+0.11 [a]	(0.02 ; 0.21)	+0.57 SD
ToA (cm^2)	-3.12	(-10.37 ; 4.14)	-0.30 SD [‡]	+3.95	(-15.15 ; 23.04)	-0.10 SD	+0.83	(-23.70 ; 25.36)	-0.17 SD [‡]
CoTh (mm)	+0.05	(-0.01 ; 0.11)	+0.42 SD	+0.10 [b]	(0.04 ; 0.16)	+0.65 SD			
TrD (mg/cm^3)	+4.63	(-13.77 ; 23.03)	+0.15 SD [‡‡]	+18.99 [a]	(1.26 ; 36.72)	+0.53 SD			
BSI (mg^2/mm^4)	+0.91	(-0.12 ; 1.94)	+0.30 SD	+3.66 [a]	(0.83 ; 6.49)	+0.61 SD			

	Ulna			Radius			Ulna + Radius[1]		
	Mean difference	95% C.I.	Z-scores	Mean difference	95% C.I.	Z-scores	Mean difference	95% C.I.	Z-scores
66% site									
BMC (g/cm)	+0.10 [d]	(0.05 ; 0.14)	+0.65 SD [‡‡]	+0.02	(-0.01 ; 0.06)	-0.05 SD	+0.14 [d]	(0.07 ; 0.22)	+0.49 SD [‡‡]
ToA (cm^2)	+14.04 [c]	(6.15 ; 21.94)	+0.59 SD [‡]	+8.80 [b]	(3.09 ; 14.51)	+0.35 SD	+22.84 [d]	(10.47 ; 35.20)	+0.51SD [‡]
CoA (mm^2)	+10.05 [d]	(6.26 ; 13.84)	+0.77 SD [‡‡]	+2.46	(-0.77 ; 5.70)	+0.09 SD	+12.36 [d]	(6.01 ; 18.70)	+0.47 SD [‡‡]
MedA (mm^2)	+3.99	(-3.86 ; 11.85)	+0.10 SD	+7.23 [a]	(0.56 ; 13.90)	+0.33 SD	+11.22	(-1.95 ; 24.39)	+0.21 SD
CoD (mg/cm^3)	-12.86	(-35.47 ; 9.75)	-0.27 SD	-15.60	(-37.18 ; 5.98)	-0.35 SD			
CoTh (mm)	+0.21 [b]	(0.07 ; 0.34)	+0.49 SD [‡‡]	-0.01	(-0.15 ; 0.12)	-0.09 SD			
SSIp (mm^3)	+35.64 [d]	(19.15 ; 52.13)	+0.82 SD [‡]	+18.46 [d]	(8.46 ; 28.47)	+0.43 SD			

The between-group differences are expressed in two forms: the mean difference with the 95% confidence interval (adjusted for weight), and Z-scores. Positive values of the Z-scores indicate Non-elite Gymnasts > Non-gymnasts. Reference for Z-score calculation: non-gymnast group. BMC: bone mineral content; ToA: total cross-sectional area; CoA: cortical cross-sectional area; MedA: medullary cross-sectional area; TrD: trabecular volumetric bone mineral density; CoD: cortical volumetric bone mineral density; CoTh: cortical thickness; BSI: bone strength index; SSIp: polar strength strain index.

[1] Masses and areas are additive, but characteristics such as densities and thicknesses are not. Therefore CoD, TrD, CoTh, BSI and SSIp were not calculated for Ulna + Radius. The differences between non-elite gymnasts and non-gymnasts are indicated in the 'Mean difference' column : [a] $p<0.05$, [b] $p<0.01$, [c] $p< 0.001$, [d] $p<0.0001$ (this also indicates that Z-scores were significantly different from 0). ≠ Radius: [‡] $p<0.05$; [‡‡] $p<0.001$

The respective contribution of the radius and ulna to the overall bone mass and size of the distal and proximal forearm (ulna + radius) varies with location. At the distal site, values of radial BMC and ToA represent approximately 70% of the corresponding values at the whole forearm whereas at the proximal site, radial BMC, ToA, CoA and CoTh represent only 43% to 46% of the corresponding values at the whole forearm in gymnasts (Table 6.2). Similar observations were made in non-gymnasts.

6.4.3 Magnitude of the Skeletal Benefits Associated with Short-Term Non-Elite Gymnastics: Comparison Between Radius and Ulna

Table 6.3 presents the between-group differences in bone parameters at the radius, ulna and radius + ulna. Differences are expressed in Z-scores to illustrate the skeletal benefits of training in non-elite artistic gymnastics. The magnitude and direction of the skeletal benefits associated with short-term recreational gymnastics participation varied between the proximal and distal sites of the radius and ulna.

6.4.3.1 Distal (4% site)

At the distal site, skeletal benefits (i.e. significant difference between gymnasts and non-gymnasts) were found for BMC, CoTh, TrD and BSI at the radius (Z-scores +0.40 to +0.65 SD, $p<0.05$). Gymnasts had a tendency to have a smaller bone cross-sectional size than non-gymnasts at the radius and ulna (Z-score -0.10 and -0.30 SD, NS). No differences were found between gymnasts and non-gymnasts at the distal ulna.

6.4.3.2 Proximal (66% site)

At the proximal radius, skeletal benefits were found for ToA and SSIp (Z-scores +0.35 to +0.43 SD, $p<0.05$). In contrast to the distal site, the proximal ulna showed greater benefits than the proximal radius: SSIp (+0.82 SD), CoA (+0.77 SD), BMC (+0.65 SD), ToA (+0.59 SD) and CoTh (+0.49 SD), ($p<0.01$). At the proximal forearm, analysing the radius only, rather than radius and ulna together, lead to an underestimation of the skeletal benefits in gymnasts for the following parameters: BMC (-0.05 vs. +0.49 SD), ToA (+0.35 vs. +0.51 SD) and CoA (+0.09 vs. +0.47 SD).

6.5 Discussion

Pre-pubertal gymnastics participation at a non-elite level was associated with bone benefits to both the ulna and radius. At the distal forearm, bone benefits were more than twofold greater for the radius than ulna in bone mass, size and strength. Proximally, the ulna displayed greater exercise-induced benefits than the radius, which is consistent with a previous study conducted in retired elite gymnasts (Ducher, et al., 2009). At the distal forearm, skeletal differences were attributed to greater trabecular volumetric bone mineral density rather than bone geometry, whereas at the proximal forearm, differences were largely due to a larger cross-sectional bone size. These results are consistent with those previously reported in racquet sports (Ducher, Prouteau, Courteix, & Benhamou, 2004; Kontulainen, et al., 2003) and pre-pubertal gymnasts (Ward, Roberts, Adams, Lanham-New, & Mughal, 2007).

The gymnasts within the current study had greater bone strength than non-gymnasts at the distal and proximal forearm following training for approximately three years. These findings suggest that training at a moderate intensity rather than the high intensity reported by elite gymnasts, is sufficient in inducing skeletal differences in upper limb bone mass, density, cross-sectional size and strength. These variations emerged despite the upper limbs being exposed to lower ground reaction forces and frequency of impacts compared with the lower limbs (Burt, et al., 2010; Daly, et al., 1999). These findings are supported by recent results obtained in recreational gymnasts and ex-gymnasts at the distal radius (Erlandson, et al., 2011).

The skeletal benefits observed in non-elite gymnasts were achieved at both the proximal ulna and radius. Specifically, at the ulna, gymnasts had more bone mass, greater bone strength and a larger bone area (total and cortical) than the non-gymnast control group. At the radius, gymnasts also had a larger total bone size and strength than the non-gymnasts. While benefits were found at both the ulna and radius, the skeletal differences were more pronounced at the proximal ulna (Z-score +0.49 to +0.82 SD) than the proximal radius (Z-score -0.05 (NS) to +0.43 SD). These results strongly support previous findings on retired elite gymnasts who had started training during their pre-pubertal years (Ducher, et al., 2009). The findings of this study therefore support the inclusion of the ulna in future investigations on gymnasts and more generally exercise-induced skeletal adaptations at the forearm, to limit the risk of underestimating the skeletal benefits.

At the distal forearm, skeletal benefits in pre-pubertal non-elite gymnasts were only significant at the radius, which contrasts previous findings in adult retired elite gymnasts who showed skeletal benefits at the distal ulna (Ducher, et al., 2009). We found pre-pubertal non-elite gymnasts had greater radial bone mass, trabecular bone mineral density and bone strength when compared with non-gymnasts, which is similar to what has previously been reported in pre-pubertal elite (Ward, et al., 2005) and recreational gymnasts (Erlandson, et al., 2011). However, these benefits were not associated with an increase in cross-sectional bone size, which is consistent with previous reports in young gymnasts (Dyson, et al., 1997; Erlandson, et al., 2011; Ward, et al., 2005) but not with previous results in adult retired gymnasts (Ducher, et al., 2009; Eser, et al., 2009). The aforementioned findings suggest that gymnastics-induced skeletal differences at the distal forearm seem to vary between young girls exposed to short-term training and adults who have completed their career.

Variations of skeletal parameters observed at the distal radius between pre-pubertal and adult gymnasts may be the result of longitudinal growth. As long bones increase in length, new bone is continuously added between the growth plate and the metaphysis. At the junction of the metaphysis and the diaphysis, metaphyseal inwaisting occurs in which trabeculae are remodelled and cross-sectional bone size decreases through periosteal resorption, until it has reached the cross-sectional size of the diaphysis (Rauch, et al., 2001). Measurements by pQCT at the distal forearm are performed in the metaphysis, i.e. a skeletal site at which the bone continually undergoes metaphyseal inwaisting. This might explain why pre-pubertal gymnasts do not experience a significant increase in bone size compared with non-gymnasts. In contrast, at the proximal forearm (diaphysis) where appositional bone growth occurs, pre-pubertal gymnasts experienced significant gains in cross-sectional bone size.

Another possibility to explain the lack of bone enlargement at the distal forearm in young gymnasts would be that the exposure to the weight-bearing component of gymnastics training in these young girls was too short and therefore primarily affected trabecular volumetric density. In support of this notion, it was suggested that repetitive loading in adult triple jumpers induced geometrical adaptations at a trabecular site (distal tibia), but possibly after the trabecular density reached its ceiling (Heinonen, Sievänen, Kyröläinen, Perttunen, & Kannus, 2001). The short-term exposure to loading in the pre-pubertal gymnasts may also explain the relatively smaller magnitude of the skeletal differences in the pre-pubertal non-elite gymnasts when compared with retired elite gymnasts (Ducher, et al., 2009). Specifically, at the distal radius bone benefits ranged between Z-score +0.40 to +0.65 SD for the pre-pubertal gymnasts versus +0.7 to +2.1 SD for the retired elite gymnasts.

At the proximal site, where the benefits were larger at the ulna than the radius, the magnitude of bone variations were +0.15 to +0.48 SD for the pre-pubertal gymnasts versus +1.0 to +1.6 SD for the adult retired gymnasts. Not only had the retired gymnasts participated in gymnastics from a very young age (5.8 ± 0.9 years, on average) but they also maintained their training throughout pubertal growth. Similarly, results from tennis, another sport typically initiated at a young age, and squash players, found skeletal benefits to be larger in adults compared with young players (Ducher, Tournaire, Meddahi-Pellé, Benhamou, & Courteix, 2006) and larger in those who began sports participation before puberty as opposed to after (Kontulainen, et al., 2003).

In addition to their longer training history, adult retired elite gymnasts would have been exposed to a higher weekly training load inducing larger ground reaction forces (Brown, et al., 1996; Seeley & Bressel, 2005) and increased muscle strength and power (Bencke, et al., 2002; Scerpella, et al., 2003) compared with the non-elite gymnasts, all of which influence skeletal adaptations. It is unknown if the smaller bone differences found in young non-elite gymnasts when compared with retired gymnasts are due to the shorter training history, lower training load and/or ground reaction forces, or a combination of these factors. Furthermore, peak in bone mineral accretion, experienced around the age of menarche (Bailey, et al., 1999), had not yet been reached by the young gymnasts in the present study.

6.5.1 Limitations

This study presents several limitations. Due to the cross-sectional nature of the investigations, the possibility of a selection bias in the group of non-elite gymnasts cannot be ruled out. At the proximal site, only two out of 58 gymnasts and three out of 28 non-gymnasts had radial cortical thickness greater than 2 mm, whereas 12 gymnasts and two non-gymnasts had ulnar cortical thickness greater than 2 mm. None of the participants had cortical thickness (radius or ulna) greater than 2.5 mm. Partial volume effect, which is known to affect measurements of bone density in bone shafts with cortices thinner than 2.5 mm (Hangartner & Gilsanz, 1996), most likely influenced the results of this study.

6.5.2 Conclusions

Pre-pubertal non-elite gymnastics participation was shown to be associated with skeletal differences at both the radius and ulna. The radius was found to have greater gymnastic-specific results at the distal forearm whereas the ulna had greater benefits at the proximal site, supporting previous findings in retired elite gymnasts. Although the skeletal benefits found at the proximal radius were significant in young non-elite gymnasts with 0.5 to 6 years of training history, the overall benefits were larger when skeletal differences in the proximal ulna were included. These findings suggest the ulna is worth investigating in future studies that aim to accurately quantify the variation in skeletal parameters induced by exercise.

CHAPTER SEVEN

NON-ELITE GYMNASTICS INDUCES MUSCULOSKELETAL BENEFITS IN THE UPPER LIMB OF EARLY PUBERTAL GIRLS: A 6-MONTH STUDY USING PERIPHERAL QUANTITATIVE COMPUTED TOMOGRAPHY

7.1 Abstract

Purpose: Little is known about the musculoskeletal development of weight-bearing loading to the upper limbs of non-elite gymnasts during early pubescent growth. The purpose of this longitudinal study was to examine the effects of non-elite female gymnastics participation on upper body musculoskeletal parameters.

Methods: Eighty-four girls, (aged 6-12 years, Tanner stages I to III) were divided into three groups based on their participation in gymnastics: high-training (HGYM), 6 to 16 hr/wk, low-training (LGYM), 1 to 5 hr/wk and non-gymnasts (NONGYM). At baseline and 6 months, total density (ToD), bone mineral content (BMC), total and cortical area (ToA, CoA), bone strength (BSI and SSI) were assessed by pQCT at the 4% and 66% forearm (radius and ulna). DXA-derived BMC and lean mass in the arms, as well as pQCT-derived forearm muscle cross sectional area (MCSA) were also obtained. Upper body muscle function was assessed with generic assessments for explosive power, strength, and endurance.

Results: Growth rate (in height) over six months was not different between groups. DXA-derived BMD and BMC, pQCT-derived BMC at 66% forearm and ToA at 66% radius as well as arm lean mass, grip strength and muscle endurance, increased over six months in NONGYM ($p<0.05$). Following body weight adjustments, arm lean mass, SSI at the 66%

forearm, ToA (66% radius), BMC and CoA (66% ulna), explosive power and muscle endurance, which were initially higher in gymnasts than NONGYM, remained higher at follow up. MCSA increased more in HGYM than both NONGYM and LGYM. At baseline, HGYM had greater BMC, ToD and BSI than NONGYM at the 4% radius, whereas LGYM had greater ToD ($p<0.05$). At six months, both groups of gymnasts had a greater ToD at the 4% radius than NONGYM (LGYM +8% greater, HGYM +15% greater, $p<0.05$). HGYM had a greater increase in BMC and BSI at the 4% radius than both NONGYM (+25-45% greater, $p<0.01$) and LGYM (+20-28% greater, $p<0.05$).

Conclusion: At baseline gymnasts showed upper limb musculoskeletal benefits, potentially resulting from an average training history of three years. Benefits were maintained, and in some instances, increased over the duration of the study. Muscle function tests consistently showed superior skills among gymnasts, independent of hours of training. Although favourable skeletal gains were seen in LGYM, HGYM had the greatest gains. Musculoskeletal benefits beyond growth-induced effects are induced by non-elite gymnastics participation during early puberty.

7.2 Introduction

Although elite gymnastics has served as a model for exercise-induced musculoskeletal adaptations (Bass, et al., 1998; Courteix, Lespessailles, Jaffre, et al., 1999; Ward, et al., 2005), the injury risk (Caine et al., 2003; Kolt & Kirkby, 1999) associated with the training volume and intensity make it unsuitable for the promotion of physical activity within the general population. Elite gymnasts typically train in excess of 25 hr/wk, up to 6 days a week for 12 months a year, from a very young age (Caine, et al., 1989). In contrast, recreational or non-elite gymnastics participation is associated with realistic training commitments, less physiological and psychological pressure, lower concerns for nutritional and hormonal disturbances, as well as a decreased injury rate than elite gymnasts (Kolt & Kirkby, 1999). As a consequence, an increasing number of studies are investigating the effects of non-elite gymnastics participation on musculoskeletal health (Dowthwaite, et al., 2006; Dowthwaite, et al., 2007; Erlandson, et al., 2011; Laing, et al., 2005; Scerpella, et al., 2003).

Musculoskeletal changes associated with non-elite gymnastics participation are expected to be smaller than changes in elite gymnastics and may vary based on weekly exposure. To detect these changes, it is necessary to control for growth and other potential confounders by conducting longitudinal investigations. Previous longitudinal studies on non-elite gymnasts relied on dual-energy X-ray absorptiometry (DXA) (Erlandson, Kontulainen, Chilibeck, Arnold, & Baxter Jones, in press; Gero, et al., 2005; Laing, et al., 2002; Laing, et al., 2005), which is not able to detect small changes in volumetric bone mineral density and geometry during growth. In contrast, peripheral quantitative computed tomography (pQCT) offers important information on the determinants of bone strength and has previously been used in several cross-sectional studies in pre- and early pubertal gymnasts (Dyson, et al., 1997; Erlandson, et al., 2011; Ward, et al., 2005). The authors are currently aware of one gymnastics study which has reported pQCT parameters longitudinally among elite male and female gymnasts (Ward, Roberts, et al., 2007).

Factors known to influence changes and development in skeletal health include impact and muscle forces (Judex & Carlson, 2009). Muscle forces are thought to be the largest forces applied on the skeleton (Frost, 2000). However, most studies use surrogate measures of muscle force and function when analysing the muscle-bone relationship. Few studies have assessed actual muscle function parameters in addition to bone among young gymnasts (Gero, et al., 2005; Scerpella, et al., 2003; Vicente-Rodriguez, et al., 2007). Existing studies assessed explosive power in the lower body with counter movement jumps (Vicente-Rodriguez, et al., 2007), upper body strength with one repetition maximums and muscle endurance with gymnastics-specific tasks (Gero, et al., 2005; Scerpella, et al., 2003). Only one study reported muscle function changes over time; reporting gymnasts had greater strength at baseline however, no difference between groups was evident at study completion (Gero, et al., 2005). Furthermore, the minimum amount of training necessary to induce positive musculoskeletal changes in young gymnasts is currently unknown. Reviews of exercise interventions in children and adolescents have shown that two to three sessions per week are typically prescribed for improving musculoskeletal health (Hind & Burrows, 2007; Hughes, Novotny, Wetzsteon, & Petit, 2007). However, gymnastics is associated with high-intensity loading, and a unique bilateral loading pattern of the upper limbs, as opposed to the majority of sports that load the lower limbs. Whether or not a single session of gymnastics per week (i.e. 2-3 hours) may be sufficient to improve short-term musculoskeletal health benefits is unclear.

The overall aim of the study was to compare changes in musculoskeletal parameters over six months in pre- and early pubertal females involved in different quantities of artistic gymnastics (high- 10.5 hr/wk and low- 3 hr/wk training gymnasts) with a group of age and gender matched non-gymnasts. We hypothesised that sports participation, specifically artistic gymnastics, in the early stages of puberty would favour upper body musculoskeletal development. Furthermore, gymnasts were expected to have greater increases in upper limb skeletal and muscle function parameters than non-gymnasts. Finally, we hypothesized a dose-response would emerge between musculoskeletal parameters and weekly gymnastics exposure.

7.3 Methods

7.3.1 Study Participants

Initially 141 pre-pubertal girls were invited to participate in this longitudinal study. A total of 94 participants completed baseline assessments three of whom were excluded as they did not meet the selection criteria. Following six months of growth and development, 91 girls completed subsequent assessment. Seven girls dropped out at follow up. Therefore, 84 young girls were included in this study. At study initiation, participants were healthy pre-pubertal girls, not taking any medication known to affect bone or muscle metabolism, and without fracture to the upper limb within the previous 12 months. Non-gymnasts were involved in less than 4 hr/wk of organised physical activity outside school and were recruited via the “bring a friend” recruitment strategy. Gymnasts were recruited from local gymnastics centres and were training between 1 and 16 hr/wk. Gymnasts had trained for at least six months in the sport and were participating at a recreational or non-elite level. After obtaining parental consent and child assent, participants were assigned to one of three groups based on their gymnastics participation: high-training gymnasts (HGYM), 6 to 16 hr/wk, low- training gymnasts (LGYM), 1 to 5 hr/wk and non-gymnasts (NONGYM). The cut-off point of 5 hr/wk used to discriminate HGYM and LGYM, was chosen based on the number of training sessions per week: LGYM participated in one gymnastics class per week (never exceeding 5 hr/wk), whereas HGYM participated in more than one class per week (always exceeding 5 hr/wk). HGYM participants involved in the study were training 16 hr/wk or less, which is significant however, this involvement is still considered a non-elite level, and is associated with normal growth and maturation (Theintz, et al., 1993). The study was approved by the University’s ethics committee.

7.3.2 Setting

Recruitment took place over a nine month period. The total duration of the study was 15 months. All assessments were conducted in the University's laboratory. The average time between baseline and follow up assessments was six months (range 5 to 8 months).

7.3.3 Power Analysis

To allow for the detection of significant differences in skeletal characteristics with a small estimated effect size (d = 0.20), with a statistical power of 90% and a significance level of 0.05, the minimum total sample size was calculated to be 84 participants (Erdfelder, et al., 1996).

7.3.4 Anthropometric Assessment

A stadiometer (SECA height rod model 220, Hamburg, Germany) with an accuracy of 0.01 cm was used to measure standing and sitting height. Body mass was recorded using digital scales (A&D Company Ltd., Tokyo, Japan) with an accuracy of 0.05 kg. Forearm length was measured from the olecranon process to the ulna styloid process using a metal measuring tape with an accuracy of 0.01 cm.

7.3.5 Body Composition and Bone Mineral Density

Whole body bone mineral density (BMD), bone mineral content (BMC), bone area, lean and fat mass were measured by dual-energy X-ray absorptiometry (DXA, Norland, XR-36 System, Fort Atkinson, Wisconsin). Body composition and bone parameters in the upper limb (including the humerus, ulna, radius, carpals, metacarpals and phalanges) were derived from the whole body scan. This method was previously used and showed good reproducibility with a CV below 1% (Ducher, et al., 2005). Measurements were performed at the predetermined scan mode (speed 180 mm/s, resolution 6.5 x 13.0 mm, source collimation 1.68 mm) with analysis software (2.5.3a). The CV in our laboratory was obtained following scanning of nine healthy university students twice, following repositioning. Specifically, CVs were: lean mass 1.3%, fat mass 3.5%, BMD 0.9%, BMC 1.1% and bone area 1.0%. All DXA scans were conducted by the same technician.

7.3.6 Volumetric Bone Mineral Density, Bone Geometry and Bone Strength

Volumetric bone mineral density and bone geometry were measured by pQCT in participants' non-dominant forearm (XCT 2000, Stratec Medizintechnik, Pforzheim, Germany). Given participants had an open growth plate at the distal radius, the reference line was positioned at the most distal portion of the growth plate, according to standard procedures (Neu, et al., 2001; Rauch & Schoenau, 2005). Two tomographic slices of 2.3 mm thickness were obtained at the 4% and 66% radius sites measured distally, with a voxel size of 0.4 mm and scan speed of 15 mm/s. Image processing and the calculation of bone parameters were conducted using the manufacturer's software package (version 6.00). Precision was obtained by scanning eight healthy adults twice, following repositioning. Young children were not used to determine precision in our laboratory due to the ethical considerations linked to repeated radiation exposure. The CV in our laboratory ranged from 0.7 to 1.4% for pQCT-derived bone parameters at the radius. All bone analyses were conducted by the same technician and quality assurance checks of the pQCT device were regularly performed.

At the 4% distal forearm, total bone mineral content (BMC), trabecular density (TrD), total bone area (ToA) density (ToD) and bone strength index (BSI) were determined. The BSI was calculated as an assessment of bone strength and was determined using the following formula: BSI= total area (ToA) * total density $(\text{ToD})^2$ (Kontulainen, et al., 2003). At this site, variables were calculated using contour and peel mode 1 with a threshold of 180 mg/cm^3.

At the 66% site BMC, cortical density (CoD), cortical area (CoA), cortical thickness (CoTh), ToA, ToD, medullary area (MedA) and the polar strength strain index (SSIp) were calculated. Cort mode 1 with a threshold of 711 mg/cm^3 was used for cortical bone and 280 mg/cm^3 for SSIp, ToA and ToD calculations. Keeping the same mode, an additional threshold (40 mg/cm^3) was applied to remove fat area from the total cross-sectional slice. What remains denotes the muscle-bone area. Muscle cross-sectional area (MCSA) was calculated by subtracting the bone area from the muscle-bone area.

7.3.7 Muscle Function

7.3.7.1 Muscle strength

A hand grip dynamometer (Smedley's dynamometer TTM, Tokyo) was individually adjusted for participants. Participants held the dynamometer with their non-dominant arm extending downwards, away from the body (Orjan, et al., 2005), squeezing the device maximally for three seconds. Participants had two familiarisation trials. The best of the three trials was recorded. An inter-day CV of 4.5% was obtained following testing of a subsample of 21 girls, one week apart.

7.3.7.2 Explosive power

The seated ball throw was adapted from a previous study (Davis, et al., 2008). However, participants aimed their throw towards a target located three meters away. Throws were repeated three times and the best trial recorded. The weight of the medicine ball was relative to 10% of the participant's body weight (range 2 to 5 kg). An inter-day CV of 3.3% was obtained following testing of a subsample of 10 girls, one week apart.

7.3.7.3 Muscle endurance

In the absence of valid paediatric muscle endurance tasks (Pate, et al., 1993) and to remove gymnastics-specific bias, two novel tasks were devised and described in detail elsewhere (chapter four). In brief, the first task required participants to perform a maximum number of weighted arm sequences during a 30 second time period. The weight applied to the arms (wrists) was relative to 5% of the participant's body weight. An inter-day CV of 2.5% was obtained for the arm sequence following testing of a subsample of eight girls, one week apart.

The second task required participants to hold an upright static position using their arms to support their own body weight between two stabilised benches. Three trials were performed, and the successful time on the third attempt was recorded. An inter-day CV of 3.6% was obtained for the static hold following testing of a subsample of eight girls, one week apart. All muscle function tasks obtained acceptable reliability as they had a CV of less than 9% (Fricke, et al., 2006).

7.3.8 Pubertal Stage

Maturation was assessed using a proxy report of Tanner's five stage model for pubertal maturation (Duke, et al., 1980). Parents and daughters were asked to complete this questionnaire together. Participants with a combined Tanner score (breast + pubic hair development) of four or less were included in this study.

7.3.9 Calcium, Protein and Total Caloric Intakes

Calcium, protein and total caloric intake were quantified with a 3-day diet recall over two school days and one weekend day. During these three days, parents and daughters completed the questionnaire together. Data were then entered into FoodWorks (dietary-analysis software Xyris Software Pty. Ltd., Highgate Hill, QLD, Australia) and average intakes were derived.

7.3.10 Questionnaires

Parents completed questionnaires about their daughter’s training background, physical activity/exercise history, injury and health status. These answers were used to verify eligibility for study participation, participant grouping and changes in activity patterns over the duration of the study.

7.3.11 Statistical Analyses

Statistical analyses were performed with SPSS for windows (version 18.0, SPSS Inc., Chicago, IL). Differences in mean and median in addition to Kolmogorov-Smirnov values were used to assess normal distribution (Peat & Barton, 2005). Data were presented as mean ± 95% confidence intervals (CI). Differences in non-parametric statistics were calculated using chi-square to test for differences in percentages between groups and Wilcoxon matched-pairs for changes over time. The muscle function assessment for static hold as well as DXA assessment of lean and fat mass and pQCT measures of trabecular area and density, total bone area, bone strength, BMC and MedA at the 4% site were log10 transformed as they failed to meet criteria for normal distribution. Paired sample t-tests were used to determine if variables changed over six months. Furthermore, musculoskeletal parameters were compared between groups using repeated measures ANCOVAs, with adjustment for body mass. Post hoc Bonferroni analyses were used to determine between-group differences and were reported as a percentage. Relationships between variables were explored with Pearson’s correlation analyses and the highest correlates entered into a stepwise multiple linear regression. Statistical significance was set at an alpha level of 0.05 for all tests with the exception of correlation analyses, for which 0.01 was set.

7.4 Results

Groups were not different for age, stature, body mass or lean mass at baseline. Furthermore, the increase in these parameters over the study duration did not differ between groups (Table 7.1). Chi-square for Tanner stage showed no differences between groups for the proportion of participants in each maturation stage. Training for the LGYM ranged from 1 to 5 hr/wk, whereas HGYM trained between 6 to 16 hr/wk. Previous gymnastics history (approximately three years of training) at study initiation was not different between gymnastics groups. Post hoc analyses showed differences between all groups for hours of weekly gymnastics participation ($p < 0.001$). Non-gymnasts commonly participated in dancing, netball, soccer and swimming (range: 0 to 4 hr/wk). No differences were found among all three groups for forearm length, calcium, protein or total caloric intake.

Table 7.2 displays BMD and BMC results for the total body and arms. Although the ANCOVA did not reveal any group by time interactions, all three groups increased in total body and arms BMC over the six months as identified by the paired sample t-test. Furthermore, total body BMD also increased for both NONGYM and LGYM but not significantly for HGYM.

Table 7.1

Descriptive Characteristics for Early Pubertal Girls Participating in Low- and High-Training Artistic Gymnasts and a Non-Gymnastic Control Group

	Non-Gymnasts			**Low Gymnasts**			**High Gymnasts**			P Value
	Baseline	6MO	% Δ	Baseline	6MO	% Δ	Baseline	6MO	% Δ	
	n = 29	n = 28		n = 30	n = 28		n = 32	n = 28		
Age (y)	8.5 (8.0-9.0)	9.0 ^{c} (8.5-9.5)	6.5 (4.0-9.0)	8.3 (7.8-8.8)	8.8 ^{c} (8.3-9.4)	5.7 (3.2-8.2)	9.0 (8.5-9.5)	9.6 ^{c} (9.1-10.2)	6.2 (3.9-8.6)	0.832
Standing Height (cm)	135.9 (133.3-138.5)	138.5 ^{c} (135.4-141.7)	2.0 (1.5-2.5)	134.7 (132.2-137.3)	138.4 ^{c} (135.6-141.2)	2.3 (2.0-2.7)	135.8 (133.1-138.6)	138.6 ^{c} (135.4-141.9)	1.9 (1.5-2.4)	0.387
Sitting Height (cm)	67.6 (65.7-69.5)	69.8 ^{c} (68.1-71.5)	3.3 (1.6-5.0)	67.0 (65.5-68.5)	69.9 ^{c} (68.1-71.8)	3.8 (2.1-5.6)	67.8 (66.0-69.6)	71.0 ^{c} (69.1-72.9)	4.4 (3.3-5.6)	0.513
Body Mass (kg)	32.1 (29.7-34.5)	34.2 ^{c} (31.2-37.2)	6.2 (4.1-8.4)	30.7 (28.4-33.1)	33.5 ^{c} (30.7-36.2)	5.6 (4.3-6.9)	30.4 (28.4-32.4)	33.0 ^{c} (30.4-35.6)	7.3 (5.8-8.8)	0.484
Tanner Breast I (N, % stage I)	24 83%	20 71%	12	25 83%	20 71% ^{c}	12	26 81%	21 75%	6	0.976
Tanner Pubic Hair I (N, % stage I)	29 100%	24 86% ^{c}	14	29 97%	27 96%	1	29 91%	22 79%	12	0.195
Total Body Lean Mass (kg)	19.0 (17.7-20.3)	20.2 ^{c} (18.6-21.9)	5.9 (3.3-8.5)	19.3 (17.9-20.6)	21.1 ^{c} (19.4-22.8)	7.7 (5.0-10.4)	20.2 (19.0-21.4)	21.8 ^{c} (20.2-23.3)	6.7 (5.2-8.2)	0.566
Total Body Fat Mass (kg)	11.6 (9.9-13.4)	12.3 ^{c} (10.4-14.3)	7.2 (2.6-11.8)	9.9 (8.8-11.1)	10.7 (9.2-12.3)	1.8 (-2.8-6.3)	8.5 (7.5-9.6)	9.6 ^{c} (8.3-10.9)	10.1 (4.3-15.8)	0.078 ^{a}
Gymnastics Training (hr/wk)	-	-	-	3.1 (2.7-3.6)	2.9 (2.3-3.5)	-8.0 (-21.0-4.9)	10.5 (9.1-11.9)	10.4 (9.1-11.8)	0.8 (-5.2-6.8)	0.545 ^{ab}

Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P value represents interaction effect for repeated measures ANOVA, except for Tanner stage where the Kruskal-Wallis significance is reported. 6-month changes (paired sample t-test): ^{a} HGYM >NONGYM ($p< 0.05$) ^{b} HGYM >LGYM ($p< 0.05$) ^{c} different from baseline ($p< 0.05$). Tanner scores for participants in stage one are reported as a raw value (number of participants) and percentage of participants.

Table 7.2

Bone Mineral Content and Density Results for Dual-Energy X-ray Absorptiometry Derived Skeletal Parameters of the Total Body and Arms

	Non-Gymnasts (n = 27)			Low Gymnasts (n = 25)			High Gymnasts (n = 27)			**P**
	Baseline	6MO	% Δ	Baseline	6MO	% Δ	Baseline	6MO	% Δ	**Value**
TB BMD (g/cm^2)	0.725 (0.702-0.749)	0.741 [b] (0.716-0.766)	2.2 (1.3-3.2)	0.707 (0.682-0.732)	0.717 [b] (0.691-0.743)	1.5 (0.1-2.8)	0.716 (0.693-0.739)	0.727 (0.704-0.751)	1.7 (-0.1-3.5)	0.750
TB BMC (g)	1351.5 (1255.1-1447.8)	1445.10 [b] (1342.2-1548.1)	7.0 (5.4-8.7)	1332.0 (1236.8-1427.2)	1410.6 [b] (1300.8-1520.5)	5.7 (3.9-7.5)	1339.5 (1247.1-1431.9)	1425.7 [b] (1319.4-1532.0)	6.3 (4.7-7.8)	0.628
Arms BMD (g/cm^2)	0.451 (0.430-0.472)	0.448 (0.428-0.467)	-0.1 (-4.1-3.9)	0.448 (0.424-0.472)	0.446 (0.422-0.470)	0.1 (-4.9-5.1)	0.434 (0.414-0.453)	0.441 (0.434-0.458)	2.3 (-1.4-6.0)	0.684 [a]
Arms BMC (g)	142.5 (132.1-152.9)	153.3 [b] (141.3-165.4)	7.8 (4.3-11.2)	152.3 (137.8-166.8)	163.0 [b] (144.3-181.6)	6.9 (0.2-13.5)	154.4 (141.2-167.5)	165.4 [b] (150.4-180.4)	7.3 (4.1-10.4)	0.974

Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P value represents interaction effect (group * time) for repeated measures ANCOVA. Six month changes (paired sample t-test): [a] NONGYM > HGYM ($p < 0.05$), [b] different from baseline ($p < 0.05$).

Table 7.3

Peripheral Quantitative Computed Tomography Results at the 4% Radius in Three Groups of Pre- and Early Pubertal Girls

	Non-Gymnasts (n = 27)			**Low Gymnasts (n = 27)**			**High Gymnasts (n = 28)**			**P**
	Baseline	6MO	% Δ	Baseline	6MO	% Δ	Baseline	6MO	% Δ	**Value**
BMC	0.656	0.699	7.8	0.673	0.729	3.5	0.728	0.874 [d]	18.4	<0.001 [ac]
(g/cm)	(0.597-0.714)	(0.633-0.764)	(0.1-15.4)	(0.619-0.726)	(0.644-0.813)	(0.1-6.8)	(0.670-0.786)	(0.790-0.957)	(15.5-21.4)	
TrD	209.98	225.34	7.4	222.62	228.57	-0.5	230.65	255.79 [d]	11.1	0.009 [a]
(mg/cm^3)	(195.24-224.72)	(209.41-241.26)	(-2.3-17.1)	(207.53-237.71)	(208.72-248.43)	(-5.3-4.2)	(219.82-241.48)	(241.63-269.95)	(8.1-14.1)	
ToA	243.97	255.23	6.4	230.22	246.78 [d]	4.6	238.34	275.18 [d]	14.9	0.001
(mm^2)	(222.06-265.88)	(233.14-277.32)	(0.6-12.1)	(214.26-246.18)	(222.29-271.27)	(0.8-8.4)	(219.84-256.84)	(253.47-296.89)	(12.3-17.5)	
ToD	275.32	274.50	0.2	295.52	295.60	-0.9	306.44	316.82 [d]	3.2	0.033 [ab]
(mg/cm^3)	(262.05-288.59)	(263.58-285.42)	(-4.4-4.8)	(282.31-308.73)	(281.91-309.29)	(-3.2-1.3)	(296.53-316.35)	(305.07-328.56)	(1.2-5.3)	
BSI	17.76	19.32	5.9	20.19	21.88	1.6	21.20	28.04 [d]	21.3	<0.001 [ac]
(mg/mm^4)	(15.82-19.71)	(16.99-21.65)	(-3.6-15.3)	(18.03-22.35)	(18.54-25.22)	(-3.8-7.0)	(19.58-22.83)	(24.49-31.59)	(16.7-25.9)	

Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P value represents interaction effect (group * time) for repeated measures ANCOVA. Six month changes (paired sample t-test): [a] HGYM > NONGYM (*p* <0.05), [b] LGYM > NONGYM (*p* <0.05), [c] HGYM > LGYM (*p* <0.05), [d] different from baseline (*p* <0.05), Bone mineral content: BMC; Trabecular density: TrD; Total area: ToA; Total density: ToD; Bone strength index: BSI

Table 7.4

Peripheral Quantitative Computed Tomography Results at the 4% Ulna in Three Groups of Pre- and Early Pubertal Girls

	Non-Gymnasts (n = 27)			**Low Gymnasts (n = 27)**			**High Gymnasts (n = 28)**			**P**
	Baseline	6MO	% Δ	Baseline	6MO	% Δ	Baseline	6MO	% Δ	**Value**
BMC	0.313	0.330	6.6	0.308	0.344 [d]	11.8	0.327	0.367 [d]	13.0	0.234
(g/cm)	(0.288-0.338)	(0.294-0.366)	(-5.1-18.4)	(0.287-0.330)	(0.300-0.388)	(0.3-23.3)	(0.305-0.349)	(0.337-0.397)	(8.0-18.0)	
TrD	265.82	263.47	0.4	271.67	269.78	-0.3	273.82	291.01 [d]	8.2	0.025
(mg/cm^3)	(248.65-282.99)	(247.50-279.44)	(-6.5-7.3)	(255.27-288.07)	(251.69-287.87)	(-3.9-3.3)	(261.63-286.00)	(277.47-304.54)	(2.0-14.5)	
ToA	109.95	111.94	2.3	104.50	106.37	3.8	106.46	116.29 [d]	9.6	0.024
(mm^2)	(102.30-117.6)	(104.82-119.06)	(-2.4-7.0)	(97.80-111.21)	(99.15-113.59)	(0.0-7.6)	(99.08-113.83)	(108.19-124.38)	(6.1-13.2)	
ToD	283.58	282.40	-0.3	296.15	303.68	2.5	308.36	313.97	3.0	0.161 [a]
(mg/cm^3)	(273.71-293.44)	(271.91-292.89)	(-3.6-3.0)	(283.35-308.95)	(288.32-319.04)	(-0.5-5.4)	(299.86-316.86)	(305.71-322.23)	(-0.6-6.6)	
BSI	8.93	9.37	7.0	9.21	10.35 [d]	14.8	10.12	11.59 [d]	17.1	0.111 [a]
(mg/mm^4)	(8.01-9.84)	(8.27-10.48)	(-5.0-19.0)	(8.32-10.10)	(9.23-11.46)	(2.2-27.5)	(9.30-10.93)	(10.41-12.78)	(7.9-26.2)	

Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P value represents interaction effect (group * time) for repeated measures ANCOVA. Six month changes (paired sample t-test): [a] HGYM > NONGYM ($p < 0.05$), [b] LGYM > NONGYM ($p < 0.05$), [c] HGYM > LGYM ($p < 0.05$), [d] different from baseline ($p < 0.05$), Bone mineral content: BMC; Trabecular density: TrD; Total area: ToA; Total density: ToD; Bone strength index: BSI

Table 7.3 and Table 7.4 display skeletal parameters at the 4% radius and ulna. Using a paired sample t-test, HGYM had the greatest changes over time with all but one parameter (ulna ToD) increasing (+3 to +21% increase, *p* <0.05). Similarly, LGYM had three parameters (radius ToA, ulna BMC and BSI) increase over time (+5 to +15% increase, *p* <0.05). No parameters at the 4% forearm increased for NONGYM. The repeated measure ANCOVA revealed group by time interactions for all variables at the 4% radius and TrD and ToA at the ulna.

Table 7.5 and Table 7.6 display skeletal parameters at the 66% radius and ulna. Consistently with findings at the 4% site, HGYM had more parameters increasing over time, followed by LGYM and NONGYM, identified with a paired sample t-test. HGYM displayed increases in forearm bone mass and cross-sectional area, radius SSI and CoTh as well as ulna ToD (+3 to +10% increase, *p* <0.05). LGYM had increases in forearm bone mass, density and strength (+2 to +9% increase, *p* <0.05). NONGYM had increases in forearm bone mass and radius ToA (+4 to +5% increase, *p* <0.05). The only group by time interaction at the 66% site was CoA and CoD at the radius

Table 7.7 displays muscle structure and function changes over time. Both groups of gymnasts had six month gains in MCSA whereas NONGYM did not. With the exception of explosive power, all other muscle parameters identified with a paired sample t-test increased over time (HGYM +7 to +103%; LGYM +5 to +91%; NONGYM + 9 to +51%, *p* <0.05).

Subsequent post hoc analyses following weight-adjusted repeated measure ANCOVAs revealed gymnasts had greater skeletal properties than NONGYM, at study completion. Specifically, at the distal forearm HGYM had greater skeletal mass, density and strength than NONGYM (+11 to +45% greater, *p* <0.05). HGYM also had greater proximal bone strength and area as well as ulna BMC than NONGYM (+6 to +25% greater, *p* >0.05). HGYM also had skeletal advantages over LGYM at both the distal radius (BMC and BSI) and proximal forearm (CoTh, ulna CoA, ToD) (+7 to +28% greater, *p* >0.05). In addition to HGYM, LGYM had greater distal radial ToD as well as proximal forearm bone strength and area, radial MedA and ulna BMC than NONGYM (+6 to +18% greater, *p* >0.05). There were two instances in which gymnasts demonstrated lower bone properties than NONGYM. HGYM had less arms BMD assessed by DXA (-2% less, *p* >0.05) and LGYM had less radial ToD at the 66% radius (-7% less, *p* >0.05) than NONGYM.

In addition to skeletal properties, gymnasts also had greater arm lean mass, explosive power and muscle endurance than NONGYM (HGYM +11 to +190%; LGYM +8 to +96% greater). HGYM also had a larger MCSA than NONGYM and LGYM as well as greater grip strength than NONGYM.

Figure 7.1 shows the raw change in bone strength at the 4% and 66% forearm. The greatest change in bone properties over the duration of the study was recorded at the 4% radius by HGYM (+21% for bone strength).

Pearson's correlation coefficient analyses revealed significant relationships for change in radial bone mass with change in MCSA (4% r = 0.34; 66% r = 0.30, *p* <0.01) and lean mass (4% r = 0.32; 66% r = 0.31, *p* <0.01). However, when change in height was considered these relationships disappeared. Multiple linear regressions were conducted following significant correlation effects. Regression analyses revealed the strongest predictors for change in bone strength at the 4% radius to be sitting height, not being pre-pubertal at study completion and training hours (R^2_{adj} = 31.2%). Specifically, change in BSI at the distal radius was equal to 18.042 + 0.278 (sitting height) + 5.722 (not being pre-pubertal) + 0.273 (training hours). The same three variables explain 26.4% of change in distal radial BMC and 22.2% of change in total density at the distal radius.

Table 7.5

Peripheral Quantitative Computed Tomography Results at the 66% Radius in Three Groups of Pre- and Early Pubertal Girls

	Non-Gymnasts (n = 27)			**Low Gymnasts (n = 27)**			**High Gymnasts (n = 28)**			**P**
	Baseline	6MO	% Δ	Baseline	6MO	% Δ	Baseline	6MO	% Δ	**Value**
BMC	0.605	0.637 [e]	3.9	0.599	0.628 [e]	4.2	0.625	0.666 [e]	6.1	0.216
(g/cm)	(0.569-0.642)	(0.592-0.682)	(0.8-6.9)	(0.556-0.642)	(0.578-0.678)	(2.3-6.0)	(0.591-0.658)	(0.629-0.704)	(4.5-7.6)	
CoA	45.27	46.71	3.0	45.00	46.99	3.1	46.80	51.42 [e]	9.4	0.013
(mm^2)	(42.42-48.12)	(42.55-50.87)	(-1.5-7.4)	(41.74-48.26)	(42.63-51.35)	(-0.6-6.8)	(43.82-49.77)	(48.14-54.70)	(6.2-12.6)	
CoD	1048.98	1043.53	-0.4	1012.25	1028.34[e]	1.7	1037.99	1035.06	-0.2	0.006
(mg/cm^3)	(1029.61-1068.36)	(1022.82-1064.24)	(-1.6-0.7)	(998.54-1025.96)	(1012.35-1044.34)	(0.5-3.0)	(1021.46-1054.52)	(1018.48-1052.73)	(-1.0-0.7)	
ToA	89.09	94.58 [e]	4.6	97.58	100.39	2.9	95.07	100.04 [e]	3.9	0.471 [ab]
(mm^2)	(84.11-94.07)	(88.46-100.70)	(1.5-7.7)	(89.05-106.10)	(92.16-108.61)	(-0.4-6.2)	(89.80-100.34)	(93.99-106.08)	(1.4-6.5)	
ToD	683.96	679.38	-0.5	621.32	631.97	1.9	662.34	671.38	2.3	0.149 [d]
(mg/cm^3)	(647.78-720.13)	(637.64-721.13)	(-3.3-2.3)	(591.27-651.37)	(596.26-667.69)	(-0.9-4.7)	(636.55-688.14)	(641.06-701.70)	(0.1-4.5)	
SSI	124.85	134.49	5.1	134.09	147.87 [e]	8.6	139.75	155.02 [e]	9.6	0.109 [ab]
(mm^3)	(115.37-134.33)	(120.43-148.56)	(-0.7-10.9)	(121.00-147.18)	(130.91-164.83)	(4.8-12.5)	(127.06-152.45)	(139.93-170.12)	(6.1-13.1)	
CoTh	1.61	1.62	1.1	1.48	1.55	2.4	1.59	1.72 [e]	9.0	0.062 [c]
	(1.49-1.72)	(1.46-1.78)	(-4.8-7.0)	(1.39-1.57)	(1.41-1.70)	(-3.5-8.4)	(1.50-1.69)	(1.62-1.83)	(3.7-14.3)	
MedA	43.82	47.87	6.4	53.33	53.39	3.1	48.27	48.60	-0.1	0.356 [b]
	(39.00-48.65)	(41.16-54.59)	(-1.9-14.6)	(46.14-60.51)	(46.32-60.46)	(-5.6-11.8)	(44.17-52.38)	(43.84-53.36)	(-6.7-6.6)	

Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P value represents interaction effect (group * time) for repeated measures ANCOVA. Six month changes (paired sample t-test): [a] HGYM > NONGYM (*p* <0.05), [b] LGYM > NONGYM (*p* <0.05), [c] HGYM > LGYM (*p* <0.05), [d] LGYM < NONGYM (*p* <0.05), [e] different from baseline (*p* <0.05). Bone mineral content: BMC; Cortical area: CoA; Total area: ToA; Total density: ToD; Strength strain index: SSI; Cortical thickness: CoTh; Medullary area: MedA

Table 7.6

Peripheral Quantitative Computed Tomography Results at the 66% Ulna in Three Groups of Pre- and Early Pubertal Girls

	Non-Gymnasts (n = 27)			**Low Gymnasts (n = 27)**			**High Gymnasts (n = 28)**			**P**
	Baseline	6MO	% Δ	Baseline	6MO	% Δ	Baseline	6MO	% Δ	**Value**
BMC	0.720	0.747 [e]	4.0	0.773	0.792 [e]	2.4	0.804	0.840 [e]	3.7	0.585 [ab]
(g/cm)	(0.675-0.766)	(0.706-0.789)	(0.8-7.2)	(0.725-0.822)	(0.743-0.842)	(0.6-4.2)	(0.766-0.843)	(0.795-0.885)	(1.6-5.9)	
CoA	50.57	51.93	3.9	57.46	58.95	2.3	60.67	64.69 [e]	5.1	0.363 [abc]
(mm^2)	(46.43-54.71)	(47.15-56.72)	(-5.2-13.0)	(53.73-61.19)	(54.10-63.80)	(-1.7-6.2)	(57.39-63.94)	(60.31-69.06)	(1.1-9.0)	
CoD	1028.33	1034.32	0.6	1006.90	1015.78	0.9	1016.68	1026.98	1.2	0.771
(mg/cm^3)	(1005.23-1051.44)	(1010.80-1057.84)	(-1.0-2.1)	(990.08-1023.71)	(997.13-1034.44)	(-0.4-2.1)	(1001.24-1032.12)	(1012.66-1041.30)	(-0.3-2.6)	
ToA	111.93	115.27	3.9	121.54	122.35	0.5	119.3	120.97	1.7	0.404
(mm^2)	(103.89-119.97)	(107.79-122.75)	(-1.2-8.9)	(112.56-130.53)	(113.94-130.77)	(-3.4-4.5)	(111.52-127.07)	(113.93-128.01)	(-2.2-5.5)	
ToD	651.11	655.90	0.9	641.12	652.64 [e]	2.4	680.16	698.03 [e]	2.6	0.309 [c]
(mg/cm^3)	(619.65-682.57)	(623.45-688.36)	(-2.5-4.2)	(620.42-661.82)	(624.09-681.19)	(-0.2-5.1)	(657.40-702.91)	(673.48-722.58)	(0.1-5.1)	
SSI	161.10	168.03	4.7	185.94	198.14 [e]	5.4	185.83	202.09	4.7	0.960 [ab]
(mm^3)	(148.07-174.12)	(153.45-182.60)	(-0.2-9.6)	(168.67-203.22)	(176.32-219.96)	(0.8-10.0)	(171.80-199.86)	(182.17-222.02)	(-0.7-10.1)	
CoTh	1.59	1.61	3.7	1.72	1.78	3.7	1.87	1.99	6.0	0.309 [ac]
	(1.44-1.74)	(1.44-1.77)	(-8.1-15.5)	(1.63-1.81)	(1.62-1.93)	(-2.6-10.1)	(1.76-1.98)	(1.86-2.12)	(-0.8-12.7)	
MedA	61.36	63.34	7.6	64.08	63.40	-1.4	58.63	56.29	0.1	0.265
	(52.58-70.14)	(54.64-72.03)	(-3.6-18.7)	(57.41-70.75)	(55.58-71.22)	(-10.2-7.4)	(51.66-65.60)	(50.63-61.94)	(-8.3-8.5)	

Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM. P value represents interaction effect (group * time) for repeated measures ANCOVA. Six month changes (paired sample t-test): [a] HGYM > NONGYM (*p* <0.05), [b] LGYM > NONGYM (*p* <0.05), [c] HGYM > LGYM (*p* <0.05), [d] LGYM < NONGYM (*p* <0.05), [e] different from baseline (*p* <0.05). Bone mineral content: BMC; Cortical area: CoA; Total area: ToA; Total density: ToD; Strength strain index: SSI; Cortical thickness: CoTh; Medullary area: MedA

Table 7.7

Muscle Structure and Function in High- and Low-Training Gymnasts and a Non-Gymnast Control Group

	Non-Gymnasts (n = 28)			Low Gymnasts (n = 28)			High Gymnasts (n = 28)			
	Baseline	6MO	% Δ	Baseline	6MO	% Δ	Baseline	6MO	% Δ	P Value
Arm Lean Mass	1531.07	1668.81 [d]	8.5	1638.11	1811.20 [d]	8.3	1820.13	1974.00 [d]	7.9	0.995 [abc]
	(1403.89-1658.25)	(1496.92-1840.71)	(2.9-14.1)	(1498.61-1777.61)	(1614.72-2007.68)	(1.5-15.0)	(1682.74-1957.51)	(1786.51-2161.49)	(2.8-13.0)	
MCSA	1565.29	1647.90	4.4	1607.17	1702.44 [d]	5.0	1743.35	1863.38 [d]	6.8	0.318 [ac]
	(1484.18-1646.40)	(1543.78-1752.02)	(-0.7-9.4)	(1498.35-1715.98)	(1582.86-1822.02)	(2.7-7.4)	(1653.30-1833.39)	(1756.63-1970.14)	(4.2-9.5)	
Grip Strength	13.93	16.27 [d]	17.6	14.73	17.07 [d]	17.4	15.55	17.20 [d]	12.3	0.306 [a]
	(12.81-15.05)	(14.86-17.68)	(10.6-24.5)	(13.12-16.35)	(15.41-18.74)	(9.9-25.0)	(14.27-16.82)	(16.00-18.39)	(5.9-18.7)	
Ball Throw	1.70	1.78	5.5	1.86	1.92	4.0	1.99	1.98	-0.5	0.191 [ab]
	(1.60-1.81)	(1.67-1.88)	(-0.3-11.2)	(1.75-1.97)	(1.81-2.02)	(0.5-7.6)	(1.90-2.09)	(1.88-2.07)	(-5.2-4.2)	
Arm Seq	18.16	20.71 [d]	17.8	21.12	23.73 [d]	17.2	23.98	25.63 [d]	10.8	0.477 [ab]
	(16.43-19.88)	(18.80-22.63)	(7.6-27.9)	(19.46-22.78)	(21.81-25.65)	(8.4-26.1)	(22.31-25.66)	(23.88-27.37)	(2.3-19.3)	
Static Hold	34.71	40.04 [d]	51.2	51.58	78.5 [d]	90.7	71.53	115.96 [d]	102.8	0.076 [ab]
	(25.21-44.20)	(30.38-49.69)	(15.4-86.9)	(39.93-63.23)	(66.42-90.58)	(54.4-127.0)	(58.33-84.74)	(92.19-139.74)	(52.8-152.8)	

Mean ± (upper and lower 95% CI) of raw data for NONGYM, LGYM and HGYM.

Muscle cross-sectional area: MCSA; Arm sequence: Arm Seq.

P value represents interaction effect (group * time) for repeated measures ANCOVA. Six month changes (paired sample t-test): [a] HGYM>NONGYM ($p< 0.05$), [b] LGYM> NONGYM ($p< 0.05$), [c] HGYM>LGYM ($p< 0.05$), [d] different from baseline ($p< 0.05$).

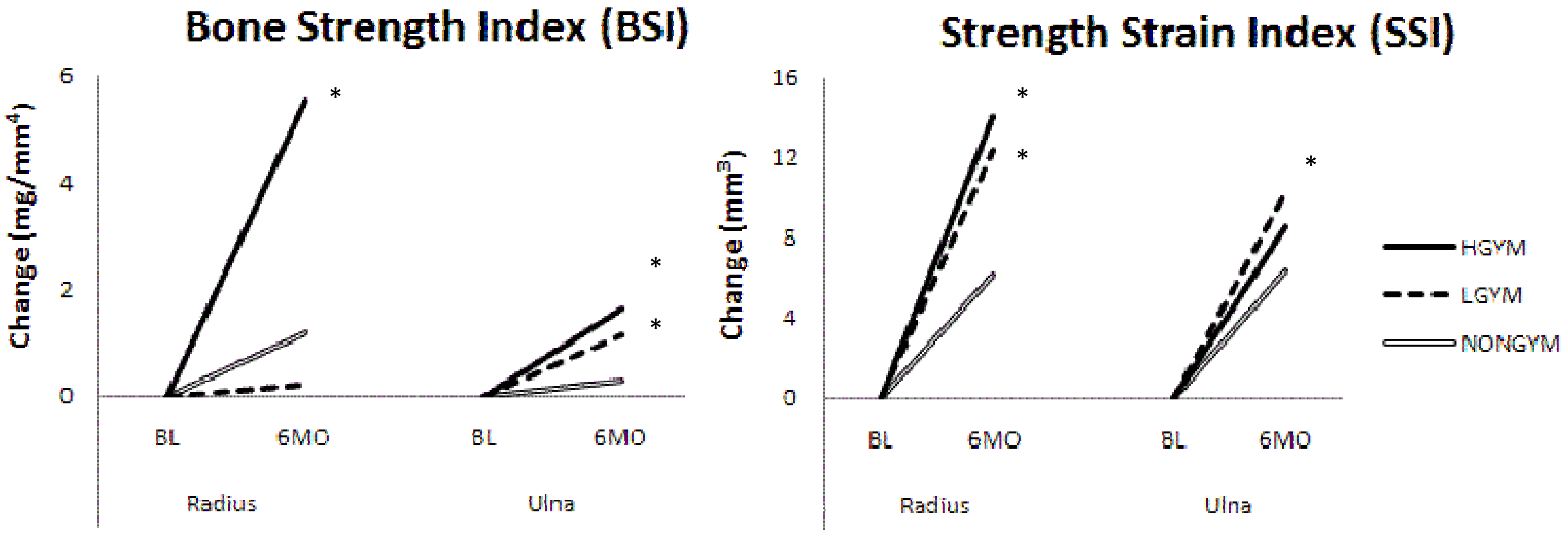

Figure 7.1. Change in bone strength over six months at the distal forearm and bone shaft in high-training gymnasts (HGYM), low-training gymnasts (LGYM) and a non-gymnastic (NONGYM) control group

Raw change in bone strength at the distal (BSI) and proximal (SSI) forearm * Significant change from baseline (BL) to six months (6MO)

7.5 Discussion

Upper limb musculoskeletal benefits were attained following six months of involvement in non-elite artistic gymnastics. Participation in one gymnastics class per week provided sufficient loading to induce positive outcomes on the upper limb musculoskeletal system. While both gymnasts with high- and low-training commitments had increased bone strength, density and size than non-gymnasts, the greatest skeletal gains were observed at the 4% radius in the high-training gymnasts (6 to 16 hr/wk). Bone accrual at the 66% radius and ulna was similar between groups; so were the improvements in muscle strength and endurance. Previous analyses of baseline data (chapter five) revealed gymnasts had higher DXA-derived arms BMC and lean mass, total density at the 4% radius, total cross-sectional bone area at the 66% radius and better muscle function than non-gymnasts ($p < 0.05$), potentially due to their gymnastics participation prior to the study.

Although, no significant increases were detected over six months for total bone density (4% radius), total (66% radius) or cortical (66% ulna) cross-sectional area and explosive power among the low-training gymnasts (1 to 5 hr/wk), these parameters were higher than non-gymnasts at study completion. Similarly, the high-training gymnasts did not display significant increases in bone strength (66% ulna), total density (4% radius) or explosive power over six months. Despite the lack of changes in these skeletal parameters, gymnasts remained superior at study completion. Once again, this may be due to the benefits gained from their previous involvement in gymnastics.

7.5.1 4% vs. 66% Sites

The distal forearm was the skeletal site that responded most to gymnastics training, over the duration of the study. In both groups of gymnasts, the greatest increase was observed in bone strength, as a result of increased bone mass and total cross-sectional area but not total volumetric bone density. The steepest increase across all variables was observed in the high-training gymnasts at the distal radius. At the 66% site, there seemed to be a suppression of medullary expansion among gymnasts. The size of the medullary cavity increased in the non-gymnasts but remained fairly constant in the gymnasts, suggesting that endocortical resorption may have been suppressed by repetitive loading. Contrasting the results at the 4% site, gymnastics-induced bone adaptations were not detected at the 66% site. Potentially, such adaptations were being masked by growth-induced effects. The growth-related changes in bone parameters observed in non-gymnasts were not different from the six month changes observed in the two groups of gymnasts. The discrepancies between sites may have been emphasized by the short time frame of the study given that the skeletal response in cortical bone may take longer than six months to detect. The greater response to loading in the distal radius may also be explained by the fact that this site, which has a much larger cross-sectional area than the distal ulna (Ducher, et al., 2009) and has direct contact with carpal bones, and bears most of the weight-bearing load and impact forces during gymnastics participation (Beunen, Malina, Claessens, Lefevre, & Thomis, 1999; DiFiori, Caine, & Malina, 2006).

While increases in total cross-sectional area and mass were similar between groups at the proximal forearm, gymnasts had greater bone strength than non-gymnasts at study completion due to an increase in bone size rather than density. Gymnasts in this study had 6% greater total cross-sectional area than non-gymnasts, which is consistent with other studies in pre-pubertal gymnasts (+9%, Ward, et al., 2005; +3%, Erlandson, et al., 2011), and somewhat less than differences reported in older post-menarcheal and adult gymnasts (+32% Dowthwaite & Scerpella, 2011; Eser, et al., 2009). Additional gains in cross-sectional area may arise in these young pre- and early pubertal gymnasts as they continue gymnastics participation through pubertal growth.

To the best of the authors' knowledge, the only other longitudinal study (randomised controlled trial) to investigate musculoskeletal health in pre- and early pubertal elite gymnasts using pQCT, tested the effects of calcium supplementation on gymnastics-induced skeletal benefits (Ward, Roberts, et al., 2007). At the distal radius, elite gymnasts showed total density changes of 2 and 8 mg/mm^3 over 12 months (calcium and placebo, respectively) (Ward, Roberts, et al., 2007). The high-training gymnasts within our study had changes of 1 mg/mm^3 over the six month period. In addition, the six month changes we observed at the bone shaft were also consistent with those previously reported for bone strength (strength strain index in HGYM +15 mm^3; LGYM +14 mm^3 vs. calcium +19 mm^3; placebo +15 mm^3), total (HGYM +5 mm^2; LGYM +3 mm^2 vs. calcium +7 mm^2; placebo +8 mm^2) and cortical cross-sectional bone area (HGYM +5 mm^2; LGYM +2 mm^2 vs. calcium +5 mm^2; placebo +6 mm^2) (Ward, Roberts, et al., 2007). The slight discrepancies between studies are likely explained by the differences in the skeletal sites scanned (66% vs. 50%), the shorter duration of the follow-up (6-months vs. 12-months) and the different levels of the gymnasts (female non-elite vs. male and female elite). On the other hand, the relatively comparable results between studies suggested pre- and early pubertal female gymnasts may not have to participate in gymnastics at an elite level, consisting of high training loads and intensities, to acquire skeletal benefits.

7.5.2 High-Training Gymnasts vs. Low-Training Gymnasts

Comparison of baseline data between the three groups (chapter five) revealed a trend towards stronger bones in low-training gymnasts compared with non-gymnasts. However, bone strength differences only reached significance between high-training gymnasts and non-gymnasts. Despite training volume remaining constant, changes in bone strength occurred in just six months for both low- and high-training gymnasts. At study completion, high-training gymnasts had greater bone strength than both low-training gymnasts (4% radius) and non-gymnasts (4% radius and ulna). Meanwhile, at the 66% forearm (radius and ulna) bone strength was greater for both groups of gymnasts than the non-gymnasts, with no differences between the two gymnastics groups. Participating in one gymnastics class per week provided sufficient loading to positively affect bone strength. At the 66% site, no additional benefits in bone strength were gained from participating in more than one class of gymnastics per week. A cross-sectional pQCT study in recreational gymnasts who had a similar training history reported differences in bone strength between gymnasts and non-gymnasts at the distal radius, but no differences in bone strength at the shaft (Erlandson, et al., 2011). These results mirror our cross-sectional findings on baseline data, but not our longitudinal findings. Altogether, these observations suggested that benefits in bone strength at the shaft may take longer to occur than benefits in metaphyseal bone.

At the 66% ulna, a dose-response relationship between training volume and skeletal adaptations emerged for cortical cross-sectional area. High- and low-training gymnasts had greater cortical bone area than non-gymnasts and the high-training gymnasts were greater than the low-training gymnasts. While similar findings were observed in other skeletal parameters, cortical cross-sectional area was the only variable that reached significance. At the 4% radius, the observed increase among high-training gymnasts tended to be greater than low-training gymnasts, again suggesting a dose-response relationship. Specifically, increases in bone strength were ten-fold greater for high- than low-training gymnasts. Furthermore, part of the variability of the six month changes in bone density, content and strength at the distal radius was explained by baseline sitting height, weekly gymnastics participation and not being pre-pubertal at follow-up (R^2_{adj} 22 to 31%). Previous non-elite gymnastics studies assessing different weekly training participation reported a dose-response relationship which benefits gymnasts with a greater weekly training exposure. High-training gymnasts had advantages in DXA-derived bone mass and forearm bone area over both low-training gymnasts and non-gymnasts (Laing, et al., 2005; Scerpella, et al., 2003).

Longitudinal gymnastics studies have used DXA rather than pQCT to determine bone accrual (Erlandson, et al., in press; Laing, et al., 2005). Our DXA results differ from others in that we did not find greater increase in total body BMC or areal BMD over six months among gymnasts when compared with non-gymnasts (Erlandson, et al., in press; Laing, et al., 2005). While DXA results illustrate significant increases over time, the only difference between groups was for areal BMD of the arms. However, DXA results showed lower arm BMD for high-training gymnasts than non-gymnasts. Limitations when reporting areal BMD from DXA in growing individuals are well established (Lu, et al., 1996; Prentice, et al., 1994). Furthermore, DXA may not be sensitive enough, over a short period of time, to establish between group differences.

7.5.3 Muscle Structure and Function

High-training gymnasts differed from low-training gymnasts in measures of muscle size and lean mass however, muscle function was not different between groups. High-training gymnasts also had greater muscle size than both low-training gymnasts and non-gymnasts (+10% and +13%, respectively). While these results confirm muscle hypertrophy is evident in young non-elite training females, they differ from previous research. Prior research reported differences between high- and low-training gymnasts for muscle function, but not lean mass (Scerpella, et al., 2003). We observed a potential dose-response relationship for arm lean mass however, not muscle function. In addition, between-group differences in muscle function were greater at study initiation than completion. This may reflect the growth and development undertaken by all participants and relative a catch-up by the non-gymnasts during the early stages of puberty. Similar results have been reported previously. Baseline differences in muscle strength between gymnasts and non-gymnasts disappeared following two years of growth (Gero, et al., 2005). The gymnasts within the current study remained superior for measures of muscle function (strength, power and endurance), potentially due to their previous experience in gymnastics and the short duration of follow-up.

7.5.4 Strengths

While a few longitudinal studies have explored bone accrual among non-elite gymnasts (Erlandson, et al., in press; Laing, et al., 2005), DXA has limitations and fails to explain the underlying mechanisms of bone accrual (i.e. increase in cross-sectional bone size, cortical area and/or volumetric BMD). This study helps explain the effect of non-elite participation in gymnastics during early puberty. Non-elite level of participation, particularly one gymnastics class per week, is more realistic and attainable for the majority of young females, compared with elite participation. While 3 hr/wk of gymnastics participation provided skeletal benefits, gains in bone strength at the distal radius are ten-fold greater for gymnasts training 10.5 hr/wk. The novel approaches to muscle function and ulna assessment are also a unique component of the current study.

7.5.5 Limitations

Longitudinal studies offer opportunities to understand more about the musculoskeletal benefits associated with gymnastics training beyond growth, so the short duration of this longitudinal study presents as a limitation. Additional longitudinal research following pre-pubertal gymnasts through pubertal growth and into retirement would be ideal. Another possibility, due to the short duration of this study, would be to increase the sample size. We may have been underpowered to detect the small effects associated with training over such a short duration. Furthermore, partial volume effect would have influenced the results of this study (Hangartner & Gilsanz, 1996). None of the participants had a cortical thickness (radius or ulna) greater than 2.5 mm. Furthermore, biochemical analyses of bone formation, absorption and maturation would have strengthened our results.

7.5.6 Conclusions

Artistic gymnastics is a unique, bilateral, weight bearing sport. Even at a low intensity, the unique loading is associated with osteogenic benefits to the upper limbs. One training session of approximately 3 hr/wk is sufficient in inducing short-term musculoskeletal adaptations. However, the greatest skeletal gains in bone mass and strength, particularly at the distal radius, were observed following more than one weekly gymnastics class. Potential dose-response associations emerged for skeletal and arm lean mass parameters but not for muscle function. Beyond the growth-induced effects associated with early pubertal maturation, non-elite participation in artistic gymnastics favours upper body musculoskeletal development.

CHAPTER EIGHT

THESIS SUMMARY

This thesis compared growth-related changes to upper limb musculoskeletal parameters in pre- and early pubertal girls who were or were not engaging in non-elite artistic gymnastics.

A review of the literature described normal musculoskeletal development during pre-pubertal growth. Strengths and weaknesses of different musculoskeletal imaging technologies were also outlined. In addition, the review identified the importance of the muscle-bone relationship and presented a rationale for assessing actual measures of muscle function and strength as a surrogate of muscle force. The effects of physical activity, specifically gymnastics participation, on musculoskeletal health during growth were also explored. Following a review of the literature, a meta-analysis was conducted to determine the magnitude of differences in bone mineral density and content between pre-pubertal girls participating in artistic gymnastics, compared with non-gymnasts. While large positive effects were observed for young gymnasts, the meta-analysis revealed the paucity of longitudinal studies in non-elite gymnasts using pQCT to determine skeletal adaptations over time. Furthermore, no studies had combined musculoskeletal parameters, as measured by pQCT, with assessment of muscle function in pre- and early pubertal non-elite gymnasts. Therefore, the purpose of this study was to longitudinally examine the effects of non-elite female artistic gymnastics participation on upper limb musculoskeletal parameters using pQCT, DXA and muscle function assessments.

8.1 Cross-Sectional Hypotheses

The two results chapters (chapter four and chapter five), which outlined the cross-sectional differences between groups, examined:

1. The association between non-elite gymnastics participation and upper limb bone mass, geometry, strength and muscle function in young girls
2. pQCT-derived structural properties of bone at the distal and proximal radius and ulna in a group of pre-pubertal non-elite gymnasts and age-matched non-gymnasts.

Specifically, it was hypothesised that ‘gymnasts would have greater bone mass, size and strength compared with non-gymnasts’. This hypothesis was supported for high-training gymnasts. Cross-sectional analyses revealed high-training gymnasts had greater bone mass, derived from both DXA (+5%) and pQCT (+8% at 4% radius), as well as greater total bone cross-sectional area (+6% at 66% radius) and strength (+21% at 4% and +10% at 66% radius) than non-gymnasts. This hypothesis was partially supported for low-training gymnasts. These gymnasts had greater DXA-derived bone mass (+4%) as well as pQCT-derived total cross-sectional area (+8% at 66% radius). While there was a trend for the low-training gymnasts to have greater bone strength than the non-gymnasts, this result was not significant.

The hypothesis, ‘gymnasts were expected to have greater lean mass and improved muscle function than non-gymnasts’ was confirmed. High-training gymnasts had more lean mass (+15%) and better muscle function (range +9 to +103%) than non-gymnasts. Low-training gymnasts also had more lean mass (+5%) as well as greater explosive power (+8%) and muscle endurance (+46%), compared with non-gymnasts. In addition, the high-training gymnasts had a greater muscle cross-sectional area (+10%) than non-gymnasts. Uncertainty surrounds whether muscle strength develops in proportion to muscle cross-sectional area in young children and whether differences in muscle strength are due to neuromuscular or biomechanical factors (De Ste Croix, 2007). Within this thesis, high-training gymnasts had greater muscle strength and size than non-gymnasts, whereas the low-training gymnasts were not different from non-gymnasts for either parameter. Based on the results, perhaps muscle strength and size develop in proportion to external stimuli in young females.

The hypothesis that 'musculoskeletal benefits of gymnasts with high-training commitments would be larger than those with low-training commitments' was rejected. Between group differences were only observed for measures of muscle size and body composition. High-training gymnasts had more lean mass (+9%) and a greater muscle cross-sectional area (+8%) than low-training gymnasts. Furthermore, the total body percent body fat was lower in high- than low-training gymnasts (-13%). While most of the other musculoskeletal parameters were higher for the gymnasts with the high-training commitments, results were not significant.

The last hypothesis applying to the cross-sectional data was that 'gymnasts would display greater structural properties of bone at the radius and ulna compared with non-gymnasts'. This hypothesis was confirmed. Specifically, gymnasts had greater bone mass (+8%), density (+8%) and strength (+16%) at the 4% radius, as well as greater cross-sectional bone area (+5%) and strength (+9%) at the 66% radius. No differences were observed between gymnasts and non-gymnasts at the 4% ulna however, at the 66% site gymnasts had greater bone mass (+10%), cross-sectional area (+9% total and +16% cortical) and strength (+16%) than non-gymnasts. At the distal forearm, skeletal benefits were greater for the gymnasts at the radius than the ulna; however, the opposite was found at the bone shaft with the ulna being more responsive than the radius.

8.2 Longitudinal Hypotheses

Following cross-sectional analysis, comparisons of six month changes between high- and low-training gymnasts were investigated (chapter seven). The longitudinal investigation aimed to compare changes in musculoskeletal parameters over six months in pre- and early pubertal females involved in different quantities of artistic gymnastics (high- 10.5 hr/wk and low- 3 hr/wk training gymnasts) with a group of age and gender matched non-gymnasts.

We hypothesised that ‘sports participation, specifically artistic gymnastics, in the early stages of puberty would favour upper body musculoskeletal development’. At study completion, high-training gymnasts had greater bone mass (+25% at 4% radius; +12% at 66% ulna), density (+15% total and +14% trabecular at 4% radius; +11% total at 4% ulna), cross-sectional area (+6% total at 66% radius; +25% cortical at 66% ulna) and strength (+45% at 4% radius; +24% at 4% ulna; +15% at 66% radius; +20% at 66% ulna) than non-gymnasts. Furthermore, high-training gymnasts had greater bone mass (+20% at 4% radius), total bone density (+7% at 66% ulna), cortical bone cross-sectional area (+10% at 66% ulna), cortical thickness (+11% at 66% radius; +12% at 66% ulna) and bone strength (+28% at 4% radius) than low-training gymnasts.

In addition, low-training gymnasts had greater bone mass (+6% at 66% ulna), density (+8% at 4% radius), cross-sectional area (+6% total at 66% radius; +14% cortical at 66% ulna), medullary area (+12% at 66% radius) and bone strength (+10% at 66% radius; + 18% at 66% ulna) than non-gymnasts. These gymnastics-induced benefits were even more pronounced when muscle function was taken into consideration. Gymnasts had greater muscle function than non-gymnasts (high-training gymnasts, range 6 to 190% greater; low-training gymnasts, range 8 to 96% greater). Muscle function was not different between the two gymnastics groups. Both high- and low-training gymnasts have upper body musculoskeletal benefits compared with non-gymnasts. Therefore, the hypothesis was supported. Gymnastics participation during pre- and early pubertal development favours musculoskeletal development in the upper body.

The hypothesis, ‘gymnasts would have greater increases in upper limb skeletal and muscle function parameters than non-gymnasts’ was partially supported. Gymnasts had greater increases in skeletal properties at both sites (4% and 66%) of the radius and ulna, ranging from +3% to +21%. The parameters that increased significantly over six months for both groups of gymnasts but not non-gymnasts were bone mass (4% ulna), total bone density (66% ulna), total cross-sectional area (4% radius) and bone strength (4% ulna; 66% radius). Muscle cross-sectional area was the only non-skeletal parameter to increase more for gymnasts than non-gymnasts over the six months.

While gymnasts had greater increases in bone parameters than non-gymnasts, the high-training gymnasts clearly had greater advantages at the distal forearm than the two other groups. At the 4% radius, increases in skeletal parameters were up to ten times higher for high-training gymnasts than the low-training gymnasts. Over and above growth-induced effects, participating in 10.5 hr/wk of gymnastics is associated with large gains (+21% increase) in bone strength.

In contrast, gymnastics participation did not seem to affect increases in skeletal parameters at the 66% forearm (non-gymnasts: +4 to +5% increase; low-training gymnasts: +2 to +9% increase; high-training gymnasts: +3 to +10% increase). Furthermore, increases in muscle function (except explosive power) occurred overtime for all groups, possibly reflecting usual growth and development.

The final hypothesis was that ‘a dose-response would emerge between musculoskeletal parameters and weekly gymnastics exposure’. Following a series of body mass adjusted ANCOVAs, a dose-response emerged between all three groups for pQCT-derived ulna CoA and DXA-derived arm lean mass: the higher the training, the greater the benefits. However, not all variables provided a dose-response. Therefore, this hypothesis was partially supported. A trend towards a dose-response was observed for all parameters at the 4% site except total cross-sectional area at both the radius and ulna. This trend was less obvious at the 66% forearm. Muscle size and muscle function also revealed a tendency for a dose-response development. Additional research is required to determine whether or not this trend continues through pubertal development and becomes more obvious, or whether it disappears.

8.3 Growth and Maturation

Elite involvement in artistic gymnastics has been associated with delayed growth and maturation (Caine, Bass, et al., 2003). Many contributing factors such as: familial association, genetic makeup, nutrition, timing and tempo of growth and maturation are often overlooked (Baxter-Jones, Maffulli, & Mirwald, 2003; Daly, Bass, Caine, & Howe, 2002). Nevertheless, a negative stigma claiming gymnastics participation delays normal growth and maturation exists. The literature suggests a threshold may exist at which gymnasts training below approximately 15 hr/wk experience normal growth and maturation (Theintz, et al., 1993). In contrast, gymnasts training in excess of this threshold may experience delayed development. As the gymnasts in the present study were non-elite gymnasts training a maximum of 16 hr/wk, normal growth and maturation was assumed.

The gymnasts within the current study grew an average of 3 to 4 cm and put on approximately 3 kg in body mass in the six months. This is consistent with normal growth rates of girls of a similar age (Kuczmarski et al., 2002). The non-gymnasts did not differ from the gymnasts, growing an average of 3 cm over the duration of the study, reinforcing the fact that non-elite gymnastics participation does not seem to alter normal growth and maturation. Among the gymnasts, most of the change in height was the result of change in sitting height as trunk length increased by 3 cm during the study. Additional measurements and longitudinal tracking are required to determine if this change in sitting height was the result of participants entering puberty, where there is an acceleration of trunk length. Furthermore, there were no differences between groups for change in Tanner stage over the six months. Gymnasts within this study did not experience short-term growth or maturation delays.

8.4 Radius vs. Ulna Comparisons

Recent literature on retired adult gymnasts has suggested skeletal adaptations, particularly at the bone shaft, may be underestimated if the ulna is neglected from analysis (Ducher, et al., 2009). Results from the cross-sectional analysis confirm these findings, showing that skeletal benefits were larger when considering adaptations at both the ulna and radius, rather than the radius alone as traditionally performed with pQCT. More specifically, at the distal forearm, the gymnastics-induced skeletal benefits were greater at the radius than ulna, whereas at the proximal forearm, the skeletal benefits were greater at the ulna than the radius. Based on these cross-sectional findings, an assumption was made that the radius at the 4% site and the ulna at the 66% site would undergo greater six month changes. While this was true at the 4% radius, increases in skeletal parameters were similar between the radius and ulna at the 66% site. Skeletal adaptations in the short duration of this study reflected normal growth and development at the 66% site. If additional data were collected, or the study involved a longer observation period, perhaps skeletal changes at the 66% ulna would have differed from the radius and more accurately revealed the overall differences in bone mass, cortical cross-sectional area and strength that existed between gymnasts and non-gymnasts at this site.

8.5 Baseline vs. Six Month Comparisons

Over the short duration of this longitudinal study, additional skeletal but not muscle parameters differed between gymnasts and non-gymnasts. Specifically, the large increases observed by the high-training gymnasts at the 4% radius resulted in additional skeletal gains. At study completion, high-training gymnasts had greater trabecular density than non-gymnasts as well as more bone mass and strength than the low-training gymnasts. These differences were not observed at baseline. Furthermore, six month increases in bone strength at the 66% radius enabled low-training gymnasts to acquire greater bone strength than the non-gymnasts. The differences in total cross-sectional area at the 66% radius and total density at the 4% and 66% radius found at baseline between gymnasts and non-gymnasts were maintained over the study duration. At study completion, both high- and low-training gymnasts had greater benefits in skeletal parameters relative to non-gymnasts. Furthermore, skeletal parameters for high-training gymnasts differed from low-training gymnasts.

8.6 pQCT vs. DXA Comparisons

By using DXA to assess skeletal changes over time, direct comparison were made between the results and previous studies. Both total body and arms BMC increased significantly in all groups over the duration of the study. These increases were not different between groups. The DXA results differ from others (Erlandson, et al., in press; Laing, et al., 2005) as increases were not greater for gymnasts than non-gymnasts in total body BMC or areal BMD over study duration. However, the study was shorter than other longitudinal studies described previously.

Findings in bone mineral density differed between DXA and pQCT measurements. Arms areal BMD derived from DXA was lower in high-training gymnasts than non-gymnasts. In contrast, pQCT-derived total bone volumetric BMD for both the distal radius and ulna, as well as trabecular volumetric BMD at the distal radius, were significantly higher in high-training gymnasts than non-gymnasts. While total and trabecular volumetric BMD were higher for high-training gymnasts, cortical volumetric BMD was lower, although not significant, in high-training gymnasts than non-gymnasts. Furthermore, pQCT results showed lower volumetric BMD in low-training gymnasts than non-gymnasts (ToD 66% radius and CoD 66% radius although, not significant at six month analysis) and high-training gymnasts (66% ulna). However, DXA-derived areal BMD in the arms showed no differences between low-training gymnasts and any other group.

Additionally, DXA results failed to find significant differences between groups for arms BMC. At the distal radius, high-training gymnasts had greater BMC than both low-training gymnasts and non-gymnasts, as measured by pQCT. At the proximal ulna, both groups of gymnasts had greater BMC than non-gymnasts.

The discrepancies observed between DXA and pQCT-derived skeletal parameters may be explained by the fact that the DXA only measures areal BMD of the whole region of interest whereas pQCT allows measuring volumetric BMD in each bone compartment (cortical and trabecular) of a 2-mm cross section of bone. The pQCT technology is therefore likely to be more sensitive to short-term longitudinal changes.

8.7 Muscle-Bone Relationship

The majority of forces that act on the skeleton during physical activity come from muscle contractions or direct contact with the ground (ground reaction forces) (Kohrt, et al., 2009). Gymnastics is a sport demanding high muscle strength and function and results in the application of high ground reaction forces, particularly to the peripheral skeleton. The study design outlined in this thesis involved three groups with varying exposure to ground reaction forces and muscle requirements. The three groups comprise of:

1. High-training gymnasts - exposed to large impact forces and have superior upper limb muscle strength and function
2. Low-training gymnasts - exposed to lower ground reaction forces, less often than high-training gymnasts however, have superior upper limb muscle function
3. Non-gymnasts - exposed to low/minimal ground reaction forces to the upper limbs and have less developed upper limb muscle strength and function

While direct impact loading was not assessed in this thesis, ground reaction forces have been well described in the literature and were shown to differ between limbs and gymnastics skills, increasing with the difficulty of the skill (Burt, et al., 2010; Davidson, Mahar, Chalmers, & Wilson, 2005; Seeley & Bressel, 2005). The results revealed high-training gymnastics participation (associated with large impacts and muscle loading) had the greatest musculoskeletal health benefits, followed by low-training gymnastics participation. While the high-training gymnasts would have been exposed to more frequent and larger impact forces than low-training gymnasts, there was no difference in muscle function between gymnastics groups. Conversely, muscle cross-sectional area and lean mass differed between high- and low-training gymnasts. Additional research is required, with investigations incorporating sports such as swimming, canoeing or kayaking that provide a weight-supported environment with high upper body muscle demands. This will help to clarify the mechanisms underlying the skeletal adaptations resulting primarily from muscle-induced loading.

Given the short duration of the longitudinal investigations, significant relationships between changes in skeletal parameters and changes in muscle parameters were not expected. However, six month changes in muscle cross-sectional area and arm lean mass correlated with changes in radius BMC at the 4% and 66% sites. Once change in height was accounted for, these relationships disappeared. It is difficult to accurately confirm if DXA-derived lean mass or pQCT-derived muscle cross sectional area as surrogate measures of muscle forces, reflect true changes in muscle strength and function. Longer follow up over 12 or 18 months might have revealed stronger relationships between changes in surrogates of muscle forces (e.g. MCSA, lean mass) and changes in bone parameters as well as additional changes in actual muscle function.

8.8 Contributions to Existing Literature

The positive influence of gymnastics participation on musculoskeletal health has previously been shown. Numerous studies and reviews have shown skeletal benefits, particularly in bone strength and geometry, in young gymnasts compared with non-gymnasts (Dowthwaite & Scerpella, 2009). However, a systematic review, including a meta-analysis that quantifies the magnitude of the gymnastics-induced benefits, has not previously been compiled in young female gymnasts. By conducting such a review, it was possible to combine the previous literature on pre-pubertal female artistic gymnasts and produce an overall effect of gymnastics participation on skeletal health.

Previously, researchers have focused on young elite gymnasts rather than recreational or non-elite gymnasts. However, recently studies have investigated the skeletal effects of participation in recreational gymnasts (Erlandson, et al., 2011; Erlandson, et al., in press; Laing, et al., 2005). The current study differed from these previous studies in recreational gymnasts by using different skeletal imaging technologies, including assessment of muscle structure and function as well as individual comparisons of the radius and ulna, rather than the radius alone. Furthermore, pQCT was used in combination with DXA to track bone and muscle parameters in these young gymnasts. Finally, within the population of non-elite gymnasts, a separation of gymnasts was made based on hours of participation as well as the number of weekly gymnastics classes. This division assisted in the investigation of the dose-response between gymnastics training and musculoskeletal adaptations.

8.9 Directions and Future Research

To strengthen the benefits outlined in this thesis, future studies should consider:

- Measuring blood and urinary markers of growth and maturation (mainly hormones) as well as bone metabolism. While the use of Tanner criteria is a valid and reliable method (Duke, et al., 1980) to assess pubertal development, the most accurate way to ensure participants are pre-pubertal or to determine pubertal status is to obtain a blood sample. Specifically, the following markers could be assessed: estrogen, 17ß-estradiol and dehydroepiandrostenedione-sulphate (DHEA-S). In addition, measuring serum concentrations of insulin-like growth factor-1 (IGF-1) and insulin-like growth factor binding proteins (IGF BPs) may provide additional information on growth- and exercise-induced changes in musculoskeletal parameters. Rather than relying solely on assessment of bone mass, geometry and strength, biochemical analyses of bone formation and absorption would provide information in bone metabolism. Specifically, bone-specific alkaline phosphatase (BSAP) could be assessed for rate of bone formation. Furthermore, bone resorption could be analysed through urinary concentrations of C- and N-terminal telopeptide (CTX and NTX). Because bone metabolism is known to change more rapidly than bone mass or geometry, its value in short-term longitudinal studies, it is strongly influenced by growth rate and pubertal status. Adjustment for these parameters is of paramount importance when investigating bone turnover in children.

- Concurrently quantifying impact loading with skeletal adaptations. Impact frequency and loading during gymnastics classes have previously been reported however, most studies fail to quantify such loading in combination with skeletal adaptations. This may be difficult as gymnastics centres offer different programs and gymnasts may come from different centres. Furthermore, divergence may exist between individual gymnasts within the same class.

- Extending the scope of the current population by adding elite gymnasts and sedentary controls. Broadening the range of exposure to loading may provide additional insights into musculoskeletal adaptations resulting from growth and involvement in physical activity. The inclusion of a weight-supported upper limb sports such as swimming may also add further insight into the role of muscle forces within the muscle-bone relationship.

- Recruiting participants prior to gymnastics participation and following them through their career into retirement. Recruiting participants prior to gymnastics initiation has been done in recreational gymnasts (Laing, et al., 2005), although not among elite or highly competitive gymnasts. Furthermore, the skeletal health of gymnasts and ex-gymnasts (Dowthwaite & Scerpella, 2011; Erlandson, et al., 2011) as well as retired gymnasts has been assessed (Ducher, et al., 2009; Eser, et al., 2009). While the logistics may be difficult, observing musculoskeletal development through the lifespan in addition to gymnastics participation would be ideal.

- Using high resolution pQCT (HR pQCT). This technology permits in vivo assessment of trabecular architecture and volumetric BMD at the distal radius. The gymnasts in this study displayed greater volumetric BMD using pQCT, and the trabecular rich site of the distal radius showed the greatest changes over time. The use of HR pQCT may reveal what caused this increase in volumetric BMD for example greater number of trabeculae, lower trabecular spacing or a thicker cortex. Specific information on trabecular number, thickness, separation, and distribution may help to better predict bone strength and fracture risk.

- Investigating whether the musculoskeletal advances associated with pre-pubertal, non-elite gymnastics participation diminish becoming less apparent during pubertal growth, when hormonal activity dominates bone metabolism.

- Including clinically relevant sites such as the lumbar spine and femoral neck using three dimensional skeletal imaging techniques such as MRI.

8.10 Final Remarks

In summary, when compared with active age- and gender-matched pre-and early pubertal girls, those participating in non-elite gymnastics had greater upper limb bone mass, cross-sectional area, volumetric bone density and strength. Non-elite involvement in gymnastics, particularly one class per week (3 hr/wk, range 1-5 hr/wk), is a realistic and attainable training load for the majority of girls, when compared with elite participation. Furthermore, this level of participation is sufficient in inducing short-term musculoskeletal adaptations to the upper limbs. Non-elite gymnastics may be easily implemented into the school curriculum or before/after school care activities.

Involvement in more than one gymnastics class per week offers additional skeletal benefits, particularly in bone mass and strength at the distal radius. In addition to normal growth and development, involvement in non-elite artistic gymnasts increases bone parameters, particularly bone strength which may decrease forearm fracture incidence. More importantly, non-elite gymnastics participation may induce lifelong skeletal benefits that ultimately reduce osteoporosis and fracture risk later in life, although additional longitudinal data are required to confirm this hypothesis.

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APPENDIX A

Quality Assessment Outlined by the STROBE Criteria

Item No		Ward et al 2007 Modified	Dowthwaite et al 2007	Dowthwaite et al 2006	Laing et al 2005	Zanker et al 2003	Jaffré et al 2003	Laing et al 2002	Lehtonen-Veromaa et al 2000(a)	Lehtonen-Veromaa et al 2000(b)
	Title and abstract									
1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1	0	0	1	0	0	1	1	0
	(b) Provide in the abstract an informative and balanced summary of what was done and what was found	1	1	1	1	1	0	1	1	1
	Introduction									
2	**Background/rationale** Explain the scientific background and rationale for the investigation being reported	1	1	1	1	1	1	1	1	1
3	**Objectives** State specific objectives, including any prespecified hypotheses	1	1	1	1	0	0	1	0	1
	Methods									
4	**Study design** Present key elements of study design early in the paper	0	1	1	1	1	0	1	1	1
5	**Setting** Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	1	1	1	1	1	1	1	1	1

Item No		Ward et al 2007 Modified	Dowthwaite et al 2007	Dowthwaite et al 2006	Laing et al 2005	Zanker et al 2003	Jaffré et al 2003	Laing et al 2002	Lehtonen-Veromaa et al 2000(a)	Lehtonen-Veromaa et al 2000(b)
6	**Participants**									
	(a) Cohort study—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up	1	NA	NA	1	NA	NA	1	1	NA
	Case-control study—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls	NA	0	NA	NA	1	NA	NA	NA	NA
	Cross-sectional study—Give the eligibility criteria, and the sources and methods of selection of participants	NA	NA	1	NA	NA	0	NA	NA	1
	(b) Cohort study—For matched studies, give matching criteria and number of exposed and unexposed	NA	NA	NA	NA	NA	NA	1	NA	NA
	Case-control study—For matched studies, give matching criteria and the number of controls per case	NA	1	NA	NA	1	NA	NA	NA	NA
7	**Variables**- BMD, BMC, etc Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	1	1	1	1	1	0	1	1	1

Item No		Ward et al 2007 Modified	Dowthwaite et al 2007	Dowthwaite et al 2006	Laing et al 2005	Zanker et al 2003	Jaffré et al 2003	Laing et al 2002	Lehtonen-Veromaa et al 2000(a)	Lehtonen-Veromaa et al 2000(b)
	Data Sources/Measurement- software/protocol to treat ROI data for DXA, pQCT									
8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	1	1	1	1	1	0	1	1	1
9	**Bias** Describe any efforts to address potential sour	1	1	1	1	1	0	1	0	1
10	**Study Size** Explain how the study size was arrived at	1	0	1	0	1	0	0	0	0
11	**Quantitative variables** Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	1	1	1	1	1	0	1	1	1
12	**Statistical Methods** (a) Describe all statistical methods, including those used to control for confounding	1	0	0	0	1	0	0	1	0
	(b) Describe any methods used to examine subgroups and interactions	1	1	1	1	1	0	1	1	1
	(c) Explain how missing data were addressed									
	(d) <u>Cohort study</u>—If applicable, explain how loss to follow-up was addressed	1	NA	NA	1	NA	NA	1	1	NA
	<u>Case-control study</u>—If applicable, explain how matching of cases and controls was addressed	NA	1	NA	NA	1	NA	NA	NA	NA

Item No		Ward et al 2007 Modified	Dowthwaite et al 2007	Dowthwaite et al 2006	Laing et al 2005	Zanker et al 2003	Jaffré et al 2003	Laing et al 2002	Lehtonen-Veromaa et al 2000(a)	Lehtonen-Veromaa et al 2000(b)
	Cross-sectional study—If applicable, describe analytical methods taking account of sampling strategy	NA	NA	NA	NA	NA	NA	NA	NA	NA
	(e) Describe any sensitivity analyses	NA	0	NA	0	NA	NA	NA	NA	NA
	Results									
	Participants									
13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	1	0	0	1	0	0	0	1	1
	(b) Give reasons for non-participation at each	1	NA	NA	1	NA	NA	0	NA	NA
	(c) Consider use of a flow diagram	1	NA	NA	NA	NA	NA	NA	NA	NA
	Descriptive Data									
14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	1	1	1	1	1	1	1	1	1
	(b) Indicate number of participants with missing data for each variable of interest	1	NA	NA	0	NA	NA	0	0	NA
	(c) Cohort study—Summarise follow-up time (eg, average and total amount)	1	NA	NA	0	NA	NA	0	0	NA
	Outcome Data									
15*	Cohort study—Report numbers of outcome events or summary measures over time	1	NA	NA	1	NA	NA	0	0	NA

Item No		Ward et al 2007 Modified	Dowthwaite et al 2007	Dowthwaite et al 2006	Laing et al 2005	Zanker et al 2003	Jaffré et al 2003	Laing et al 2002	Lehtonen-Veromaa et al 2000(a)	Lehtonen-Veromaa et al 2000(b)
	Case-control study—Report numbers in each exposure category, or summary measures of exposure	NA	1	NA	NA	1	NA	NA	NA	NA
	Cross-sectional study—Report numbers of outcome events or summary measures	NA	NA	1	NA	NA	1	NA	NA	1
	Main Results									
16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	1	0	0	1	1	1	1	1	0
	(b) Report category boundaries when continuous variables were categorized	0	NA	1	0	1	NA	1	NA	NA
	(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Other analyses									
17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	1	1	1	1	1	1	1	1	1
	Discussion									
	Key Results									
18	Summarise key results with reference to study objectives	1	1	1	1	1	1	1	1	1

Item No		Ward et al 2007 Modified	Dowthwaite et al 2007	Dowthwaite et al 2006	Laing et al 2005	Zanker et al 2003	Jaffré et al 2003	Laing et al 2002	Lehtonen-Veromaa et al 2000(a)	Lehtonen-Veromaa et al 2000(b)
	Limitations									
19	Discuss limitations of the study, taking into account sources of potential bias or imprecision	1	1	1	1	1	0	1	0	0
	Discuss both direction and magnitude of any potential bias	1	0	0	1	1	0	1	0	0
	Interpretation									
20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	1	1	1	1	1	0	1	1	1
	Generalisability - Conclusion									
21	Discuss the generalisability (external validity) of the study results	0	0	1	1	1	0	1	1	1
	Other Information									
	Funding									
22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	1	1	1	1	0	0	0	1	1
	Raw score	28	19	21	25	24	7	23	20	19
	%	90%	68%	81%	81%	86%	28%	74%	71%	76%

Item No		Courteix et al 1999(a)	Courteix et al 1999(b)	Nickols-Richardson et al 1999	Courteix et al 1998(a)	Courteix et al 1998(b)	Bass et al 1998	Dyson et al 1997	Cassell et al 1996
	Title and abstract								
1	(a) Indicate the study's design with a commonly used term in the title or the abstract	0	0	1	0	1	1	0	0
	(b) Provide in the abstract an informative and balanced summary of what was done and what was found	1	1	1	1	1	1	1	1
	Introduction								
2	**Background/rationale** Explain the scientific background and rationale for the investigation being reported	1	1	1	1	1	1	1	1
3	**Objectives** State specific objectives, including any prespecified hypotheses	1	0	1	0	0	0	1	1
	Methods								
4	**Study design** Present key elements of study design early in the paper	1	0	1	0	0	1	0	0
5	**Setting** Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	1	1	1	1	1	1	1	1

Item No		Courteix et al 1999(a)	Courteix et al 1999(b)	Nickols-Richardson et al 1999	Courteix et al 1998(a)	Courteix et al 1998(b)	Bass et al 1998	Dyson et al 1997	Cassell et al 1996
	Participants								
6	(a) Cohort study—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up	1	NA	1	NA	NA	1	NA	NA
	Case-control study—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls	NA	NA	NA	NA	NA	NA	NA	NA
	Cross-sectional study—Give the eligibility criteria, and the sources and methods of selection of participants	NA	1	NA	1	1	NA	1	1
	(b) Cohort study—For matched studies, give matching criteria and number of exposed and unexposed	NA	NA	1	NA	NA	1	NA	NA
	Case-control study—For matched studies, give matching criteria and the number of controls per case	NA	NA	NA	NA	NA	NA	NA	NA
7	**Variables**- BMD, BMC, etc Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	1	1	1	1	1	1	1	1

Item No		Courteix et al 1999(a)	Courteix et al 1999(b)	Nickols-Richardson et al 1999	Courteix et al 1998(a)	Courteix et al 1998(b)	Bass et al 1998	Dyson et al 1997	Cassell et al 1996
	Data Sources/Measurement- software/protocol to treat ROI data for DXA, pQCT								
8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	1	1	1	1	1	1	1	1
9	**Bias** Describe any efforts to address potential sour	0	0	1	0	1	1	1	0
10	**Study Size** Explain how the study size was arrived at	0	0	0	0	0	0	0	0
11	**Quantitative variables** Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	1	1	1	1	1	1	1	1
12	**Statistical Methods**								
	(a) Describe all statistical methods, including those used to control for confounding	0	0	0	0	0	0	0	0
	(b) Describe any methods used to examine subgroups and interactions	1	1	1	1	1	1	1	1
	(c) Explain how missing data were addressed								
	(d) Cohort study—If applicable, explain how loss to follow-up was addressed	1	NA	1	NA	NA	0	NA	NA
	Case-control study—If applicable, explain how matching of cases and controls was addressed	NA	NA	NA	NA	NA	NA	NA	NA

Item No		Courteix et al 1999(a)	Courteix et al 1999(b)	Nickols-Richardson et al 1999	Courteix et al 1998(a)	Courteix et al 1998(b)	Bass et al 1998	Dyson et al 1997	Cassell et al 1996
	Cross-sectional study—If applicable, describe analytical methods taking account of sampling strategy	NA	NA	NA	NA	NA	NA	NA	NA
	(e) Describe any sensitivity analyses	1	1	NA	1	0	0	NA	NA
	Results								
	Participants								
13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	0	1	0	0	0	0	0	0
	(b) Give reasons for non-participation at each	0	NA	1	NA	NA	0	NA	NA
	(c) Consider use of a flow diagram	NA	NA	NA	NA	NA	NA	NA	NA
	Descriptive Data								
14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	1	1	1	0	1	1	1	1
	(b) Indicate number of participants with missing data for each variable of interest	1	NA	1	NA	NA	0	NA	NA
	(c) Cohort study—Summarise follow-up time (eg, average and total amount)	0	NA	0	NA	NA	0	NA	NA
	Outcome Data								
15*	Cohort study—Report numbers of outcome events or summary measures over time	1	1	1	NA	NA	1	NA	NA

Item No		Courteix et al 1999(a)	Courteix et al 1999(b)	Nickols-Richardson et al 1999	Courteix et al 1998(a)	Courteix et al 1998(b)	Bass et al 1998	Dyson et al 1997	Cassell et al 1996
	Case-control study—Report numbers in each exposure category, or summary measures of exposure	NA	NA	NA	NA	NA	NA	NA	NA
	Cross-sectional study—Report numbers of outcome events or summary measures	NA	1	NA	1	1	NA	1	
16	**Main Results**								
	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	1	1	1	1	1	1	0	1
	(b) Report category boundaries when continuous variables were categorized	NA	NA	1	NA	NA	NA	1	NA
	(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA	NA	NA	NA	NA	NA	NA	NA
17	**Other analyses** Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	1	1	1	1	1	1	1	1
	Discussion								
18	**Key Results** Summarise key results with reference to study objectives	1	1	1	1	1	1	1	1

Item No		Courteix et al 1999(a)	Courteix et al 1999(b)	Nickols-Richardson et al 1999	Courteix et al 1998(a)	Courteix et al 1998(b)	Bass et al 1998	Dyson et al 1997	Cassell et al 1996
	Limitations								
19	Discuss limitations of the study, taking into account sources of potential bias or imprecision	0	0	0	0	0	0	0	0
	Discuss both direction and magnitude of any potential bias	0	0	0	0	0	1	0	0
	Interpretation								
20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	1	1	1	1	1	1	1	1
	Generalisability - Conclusion								
21	Discuss the generalisability (external validity) of the study results	0	0	0	0	0	1	0	0
	Other Information								
	Funding								
22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	1	0	1	0	1	1	1	1
	Raw score	20	17	24	14	17	21	17	15
	%	67%	63%	77%	54%	65%	68%	65%	63%

APPENDIX B

DXA Bone Mineral Content Meta-Analysis Table

Author	Design	n	Region	Individual Variables			Overall		
				ES	95% CI	95% CI	ES	95% CI	95% CI
Ward et al., 2007	RCT	10	TB	-0.557	-1.510	0.395	-0.253	-1.205	0.700
			LS	0.052	-0.900	1.004			
Dowthwaite et al., 2007	CS	12	ultradistal R	1.907	1.068	2.746	1.851	1.011	2.690
			1/3 distal R	1.795	0.955	2.634			
Dowthwaite et al., 2006	CS	12	LS	1.434	0.595	2.273	1.434	0.595	2.273
			F	1.452	0.613	2.291			
			FN	0.713	-0.126	1.552			
Laing et al., 2005	LT	65	TB	0.000	-0.329	0.329	-0.004	-0.333	0.325
			LS	-0.003	-0.332	0.326			
			TPF	-0.006	-0.335	0.323			
			F	-0.011	-0.340	0.318			
Zanker et al., 2003	CS	10	TB	0.393	-0.483	1.270	0.470	-0.407	1.347
			LS	0.547	-0.330	1.423			
Laing et al., 2002	CS	7	TB	0.348	-0.617	1.314	0.629	-0.337	1.595
			LS	0.719	-0.247	1.685			
			FN	0.539	-0.427	1.505			
			T	0.475	-0.490	1.441			
			TPF	0.798	-0.168	1.764			
			R	1.543	0.578	2.509			
Courteix et al., 1999	LT	14	TB	0.000	-0.676	0.676	0.163	-0.484	0.811
			LS	0.015	-0.662	0.691			
			FN	0.227	-0.449	0.903			
			T	0.050	-0.626	0.726			
			WT	1.015	0.338	1.691			
			R	0.068	-0.609	0.744			
			Distal R	0.588	-0.088	1.264			
			Mid R	0.112	-0.564	0.789			
Courteix et al., 1999	CS	27	TB	-0.344	-0.962	0.274	0.163	-0.484	0.811
			LS	-1.757	-2.375	-1.138			
			FN	0.214	-0.404	0.833			
			T	0.225	-0.393	0.843			
			WT	0.553	-0.065	1.172			
			Head	-1.103	-1.722	-0.485			
			Mid R	0.419	-0.199	1.038			
			Distal R	1.007	0.389	1.626			
Courteix et al., 1998	CS	18	TB	-0.431	-1.144	0.283	0.064	-0.650	0.777
			LS	-0.097	-0.810	0.616			
			FN	0.100	-0.613	0.813			
			T	0.027	-0.686	0.741			
			WT	0.834	0.120	1.547			
			R	0.651	-0.062	1.365			
				Overall model			0.462	0.041	0.884
				I^2				69%	

APPENDIX C

DXA Bone Area Meta-Analysis Table

Author	Design	n	Region	Individual Variables			Overall		
				ES	**95% CI**	**95% CI**	**ES**	**95% CI**	**95% CI**
Dowthwite et al., 2006			LS	0.760	-0.080	1.599			
			F	1.024	0.185	1.863	0.760	-0.080	1.599
	CS	12	FN	-0.180	-1.020	0.659			
			TB	-0.536	-0.865	-0.207			
Laing et al., 2005			LS	-0.439	-0.769	-0.110	-0.413	-0.743	-0.084
			TPF	-0.371	-0.700	-0.042			
	LT	65	F	-0.387	-0.717	-0.058			
Zanker et al., 2003			TB	0.040	-0.836	0.917	0.020	-0.856	0.897
	CS	10	LS	0.000	-0.877	0.877			
			TB	0.106	-0.860	1.072			
			LS	0.209	-0.756	1.175			
Laing et al., 2002	CS	7	TPF	-0.037	-1.003	0.929	0.082	-0.884	1.048
			R	0.469	-0.497	1.435			
			FN	-0.708	-1.674	0.258			
			T	0.059	-0.907	1.025			
				Overall model			0.028	-0.525	0.581
				I^2			58%		

APPENDIX D

Ethics Approval

Human Research Ethics Committee

Committee Approval Form

Principal Investigator/Supervisor: Professor Geraldine Naughton Sydney Campus

Co-Investigators: Dr. David Greene Sydney Campus

Student Researcher: Ms Lauren Burt Sydney Campus

Ethics approval has been granted for the following project:
Upper body bone strength and muscle function in recreational artistic gymnasts. (Bone strength and muscle function in artistic gymnasts).

for the period: 12 September 2008 to 30 September 2011 (exteded from original date 28 February 2009)

Human Research Ethics Committee (HREC) Register Number: N200708 77

The following standard conditions as stipulated in the *National Statement on Ethical Conduct in Research Involving Humans* (2007) apply:

(i) that Principal Investigators / Supervisors provide, on the form supplied by the Human Research Ethics Committee, annual reports on matters such as:
  - security of records
  - compliance with approved consent procedures and documentation
  - compliance with special conditions, and

(ii) that researchers report to the HREC immediately any matter that might affect the ethical acceptability of the protocol, such as:
  - proposed changes to the protocol
  - unforeseen circumstances or events
  - adverse effects on participants

The HREC will conduct an audit each year of all projects deemed to be of more than low risk. There will also be random audits of a sample of projects considered to be of negligible risk and low risk on all campuses each year.

Within one month of the conclusion of the project, researchers are required to complete a *Final Report Form* and submit it to the local Research Services Officer.

If the project continues for more than one year, researchers are required to complete an *Annual Progress Report Form* and submit it to the local Research Services Officer within one month of the anniversary date of the ethics approval.

K. Pashley.

Signed: Date: 12 September 2008
(Research Services Officer, McAuley Campus)

APPENDIX E

Parental Consent and Child Assent Forms

PARENTS/GUARDIANS CONSENT FORM

Copy for Researcher

Doctor of Philosophy Research Project Title:
Upper body bone strength and muscle function in recreational artistic gymnasts

Supervisor:	**Co Supervisor:**	**Student Researcher:**
Professor Geraldine Naughton	Dr. David Greene	Ms Lauren Burt

Research Degree:
Doctor of Philosophy (PhD) – Exercise Science

I …………………………………(name of parent / guardian) have read the details of the study involving upper body bone strength and muscle function in recreational artistic gymnasts. I understand that data will be collected on two occasions during the 6-month study and will involve measures of anthropometry, DXA and pQCT bone scans, completion of questionnaires (nutrition, physical activity, sporting involvement, medical health and injury), muscle strength and function tasks. I have read the section on 'Bone Scan Safety' in the enclosed information letter and understand that the DXA and pQCT scans will involve exposure to very small doses of radiation (0.0042 mSv). I understand the testing sessions will take approximately two hours. I am aware that group results may be published in scientific journals and presented at conferences. I understand the information provided in the information letter. Any questions I have asked have been answered to my satisfaction.

I agree that my child, nominated below, may participate in the following

Anthropometry	☐ Yes	☐ No
DXA and pQCT scans	☐ Yes	☐ No
(which I acknowledge incurs exposure to small amounts of radiation)		
Questionnaires	☐ Yes	☐ No
Muscle strength and function tasks	☐ Yes	☐ No

I acknowledge that I can withdraw my consent at any time without comment or penalty.
I agree that research data collected for the study may be published or may be provided to other researchers in a form that does not identify my child in any way.

NAME OF PARENT/GUARDIAN: ……………………………………………………………………………
(block letters)

NAME OF CHILD ……………………………………………………………………………………
(block letters)

PARENT/GUARDIAN SIGNATURE ……………………………………DATE……/………/………

Supervisor: Professor Geraldine Naughton Signature: Date:

Co Supervisor: Dr. David Greene Signature: Date:

Student Researcher: Ms Lauren Burt Signature: Date:

ACU National

CHILD ASSENT FORM

Copy for Researcher

Doctor of Philosophy Research Project Title:
Upper body bone strength and muscle function in recreational artistic gymnasts

Supervisor:	**Co Supervisor:**	**Student Researcher:**
Professor Geraldine Naughton	Dr. David Greene	Ms Lauren Burt

Research Degree:
Doctor of Philosophy (PhD) – Exercise Science

I ……………..………..…………..(the participant aged under 18 years) understand what this research project is designed to explore. What I will be required to do has been explained to me. I understand that data will be collected on two occasions and will involve measures of my height and weight, bone scans, questionnaires and tasks that require me to use my muscles. I agree to take part in the project, realising that I can withdraw at any time without having to give a reason for my decision.

By signing below, you are indicating that you agree to participate in the project.

NAME OF PARTICIPANT: ....
(block letters)

SIGNATURE: ....   DATE......./........../..........

Supervisor: Professor Geraldine Naughton	Signature	Date:
Co Supervisor: Dr. David Greene	Signature	Date:
Student Researcher: Ms Lauren Burt	Signature	Date:

APPENDIX F

Information Letter

ACU National

INFORMATION LETTER TO PARENTS/GUARDIANS OF PARTICIPANTS

Doctor of Philosophy, Research Project Title:
Upper body bone strength and muscle function in recreational artistic gymnasts

Supervisor:	**Co Supervisor:**	**Student Researcher:**
Professor Geraldine Naughton	Dr. David Greene	Ms Lauren Burt

Research Degree:
Doctor of Philosophy (PhD) – Exercise Science

Dear Parent/Guardian,

Your daughter is invited to participate in a research project which endeavors to quantify the muscle-bone relationship of young gymnasts. We are particularly interested in the upper body strength gains and bone adaptations that occur with growth and gymnastics.

The project is recruiting females aged between 7 to 10 years. We are recruiting females from artistic gymnastics and an age-matched group who participate in less than three hours per week of organised sporting activity outside school and who have not participated in gymnastics training in the past 12 months.

Your daughter will be assessed twice over a six month study period (baseline & six months). Testing will take place at the Australian Catholic University at Strathfield. Each individual testing session will require a single visit of approximately two hours. If required, transport to and from this venue can be arranged. The following tests will be conducted at each testing session:

- **Anthropometry measures** – weight and standing and sitting heights will be measured along with some general body dimension measurements such as upper limb length, shoulder girth, elbow and shoulder angle and flexibility, and flexed muscle circumference. This component of testing is expected to take about 10 minutes.
- **Dual energy x-ray absorptiometry (DXA)** – this scan will assess the bone, muscle and fat content of your daughter. This scan is completely non-invasive and painless and is expected to take approximately 15 minutes.
- **Peripheral quantitative computed tomography (pQCT)** – this scan will assess, in the most accurate way possible, your daughter's bone geometry, strength and density. A non-invasive and painless scan is taken of your daughter's non-dominant forearm. This scan is expected to take about 10 minutes.
    - ➢ Both the DXA and pQCT scans use ionizing radiation. The radiation exposure is extremely small (i.e.: less than 1 millisieverts (mSv)). Exposure from a normal chest x-ray is 50 mSv, while a return transatlantic flight exposes travellers to 80 mSv.

- **Nutritional analyses** - dietary calcium and energy intake will be determined by a 3-day (two week days and one weekend day) food diary. Instructions for completing the food diary will be provided with self-addressed stamped envelopes to assist in the return of completed diaries. Your daughter will need to take the diary home to complete and will need your help.
- **Physical activity** - physical activity levels will be assessed using a 3-day Physical Activity Record (two week days and one weekend day). You will be asked to recall activity in 15 minutes intervals for three 24 hour periods. Again, instructions regarding completion of the physical activity diary will be provided to you and your daughter as well as self-addressed stamped envelopes to assist in the return of completed diaries. To help quantify the questionnaire, a random selection of participants will be selected to wear a small movement sensor on the hip (5 x 4 x 1.5 cm) during the three days of the physical activity record.
- **Sporting involvement, physical health and injuries** – during initial and final testing sessions, your daughter's current sporting involvement, physical health and injury history will be assessed through a survey.
- **Muscle strength and function** – Muscle strength will be assessed with a hand grip dynamometer. Two muscle function tasks will be performed. The first task requires participants to perform a maximum number of weighted arm movements in bouts of 30 second activity with rest in-between. The weight applied to the arms will be relative to the participant's body weight. Through the use of velcro adjustable wrists weights, a total of 5% of the participant's body weight will be added to each arm. The second task requires participants to support their own body weight between two objects for as long as possible. To assess how joints and muscles respond to the tasks, reflective markers and surface electromyography sensors will be placed on specific areas of the arms and back. Surface electromyography will be used to evaluate muscle activity. Videotaping will help assess time to fatigue.

Bone scan safety

As stated above, this research involves exposure to a very small amount of radiation using Dual Energy X-ray Absorptiometry (DXA) and Peripheral Quantitative Computed Tomography (pQCT). The Australian Radiation Protection and Nuclear Safety Agency's Guidelines (http://www.arpansa.gov.au/pubs/rps/rps8.pdf) requires us to communicate the following statement: As part of everyday living, everyone is exposed to naturally occurring background radiation and receives a dose of about 2 mSv each year. The effective dose from this study is about 0.0084 mSv (0.008 mSv for the DXA scans and 0.0004 mSv for the pQCT). At this dose level, no harmful effects of radiation have been demonstrated as any effect is too small to measure. The risk is minimal (dose < 0.2 mSv). There will a total of two scans over six months. Ms. Burt will be conducting the scans. She has extensive training and experience using the DXA and pQCT scanners and has completed a radiation safety course for these instruments. It is advised that you maintain a copy of this radiation information for a minimum of five years.

Feedback

As a participant, your daughter will receive feedback on her bone strength and density as well as information regarding her upper body muscle strength/endurance. Follow-up testing will enable your daughter to evaluate her growth and training progress across the test period. There will be no financial expense relating to participation in this study.

You and your daughter are free to choose not to participate in the study and may withdraw from the study at any time without providing a reason and with no penalty. Withdrawing will not disadvantage your daughter.

Data collected during the study will remain within the confidence of the researchers. Reports will not identify your daughter in any way and only group results will be made available. Group results will be published in scientific journals and presented at scientific conferences. Data will be kept securely within the School of Exercise Science office at the Australian Catholic University, Strathfield, NSW.

If at any stage during the study you require additional information or have any further queries or concerns, please do not hesitate to contact the research supervisor.
Supervisor: Professor Geraldine Naughton
Phone: (03) 9953 3034 Email: geraldine.naughton@acu.edu.au
Address: C/I- School of Exercise Science
Australian Catholic University
Locked Bag 4115
Fitzroy, VIC 3065

This study has been approved by the *Human Research Ethics Committee* at the Australian Catholic University.

In the event that you have any complaint or concern about the way you or your daughter have been treated during the study, or you have any query that the supervisor or researcher have not been able to satisfy, you may call or write to the chair of the Human Research Ethics Committee care of the nearest branch of the Research Services Unit.

NSW/ACT: Chair HREC, C/o Research Services
Australian Catholic University
Locked Bag 4115
Fitzroy, VIC 3065
Phone: (03) 9953 3158 Fax: (03) 9953 3315

Any complaint or concern will be treated in confidence and fully investigated. The participant will be informed of the outcome.

If you agree to allow your daughter to participate in this study, you should sign both copies of the Consent Form, retain one copy for your records and return the other copy to the researcher.

Sincere thanks,

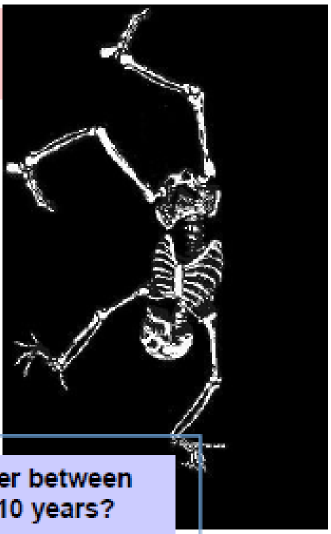
Professor Geraldine Naughton
Dr. David Greene
Ms Lauren Burt

APPENDIX G

Information Flyers

ACU National
Australian Catholic University
Brisbane Sydney Canberra Ballarat Melbourne

Does your daughter have strong muscles & bones?



The best way to ensure strong muscles and bones for life is to start early. Research has shown that sport participation throughout childhood will positively influence peak bone mass & may decrease the risk of osteoporosis later in life (Bass et al., 1998).

Bone strength is particularly interesting during late childhood. At this time bone mass & muscle strength lag behind body weight & height. This imbalance leads to bone instability & fracture in the event of a fall (Rauch et al., 2001).

The Australian Catholic University in partnership with the YMCA & the NSW Sporting Injuries Committee are researching the risk of forearm fracture in young pre-pubertal gymnasts & non-gymnasts aged 7 to 10 years.

Is your daughter between the age of 7 & 10 years?

Would you like her bone density & strength checked using state of the art technology, FREE OF CHARGE?

YMCA

What is involved?

- Two trips to our Strathfield campus, six months apart at a time that is convenient for you & your family
- Two bone density scans
- Muscle strength & function tasks
- Questionnaires

Participation Benefits
Individualised feedback on muscle & bone strength, bone density & calcium intake relative to norm scores

This project has ethical approval from the Australian Catholic University's ethics committee.

All tests will be conducted at the Australian Catholic University (Strathfield) by qualified professionals.

Travel to and from the University can be arranged.

To help create a fun & friendly atmosphere please bring a buddy!

Australian Catholic University
School of Exercise Science

Professor Geraldine Naughton
Dr. David Greene
Ms. Lauren Burt

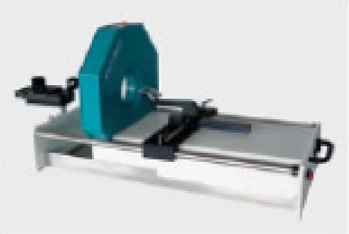
Please call or email Lauren for more information on

Study requirements

There will be no financial expense relating to participation in this study

What we are measuring & how.

- Physical activity, food intake, maturation & injuries
  - Questionnaires
- Bone strength, density & geometry- Peripheral Quantitative Computed Tomography scan (arm)
- Body composition - Dual-energy X-ray absorptiometry scan (body)
- Muscle strength - medicine ball throw, hand grip strength test
- Muscle function - body weight support movement & arm sequence touching targets



Additional information

This project has ethical approval from the Australian Catholic University's ethics committee.

All tests will be conducted at the Australian Catholic University (Strathfield) by qualified professionals, at a time that fits into your schedule.

To help create a fun & friendly atmosphere please bring a buddy!

A total of two testing sessions will be required, 6 months apart.

Travel to and from the University can be arranged.

If you have any questions or concerns please contact

Lauren Burt

ACU National

Australian Catholic University

Brisbane Sydney Canberra Ballarat Melbourne

Does your daughter have strong muscles & bones?

centre of COPAL

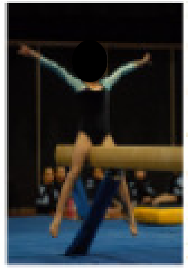
physical activity across the lifespan

Lauren Burt

YMCA

Strong muscles, strong bones

The best way to ensure strong muscles and bone for life is to start early. Research has shown that sport participation throughout childhood will positively influence peak bone mass & may decrease the risk of osteoporosis later in life (Bass et al., 1998).



Bone strength is particularly interesting during late childhood. At this time bone mass & muscle strength lag behind body weight & height. This imbalance leads to bone instability & fracture in event of a fall (Rauch et al., 2001).

The Australian Catholic University in partnership with the YMCA & the NSW Sporting Injuries Committee are researching the risk of forearm fracture young pre-pubertal girls 7 to 10 years.

Participants

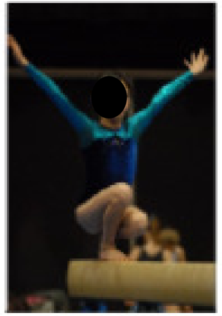
We are recruiting

- Girls
- 7 to 10 years old
- Gymnasts - training 1 to 16 hrs/wk
- Non-gymnasts - training < 3 hrs/wk

Participation benefits

Every participant will receive personalised information outlining

- Bone strength
- Bone density
- Muscle strength
- Muscle size
- Body composition



And how their results relate to age & gender related norms.

What are the risks?

A small amount of radiation is associated with the bone & body composition scans.

Technique	Patient Dose (µSv)
CT Scan (body)	5,000 – 15,000
X – ray (spine)	600 – 1,700
X – ray (chest)	50
Background	2,000 / year
Flight (Darwin-Perth)	16

The combined dose of radiation from this study will be 8.2 µSv. At this dose level, no harmful effects of radiation have been demonstrated as any effect is too small to measure.

APPENDIX H

General Health and Injury Questionnaire (six month version)

Instructions: Parents/guardians are asked to fill this out on behalf of the participant.

Please answer all questions. Where further information is needed, please give as much detail as possible. Mark all answers with an “X” in the box and write answers in the space provided. Once the survey is complete, please place it in the envelope provided and return it to the research supervisor.

Participant Name:____

Street Address (if changed in the last 6 months):__________________________

Suburb:____________________________ Postcode:____________

Email (If changed in the last 6 months): _______________________________

Phone Number(s):____

1. Is your daughter currently participating in gymnastics?

☐ Yes ☐ No

If “YES”, please go to question 3

2. Has your daughter ever participated in gymnastics?

☐ Yes ☐ No

If YES when did she stop participation? ________________________

If “No”, please go to question 6.

3. How many years has/had your daughter been training in gymnastics?

____

4. On average over the past 6 months, how many hours per week did your daughter train in gymnastics?

____

5. What level/class is your daughter currently in? ____________________

OR What level/class did your daughter reach? ____________________

6. What sports/activities (such as netball or dance) is your daughter involved in outside school? How many hours does she train/compete each week?

If your daughter is a gymnast please exclude gymnastics training

____

____

____

____

7. For a typical school week, please write the time that your daughter goes to sleep and wakes up.

	Monday	Tuesday	Wednesday	Thursday	Friday
Wakes Up					
Goes to Bed					

8. Has your daughter broken/fractured any bones in the last 6 months?

☐ Yes ☐ No

If yes,

What bones has she broken/fractured?________________________________

In what month did this incident occur?________________________________

Was the incident the result of

☐ free play

☐ gymnastics

☐ other organised sport participation (e.g. Soccer)

☐ other ____________________________

9. Over the past 6 months has your daughter had any injuries?

☐ Yes ☐ No

If you answered **yes** to **question 9**, please complete the following table (page 4)

Injuries in the past 6 months (if more than four, please attach another sheet)

	Injury 1	Injury 2	Injury 3	Injury 4
Type of injury				
Site of injury (eg. Ankle, wrist, back)				
How the injury occurred?				
Did the injury occur during organised sport participation or free play?				
If during sport, did the injury arise during training or competition?				
Approximately, in which month did it occur?				
Does the injury still trouble your child? (eg. Still needs taping or still has some pain)				
Number of days lost in training or competition				

10. Is your child currently taking any supplement(s) or medication(s)?

☐ Yes ☐ No

If "yes", please list them: ____

____

____

____

11. Please describe any other medical/health/injury information that has resulted in missed training or absences from school that you feel is important to the study.

____

____

____

____

____

____

Thank you for your participation!

APPENDIX I

Pubertal Maturation Questionnaire

Upper body bone strength and muscle function in recreational artistic gymnasts

Information about puberty for the PhD Study of Ms Lauren Burt

Dear Parents,

We would firstly like to take this opportunity to thank you for your cooperation and enthusiasm in our study of young gymnasts.

An essential component of studies involving young females is being able to describe the stage of puberty they are going through. This can be done with your help.

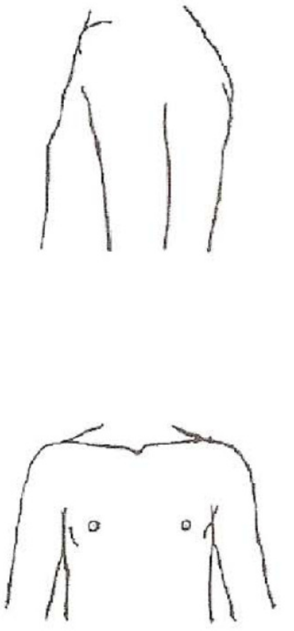
Enclosed with this letter are two pages of pictures showing the stages of female puberty from 1 (where puberty has not started) through to 5 (puberty is completed). We would like you to circle the stage of development you believe your daughter is at now. Please return the papers in the envelope provided.

Once again thank you for your participation and assistance.

Professor Geraldine Naughton (Supervisor)
Dr. David Greene (Co supervisor)
Ms. Lauren Burt (Research Student)

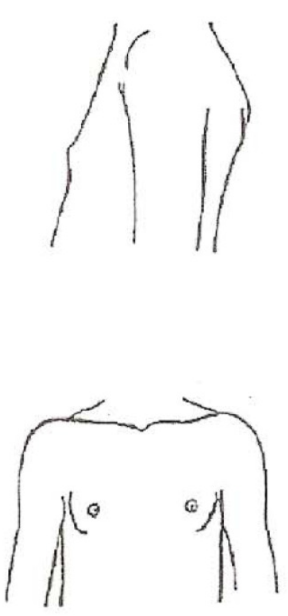
The pictures on this page show different stages of how the breasts grow. A girl can go through each of the 5 stages as shown. Please look at each of the pictures. Read the sentences. Put an x on the line above the picture which is closest to your stage of growth..

Picture 1 ___



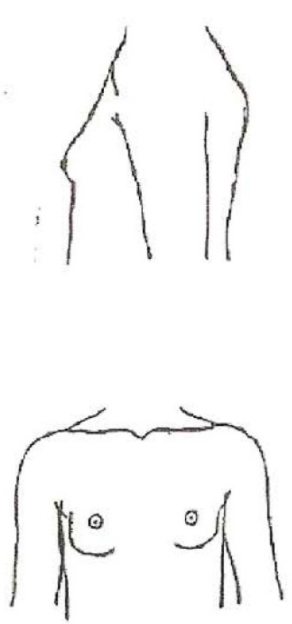
The nipple is raised a little in this stage. The rest of the breast is still flat.

Picture 2 ___



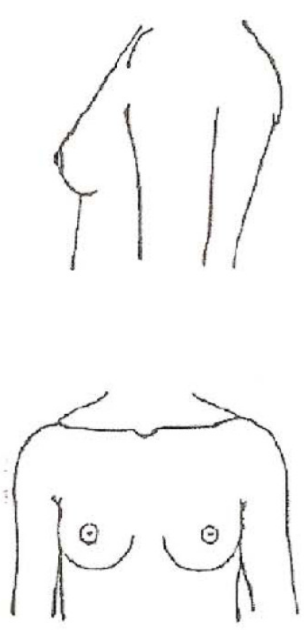
This is the breast bud stage. In this stage the nipple is raised more than in stage 1. The breast is a small mound. The areola is larger than in stage 1.

Picture 3 ___



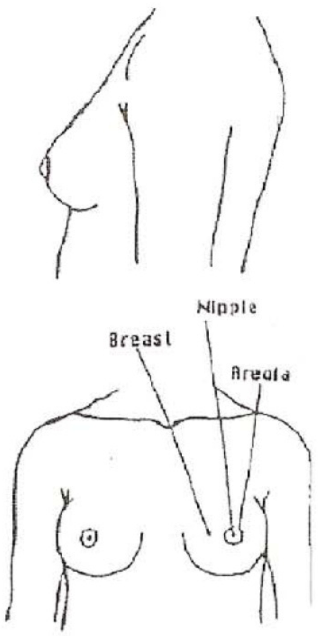
The areola and the breast are both larger than in stage 2. The areola does not stick out away from the breast.

Picture 4 ___



The areola and the nipple make up a mound that sticks up above the shape of the breast. (Note: this stage may not happen at all for some girls. Some girls go from stage 3 to stage 5, with no stage 4.)

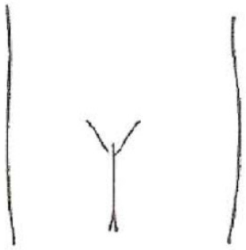
Picture 5 ___



This is the mature adult stage. The breasts are fully grown. Only the nipple sticks out in this stage. The areola has moved back to the general shape of the breast.

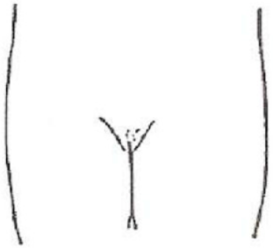
The drawings on this page show <u>different amounts of female pubic hair</u>.
Please look at each of the drawings and read the sentences under the drawings.
Then check the drawing that is <u>closest</u> to your stage of hair development.

Picture 1 ___



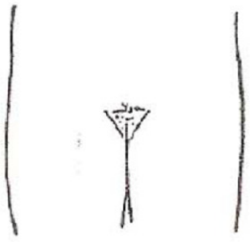
There is no pubic hair at all.

Picture 2 ___



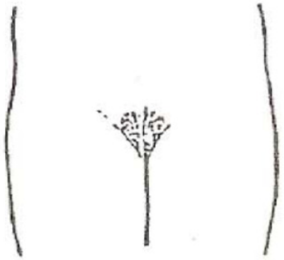
There is a small amount of long, lightly colored hair. This hair may be straight or a little curly

Picture 3 ___



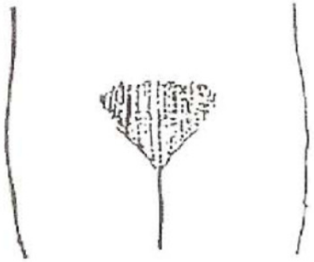
There is hair that is darker, curlier and thinly spread out to cover a somewhat larger area than in stage 2.

Picture 4 ___



The hair is thicker and more spread out, covering a larger area than in stage 3.

Picture 5 ___



The hair now is widely spread covering a large area, like that of an adult female.

Figure 3.12 Self-assessment of pubic hair development for girls.

Note. The following introduction (written and/or verbal) is given to the child prior to the assessment.

"As you keep growing over the next few years, you will see changes in your body. These changes happen at different ages for different children, and you may already be seeing some changes. Others may have already gone through some changes. Sometimes it is important to know how a person is growing without having a doctor examine them. It can be hard for a person to describe herself or himself in words, so doctors have drawings of stages that all children go through. Five drawings of pubic hair growth are attached for you to look at.

"We want to know how well you can select your stage of growth from the set of drawings. All you need to do is pick the drawing that looks like you do now. Put a check mark above the drawing that is closest to your stage of development, then put the sheet in the envelope and seal it so your answer will be kept private."

Reprinted from Morris and Udry (1980).

APPENDIX J

Food and Activity Diary

MY FOOD AND ACTIVITY RECORD BOOK

This record book belongs to: ______________________

Date of birth: ______________________

Section 1: Activity record

Section 2: Food record

Section 3: Calcium

Three day food and activity record:

Two school days and one weekend day

DAY 1 – Date: ____________________

DAY 2 – Date: ____________________

DAY 3 – Date: ____________________

For further information, please contact

Lauren Burt

SECTION 1 – ACTIVITY RECORD

1. How many times in the past 14 days have you done at least 20 minutes of exercise hard enough to make you breathe heavily and make your heart beat fast? (Hard exercise includes, for example, playing basketball, jogging, or fast bicycling; include time in physical education class at school)
   ( ) None
   ( ) 1 to 2 days
   ( ) 3 to 5 days
   ( ) 6 to 8 days
   ( ) 9 or more days
2. How many times in the past 14 days have you done at least 20 minutes of light exercise that was not hard enough to make you breathe heavily and make your heart beat fast? (Light exercise includes walking or slow biking; include time in physical education class)
   ( ) None
   ( ) 1 to 2 days
   ( ) 3 to 5 days
   ( ) 6 to 8 days
   ( ) 9 or more days
3. During a normal week how many hours a day do you watch television and videos or play computer or video games before or after school?
   ( ) None
   ( ) 1 hour or less
   ( ) 2 to 3 hours
   ( ) 4 to 5 hours
   ( ) 6 or more hours
4. During the past 12 months, how many team or individual sports or activities did you participate in a competitive level, such as school sports, club or out-of-school programs?
   ( ) None
   ( ) 1 activity
   ( ) 2 activities
   ( ) 3 activities
   ( ) 4 or more activities
   What activities did you train or compete in?

5. Please complete the following table outlining all sports or activities you have trained/competed in during the last 12 months.

Activity	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**Months per year**	**Days per week**	**Minutes per day**
E.g. Soccer				*X*	*X*	*X*	*X*	*X*					*5*	*2*	*60*

6. Circle all activities that you did <u>at least 10 times</u> in the PAST YEAR. Do NOT include time spent in school physical education classes/sport. Make sure you include all sport teams that you participated in during last year.

Aerobics
Baseball
Basketball
Bowling
Cheerleading
Cricket
Cycling
Dance Class
Gymnastics
Hockey
Horse Riding

Ice Skating
Little Athletics
Martial Arts
Netball
Oztag
Skateboarding
Snow Skiing
Soccer
Softball
Swimming (laps)
Tennis

Volleyball

Others:

SECTION 2: FOOD RECORD

Please write down everything you eat and drink for the same three days that you keep your activity record.

This is not a test. There are no right or wrong answers. Please do not report the foods you think you should be eating, but are not or the foods eaten by someone else in your household.

HOW TO FILL IN YOUR RECORD

- Fill in the date and day of the week at the top of the record sheet.
- Use as many pages as you need for each day’s record (number each page).
- Start a new page for a new day.

<u>Column 1 – Time</u>

- Every time you have something to eat or drink, write down the time you started.
- Write down « am » for morning and « pm » for afternoon or evening.

<u>Column 2 – What you are measuring</u>

Name and full description of all food and drink.

- Write down everything you eat and drink. This include snacks, water, vitamins and mineral supplements. Eat as you normally would !
- For each food and drink use a new line.
- Measure each food individually, for example, bread and margarine are each separate foods and are recorded on separate lines.
- Always record cooking methods such as boiling, frying, etc.
- Give a detailed description of the food or drink and brand names, for example :

  Arnott’s Milk arrowroot Biscuit
  Tip Top White Bread

- Record directly into this book while you still remember, such as while you are making a school lunch.
- Write down a cut of meat, that is lamb loin chop, chicken leg, rump steak etc.

- Write down if the fat on meat or skin on chicken was eaten or not eaten.

Column 3 – Amount eaten

In order to get the best estimate of your nutrient intake we need an accurate estimate of quantities of food and drink consumed.

- Estimate everything as accurately as possible in either **metric cups or spoonfuls** eg teaspoons, tablespoons (level or rounded) such as for breakfast cereal, rice, vegetables or spaghetti, or use a **metric measuring tape or ruler** to give length and width such as for sausage rolls, bananas, etc.

RECIPES

This includes mashed potato, mixed vegetables dishes, gravies and sauces.

- On a separate page record the individual ingredient with quantities. Report the total amount made and the amount of total recipe consumed. See example attached on blue paper.

EATING OUT

- Estimate food eaten as described above.
- Record the main ingredients in the food if recipe is unknown.
- Record where the food came from, such as McDonald's.
- Record weights on wrappers, drink cans and other food containers.

DRINKS

- Measure these in **metric cups or in litre measurements**.
- For cordial, measure the volume of cordial concentrate first then the volume of water added.
- If diluting fruit juice, measure fruit juice and water separately.

SCHOOL LUNCHES

- Estimate these as you prepare them and estimate any left overs in the lunch box.
- Record any extra food eaten at school.

- For canteen lunches, record as described in the Eating Out section.

To assist you in describing amounts of food and drink in household measures, please refer to the following pages.

SALT

(Circle the appropriate answer to each question)

- Do you add salt to food when you cook ?

  Always Sometimes Rarely Never

- Do you add salt to your food after cooking ?

  Always Sometimes Rarely Never

- Do you add salt to specific foods (eg chips, tomatoes and eggs)?

  Yes No

DATE :____________________ DAY OF WEEK : ____________________

Column 1 Time	**Column 2** Name, type, brand, cooking method	**Column 3** Amount	**Leave blank**

DATE :____________________ DAY OF WEEK : ____________________

Column 1 Time	**Column 2** Name, type, brand, cooking method	**Column 3** Amount	**Leave** **blank**

DATE :____________________ DAY OF WEEK : ____________________

Column 1 Time	**Column 2** Name, type, brand, cooking method	**Column 3** Amount	**Leave blank**

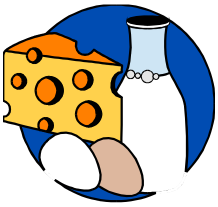
RECIPE SHEET

Name of recipe : ____

Individual Ingredients	Weight or metric measure

Final total cooked weight or amount : ________________________

SECTION 3 – CALCIUM
HOW TO ANSWER



How often did you eat these foods last week ?

Not last week : **N**
Times a week : **1W, 2W, 3W,** and so on**.**
Times a day : **1D, 2D, 3D**, and so on.
Please give an answer for every food !

DAIRY FOODS AND EGGS

		How often	**Comments**
Glass of plain milk	medium glass		
(excludes milk on cereal and in hot drinks)			
Glass of flavoured milk	medium glass		
Milk shake	regular size		
Thick shake	regular size		
Cheese	20 g. (1 slice)		
(including cheddar, colby, edam, brie/camembert)			
Reduced fat cheese	20 g. (1 slice)		
Cottage cheese	100 g. (½ carton)		
Cheese Spread	25 g. (1 tbspoon)		
Cheese sauce/cream sauce	3 tbspoon		
(eg : on meat/pasta)			
Cream	1 tbspoon		
Yoghurt	200 g. (1 carton)		
Ice cream	2 scoops		
Custard	½ cup		
Custard (no added sugar)	½ cup		
Fried egg	1 egg		
Boiled egg/poached	1 egg		
Omelette/scrambled eggs	2 eggs		

DAIRY FOODS AND EGGS I HAVE EATEN THAT HAVE NOT BEEN MENTIONED :

If you had any other dairy foods or eggs in the last 7 days (last week) that we have not mentioned, please write them down below and tell us how often you have them using the same code as before (eg : 1D, 3W).

Name of food	Your usual serve size	How often

Q1. When you drank milk or added it to cereal etc., did you use :

(Please circle one number)

1. Whole milk
2. Shape
3. Reduced fat milk (eg : lite white)
4. Skim milk
5. Farmers best
6. Something else.

   Please describe : ____

Q2. When you ate yoghurt, what type was it ?

(Please circle one number)

1. Plain
2. Plain, low fat
3. Fruit flavoured
4. Fruit flavoured, low fat
5. Diet fruit flavoured (sweetened with Nutrasweet)
6. I did not eat yoghurt.

When completed, please place this questionnaire in the envelope provided, seal the envelope and forward it to :

Your gymnastics coach (if applicable) **OR** **Lauren Burt**

School of Exercise Science
Australian Catholic
University
Locked Bag 2002
Strathfield, NSW 2135

APPENDIX K

Data Collection Sheets

Name: ______________________________ Date: __________

☐ Baseline ☐ 6 months ID: __________

Date of Birth: ______________ Age today: ________

☐ Right ☐ Left Handed

Anthropometry

Standing height: ____________

Sitting height: ____________

Weight: ____________

Limb length: Total Arm ____________ Forearm ____________

Flexed muscle circumference: ____________

DXA scan ☐ Yes ☐ No

Bone Analysis

pQCT scan ☐ Yes ☐ No

☐ Left ☐ Right

Scan number ____________

Gip Strength

- Familiarisation trials x 2

	Trial 1	**Trial 2**	**Trial 3**
Left			
Right			

Medicine Ball throw

- Ball weight ____________
- Familiarisation trials x 2

Trial 1	Trial 2	Trial 3

Muscle Function Tasks

Task 1 – Arm sequence

Required weight 5% BW:_______________

	Trial 1	Trial 2	Trial 3
Number of sequences			
RPE			

30 seconds work followed by 30 seconds rest. Repeat 3 times

Task 2 – Body weight support

Adjust the distance of the benches (elbow to fingertips)

Bend arms 120˚

	Trial 1	Trial 2	Trial 3
Time (sec)			
RPE			

APPENDIX L

Presented Abstracts

Presented Abstracts

Year	**Details**
2010	**Burt, L.A.**, Naughton, G.A., Greene, D.A., & Ducher, G. Upper body bone strength in pre-pubertal, non-elite gymnasts and non-gymnasts. **Journal of Science and Medicine in Sport**; 13 (suppl 1): e24
2010	**Burt, L.A.**, Naughton, G.A., Greene, D.A., & Ducher, G. Recreational gymnastics: strengthening the musculoskeletal system in young girls. **Journal of Bone and Mineral Research**; 25 (suppl 1): SU0015
2010	**Burt, L.A.,** Naughton, G.A., Ducher, G., & Greene, D.A., Upper body bone and muscle profiles in non-elite pre-pubertal female gymnasts. **Journal of Science and Medicine in Sport**; 12, (suppl 2): e20
2009	Higham, D.G., Naughton, G.A. & **Burt, L.A**. Four day observation of hydration profiles of adolescent swimmers and controls. **Journal of Science and Medicine in Sport**; 12 (suppl 1): S14
2007	**Burt, L.A.**, Naughton, G.A., Landeo, R. & Higham, D.G. Effects of participation level, apparatus and training phase on training load of young female gymnasts. **Journal of Science and Medicine in Sport**; 10 (suppl 1): p115

APPENDIX M

Peer Reviewed Publications

Journal Articles

Year	Details
	Burt, L.A., Greene, D.A., Ducher, G. & Naughton, G.A. Skeletal adaptations associated with pre-pubertal gymnastics participation: A meta-analysis. *Pediatric Exercise Science* (*submitted May, 2011*)
	Burt, L.A., Naughton, G.A., Greene, D.A. & Ducher, G. Skeletal adaptations of the ulna and radius in pre-pubertal non-elite female gymnasts. *Journal of Musculoskeletal and Neuronal Interactions* (*accepted with changes, May, 2011*).
	Burt, L.A., Naughton, G.A., Greene, D.A., Courteix, D & Ducher, G. Non-elite gymnastics participation is associated with greater bone strength, muscle size and function in pre- and early pubertal girls. *Osteoporosis International* (*accepted for publication, May, 2011*).
2011	Ferry, B., Duclos, M., **Burt, L.A.**, Therre, P., Le Gall, F., Jaffré, C. & Courteix, D. Bone geometry and strength adaptations to physical constraints inherent in different sports: comparison between elite female soccer players and swimmers. *Journal of Bone and Mineral Metabolism (in press).* DOI 10.1007/s00774-010-0226-8
2010	**Burt, L.A.**, Naughton, G.A., Higham, D.G. & Landeo, R. Quantifying training load in pre-pubertal artistic gymnastics. *Science of Gymnastics Journal, 2(3), 5-14.*
2009	Higham, D.G., Naughton, G.A., **Burt, L.A.** & Shi, X. Comparison of fluid balance between competitive swimmers and less active adolescents. *International Journal of Sport Nutrition and Exercise Metabolism*, 19(3), 259-274.

Conference Proceedings

Year	Details
2008	**Burt, L.A.**, Naughton, G.A., Landeo, R. & Higham, D.G. Comparison of training loads between two participation levels, apparatus and training phases of female gymnasts. *In:* T. Jurimae, N. Armstrong & J. Jurimae (Eds.) *Children and Exercise XXIVXXIV: The Proceedings of the 24th Pediatric Work Physiology Meeting.* Routledge, Taylor and Francis Group, London (pp. 219-222).
2007	**Burt, L.A.**, Naughton, G.A., & Landeo, R. Quantifying impacts during beam and floor training in pre-adolescent girls from two competitive streams in artistic gymnastics. In Menzel, H.,-J. & Chagas, M.H. (Eds.), *Proceedings of the XXVth International Symposium on Biomechanics in Sports*. Ouro Preto, Brazil: Federal University of Minas Gerais. (pp 354-357).

APPENDIX N

Awards

Awards

Year	Award
2010	Australian Catholic University Three Minute Thesis - Competition Finalist
2008	NSW Sporting Injuries Committee, Young Investigator Award - David Garlick Memorial Scholarship
2008	Australian Postgraduate Award
2007	NSW Sporting Injuries Committee – Sports Safety Award - Outstanding Achievement in Applied Research by a Research Team (Bronze Award)
2007	University Medal - Australian Catholic University
2007	Health Sciences Faculty Medal - Australian Catholic University
2006	Australian Federation of University Women (NSW) - Jamieson Award
2005	Zonta Sydney North Award - Most Outstanding Female Student in Exercise Science