A COMPARISON OF BONE MINERAL CONTENT BETWEEN PREMENARCHEAL ELITE GYMNASTS AND NORMALLY ACTIVE GIRLS

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ABSTRACT

Thirty premenarcheal elite gymnasts (training >15 hrs./wk and competing at provincial level or higher) ranging in age from 8 to 15 years (M = 11.65, SD = 1.90) were age matched to 30 normally active girls ranging in age from 8 to 15 years (M = 11.52, SD = 1.76) to determine whether gymnasts would have a greater bone mineral content (BMC). Gymnastics training sessions were analysed to determine the magnitude and frequency of loads encountered. Potential confounding variables were: age, height, weight, pubic hair (PH) status, percent body fat, bone mineral free lean mass, current total caloric, calcium and Vitamin D intake, and physical activity level. The gymnasts were significantly shorter ($p<0.05$) and lighter ($p<0.05$) and had a significantly lower percentage of body fat ($p<0.001$) than controls. There was no difference in maturity status between groups. Differences in BMC between the groups were assessed with ANCOVA using height and weight as covariates. Gymnasts demonstrated significantly greater BMC than controls at all sites, total body ($p<.001$), AP lumbar spine ($p<.001$), and all regions of the proximal femur ($p<.001$) (total, femoral neck, trochanter, and intertrochanter). The gymnasts experienced loads up to 10 times body weight on hands and feet with over 700 foot contacts and over 100 hand contacts in a typical 4-hour training session. The results confirm that the loading associated with gymnastics has osteogenic benefits in premenarcheal children; however, further investigation is required to determine the optimum training prescription for safely optimizing bone mineral acquisition during the growing years.

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Finally, to my mom and all the rest of my family who deserve many thanks for their unending support and encouragement, and for always believing in me. My love for them knows no bounds.

DEDICATION

This thesis is dedicated to my husband Valentine, who dragged me out of bed countless mornings, brought me endless cups of coffee, and has more patience than Job. I couldn't have finished this without you. You are a remarkable man and I love you with all my heart.

In the battle of life it is not the critic that counts; not the man who points out how the strong man stumbled, or where the doer of a deed could have done better. The credit belongs to the man who is actually in the arena; whose face is marred with dust and sweat and blood; who strives valiantly, who errs and comes short again and again because there is no effort without error and shortcoming; who does actually strive to do the deeds; who knows the great enthusiasms, the great devotion, spends himself in a worthy cause; who at the best knows in the end the triumph of high achievement; and who at worst, fails while daring greatly, so that his place shall never be with those cold and timid souls who have tasted neither victory nor defeat.

- Theodore Roosevelt

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LIST OF ABBREVIATIONS

ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
AP	Anterior-Posterior
BMC	Bone Mineral Content
BMD	Bone Mineral Density
DXA	Dual Energy X-ray Absorptiometry
FN	Femoral Neck
ICRP	International Commission on Radiological Protection
L1	First Lumbar Vertebra
LS	Lumbar Spine
MES	Minimum Effective Strain
NUTS	Nutritional Assessment System
O/A	Oligomenorrheic/Amenorrheic
PAQ-C	Physical Activity Questionnaire for Older Children
PBDS	Saskatchewan Paediatric Bone Density Study
PH	Pubic Hair
PHV	Peak Height Velocity
QCT	Quantitative Computed Tomography
SPSS	Statistical Package for the Social Sciences
T12	Twelfth Thoracic Vertebra
TB	Total body

OPERATIONAL DEFINITIONS

Strain	a slight deformation in bone occurring when a mechanical load is applied
Stress	the resistance of intermolecular bonds within bone to a "strain"
Modelling	the process by which osteoblasts add mineral at bone surfaces where strain occurs and osteoclasts remove mineral from areas where strain is absent, resulting in the shifting of bone mass to provide better architectural support
Remodelling	a cyclical process of bone resorption and formation stimulated by strain, usually resulting in a net loss of bone over time

LIST OF APPENDICES

1. SCIENTIFIC FRAMEWORK

1.1 Introduction

Osteoporosis is defined as a disease process characterised by low bone mass and microarchitectural deterioration of bone tissue leading to enhanced bone fragility and a consequent increase in fracture risk ("The Consensus Development Conference,"1993). It is a major health problem in Canada, affecting up to 1 in 4 women over 50. In fact, women's mortality rates for osteoporosis-related fractures are greater than the combined mortality rates from cancers of the breast and ovaries. The number of Canadian men with osteoporosis is also increasing with 1 in 8 men over the age of 50 affected (Hanley and Josse, 1996). According to epidemiologic projections, the annual number of osteoporosis-related hip fractures world wide will rise to 6.26 million by the year 2050 (Kannus et al., 1996). Unless decisive steps for preventive intervention are taken now, a catastrophic global epidemic of osteoporosis seems inevitable (Riggs and Melton, 1995).

Low bone mineral density (BMD) has been identified as a major risk factor for osteoporosis. Low bone mineral density is the result of one or more of the following: failure to attain a sufficiently high level of bone mass during the growing years, failure to maintain peak bone mass for a sufficient period of time during the adult years, and unusually accelerated bone loss in later years (Chestnut, 1991).

A high bone mineral content (BMC) accumulated during the growing years may be the best single protection against osteoporosis in later life (Hui, Slemenda, and Johnston, 1989). In wild animals, by the time growth ceases, the skeleton must be as strong as it will need to be, and any mechanism that significantly increases bone mass and strength after that would be of little purpose (Parfitt, 1994). At some sites up to 90% of adult human bone mass is laid down by the end of adolescence (Glastre et al., 1990). Haapasalo et al. (1998) cite strong evidence that 95-99% of the peak bone mass is gained during the first two decades of life.

Heredity is thought to be the major factor affecting bone acquisition during growth; however, other determinants including diet, endocrine status, and physical activity may account for nearly 50% of the variance in bone mineral density (McKay, 1995).

The two major dietary factors that affect bone accretion are calcium and Vitamin D. Calcium contributes to the formation of hydroxyapatite crystals which are the main constituents of the mineral fraction of bone while Vitamin D affects bone indirectly by its influence over bone's absorption of calcium; and may directly affect osteoblast function (Gallagher, 1993, as cited in Kirchner, Lewis, and O'Connor, 1995).

Growth hormone, insulin-like growth factor, thyroid hormones, and sex steroids also play a role in bone accretion. Growth hormone appears to be the most important contributor in bone accretion before puberty (Barr, 1995). During adolescence estrogen is for bone mineralization. Estrogen's major function is in the inhibition of osteoclatic activation resulting in a decrease in bone resorption (Keeting, et al., 1991). Many studies on amenorrheic, or oligomenorrheic athletes show decreased BMD with cessation of menstruation. The decreased BMD has been attributed to the persistent low level of endogenous estrogen.

Probably the most important functional influence on BMD and architecture is the load-bearing experienced during physical activity. Data obtained from animal studies, cell and organ cultures provide indisputable evidence that mechanical loading of bone increases both the quality and quantity of the skeleton when adequate nutrition and hormonal normalcy are present (Smith and Gilligan, 1996). The importance of physical activity in reducing the rate of adult bone loss has been widely studied and there are a number of excellent reviews on this topic (Bailey and McCulloch, 1990; Chilibeck, Sale, and Webber, 1995; Snow-Harter and Marcus, 1991).

Studies have demonstrated that growing animals have a greater capacity to add new bone than do adult animals. In a recent review of the literature on physical activity and children Bailey, Faulkner and McKay (1996) concluded that the evidence is highly suggestive that bone mineral content in children can be enhanced by physical activity. Studies comparing different types of exercise show that those exercises involving high impacts are the most osteogenic. High impact exercises include such activities as running while carrying a weight or landings and takeoffs in gymnastics. However, the optimum load for bone mineral accretion during growth in humans has not yet been quantified, and no exercise prescription has yet been researched.

Bailey et al. (1996) stated that, while equivocal, studies of physical activity in childhood strongly suggest that the loading factors associated with physical activity can enhance bone mineral in children. However, many of the studies of children are retrospective, many of them do not focus specifically on pre-pubertal children, and many of them used BMD measurements for their comparisons: this is particularly problematic in children and has led to some confusion about the magnitude of change in BMD during the growing years (Faulkner et al., 1996).

The purpose of this study was to compare gymnasts to normally active controls to investigate if high impact exercise can increase the bone mineral content in premenarcheal children. In order to control for bone size, bone mineral content was adjusted for differences in height and weight (Prentice, Parsons, and Cole, 1994). The control group, a subset of a study setting norms for Canadians of different ages allowed comparison of gymnasts to normative data; this approach has not been applied in previous studies. A unique aspect of the study was the detailed assessment of the type and intensity of loads experienced during gymnastics training. Loading of the skeleton through physical activities is thought to be important in bone mineral accrual; however the optimum quantity, type and duration of loading has not been clarified. The results of this study will contribute to furthering our knowledge in this area; and in the longer term may allow for more specific prescription for optimizing bone mineral acquisition during the growing years.

1.2 Review of Literature

1.2.1 Composition of Bone

The human skeleton is made-up of 206 individual bones. Its function is to serve as a framework for the body, protect vital tissues and organs, and facilitate movement by acting as a sequence of levers. The skeleton also plays a role in body processes such as immune system function and calcium and phosphate homeostasis.

The skeleton is comprised of approximately 75-80% cortical bone and 20-25% trabecular bone. Cortical or compact bone is a densely compacted tissue that forms the outer surface of all bones and is found primarily in the appendicular skeleton. It provides structure and ensures the integrity of the skeleton. Cancellous or trabecular bone is a spongy lattice-like structure made up of boney rods called trabeculae situated inside the cortical shell in some of the flat bones, the vertebral bodies, and the metaphyses of the long bones. Cancellous bone is architecturally adapted to withstand mechanical stress and is more responsive to the metabolic demands of the skeleton because of its higher ratio of surface area to volume.

Bone is primarily a composition of collagen fibres, proteins, and minerals in the form of hydroxyapatite. The hydroxyapatite crystals have a high strength component and account for 80-90% of bone strength (Mazess and Wahner, 1988). The collagen fibres are tension-resisting and allow the bone to bend rather than break in response to strong forces. Bone remains elastic up to approximately three-quarters of its breaking stress (Ascenzi and Bell, 1971). In living human bone the amount of strength due to architectural structure cannot be measured directly, thus the robustness or fragility are often estimated by a measurement of the bone's mineral content.

1.2.2 Measurement of Bone Mineral Content (BMC)

Measurement of BMC has long been a challenge to researchers. Various measurement techniques have been used including: radiographic photo density, neutron activation analysis, single photon absorptiometry, dual energy X-ray absorptiometry (DXA), quantitative computed tomography (QCT) and broadband ultrasound attenuation. Currently, DXA is the most widely used technique because of its low precision error, low radiation exposure and its capacity to measure multiple skeletal sites. (Miller, Bonnick, and Rosen, 1995).

QCT has the advantage of taking a three-dimensional image which provides a true volumetric measurement. Other instruments, such as DXA, measure in only one plane. BMC is then divided by the area scanned, in a calculated estimate of the bone volume. The bone mineral areal density (BMD) measurement is expressed in gm/cm^2. This process provides a better picture of the "density" of the bone mineral than BMC but is not a measure of true density because absorptiometry provides no information about the depth of bone in the scan nor does it distinguish between osseous and nonosseous areas within the bone envelope. In discussing the merits and limitations of these measurements, Compston (1995) cautions that BMD is an areal density and not a true volumetric density, " . . . the correction of BMC for area removes some but not all of its dependency on bone size.". While it has been shown to be a useful predictor of future fracture risk and to provide good discrimination between patients with osteoporosis and normal individuals, Prentice et al. (1994) and Winter and Nevill (1996) discourage comparisons of groups based on mean values of ratio measurements, such as BMD, because of the distortion introduced when using a ratio standard.

Expression of data as BMD implies that BMC is directly proportional to the area scanned; in other words, a 1% increase in BMC is matched by a 1% increase in bone width. There is absolutely no theoretical basis to support this assumption. It is just as possible for BMC to increase 0.5% or 2% with a 1% increase in width. If BMD is used in research studies when BMC and bone width is not one of simple direct proportion, part of the variation in BMD within a population will be due to differences in bone size between individuals but will not appear as such. This can lead to inaccurate associations between BMD and other variables, such as dietary intake and energy expenditure which are themselves related to bone size through their dependence on overall body size.

Prentice et al. (1994) recommend the use of multiple-regression models using BMC as the dependent variable and the area scanned, weight and height as independent variables. Using this method, size adjustment is defined by the data set under consideration and avoids the possibility of size-related artefacts that may result when data are forced to fit predefined relationships.

1.2.3 Changes in Bone Due to Growth

Growth is the attainment of size of a given tissue by an increase in the number of cells (hyperplasia), size of cells (hypertrophy), or an increase in the size of the cellular matrix. It is the expression of the genetic program and is under the control of the endocrine system (Ohlsson et al., 1993). In the case of bone growth, it is the process of enlargement of the skeleton and occurs in two ways. The first is longitudinal growth resulting from cell proliferation and ossification (endochondral ossification) occurring at physes (growth plates). This process takes place both at epiphyseal physes (between the ends of long bones and their shafts), and apophyseal physes (between condyles, trochanters, etc. and shafts). It should be noted that the epiphyseal physes are mainly subjected to compression forces while the apophyseal physes are subjected mainly to traction forces.

The second type of bone growth is circumferential growth via appositional growth on the inner (endosteal) and the outer (periosteal) surfaces. Garn demonstrated that the adolescent growth spurt is the only time there is substantial gain on both inner and outer bone surfaces and was driven mainly by hormone production (as reported in Parfitt, 1994).

Bone mineralization increases progressively in early childhood and then accelerates during adolescence. In a study by Faulkner et al. (1996) results indicated that total body BMC increased nearly threefold in females between 8 and 17 years of age. Bailey (1997) reported that at the age of peak height velocity both boys and girls have attained approximately 90% of adult status in height, 70% of adult status in BMC at the femoral neck, and approximately 60% at the lumbar spine and total body. In their recent publication of a six-year longitudinal study in children, Bailey, McKay, Mirwald, Crocker, and Faulkner (1999) demonstrated over 80% of total body (TB) BMC was accrued by one year following menarche. In this study the average age for peak height velocity (PHV) in girls occurred at 11.77 years followed by peak BMC velocity at 12.54 years and menarche at 12.7 years. During the two years surrounding peak BMC velocity these girls accrued 26% of the total estimated adult TB BMC (assuming approximately 2200 gm.) and 32% of estimated adult spine BMC (assuming approximately 60 gm.). The same group have previously reported that as much as 30% of total adult bone mineral is accrued in the 3 years around this pubertal time period (Bailey, Faulkner and McKay, 1996). Bailey (1997) reported that in the 4 years surrounding PHV, 35% of total body and lumbar spine (LS), and 27% of femoral neck (FN), BMC is accrued. In summary, as much bone mineral is being laid down during the adolescent years as most people will lose during their entire adult lives. (Bailey, 1997).

The ability of bone to adapt to mechanical loading is much greater during growth, particularly adolescence, than after maturity. (Parfitt, 1994). Bailey et al. (1999) demonstrated that the growing skeleton responds to increased everyday physical activity by increased bone mineral accrual. They illustrated that physical activity can increase the accrual rate of BMC during the 2 years around peak height velocity for children and can result in as much as 17% greater TB, 18% greater LS, and 11% greater FN BMC in active girls 1 year after the age of peak BMC velocity. Cumming et al. (1993) suggested that a 10% increase in adult BMD at the FN reduces the risk of fracture at that site by one half. Thus, the clinical significance of increases in bone accrual as demonstrated above, if retained into adulthood, can be easily seen.

1.2.4 Changes in Bone Due to Mechanical Loading

When a mechanical load is applied to a bone it causes a slight deformation or "strain" which is resisted by intermolecular bonds "stress". It is thought that there are two main processes by which bone changes due to mechanical loading: modelling and remodelling.

"Modelling" is the addition and resorption of bone at separate and discrete anatomical sites. Accretion occurs without prior resorption, to surfaces where strain occurs and over time results in a net gain in bone tissue. Osteoblasts in formation drifts add new bone and osteoclasts in resorption drifts remove bone over broad regions of a bone's surface (Frost, 1990). Modelling dictates the formation and resorption of bone at each anatomical site in response to mechanical loading factors. Bone mass is added and internal restructuring provides better architectural support at high-load locations. Modelling occurs primarily, but not exclusively, during the growing years (Burr et al., 1989).

Although remodelling is also stimulated by mechanical loading it is different from modelling in that it is cyclical, is characterised by simultaneous resorption and formation occurring on the same surface, and usually results in a net loss of bone. It is a maintenance function that replaces fatigue-damaged bone with new bone and maintains mineral homeostasis. It consists of three phases, an activation phase, which is followed by a resorption phase and then a formation phase. At any give time, about 20% of the skeleton is undergoing remodelling (Parfitt, 1994). Each remodelling cycle takes approximately four months in humans and continues throughout life.

1.2.4.1 Theories of Bone Adaptation to Mechanical Loading

The adaptation of bone to mechanical loading was first described by Julius Wolff in 1892. He stated "every change in the . . . function of bone . . . is followed by certain definite changes in . . . internal architecture and external conformation in accordance with mathematical laws." (as cited in Treharne, 1981). However, he did not propose any principles as to how bone adapted to these mechanical loads. In a 1964 book "The Laws of Bone Structure", Frost proposed his minimum effective strain (MES) hypothesis on the process of bone adaptation to mechanical loading. The MES theory suggested that there was a strain level within bone that had to be exceeded for any changes in bone architecture to occur and that strains below this set-point would not evoke a modification. Throughout the 1970's and 80's Frost revised and refined his original theory eventually renaming it the "mechanostat theory". Bailey et al. (1996) describe Frost's mechanostat theory as follows:

> ...it maintains that bone adaptation is dependent on the mechanical environment described by four mechanical usage windows. Each window is defined by minimum effective strain thresholds. The window within which a less than adequate mechanical stimulus is provided is called the trivial loading zone, in which remodelling will be the predominant process, with a resultant loss of bone. The physiological loading zone is defined by a lower threshold called the remodelling MES and an upper threshold called the modelling MES. Within this window the mechanical loading stimulus is sufficient to control the remodelling process such that bone remodelling remains in a steady state, and there is little or no effect on bone turnover. The overload zone is entered when loads exceed the upper set point of the physiological loading zone and elicit a modelling response. In this situation, bone is added and structurally ordered to respond to a new level of mechanical demand. Extremely high loads that induce very high strains push bone into a repair zone, whereby disorganised (woven) bone of poor quality is added to meet an acute need. The resulting bone is subsequently replaced by better-organised bone.

Although the mechanostat theory is still driving much of the research, alternative models to describe the relationship between mechanical loading and bone adaptation have been proposed. Numerous researchers now believe that remodelling events occur in response to microdamage of the bone from repetitive strains. Carter, Caler, Spengler, and Frankel, (1981) and Martin and Burr (1982) claim that the function of remodelling is to repair microdamage caused by repetitive mechanical strains. Carter (1984) also stated that the adaptation of bone to mechanical loading must be site specific and that microdamage caused by compression caused a greater osteogenic reaction than that caused by traction strains (Carter et al., 1981). Despite evidence that microdamage does accumulate and influence internal modelling (Burr, Martin, Schlaffer, and Radin, 1985; Carter et al., 1981; Martin and Burr, 1982), there is no evidence that it also influences surface modelling to affect bone form. If functional adaptation was 'damage driven' one would expect surface adaptation to follow increased levels of internal replacement, which is not the case (Lanyon, Goodship, Pye, and Macfie, 1982). As well, functional adaptations can be induced by strains of insufficient magnitude to induce appreciable microdamage (Lanyon et al., 1982; Rubin and Lanyon, 1984) which means these adaptations must be caused by some other mechanism. Carter (1984) suggested that bone hypertrophy and atrophy may be controlled by two different stimuli, and that microdamage may be only one of many control stimuli affecting an increase in bone mass. He also suggested that immature bone may be more sensitive to alterations in cyclic strain than mature bone and structural adaptation due to cyclic loading may not be a linear response. This curvilinear response theory is one of the most important differences between Carter's 1984 hypothesis and Frost's mechanostat theory (Frost, 1992), which predicts a linear response between mechanical loading and bone adaptation.

Turner (1992) suggests that bone adaptation may be under the influence of epigenetic regulation that can be influenced by a number of factors, including positive feedback loops. In epigenetic regulation the system is driven to one of many steady-state levels, called attractors. It has been suggested that the rapid response of woven bone to mechanical loading may be a result of epigenetic regulation since this response would not occur rapidly enough under homeostatic regulation. Although epigenetic regulation seems a plausible theory, it is still incompletely described in relation to bone formation.

1.2.4.2 Studies Exploring Bone Adaptation to Mechanical Loading

Most studies comparing the effects of mechanical loading on bone categorise exercise loads as: 1) active loading where the body weight is supported and loading of the bone is a result of the pull of muscles, for example swimming and rowing; 2) weight-bearing where the athlete's body weight represents the mechanical load, activities such as walking, running, and soccer; and 3) impact loading where subjects experience high volume, immediate loads such as landings in dance and gymnastics. Unfortunately, the use of the term "active loading" implies that the other categories aren't active, but of course all exercise loading is active (versus being passive). Similarly, assigning the term "impact loading" to one group implies that the other categories do not incorporate impact loading. Clearly all weight-bearing sports involve some form of impact, with the exception of weight lifting that is a more static stress. Loading terminology is unclear and confusing as evidenced by the fact that different studies will categorise the same sport differently. In this study, physical activities and loads will not be categorised. Rather, studies will be described and compared by the different mechanical loading parameters necessary to cause adaptation.

It is important to remember when reviewing loading studies that bone adapts to a strain, consisting not only of the amount of force applied, but also the type of force (tension, compression, torsion, or shear), the distribution of the force and the rate (speed) at which the force is applied. Bone adaptation due to mechanical loading is further affected by the duration of each loading session, reported as number of loading cycles/session, and the frequency of loading sessions.

1.2.4.3 Studies of Animals

In animals the greatest rate of change in bone mass is observed when loading forces are totally removed. Immobilisation leads to rapid and severe atrophy of bone tissue with trabecular bone losing up to 1% of its volume per week and cortical bone losing somewhat less (Hogan, 1985 as cited in Davison, 1995). Lanyon et al. (1982) found 10-14% resorptive remodelling in functionally-deprived rooster ulna over six weeks. Devastating effects have been found in immature rats where immobilisation resulted in a decrease in the size and weight of long bones, a distortion in the shape of long bones, retarded epiphyseal ossification, and a decrease in overall body weight and length (Li, Webser, Chow, and Woodbury, 1990). In a recent "in vitro" study, Van Loon et al. (1995) looked at the effect of the microgravity conditions of spaceflight on the cartilaginous long bones of foetal mice. They found that the loss of bone during spaceflight was the result of both impaired mineralization and increased resorption.

Conversely, the osteogenic effects of loading are well established. Studies in which one of a pair of load-bearing bones was removed showed consistently that the remaining bone increased in cross-sectional area until the strain level was within normal limits (Lanyon et al., 1982; Meade, Cowin, Klawitter, VanBuskirk and Skinner, 1984). However, further investigation of the effects of different loading parameters are required.

Lanyon et al. (1982) discovered the importance of strain distribution in their study of the sheep radius after resectioning the ulna. They found that strains at a level normally encountered in functional loading resulted in bone accretion as the load distribution was changed.

Type of load (strain) is also important. In 1984, Lanyon and Rubin used the isolated turkey ulna to test different types of loading patterns including: unloaded, statically loaded, and impact. The unloaded and statically loaded groups showed similar results with a 13% decrease in cross-sectional area whereas the dynamically loaded group showed a 24% increase. When Pead and Lanyon (1990) compared the osteogenic effect of two different types of load in avian ulna they found the strains produced by loading in longitudinal compression appeared more osteogenic than the same strains produced by loading in torsion.

Research on the magnitude of the load has shown that the MES is surprisingly similar among species, being between 0.0008-0.002 unit bone surface strain (0.08-0.2% change in length) [Rubin, 1984], with a strain magnitude of greater than 1000μE required for bone accretion (Rubin and Lanyon, 1984; Rubin and Lanyon, 1985; Turner, Forwood, Rho, and Yoshikawa, 1994). There seems a linear relationship between change in bone area and peak strain magnitude between 0 - 4000μE. "In vivo" loading studies in animals demonstrate a threshold response and a dose-response relationship between loading and bone formation (Pead, Suswillo, Skerry, Vedi, and Lanyon, 1988; Rubin and Lanyon, 1985).

Exercise intervention studies in animals indicate that frequency and duration of loading, as well as intensity, may affect bone response. Rubin and Lanyon (1985) studied functionally isolated, externally loaded avian ulna preparations and found that as few as 4 dynamic loading cycles per day were enough to prevent the resorption that normally accompanies reduced loading. An increasing osteogenic effect was seen past that, with saturation occurring in as few as 36 loading cycles per day at 0.5 Hz (total 72 seconds). This resulted in an increase in bone formation proportional to peak strain magnitude. Rubin and Lanyon concluded that to maintain functional levels of bone mass, daily loading intervals are required.

These findings were supported by van der Wiel et al. (1995), who compared loading strain to loading duration. They used 4 groups of female rats exercising on a motor-driven exercise belt for 17 weeks, 5 days per week at an average velocity of 20 m/min. Group 1 served as controls; group 2 trained for 30 minutes per day; group 3 trained 30 minutes per day with a 50 gram backpack; and group 4 trained 15 minutes per day with a 50 gram backpack. BMC of the lower extremities was measured at 0, 6 and 17 weeks. Although no significant increases were found at 6 weeks in group 2 and 3, group 4 showed a significant increase compared to controls (15% to 8% respectively). After 17 weeks the exercising groups had all increased significantly: controls increased 6%, group 2 increased 16%, group 3 increased 15%, and group 4 increased 20%. The most significant increase was made by the group that exercised with the highest load for the shortest duration.

Animal studies suggest that mature and immature bone respond differently to mechanical usage. Rubin, Bain, and Mcleod (1992) reported that functionally isolated ulna in younger turkeys resulted in an increase in loaded limb cross-sectional area by 30.2% whereas older turkeys showed no increase. Rubin and Bain (1989) showed that mechanical loads that were osteogenic in young turkeys were unable to elicit adaptive responses in older animals.

It is difficult to compare many of the animal studies due to the variability in species, ages of animals, different methods, and volumes of loading used; and problems involved in "in vivo" methods such as trauma from surgery, distinguishing normal from artificial strain, etc. In spite of these limitations the evidence from animal studies is consistent enough for some results to be conclusive. Young animals adapt to load much better than old animals, dynamic loading results in the greatest positive adaptation, higher magnitude strains result in greater adaptation, and bones adapt until strain level is normalised; however, the specifics of mechanical loading and its application must be investigated further.

1.2.4.4 Studies of Adults

Studies of weight-bearing exercise and comparisons of athletic populations involving different amounts of loading in humans have generally supported the results found in the animal studies. Exercise intervention studies have been only minimally supportive. Smith, Smith, Ensign, and Shea (1984) showed no effect on bone status in adult women and Heinonen, Oja, Sievanen, Pasanen, and Vuori (1998) found that although there was a significant decrease in the unloaded distal radius a callisthenics program resulted in no decrease in BMC at the femoral neck. Results from Danz et al. (1998) also showed minimised bone loss while Bassey (1996), Dalsky et al. (1988), Iwamoto, Takeda, Otani, and Yabe (1998), and Snow-Harter, Bouxsein, Lewis, Carter and Marcus (1992) demonstrated marginally increased bone mass. Common criticisms of adult exercise studies are: that the intervention has not been of sufficient magnitude to produce results and that the intervention period has been too short to allow the modelling process to be completed. Preisinger, Alacamlioglu, Pils, Saradeth, and Schneider (1995) evaluated the long-term efficacy of an exercise program on bone mass in postmenopausal women and concluded that in untrained postmenopausal women poor compliance with regular physical activities was the major factor explaining the lack of bone response.

In athletic populations results are more conclusive. Non-weight-bearing activities such as swimming, which has the lowest magnitude of loading, demonstrated the lowest BMD (Cassell et al., 1993; Grimston, Willows, and Hanley, 1993; Taaffe et al., 1995). Higher BMD values were found in normally active control groups, which in turn were less than sports of medium magnitude loading such as running and soccer where athletes support their body weight (Heinonen et al., 1993; Risser et al., 1990). The highest BMD values were consistently found in athletes who experience high magnitude loading such as weight lifters (Conroy et al., 1993; Heinonen et al., 1993) and high impact loading sports such as gymnastics (Kirchner et al., 1995; Robinson et al., 1995). The latter showed increases in BMD great enough to counteract the deleterious effects of menstrual disturbances in young female gymnasts. Studies on figure skaters (Slemenda , Reister, Miller, Christian, and Johnston, 1994) and ballet dancers (Young, Formica, Szmukler, and Seeman, 1994) with menstrual disorders have shown that the expected reduced level of bone density was mitigated by the effects of mechanical loading at the load-bearing sites. However, due to the fact that human studies are non-invasive, identification and quantification of the most osteogenic strain loads is difficult.

The magnitude of the mechanical load is usually quantified using Kistler force platforms to measure ground reaction forces as subjects locomote or land from different heights. The force is measured in Newton meters and converted to a body weight equivalent. Various studies have reported quantification of the mechanical load experienced during different activities (Appendix G).

In 1982 Capozzo and Gazzani reported that running imparts forces to the lumbar vertebrae of approximately 2 times body weight. In 1988 Cavanaugh and Cann stated that brisk walking involved spine loading equivalent to approximately 1 time body weight. Studies of children 12-14 years old have shown the vertical ground reaction forces due to the impact at touchdown of the support leg during running average approximately 3 times body weight and studies in adults have shown similar results (3-5 times body weight) [Grimston, Engsberg, Kloiber, and Hanley, 1991; Nigg, 1988; Nigg and Morlock, 1987]. Engsberg, Lee, Patterson, and Harder (1991) and Nigg (1985) report impact forces of 3 - 5 times body weight during running. Bassey and Ramsdale (1995) reported a negligible damping by soft tissue and stated the ground reaction force was a reasonable measure of the impact force administered axially to the shaft of the femur. They reported loads on femoral implants in one patient of 3.0-3.5 times body weight for jumps and from1.5-2.5 times body weight for heel drops from toes in bare feet on a bare floor with knees and hips extended. A mean ground reaction force of 2.73 times body weight was recorded for a group of women doing the same heel drops.

External ground reaction forces imposed by landing from a jump, such as would be expected to occur during gymnastics, tumbling, and dance routines, have been determined to reach values as high as 10 times body weight (Lees, 1981; Nigg, 1985). McNitt-Gray, Munkasy, Welch and Heino (1994) reported a range of reaction forces during the take-off and landing of three tumbling skills. Horizontal and vertical forces were measured for the tuck single back somersault, the layout single back somersault, and the tuck double back somersault. No significant differences were found in the takeoff of the three skills with combined (horizontal and vertical) forces of approximately 6 to 9 times body weight. Combined landing forces of approximately 7 to 11 times body weight were found in the layout back somersault, and 9 to 13 times body weight were found in tuck back somersaults. Double back somersaults were not landed consistently enough to be measured.

Bruggerman (1994) and Oka, Okamoto, and Kumamoto (1989) measured forces 2 to 3 times body weight on tumbling and vaulting. Hay, Putnam and Wilson (1979) reported attenuate traction forces of 7 times body weight on asymmetric bars and Neal, Kippers, Plooy, and Forwood (1995) recounted peak reaction forces at the hands of 2.2 times body weight in a wind-up giant swing on high bar. Panzer, Wood, Bates and Mason (1988) reported vertical impact forces of 13 times body weight and horizontal forces of approximately 7 times body weight for a single leg during a double back somersault.

It has been suggested that the rate at which the strain is applied is as important as the magnitude in the adaptive response in bone (Lanyon and Rubin, 1984). In animal and heel drop studies, the magnitude of impact forces during landings tend to increase as the impact velocity increases with impact velocities of 8.5 m/sec. generating ground reaction forces of 8 to 14 times body weight. Many studies (Bassey and Ramsdale, 1994; Lanyon, 1987; O'Connor, Lanyon, and Macfie, 1982; Rubin and Lanyon, 1987) have suggested that high strain rates may be even more osteogenic than absolute peak forces of loads. Bassey and Ramsdale (1995) reported a linear relationship between peak ground reaction forces and rate of rise of the force in heel drop exercises.

The third important strain variable affecting the adaptation of bone is an unusual strain distribution. In an attempt to reproduce in humans, Lanyon's reporting of the osteogenic properties of unusual strain distribution in animals, Heinonen et al. (1995) studied 59 competitive Finnish female athletes involved in aerobic dance (27), squash and (18), speed skating (14). They hypothesised that since the training involved in these sports characteristically produces versatile impact-type loading (accelerating and decelerating movements) and pliant movements on the skeleton resulting in high strain rates and versatile distribution of strain on the target bone the athletes would demonstrate greater site-specific BMD than controls. The controls consisted of two reference groups: physically active referents (5 various types of exercise sessions per week), and sedentary referents. The main finding of this study agreed with previous findings by Heinonen et al. (1993). They found that athletes whose training caused strain of high magnitude, high strain rates or both (weight lifters and squash players) had the highest weight-adjusted BMD values at all measured sites. Furthermore, all athletic groups had significantly higher BMD values than the sedentary referents at the loaded sites, with the exception of the calcaneous of the dancers and the patella of the squash players. Heinonen and colleagues concluded that the increase of BMD values seen in the athletes, especially the squash players, was probably due to the acceleration and deceleration, as the relationship between force and acceleration/deceleration ($F = m \times a$) may produce high stresses and thus effective strain on bones.

Muller, Putz, and Kenn (1993) demonstrated the importance of strain distribution when they examined the distribution of subchondral mineralization in the glenoid cavity using CT-Osteo-absorptiometry in healthy people, athletes and patients. They found that in young people two density maxima were found ventrally and dorsally in the glenoid cavity and that older persons' maxima is generally centrally located indicating different joint mechanics in different ages depending on decreasing physiological incongruence. In gymnasts the overall mineralization is significantly higher, and the maxima are found centrally or shifted dorsally. These findings suggest greater stability of the shoulder joint compared to patients with recurrent dislocation whose highest density is shifted to the edges of the glenoid cavity.

In animal experiments very brief regular loading produced substantial increases in bone mineral (Rubin and Lanyon, 1984). In 1996, Bassey modelled her intervention study after the animal experiments. She compared high impact exercise with low impact exercise interventions or no intervention over 6 months in eumenorrheic women. The high impact exercise consisted of 50 two-legged vertical jumps per day at a rate of 1 -2 Hz, made with bare feet, using an arm swing and a soft knee landing. Bassey found that only the high impact exercise provided by the daily brief bouts (60 seconds) of jumping increased BMD significantly in the proximal femur.

In 1987, Frost concluded that the magnitude of mechanical forces appeared to be more important than frequency: a case in point was that marathon runners did not have the massive bone structures of weightlifters, (barring, of course, natural selection). Heinonen et al. (1993) supported these findings. Bassey and Ramsdale (1995) state that in a review of exercise interventions on postmenopausal women they found the most successful interventions contained a variety of exercises, which optimise exposure to unusual strain distribution, and provided more than 50 footfalls per session 2 or 3 times a week. They stated that 50 repetitions may not be optimal, but that repetitive animal interventions and jumping in young women using equally few repetitions applied daily were effective.

In summary, a review of the effect of mechanical loading on BMD in adults supports Lanyon's (1992) conclusions that the most osteogenic response to loading is produced by high strains, high strain rates, and unusual strain distributions; or, that short periods of diverse weight-bearing activity are far more effective than long periods of repetitive loading that involve lower peak loads applied in habitual loading situations.

1.2.4.5 Studies of Children

Two distinct skeletal processes occur during skeletal maturation: bone growth and bone modelling. Modelling, which is under the influence of local factors, such as mechanical load, may alter the growth pattern and its organisation of tissue components to produce macroarchitectural features. During skeletal maturation, the modelling process must be optimised to maximise bone accretion. Appropriate mechanical load during the critical period of rapid skeletal growth and modelling in children would therefore appear important for skeletal health (Grimston et al., 1993). Parfitt (1994) agrees with this, stating that in both the axial and appendicular skeleton, about half of peak adult bone mass is accumulated during the adolescent growth spurt. "Throughout growth, but particularly during adolescence, the ability of bone to adapt to mechanical loading is much greater than after maturity." (Parfitt, 1994). This is supported by Kroger, Kotaniemi, Kroger, and Alhava (1993) who found that puberty and genetics had a significant effect on the development of bone mass and density, and that most of the increase in bone mass in females takes place at the time of menarche.

Attention has recently been directed towards investigating the importance of physical activity on BMD during the childhood and adolescent years. Bailey (1995), Bailey and Martin (1994), and Loucks (1988) have thoroughly reviewed this area. In a retrospective activity study assessing the effect of childhood physical activity on BMD status as an adult, results at non-weight bearing sites were mixed, while weight bearing sites showed a positive correlation between childhood physical activity and adult BMD (Welten et al., 1994). Bailey et al. (1996) stated that, while equivocal, studies of physical activity in childhood strongly suggest that the loading factors associated with physical activity can enhance bone mineral in children.

In a three-year observational study by Slemenda et al. (1994) on the factors that influenced the rate of skeletal mineralization in 90 children, physical activity was measured every 6 months by questionnaire. Slemenda and colleagues found that physical activity was associated with more rapid mineralization in prepubertal children and reported a 29% increase in BMC at the lumbar spine in the 3 years around the onset of puberty.

In 1999 Bailey et al. published the results from their six-year longitudinal study on the influence of physical activity on bone mineral accrual in growing children. They analysed 6 years of data from 53 girls and 60 boys. Their results illustrated that physical activity can increase the accrual rate of BMC during the 2 years around peak height velocity for children. This can result in as much as 17% greater TB, 18% greater LS, and 11% greater FN BMC in active girls 1 year after the age of peak BMC velocity.

Studies comparing children in sports of different loading types support the osteogenic properties of physical activity. Swimmers consistently have lower bone densities than children in weight-bearing sports, and quite often lower densities than children who are sedentary (Cassell et al., 1993; McCulloch et al., 1992; Taaffe et al., 1995). Any increase in bone density which may result from the loading of the muscle pull is not enough to counteract the decrease in bone density due to the absence of loading on the bone concomitant with the buoyancy of the water. Alternatively, swimmers with lower bone mineral density may be better suited for swimming due to their greater buoyancy.

Bailey, Faulkner, and McKay (1996) found the strongest support for the beneficial effects of mechanical loading on the growing skeleton in unilateral control studies where only one side of the body was stressed. The other side was used as a control for genetics, nutrition, and the hormonal milieu. Differences in bone mineralization were attributed to the different loading patterns of the two limbs.

Bailey, Faulkner, Kimber, Dzus, and Yong-Hing (1997) reported 12-15% greater BMD in the non-involved side over the involved side for all regions of the proximal femur, except the femoral neck, for children with unilateral Legg Calve Perthes Disease (LCPD). In LCPD the non-involved normal hip experiences increased mechanical loading due to reduced loading of the involved painful hip. They also found that the non-involved hip demonstrated significantly greater BMD at all sites, except the trochanter, when compared to chronologically age-matched norms.

Parfitt (1994) cites a study by Jones et al. (1977) on male and female tennis players who had started playing before their adolescent growth spurt. Players showed a 41% increase in cortical cross-sectional area of the playing arm, with 34% gained on the outside and 7% on inside. This difference is far greater than can be accounted for by handedness or by periosteal reactions to repetitive trauma. Parfitt compared these results to a study in older tennis players who had been playing for longer but started after their growth spurt. The older players showed only 11% greater bone mass in their playing arm. The difference in the increase in bone mass between the two studies was attributed to the adolescent growth spurt, which is the only time in life when there is a substantial gain of cortical bone on both inner and outer surfaces. Haapasalo et al. (1994) supported Parfitt's findings. In a study of female squash players they found side-to-side differences to be significantly larger in players who had started playing before or around menarche than in those who began playing after menarche (22% to 9%). Kannus et al. (1996) compared the BMC of 105 female national level squash and tennis players and 50 healthy female controls at the proximal humerus, humeral shaft, radial shaft, distal radius, and right calcaneus. The players who started their playing career before or at menarche exhibited a difference 2 to 4 times higher than those who started after menarche. Kannus and colleagues recommended that physical activity should be started no later than at puberty to be maximally effective for bone gain.

1.2.4.6 Studies of Gymnasts

As further investigations have been undertaken to determine the type of physical activity most conducive to bone accrual, gymnastics has received much attention.

Studies of the effect of gymnastics participation on bone mineral accretion consistently demonstrate a significantly positive effect.

Fehling, Alekel, Clasey, Rector and Stillman (1995) compared the bone mineral density of collegiate female athletes in impact loading sports: volleyball players and gymnasts, to active loading swimmers, and a group of sedentary controls. The volleyball and gymnastics groups had significantly greater BMD than the swimming and control groups at the AP lumbar spine, femoral neck, Ward's triangle, total body, right leg, and pelvis. The BMD in the gymnastics group was significantly greater than all groups in both right and left arm and there were no differences in BMD between the swimming group and control group at any site.

Nichols et al. (1994) examined the effects of 27 weeks of gymnastics training on the bone mineral density at the lumbar spine and femoral neck of female intercollegiate athletes compared to sedentary controls. They found the gymnasts' BMD was greater than controls and U.S. norms for their age group at both sites at the beginning of the study and that the gymnasts' BMD increased at the femoral neck; and increased significantly at the lumbar spine. The effects of gymnastics training showed increased BMD even though gymnasts often demonstrated a greater prevalence of amenorrhea and oligomenorrhea. This effect was more profound at the weight-bearing sites, but was demonstrated in the spine as well which indicates gymnastics can have an overall positive effect on bone mineral density even in conditions of low circulating estrogen.

Kirchner et al. (1995) matched female college gymnasts to controls by age, height and weight. Gymnasts demonstrated a significantly greater occurrence of menstrual cycle interruption. In spite of this, gymnasts still exhibited significantly greater BMD at all sites (lumbar spine, total proximal femur, femoral neck, Ward's triangle and total body).

Kirchner, Lewis and O'Connor (1996) found similar results when they studied the effect of past gymnastics participation on adult bone mass. They compared former female college gymnasts and controls and looked at the relationships between current and former activity levels, diet, menstrual history and BMD. The BMD values of the former gymnasts were significantly higher for the lumbar spine, femoral neck, Ward's triangle, and total body, even when the influences of current and past physical activity levels were controlled statistically. Further, there was no significant difference between BMD values for former gymnasts who had always had regular menstrual cycles and those who had experienced some kind of menstrual dysfunction.

Fehling et al. (1995) also found that in spite of a higher prevalence of menstrual irregularities, gymnasts did not have a compromised BMD. They hypothesised that estrogen levels were not sufficient to support normal menstrual cycles, but were enough to provide a bone mass protective effect.

Robinson et al. (1995) proffered a slightly different explanation when they compared collegiate gymnasts and runners with a high prevalence of menstrual dysfunction (47% and 30% respectively) to nonathletic controls with a significantly higher percent body fat. BMD was significantly higher in gymnasts than runners at all sites (including total body) and higher at the lumbar spine and all regions of the hip than controls. When gymnasts' BMD values were compared to published norms (expected mean value for age) they were higher than predicted for both lumbar spine and femoral neck. The authors stated that estrogen operates in much the same way as Rubin and Lanyon's mechanical usage model. That is, high or normal estrogen levels lower the modelling and remodelling set points, whereas low levels increase them. In the latter case, higher mechanical loads are then required to maintain or increase bone mass. Their results demonstrated that the extreme mechanical forces generated by competitive gymnastics were high enough to overcome the higher set points expected among these amenorrheic athletes.

This same positive effect of gymnastics on BMD was demonstrated when gymnasts experienced later onset of menses. Lindholm, Hagenfeldt and Ringertz (1995) compared young women who had been in elite gymnastics training during their prepubertal and pubertal years to controls of comparable age. The gymnasts' mean age of menarche was 14.8 ± 1.8 and the controls was 12.1 ± 1.4. During the years preceding the study, physical activity among the former gymnasts had declined. The authors stated that although the gymnasts had had a delayed puberty, no differences were found in total body or spinal bone mineral areal mass (BMA) compared to the controls, and a significantly higher BMA was demonstrated in the arms.

Robinson et al. (1995) supported these findings. In their study gymnasts had a significantly later age of menarche (mean age 16.2±1.7) compared with runners (mean age 14.4±1.7) and controls (mean age 13.0±1.2) and began training at an earlier age (mean 8 years) than the runners (mean 15.9 years). BMD was significantly higher in gymnasts than runners at all sites, including total body, and higher at the lumbar spine and all regions of the hip than controls. When gymnasts' BMD values were compared to published norms (expected mean value for age) they were higher than predicted for both lumbar spine and femoral neck

It is important to note however that care should be taken when reviewing the literature on menarche. It has been well demonstrated that gymnasts are often 1 to 2 years skeletally younger than their chronological age, i.e. 1.5 years (Claessens, Lefevre, Beunen, DeSmet, and Veer, 1996), 1.6 years (Theintz, Howald, Wiss, and Sizonenko, 1993), 1.7 years (Weimann, Witzel, Schwidergall, Bohles, 1998), and 2 years (Keller and Frohner, 1989). Menarche should only be considered late if bone age rather than chronological age is the measurement criterion and age of menarche of the subjects' mothers is considered.

In keeping with the available evidence that suggests that the skeleton may be most responsive to exercise during growth, other studies have been directed at gymnastics training in young (pre-, peri-, and post-pubertal) athletes. These studies overwhelmingly support the positive effect of gymnastics on bone accrual during growth.

Cassell, Benedict and Specker (1996) studied 7-9 year old female gymnasts, swimmers, and controls. Gymnasts were lighter than both swimmers and controls ($p=0.001$). Gymnasts exhibited a greater increase in total body BMD per unit in body weight (interaction term between body weight and sport, $p<0.001$) as compared to swimmers and controls who were not significantly different. Cassell et al. found that a relationship between total body BMD and total weight differed depending on the sport. They concluded from this that weight-bearing activity is necessary to produce an increase in bone mass and can be observed in children as young as 7 years of age.

Padro, Eisenman, Sands, Beveridge, and Chan (1995) examined the bone density of the lumbar spine, tibia, and radius of weight and height-matched prepubescent female gymnasts training 20 hr/wk and sedentary controls. They found the gymnasts had significantly greater mean bone density in the lumbar spine and tibia.

Bass et al. (1995) studied prepubertal elite female gymnasts and bone age-matched controls. On first measurement they found the gymnasts had significantly greater BMD at all sites (arms, legs and spine) than the controls and BMD was 10 to 15% higher than the bone age-predicted mean. When they separated the gymnasts in two groups by age, younger (mean 8 yr.) and older, (mean 10.3 yr.), they found the younger group had no anthropometric differences from the controls but had slightly higher BMD at all sites. The older group was slightly shorter in height and lower limb lengths but had significantly greater BMD at all sites than the controls. A six-month follow up showed that the gymnasts accrued 190% more bone than controls.

In 1998 Bass et al. compared BMD in prepubertal gymnasts and bone-age matched controls (9.2 +/- 0.2 yr.) and in retired female gymnasts and controls matched for age, height, and weight. The areal BMD of the prepubertal gymnasts was 0.7-1.9 SD greater than controls at the weight-bearing sites and increased over 12 months of training by 30-85% more than the prepubertal controls at all sites, except the skull. The estimated volumetric BMD also increased significantly in the gymnasts but not in the controls. In the retired gymnasts the areal BMD was 0.5-1.5 SD higher than the mean in controls at all sites, except the skull and did not diminish with increasing duration since retirement. The authors concluded that increments achieved by vigorous exercise during puberty are large and are likely to reduce fracture risk in adulthood 2- to 4-fold.

Courteix et al. (1998) supported these findings as well in their study of elite prepubertal girls, at the starting phase of their peak bone mass acquisition. They concluded that physical activity in childhood could be an important factor in bone mineral acquisition in prepubertal girls, but only if the sport can induce bone strains during a long-term program.

Nickols-Richardson, O'Connor, Shapses and Lewis (1999) conducted a prospective study on young female gymnasts and controls. They found that not only did the gymnasts have higher starting values at the TB, LS, and proximal femur but that gymnasts increased their BMD at a greater rate than controls. They concluded that gymnastics training in childhood helps maximise peak BMD.

The positive effect of gymnastics training on BMD has been demonstrated at all ages and in spite of a higher incidence of menstrual dysfunction or a later onset of menarche. However, before prescribing gymnastics training as a means of optimizing bone mineral content, a closer look into the specific loading parameters of gymnastics training is required.

In animal studies strain magnitude was a significant factor in the acquisition of bone mineral. The loads experienced in gymnastics training can be of extremely high magnitude. Gymnasts can experience vertical ground reaction forces of up to 14 times body weight during some skills. Fehling et al. (1995) demonstrated that in gymnastics and volleyball the high magnitude, short duration stimuli experienced daily had an osteogenic effect. The osteogenic effect and site specificity of loading was demonstrated by the fact that gymnasts had 11% greater BMD in the arms than volleyball players. The gymnasts were continually loading their arms through both compression (landings and takeoffs from hands) and traction (swings), while the volleyball players didn't experience any significant loading in their arms.

To elucidate the skeletal effects of different loading patterns, including repetitive muscular contraction, Taaffe et al. (1995) compared the BMD of two groups of chronically trained eumenorrheic college athletes to 19 nonathletic controls. The two athletic groups had distinctly different loading patterns. The gymnasts were considered to have high-impact weight-bearing training, while the swimmers were categorised as nonweight-bearing. Both athletic groups trained approximately 20 hrs/wk., did 2 hrs/wk. of resistance and aerobic training, and 2-3 days/wk. of weight training. The gymnasts exhibited higher BMD at both axial and appendicular sites than did their nonathletic counterparts. However, BMD of equivalently trained swimmers did not differ appreciably from that of nonathletic controls, except at the femoral neck, where it was actually lower than control values. They concluded that the high-impact weight-bearing activities in gymnastics was a powerful osteogenic stimulus. Based on Frost's theory of mechanical usage set points, the hyper-vigorous mechanical usage and subsequent bone strains generated in gymnastics may result in both increased bone mass through modelling and conservation of bone by remodelling, resulting in augmented bone mass.

Grimston et al. (1993) matched 17 children (8 males and 9 females) between the ages of 10 and 16 in impact loading sports to 17 competitive swimmers by race, gender, stage of puberty, and body weight. Impact loading sports were those producing ground reaction forces at landing of greater than or equal to 3 times body weight: running (3), gymnastics (5), tumbling (7), and dance (2). Age, height, years training, average training time/day, and diet were not significantly different between the two groups. Significantly greater values were found in femoral neck BMD and hours/day spent in weight-bearing activity for the impact load groups and at the lumbar spine for the impact load males.

Robinson et al. (1995) also found gymnasts exhibited higher BMD when they compared collegiate gymnasts and runners. They found these results surprising at first because the two groups were so closely matched with respect to body weight, percent fat, and prevalence of current and historical menstrual dysfunction. They concluded that the higher impact forces resulting from gymnastics training are more stimulatory to bone mass accretion than the lower impact forces of running and were able to override the resorptive effect of low reproductive hormones, thus showing the magnitude of loading is more important than the number of repetitions.

In a further investigation into the osteogenic effects of gymnastics training, Taaffe, Robinson, Snow, and Marcus (1997) monitored longitudinal changes in regional and total body BMD in two cohorts of collegiate women gymnasts, runners, swimmers, and controls. Gymnasts showed greater increases (often reaching significance) in lumbar spine and femoral neck than other athletes and controls at both 8 and 12 months. This occurred despite high initial BMD values and independent of reproductive hormone status. The authors concluded that this evidence supported the view that high impact loading, rather than selection bias, underlies high BMD values characteristic of women gymnasts.

Wu, Ishizaki, Kato, Kuroda, and Fukashiro (1998) provided further evidence when they examined the side-to-side differences in the BMD of the proximal femur of female rhythmic gymnasts to determine the effects of loading differences on the landing and takeoff legs. Three groups of college women were studied, regulars who trained approx. 28 hr/wk, substitutes who trained approximately 12 hr/wk, and nonathletic controls. In the regulars the BMD measurements in the takeoff leg were significantly greater, 4.7 to 9.6% higher, than the landing leg even though it was only slightly stronger. In the substitutes the BMD in the takeoff leg was also greater however not significantly with no difference in strength. The controls exhibited virtually no difference in BMD with overall strength measurements higher in the right leg. Vertical ground reaction force measurements indicated the peak force was greater in take-off than in landing, and the unit time force during take-off was significantly greater than that during landing. The authors concluded that greater BMD in the take-off leg was due to greater force applied over a longer period of time. They further concluded that the greater BMD in regulars over substitutes was due to greater hours of practice.

Recently, Daly, Rich, Klein and Bass (1999) measured the loads and impacts per session in elite male gymnasts approximately pubertal stage 2. They reported that the gymnasts encountered on average 102 and 217 impacts per session on the upper and lower extremities, respectively, with peak magnitudes of 3.6 and 10.4 times body weight.

Nichols et al. (1994) reported increases in the BMD of collegiate gymnasts over 27 weeks of training as surprising for 3 reasons: the short training period, the similarity of the 27 weeks training to previous training, and the high initial BMD values of the gymnasts. Remodelling of trabecular bone is thought to occur within 16-18 weeks, but an exact time for increase in BMD is not known (Snow-Harter and Marcus, 1991). It was thought that the type and intensity would not have been different enough to cause an MES over and above the current set point (as described in Frost's Mechanostat Theory). However, the significant gain in lean tissue mass would indicate that the training was either quite different or significantly more intense. Keith Russell, former Canadian National Men's Gymnastic Coach, states that type and intensity of training changes significantly from pre-season to competitive season (K. W. Russell, personal communication, September 15, 1995). Weight-training and conditioning seen at the start of the year is gradually replaced by more skill practice that provides higher compression, traction, and torsion loading. Nichols et al. thought that since the gymnasts' initial BMD values were so high they would not increase; however, since little is known about maximum BMD values in females, especially those involved in intense high-impact loading sports, increases may not be surprising.

LaRiviere, Snow-Harter, and Robinson (1995) followed competitive female gymnasts (mean age 19.4 at start of study) over 2 years. The total body BMD increased significantly during each of the training years with the leg and lumbar spine accounting for the greater increases. During the summer term, leg, lumbar spine and femoral neck BMD all decreased significantly. LaRiviere et al. concluded that the high loads from gymnastics training increased bone mass and that bone mineral acquisition relies on continuation of loading.

1.2.4.7 Summary

Obtaining and maintaining high levels of bone mineral is the single best defence against osteoporosis. In fact, a 10% increase in adult BMD at the femoral neck reduces the risk of fracture at that site by one half (Cumming et al., 1993). Since more than 90% of adult bone mineral is present by the end of skeletal maturation and any gains after growth has ceased are minimal, adolescence is a critical time for bone mineral accretion. Bailey (1997) reported that in the 4 years surrounding PHV, a time when growth and modelling are operating together, 35% of total body and lumbar spine, and 27% of femoral neck BMC is accrued.

Animal studies suggest immature bone responds more readily to mechanical usage. Rubin et al. (1992) illustrated that young turkeys increased loaded-limb cross-sectional area 30.2% more than older turkeys. Recent studies in children support these findings. Bailey et al. (1999) illustrated that physical activity can increase the accrual rate of BMC during the 2 years around peak for children and can result in as much as 17% greater TB, 18% greater LS, and 11% greater FN BMC in active girls 1 year after the age of peak BMC velocity. However, many of the studies of children are retrospective, do not focus specifically on pre-pubertal children, and use BMD as their measurement for comparisons (Faulkner et al., 1996).

Unfortunately BMD, as an areal density, is dependent on bone size. When comparing children, whose bones are changing size so rapidly, confusion can result about the magnitude of change in BMD during the growing years (Compston, 1995). The influence of size-dependent variables, ie: calcium intake, adiposity, and physical activity, can lead to artificial over- or under-estimation of BMD. To overcome the problem in this study BMC was measured, with height and weight treated as covariates.

It is important to remember when reviewing loading studies that bone adapts to a strain, consisting not only of the amount of force applied but the duration of each loading session, reported as number of loading cycles/session, the frequency of loading sessions, and the duration of the training program. Animal studies have shown that loads of high magnitude result in the greatest increases (van der Wiel et al., 1995) and these effects have been supported in human studies. Gymnastics, where athletes can experience loads up to 14 times their body weight, has consistently shown the greatest increases in BMC compared to other sports (Kirchner et al., 1995; Robinson et al., 1995).

It is generally accepted that the compression forces experienced in a sport such as gymnastics are the most osteogenic. However further work needs to be done on measuring the specific properties of the forces. I extrapolated from the literature load quantifications for specific gymnastic skills that have been previously measured and analysed training sessions to determine the number of time each of the skills is performed. This description of the magnitude of the load, number of loading cycles/session, and the frequency of loading sessions is the beginning of the process of load quantification and correlates well with measurements Daly et al. made in their study of young male gymnasts in 1999. Courteix et al., 1998, concluded that bone strains must be sustained over a long-term program to ensure a sustainable osteogenic effect. Therefore, a close look at the frequency and duration of training programs is required.

Unfortunately, most gymnastics studies have looked at college-aged gymnasts and have been retrospective, cross-sectional, or of short duration. Only recently have researchers turned their attention toward pre-pubertal gymnasts. Data from young gymnasts has consistently demonstrated osteogenic benefits (Bass et al., 1998; Cassell, et al., 1996; Courteix et al., 1998) but there is still a lack of long-term data on the positive and negative effects of gymnastics training on growing children and further measurement needs to be done on the specific variables of the training programs.

The purpose of this study was to compare BMC between premenarcheal female gymnasts and age and maturity matched controls. In order to adjust for the effects of size on BMC, both height and weight were treated as covariates as they would have a direct influence on bone size. This should give a more accurate picture of the effect of gymnastics training on BMC in young girls. The gymnasts were also compared to recently established Canadian norms for height, weight, and total body BMC. Further, training sessions were analysed to determine the magnitude and frequency of loads experienced by these young gymnasts. This description will be the first step in the process of discovering the most effective exercise program for optimisation of BMC in growing children.

1.3 Hypothesis

The major hypothesis was that gymnasts would have a greater bone mineral content (after controlling for size) than age and maturity matched, normally active controls. The sub-hypothesis was that gymnasts would exhibit greater BMC than controls (after adjusting for size) at the: a) total body, b) AP lumbar spine, and c) four femoral sites: total femur, femoral neck, intertrochanter, and trochanter.

2. METHODS

2.1 Research Design

A cross-sectional comparison of two independent samples was used.

2.2 Subjects

Subjects for the study included two groups of premenarcheal girls. The first group was a convenience sample of 30 elite female gymnasts from the Saskatoon area. Gymnasts were considered elite if they were competing at provincial level or higher and training a minimum of 15 hours per week. They had to have been involved in gymnastics for at least 2 years prior to the study. Sample size was limited by the number of girls in Saskatoon meeting these criteria. The average length of gymnastics participation in this group previous to the study was 5.2 years. Gymnasts ranged in age from 8 to 15 years (X = 11.65, SD = 1.90).

Information sessions about the study, including its purpose, measurements, time commitment, and potential risks were given to coaches, parents and gymnasts. Consent forms and a letter explaining the purpose, procedures and risks of the study were given to each parent/child (Appendix A). A follow-up telephone call was made to potential participants who had not returned their forms. A final call was made to confirm participation by the gymnast and to answer any questions.

The second group, used as the control group, was a subset of 30 normally active premenarcheal girls ranging in age from 8 to 15 years (X = 11.52, SD = 1.76) selected from the University of Saskatchewan Paediatric Bone Density Study (PBDS) cohort. Premenarcheal subjects from the PBDS were age-matched with the gymnasts.

2.3 Procedures

This study was approved by both the University of Saskatchewan and Royal University Hospital ethics committees as a sub-study of the PBDS (Appendix B).

All measurements for each subject took place on the same day in the Department of Nuclear Medicine at the Royal University Hospital in Saskatoon, Sask.

2.3.1 Bone Densitometry

Dual energy x-ray absorptiometry (DXA) measurements of BMC were performed with the Hologic QDR 2000 bone densitometer. The array scanning mode was used to collect total body (TB), anterior-posterior (AP) spine and proximal femur data on the 30 premenarcheal gymnasts.

During the scan, x-ray photons of alternately low (70kVp) and high (140kVp) energy voltages are passed through the subject and compared to known bone and tissue values, pixel-by-pixel. The radiation entrance dose ranges from 1 mrem for the total body to 12 mrem for the AP lumbar spine. The effective dose equivalent for the entire protocol is 5.61 mrem when the surface doses are corrected for body attenuation, type and volume of tissue, and the reproductive capacity of the subject. This is in accordance with the protocols established by the International Commission of Radiological Protection (ICRP 60, 1990).

Subjects wore plain, loose fitting shorts and t-shirt with no metal zippers or buttons. All jewellery, belts, glasses, hair ornaments, socks, and footwear were removed. Subjects were screened for pregnancy and their biographical data, height and weight were recorded on hospital forms and entered into the Hologic system file prior to commencement of the scanning procedure. A menstrual history questionnaire was used to screen all participants for premenarcheal status (Appendix C). The same technician scanned all subjects and analysed all results.

Quality control phantom scans were performed daily. The short term precision values "in vivo" are 0.9% at the femoral neck, 1.1% for the total proximal femur, 0.7% for the AP lumbar spine, and 0.5% for the total body (Wallace, 1995). These values are in agreement with Devogelaer, Baudoux and Nagant de Deuxchaisnes (1992).

2.3.1.1 Total Body Protocol

To collect total body BMC data the body is centered and straightened along the midline within the rectangular region outlined for the total body on the scan mat. The head is positioned with the chin raised and the shoulders depressed. This prevents the overlap of the mandible and the superior aspect of the scapula on the scan image. The hands are prone and equidistant from the torso on either side of, but not touching, the body. The feet are internally rotated with the great toes touching and then taped to immobilise this region and to maximise femoral neck display during analysis. The soft tissue calibration wedge (Step Phantom) is positioned within the scan area at least 2 cm. from the subject to act as a comparison for soft tissue analysis. The TB scan requires 5 minutes and 20 seconds.

2.3.1.2 AP Lumbar Spine Protocol

The individual is positioned supine within the vertical lines marked at the head and the foot of the scan mat with the lumbar spine within the horizontal hip/spine center lines. The spine is positioned in a straight line along the solid line marked in the center of the scan mat. To remove the arms from the scan zone and raise the ribs away from the region of interest, the subject's hands are placed beneath the head and both elbows are supported with small pillows. A box is placed beneath the subject's lower legs to reduce the natural lordotic curve of the lumbar spine and to place the spine in contact with the table. To confirm positioning, the laser dot is moved from two inches below the level of the iliac crest to the sternal notch. It should describe a straight line between the umbilicus and xiphoid process. The subject is instructed to remain motionless during the scan which takes approximately 1.5 minutes along the length from the third or fourth lumbar vertebrae (L3 - L4) to the first lumbar or twelfth thoracic vertebrae (T12 - L1) in the array spine mode.

2.3.1.3 Proximal Femur Protocol

For the left proximal femur scan, the subject is positioned supine in a straight line on the table. The iliac crest must be beneath the mid-vertical scan line on the mat. The left foot is inverted approximately 30 degrees and fixed to a lucite positioning wedge with a nylon strap. The center of the fixture wedge is aligned with the midline of the subject and the leg is slightly abducted at the hip. The arms are positioned at the sides outside the scan zone. A few preliminary lines are scanned and the starting point for the tube arm is repositioned, if required, from the computer consul. No repositioning of the subject is necessary. Total scan time is approximately 3 minutes.

2.3.1.4 Scan Analysis Protocol

All scans were analysed according to the procedures outlined in the Hologic QDR Operator's Manual and User's Guide. Hologic system global software Version 7.1 was used for analyses, using software version 4.42A for the total body and AP spine, and version 4.55A for the proximal femur.

2.3.2 Anthropometry

Stretched stature was measured with subjects in bare feet using a wall stadiometer. Measurements were taken to the nearest 0.1 cm. Subjects' weight was measured using a calibrated electronic scale and recorded in kilograms to the nearest 0.1 kg. Percent body fat and bone free lean tissue were measured by DXA.

2.3.3 Dietary Evaluation

Current dietary intake was determined during a personal interview. Trained personnel administered a 24-hour food recall (Appendix C) as implemented in the Saskatchewan Nutrition Survey (1993). Once all food eaten the previous day had been recorded, pictures and measures were used to help subjects determine portion sizes. The reliability and accuracy of this method are discussed by Krall and Dwyer (1987). Calcium and Vitamin D intakes were determined using the Nutritional Assessment Systems (NUTS) program, version 3.7 (Quilchena Consulting Limited, Victoria). All dietary analyses were performed by the same researcher.

2.3.4 Physical Activity Evaluation

Subjects completed the Physical Activity Questionnaire for Older Children (PAQ-C) which assessed their physical activity level during the previous 7-day period (Appendix D). This questionnaire has been validated by Crocker, Bailey, Faulkner, Kowalski, and McGrath (1997).

2.3.5 Maturity Assessment

A menstrual history questionnaire was used to screen all participants for premenarcheal status (Appendix E). Then each subject completed a pubic hair self-assessment (Appendix F) adapted from Morris and Udry (1980) to determine their maturational stage. A trained technician explained the procedure to each subject individually and emphasised the confidentiality of the results. The subject was then left alone in the room to complete the self-assessment and place it in a sealed envelope before returning it to the technician. This method correlates significantly with physician's assessment of pubertal development, reliability coefficients of 0.82, 0.86, 0.91 respectively (Brooks-Gunn, Warren, Rosso, and Garguilo, 1987; Neinstein, 1982; Duke, Litt, and Gross, 1980). The accuracy and reliability of children reporting their own sexual development has been demonstrated and is reviewed by Faulkner (1996).

2.3.6 Assessment of Mechanical Loading

Two gymnasts were randomly chosen and a typical training session was videotaped. Each videotape was then analysed and the number and type of skills recorded. The skills were then further broken down into takeoffs and landings from both the feet and hands and a mechanical load was estimated. The amount of the load depended on: corresponding loads for the same or similar skills in the literature (Appendix G), speed at which skill was performed, landing surface, and skill level of the gymnast. Only estimates of vertical loading were assigned even though significant horizontal and torsion loading occurred because little direct measurement of these types of loads has been done.

2.4 Statistical Analyses

Gymnasts' heights, weights, and total body BMC were fitted to normal population growth curves recently developed for the PBDS by Mirwald, Drinkwater, McKay, Bailey, and Faulkner (1996) using Grostat II. Provisional growth standards were developed to determine the prescribed centiles (10, 25, 50, 75, 90) based on 1080 total body scans in boys and girls from ages 8 to 18. Height, weight and BMC of only those gymnasts older than 9.5 years (n=25) were compared as no younger ages existed in the provisional growth standards. As expected, the gymnasts were lighter and shorter than age norms, being just over the 10th centile for height and just under the 25th centile for weight; however their total body BMC fell just under the 50th centile.

The relatively high total body BMC measurement in conjunction with the lower height and weight would indicate greater bone mineral density.

Descriptive statistics of the following variables were generated to compare the two groups in this study on various factors that may affect BMC: age, height, weight, maturational status (based on pubic hair assessment), body composition (% body fat and bone mineral free lean mass), current calcium and Vitamin D intake, and physical activity level. Physical activity level and PH status were analysed as interval data based on the assumption that the conclusions drawn from ordinal scales are often the same as interval (Diekhoff, 1992).

Statistical analysis was performed using Statistical Package for Social Sciences (SPSS) Information Analysis System (Version 7.0). To determine if there was an overall difference in BMC between the gymnastics and controls, analyses of covariance (ANCOVA) were run for the following sites: total body, AP lumbar spine, proximal femur, femoral neck, intertrochanter, and trochanter, with BMC as the dependent variable and height and weight the covariates. Height and weight were used as covariates because of their significant correlation with bone size and the fact that they were significantly different between groups. A Bonferoni correction was run to control the inflation of alpha that may occur with multiple analyses (Vincent, 1995).

An alpha level of 0.05 using a two-tailed test of significance was selected for all other analyses. A two-tailed test was chosen to allow for the possibility that there may be a significant difference in either direction, i.e. gymnasts may have significantly greater or lesser BMC than controls.

3. RESULTS & DISCUSSION

This section will be divided into two subsections: 1. descriptive data for both gymnasts and controls on factors that effect BMC and 2. statistical data on specific measurement sites.

3.1 Descriptive Data

Several factors were assessed to determine if there were any differences between the two groups that might contribute to differences in BMC other than gymnastic training. The variables chosen as potential confounding variables were: age, height, weight, PH status, percent body fat, bone mineral free lean mass, current total caloric intake, calcium and Vitamin D intake, and physical activity level. Independent t-tests were performed (Tables 3.1 and 3.2) and there were significant differences in only three of the variables. The gymnasts were significantly shorter ($p<0.05$) and lighter ($p<0.05$) than the controls and had a significantly lower percentage of body fat ($p<0.001$). Total caloric intake was quite different but did not reach significance. There was no difference in maturity status between groups. Some studies have shown that gains in BMC during adolescence are more a function of pubertal stage than chronological age, (Grimston, Morrison, Harder, and Hanley, 1992; Rico et al., 1993) thus it was important to control for maturational differences. Although physical activity status was not significant is should be noted that the PAQ-C avoids extremely high or low activity scores because of it being measured on a five point scale (Crocker et al., 1997). Therefore, it is not the ideal instrument to quantify physical activity in athletic populations.

Table 3.1 Descriptive data and independent t-tests for age, height, weight, bone mineral-free lean mass, fat mass, and PH status.

Variables	mean	range	SD	t	p*
Age				-0.27	0.78
Gymnasts	11.7	8.8-15.5	1.9		
Controls	11.5	8.8-15.2	1.8		
Height (cm.)				2.22	*0.03
Gymnasts	144.2	122.1-165.8	12.9		
Controls	151.3	129.0-179.4	12.0		
Weight (kg.)				2.26	*0.03
Gymnasts	36.8	24.7-59.8	9.8		
Controls	42.8	24.1-63.1	10.6		
Bone-free lean (kg.)				-0.22	0.83
Gymnasts	28.8	19.8-44.6	7.1		
Controls	28.4	19.4-43.3	5.9		
Body Fat (%)				7.60	*0.00
Gymnasts	15.9	9.3-25.2	4.2		
Controls	27.9	14.5-47.8	8.2		
Tanner Stage (1 to 5)				1.73	0.09
Gymnasts	2.3	1.0-4.0	1.1		
Controls	2.8	1.0-5.0	1.4		

*two-tailed significance

Table 3.2 Descriptive data and independent t-tests for total energy, calcium and Vitamin D intake, and physical activity rating.

Variables	mean	range	SD	t	p*
Energy (kj)				1.98	0.05
Gymnasts	6535	2562-9993	1900		
Controls	7555	3153-12758	2097		
Energy (% of RDI)				-0.49	0.63
Gymnasts	77	22-122	25		
Controls	74	35-125	26		
Calcium (mg)				0.74	0.46
Gymnasts	1008	264-2215	532		
Controls	1098	3153-12758	401		
Vitamin D (iu)				-0.86	0.39
Gymnasts	316	7-742	239		
Controls	272	81-635	142		
Physical Activity Rating (1 to 5)				-0.73	0.47
Gymnasts	3.17	2.03-4.39	0.50		
Controls	3.06	1.70-4.43	0.65		

*two-tailed significance

3.2 Analysis of Difference between BMC Values

An analysis of covariance was used to examine the difference in BMC between the two groups. Height and weight were entered as covariates. Using this method, size adjustment is defined by the data set under consideration and avoids the possibility of size-related artifacts which may result when data are forced to fit predefined relationships (Prentice et al., 1994). Results from the ANCOVA analyses are provided in Appendix H. Original and adjusted BMC values at the various sites are presented in Table 3.3.

Table 3.3 Bone mineral content original and adjusted values and levels of significance at total body, AP lumbar spine, proximal femur, femoral neck, intertrochanter, and trochanter.

Site	original mean (gm.)	SD	adjusted mean	p<
Total Body				0.001
Gymnasts	1262.	404.1	1376.8	
Controls	1280.	395.7	1166.5	
AP Lumbar Spine				0.001
Gymnasts	33.	10.5	36.5	
Controls	32.	11.9	29.2	
Proximal Femur				0.001
Gymnasts	20.	5.9	22.3	
Controls	19.	6.1	18.1	
Femoral Neck				0.001
Gymnasts	3.	.6	3.4	
Controls	3.	.8	3.0	
Intertrochanter				0.001
Gymnasts	12.	3.8	13.6	
Controls	11.	3.8	10.7	
Trochanter				0.001
Gymnasts	4.	1.7	5.3	
Controls	4.	1.8	4.4	

The hypothesis, that gymnasts would exhibit greater total body BMC, was confirmed when differences in BMC between the groups were assessed with ANCOVA using height and weight as covariates. Gymnasts demonstrated significantly greater

BMC than controls at all sites, total body ($p<.001$), AP lumbar spine ($p<.001$), and all sites measured on the proximal femur ($p<.001$) (femur, femoral neck, trochanter, and intertrochanter).

Previous studies involving prepubertal gymnasts have described the positive effects of impact loading on bone mineral content (Bass et al., 1998; Cassell et al., 1996; Courteix et al, 1998; Dyson, Blimkie, Webber and Adachi, 1995; Padro et al., 1995). Investigators in these studies divided the BMC by the area scanned in an attempt to adjust for the thickness of bone. This can result in an inaccurate assessment of BMD especially when comparing skeletons of different sizes in younger children (Compston, 1995) and may have led to incorrect conclusions concerning the relationship of BMD and impact loading in these studies. (Prentice et al., 1994).

Other approaches have been taken to correct for the effect of size on BMD measurements. Davison (1995) corrected DXA BMD measurements with ultrasound measurements of bone thickness at the radius. His findings still supported the osteogenic benefits of previous studies of gymnasts. Daly, Rich, Klein, and Bass (1999) also supported these findings when they used ultrasound measurements in their 18-month longitudinal study of gymnastics training in pre- and peri-pubertal male gymnasts.

My study overcomes the problem of inadequate correction for bone thickness by controlling for height and weight as suggested by Prentice et al. (1994). This ensures adequate adjustment for bone and body size for the data set being studied and assures that differences in BMC are not due to artificial over- or under-estimates of bone size. Gymnasts demonstrated significantly greater BMC than controls at all sites, total body

($p<.001$), AP lumbar spine ($p<.001$), and all sites measured on the proximal femur ($p<.001$). Since there were no significant differences in any of the other variables that may be attributed to bone mineral accrual, the results support the osteogenic effect of mechanical loading in gymnastics.

The evidence supporting a positive relationship between load magnitude and bone density adaptation is overwhelming, especially in gymnastics. It was then necessary to begin to explore the magnitude and volume of loading these young gymnasts experience. The mechanical loading occurring in a typical training session was quantified by analysing video-taped training sessions for two randomly selected gymnasts (Table 3.4 and 3.5). When compared with findings by Daly et al. (1999) the gymnasts sampled in this study encountered a significantly greater number of impacts per session on the lower extremities, 887 impacts to 217, but a slightly lower number of impacts on the upper extremities, 94 to 102. These differences could be due to the difference in male and female gymnastics training or to the small sample size. Although peak magnitudes were not directly measured in the current study, estimates based on the literature closely matched those directly measured in the study by Daly et al.

Table 3.4 Descriptive summary of loads experienced by Gymnast A during a typical training session.

	Takeoff				Landing			
	Feet		Hands		Feet			Hands
	(*x* times body weight)							
Skill	<5	5-10	<5	5-10	<5	5-10	>10	5-10
Floor Exercise								
prone fall	4							
tuck jump 1/1 twist	12				12			
leap 1/1 twist	10				10			
split jump	7				7			
roundoff	29		29			29		
backward handspring				25		25		
backward salto						10		
bkwd salto 1 twist[a]						3		
bkwd salto 1 1/2 twist[b]						7		
bkwd salto 2 twist[c]						3		
double bkwd salto							7	
forward salto		4				4		
drop land to forward salto		9				9		
snap land to backward salto		7				7		
Vault								
handspring vault		4	4		4			
handspring forward salto		11	11			11		
Asymmetric Bars[d]								
kip					7			
kip to handstand					7			
sole swing					2			
long swing					13			
grip change in handstand					6			
drop high to low in hang						5		
release to handstand					8			
giant circles						28		
single bkwd salto dismount[e]						4		
double bkwd salto dismount[e]						1		
Beam								
tuck jump	7				7			
tuck jump 1/2 twist	16				16			
split jump	21				21			
back jump onto hands	8							8
aerial cartwheel	8				8			
frwd handspring dismount	1		1			1		
- with double twist	7		7			7		
fall to feet			10					
Trampoline								
landing:%								
- feet					250	127		
- hands						18		
forward salto						2		
backward salto						33		
bkwd salto 1 twist to mat						5		
bkwd salto 2 twist to mat						19		
Total	130	35	62	25	378	358	7	8

[a] no takeoffs recorded as these skills were part of tumbling passes
[b] release from giant circle
[c] no takeoffs recorded as they are part of the previous landing
[d] no discrete takeoff and landings in swings;
all loads represent the maximum force experienced for that skill

Table 3.5 Descriptive summary of loads experienced by Gymnast B during a typical training session.

	Takeoff				Landing	
	Feet		Hands		Feet	
	(*x* times body weight)					
Skill	<5	5-10	<5	5-10	<5	5-10
Floor Event						
split leap from run[a]	23				23	
split jump from punch		9			9	
one foot hop	5				5	
stag leap	32				32	
one foot leap half twist	66				66	
one foot leap full twist	45				45	
forward walkover	3		3		3	
side skips	20				20	
high knee skips	57				57	
roundoff	20		20			10
back handspring		10	10			10
back handspring walkover[b]	14		14		14	
donkey kicks				33	33	
handspring from stand	3		3		3	
Vault						
beatboard takeoff		10			10	
handspring land flat back		7	7			
forward salto		9				9
fwd salto land chest height		2			2	
Bars						
glide swing to kip			35			
Beam						
skip with high knees	23				23	
two foot tuck/stag jump	11				11	
front walkover	10		10		10	
back walkover	2		2		2	
back handspring walkover	5		5		5	
back handspring	9		9			9
fall to feet					7	
forward salto dismount		3				3
Total	348	50	118	33	380	41

[a] one foot takeoff and landing
[b] less force from standing takeoff

One of the limitations of this study was that direct force platform measurement was not possible. The values listed in the tables are estimates taken from the literature and adjusted according to contributing factors. The values are conservative in that landing values only were allocated to skills in tumbling passes and recent literature suggests that takeoffs generally impart higher values than landing (Wu et al., 1998). The speed at which the gymnast performed the skill was taken into account. For example, a back handspring performed on the beam would be done at a slower speed than on the floor so the mechanical load would be slightly less (Force = mass x acceleration). On the other hand, the beam is a much harder surface than the floor so the mechanical load would be slightly greater due to less impact absorbed by the surface. The final consideration was the skill level of the gymnast. Nigg (1988) states that the impact forces increase if the movement is less controlled. Thus, less skilled gymnasts would experience higher loads. In assessing loads, slightly higher values were granted to those skills in which the gymnast exhibited less control.

This study clearly supports earlier findings that gymnastics training in prepubertal children has significant positive osteogenic effects (Bass et al., 1995; Cassell et al., 1996; Nickols-Richardson et al., 1999). Higher BMC values found in these young gymnasts, who experience loads up to 10 times their body weight on both their hands and feet, supports earlier research in athletes where the highest BMD values were consistently found in athletes who experience high magnitude loading such as weight lifters (Conroy et al., 1993; Heinonen et al., 1993) and high impact loading sports such as gymnastics (Kirchner et al., 1995; Robinson et al., 1995).

Increased velocity (Bassey and Ramsdale, 1994) and unusual strain distribution (Heinonen et al., 1995) have also been shown to have osteogenic effects. Although not specifically measured in this study, it is commonly accepted that gymnasts perform tumbling passes in floor exercises and vaults at velocities far greater than the 1-2 Hz Bassey found effective in increasing BMD in eumenorrheic women in 1996. Unusual strain distribution, another critical loading variable, is not only encountered with acceleration and deceleration, as in the study by Heinonen et al. in 1995, but also results from the different types of forces experienced in gymnastics, ie: tension, compression, torsion, and shear forces.

With sufficient magnitude, velocity and unusual distribution of the strain positive osteogenic benefits can result from very few repetitions. Bassey (1996) found that 60 seconds of 2-legged vertical jumps daily were enough to increase BMD over a 6 month intervention, and Bassey and Ramsdale (1995) achieved positive results with 50 footfalls 2 or 3 times per week. The gymnasts in the current study experienced over 700 contacts on their feet and over 100 on their hands in a typical 4-hour training session and trained more than 15 to 30 hours per week. This would seem a much higher frequency and duration than required to result in maximum osteogenesis. More research needs to be done into the optimum loading program required for maximum osteogenic accretion.

Although it is has been demonstrated that higher BMD in child gymnasts carries over into adulthood (Bass et al., 1998) and it is clear that gymnastic training resulted in increased BMC in this study, other factors should be considered before recommending gymnastics training of this intensity in circumpubertal girls. Several studies have suggested that gymnastics may inhibit growth. Bass and colleagues (1995) concluded that the prepubertal years may be the most opportune time to increase bone density but may result in shorter stature.

Theintz, Howald, Allemann, and Sizonenko's (1989) findings at the beginning of their longitudinal study did not support this theory. When they compared young elite female gymnasts, moderately trained swimmers and sedentary controls at the beginning of a longitudinal study of physical activity and growth, the patterns of recalled parental growth and pubertal maturation for each group were analysed. Parents of gymnasts were significantly lighter and shorter than those of swimmers and controls; consequently target heights of gymnasts were also significantly shorter. Although gymnasts had already undergone at least 5 years of progressively intense training, their relative shortness of stature was still appropriate for parental heights.

In 1993 when Theintz, et al. published their findings at the end of 2.35 years of study, growth velocity of gymnasts was significantly lower than that of swimmers. The height standard deviation score of the gymnasts decreased significantly with time as did their predicted final height. A marked stunting of leg-length growth in gymnasts from 12 years of bone age, resulted in a marked difference in overall sitting-height/leg-length ratio. The authors concluded that heavy training in gymnastics (>18 hr/wk) starting before, and maintained throughout, puberty can alter growth rate to such an extent that full adult height will not be reached.

Tveit-Milligan, Spindler and Nichols (1993) studied identical triplets, one of whom was a highly ranked competitive gymnast. Baseline measurements were conducted when the sisters were 11.5 years of age and repeated 18 and 24 months later. The gymnast had been in training and competitions for 5 years at the time of initial measurement when her height fell between that of her sisters. The gymnast retired 8 months into the study and at the 18-month measurement, 10 months after retirement, she had grown 10.2 cm. compared with 4.9 and 5.8 cm. for her sisters. The authors concluded from these data that the gymnast may have undergone mild growth retardation during her years in training and competition, followed by catch-up growth in the 10 months after retirement.

Other studies have not supported the theory that early participation in sports, especially gymnastics, inhibits growth. Keller and Frohner (1989) conducted a 3-year longitudinal study on young male gymnasts in Germany where short-limbed children are recruited, trained for 6 hours/week for 3 years and, if successful, enter a training academy for gymnastics. Baseline measurements were taken as the boys entered the academy at 12.3 +/-1.4 years of age. At this point the gymnasts' skeletal age was 2 years behind their chronological age. They were described as characteristically short-statured, broad-shouldered, with relatively short limbs, increased lean body mass and reduced body fat. The gymnasts' growth followed a normal curve and the SD from the normal population did not differ during the three years that demonstrated the delay in growth and short stature typical of gymnasts. Both mothers and fathers of the gymnasts were below the 50th percentile in height. This evidence led the authors to conclude that the delay of growth, skeletal maturity, and puberty was determined as a result of pre-selection rather than intense training.

Malina (1994) conducted longitudinal studies of active and non-active boys and girls. He compared final height, age at peak height velocity and growth rate in active and non-active boys, and in two samples of boys regularly training in sport. There were no differences in size, age at PHV, and PHV between the two groups, but the parameters of adolescent spurt for boys regularly involved in sport were characteristic of early maturers. In girls, Malina found gymnasts, swimmer, track athletes, and rowers indicated a stable pattern relative to reference data for nonathletes; that is: swimmers, track athletes, and rowers were already taller and gymnasts already shorter than average during childhood and adolescence. He concluded that regular physical activity, sport participation, and training for sport have no effect on attained stature, timing of PHV, and rate of growth in stature.

Daly, Rich, and Klein (1997) support these findings. In their study of male gymnasts they used biochemical markers to detect potential growth problems. Gymnasts' serum levels of alkaline phosphatase and osteocalcin did not differ from normally active controls.

It has been suggested that inhibited growth may be the result of a diet insufficient to sustain high levels of physical activity and growth. Benardot, Schwarz, and Wilzenfield Heller (1989) reviewed the food intakes of 51 junior elite gymnasts to determine if it was sufficient to support their athletic lifestyles. Subjects, aged 7 to 14 years (mean = 9.4 yr.), were divided into 2 groups: 7 to 10 yrs and 11 to 14 yrs, to compare food intakes and recommended daily allowances (RDA). Mean energy intake for the younger group was 1,651 kcal. and 1,760 kcal. for the older group with 15% from protein, 52% from carbohydrates, and 32% from fat in both groups. The averages for both groups were above the recommended daily supplement for protein, carbohydrates, fat, the vitamins: thiamin, riboflavin, niacin, vitamin C, and vitamin A. Average intakes of calcium, potassium, and sodium were within safe limits but the intake of phosphorous and iron were low in both groups. Upon closer inspection of the data the authors found that all but one of the older gymnasts and 40% of the younger group had insufficient iron intake while 55% of the older group and 50% of the younger group had intakes lower than the RDA for calcium. The authors concluded that the low iron intakes may be insufficient to meet the gymnasts' needs for growth, development and physical performance, and cautioned against using group means for nutritional evaluation as the results can be extremely misleading

Another potentially dangerous aspect of intense gymnast training during puberty is risk of injury. Bailey (1997) demonstrated that peak velocity in BMC occurred approximately 1 year after peak height velocity. This suggests a period of relative weakness in long bones during the adolescent growth spurt that can result in increased fracture risk following peak height velocity.

"Gymnast wrist" is another danger in adolescent gymnasts. It is a condition resulting from premature closure of the distal radius resulting in an ulnar variance. At the World Championships Artistic Gymnastics in Rotterdam in 1987, DeSmet, Claessens, Lefevre, and Beunen (1994) took posterior-anterior radiographs of the left hands and wrists of all female finalists. Of the 191 radiographs, 156 wrists showed open growth plates while 35 were closed. The authors found a marked increase in the ulnar length in adult as well as immature gymnasts compared to nonathletes. The changes in relative ulnar length were correlated to weight, height, and skeletal age of the athletes.

The authors concluded that repetitive injury and compression of the wrist leads to a premature closure of the distal radial growth plate resulting in ulnar overgrowth.

In 1997 Caine, Howe, Ross, and Bergman conducted a critical review of the literature on this stress-related injury. Their results support the plausibility of stress-related distal radius physeal arrest with secondary ulnar-radial length difference but evidence was inadequate to be conclusive due mainly to lack of rigor in study designs.

4. SUMMARY & CONCLUSIONS

This study demonstrated that gymnasts have a greater bone mineral content (after controlling for size) than age and maturity matched, normally active controls. This is true at all sites: a) total body, b) AP lumbar spine, and c) the four femoral sites: total femur, femoral neck, intertrochanter, and trochanter. Therefore, we accept the major hypothesis and sub-hypotheses.

Results from this study indicate that the high impact loading associated with gymnastics increases BMC in premenarcheal female athletes, which may eventually lead to higher peak bone mass and therefore a decreased risk of osteoporosis in later life. The magnitude and volume of impacts experienced in a typical training program for these young elite gymnasts were described as the first step in the process of discovering the most effective exercise program for optimisation of BMC in growing children.

Recommendations for future research in this area include:

1. longitudinal studies involving young gymnasts and their long-terms effects on the skeletal health of growing children;
2. studies to measure the specific loading parameters that are most effective for optimisation of BMC in growing children;
3. follow up studies on premenarcheal gymnasts and children previously studied to determine the carryover effects of higher BMC in childhood into adulthood and its significance in decreasing the risks of osteoporosis; and

4. more research into the precise measurement of BMC in growing children to allow for more accurate comparisons between groups.

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6. APPENDICES

Appendix A

Gymnast Bone Density Study
Consent Form

Procedures:

Your child's participation in this project will involve one session:

1. The session, of approximately one hour, will be conducted in the Department of Medical Imaging at the Royal University Hospital. All measurements will be done by qualified hospital technicians.and research personnel.

a) Your child's total body bone status will be evaluated by a bone densitometer and the bone density of the left hip and lumbar spine (lower back) will be measured. This procedure is painless and routinely used in the practice of modern medicine and there is a minimal radiation exposure. The total exposure will be less than 10 millirem which is similar to the background radiation one would receive making a return flight from Saskatoon to Halifax on a commercial airline. For comparative purposes, the average annual background radiation in Saskatchewan due to natural sources is approximately 150 millirem per year and the between-location variability is greater than this procedure. The current permissible level for the general population is 500 millirem per year. The typical exposure from a routine dental x-ray is over 50 millirem. These values can be used to compare the relative risk of the less than 10 millirem exposure from the bone density procedure.

b) Your child's body dimensions will be measured (height, weight, segment girths, bone breadths, limb lengths and skinfolds).

c) Your child will complete interview questionnaires about physical activity, maturity status, health, and diet.

Rights and Welfare of the Individual:

It is understood that your child will be free to withdraw from any or all parts of the study at any time without penalty. Your child's identity will remain confidential and only those directly involved in the study (nameiv the investigators, project assistants, and Medical Imaging staff) will have access to your child's records and results. All individual results will remain strictly confidential.

Please be assured that you may ask questions at any time. We welcome your comments and suggestions and will be glad to discuss your child's results with you and your child. Should you have any concerns about this study or wish further information please contact either Jay Magnus (966-6994), Keith Russell (966-6470) or Dr. Bob Faulkner (966-6469).

....2

Gymnast Bone Density Study
Consent Agreement

Parent's Statement:

I, ______________________________, understand the purpose and procedures of this
(please print your name)
study as described and I voluntarily agree to allow my child to participate. I understand that at any time during the study, she will be free to withdraw without jeopardizing any medical management, employment or educational opportunities. I understand the contents of the consent form, the proposed procedures and possible risks.

I have had the opportunity to ask questions and have received satisfactory answers to all inquiries regarding this study.

______________________________ ________________
Signature of Parent or Guardian Date

Child's Statement:

I understand the purpose and procedures of this study as described and I voluntarily agree to participate. I understand that at any time during the study, I will be free to withdraw without jeopardizing any medical management, employment or educational opportunities. I understand the contents of the consent form, the proposed procedures and possible risks.

I have had the opportunity to ask questions and have received satisfactory answers to all inquiries regarding this study.

______________________________ ________________
Signature of Child Date

______________________________ ________________
Signature of Investigator Date

Child's Information:

Saskatchewan Health #:________________________ Birthdate:________________
(month/day/year)

School:________________________________ Grade:____________________

Guardian(s) First Name(s):__________/__________ Telephone:________________

Address:____/____________
(Postal Code)

Appendix B

UNIVERSITY ADVISORY COMMITTEE ON ETHICS IN HUMAN EXPERIMENTATION

(Medical Ethics)

NAME AND EC #: Dr. D.A. Bailey
Physical Education

88-102
NHRDP (#6608-1261-OS)

DATE: February 15, 1994

The revised consent form for the study entitled "A mixed Longitudinal Study of Bone Density Change During the Adolescent Years in Boys and Girls with Special Reference to Physical Activity Patterns and Nutritional Factors" has been reviewed by the University Advisory Committee on Ethics in Human Experimentation (Medical Sciences) and approval has been provided for renewal of the study.

Therefore you are free to proceed with the project subject to the following conditions:

APPROVED.

Please submit the revisions requested in 1(a) to the Director of Research Services, Room 210 Kirk Hall.

2. Any significant changes to your protocol should be reported to the Director of Research Services for Committee consideration in advance of its implementation.

3. Please submit to the Committee all adverse events reports received from the study sponsor.

4. Upon discontinuation or closure of the research study, please notify the Director of Research Services in writing.

E. A. McKenna
Chair
University Advisory Committee on Ethics in Human Experimentation

cc: Royal University Hospital

Appendix C

UNIVERSITY OF SASKATCHEWAN

NAME: ______________________________ AGE: ________ DATE: ________________

DAY RECALLED: ____________________ GRADE: _______________

Time	Food Item	Type & Preparation	Amount	Where bought or Brand Name
Breakfast				
Between				
Breakfast &				
Noon Meal				
Noon Meal				
Afternoon				
Evening Meal				
Before Bed				

CIRCLE THE CORRECT ANSWER:

Was intake usual for the day? Yes No
If no, indicate why: (were you sick?)

Did you take a vitamin pill during this time? Yes No
If Yes, indicate type or brand:

Appendix D

BONE DENSITY ACTIVITY QUESTIONNAIRE (ELEMENTARY SCHOOL)
OCTOBER 1995

Name: ______________________________ Age: __________

Sex: M _____ F _____ Grade: __________

Teacher: ______________________________

We are trying to find out about your physical activity levels that you have done **in the last 7 days** (in the last week). This includes sports or dance that make you sweat or make your legs feel tired, or games that make you huff and puff, like tag, skipping, running, climbing and others.

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

---

1. PHYSICAL ACTIVITY IN YOUR SPARE TIME
Have you done any of the following activities in the past 7 days (last week)? If yes, how many times?

Tick Only One Circle Per Row

	No	1-2	3-4	5-6	7 times or more
Skipping	O	O	O	O	O
Roller Blading	O	O	O	O	O
Creative Playground	O	O	O	O	O
Tag	O	O	O	O	O
Walking for exercise	O	O	O	O	O
Bicycling	O	O	O	O	O
Jogging or running	O	O	O	O	O
Aerobics	O	O	O	O	O
Swimming	O	O	O	O	O
Baseball, softball	O	O	O	O	O
Dance	O	O	O	O	O
Football	O	O	O	O	O
Badminton	O	O	O	O	O
Skateboarding	O	O	O	O	O
Soccer	O	O	O	O	O
Street hockey	O	O	O	O	O
Volleyball	O	O	O	O	O
Floor hockey	O	O	O	O	O
Basketball	O	O	O	O	O
Ice skating	O	O	O	O	O
Cross-country skiing	O	O	O	O	O
Ice hockey/Ringette	O	O	O	O	O
Other:					
____________________	O	O	O	O	O
____________________	O	O	O	O	O

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

I don't do PE	O	
Hardly ever	O	check
Sometimes	O	one
Quite often	O	only
Always	O	

3. **In the last 7 days what did you do most of the time at <u>RECESS</u>?**

Sat down (talking, reading, doing school work) .	O	
Stood around or walked around	O	check
Ran around or walked around	O	one
Ran around and played quite a bit	O	only
Ran and played hard most of the time . . .	O	

4. **In the last 7 days, what did you normally do <u>AT LUNCH</u> (besides eating lunch)?**

Sat down (talking, reading, doing school work). .	O	
Stood around or walked around.	O	check
Ran or played a little bit.	O	one
Ran around and played quite a bit	O	only
Ran and played hard most of the time . . .	O	

5. **In the last 7 days, on how many days <u>RIGHT AFTER SCHOOL</u>, did you do sports, danced, or played games in which you were very active?**

None	O	
1 time last week	O	check
2 or 3 times last week	O	one
4 times last week	O	only
5 times last week	O	

6. **In the last 7 days, on how many <u>EVENINGS</u> did you do sports, danced, or played games in which you were very active?**

None	O	
1 time last week	O	check
2 or 3 times last week	O	one
4 times last week	O	only
6 -7 times last week	O	

7 **<u>ON THE LAST WEEKEND</u>, how many times did you do sports, danced, or played games in which you were very active?**

None .	.	O
1 time .	.	O check
2 - 3 times	.	O one
4 - 5 times	.	O only
6 or more times		O

8. **Which <u>ONE</u> of the following describes you best for the last 7 days? **Read ALL FIVE statements before deciding on the one answer that describes you****

A)	All or most of my free time was spent doing things that involve little physical effort . .	O
B)	I sometimes (1-2 times last week) did physical things in my free time (e.g. played sports, went running, swimming, bike riding, did aerobics) .	O
C)	I often (3-4 times last week) did physical things in my free time	O
D)	I quite often (5-6 times last week) did physical things in my free time	O
E)	I very often (7 or more times last week) did physical things in my free time .	O

9. **Were you sick last week, or did anything prevent you from doing your normal physical activities?**

Yes	O check
No	O one

If Yes, what prevented you? ____________________

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

		None	Little Bit	Medium	Often	Very Often
A)	Monday	O	O	O	O	O
B)	Tuesday	O	O	O	O	O
C)	Wednesday	O	O	O	O	O
D)	Thursday	O	O	O	O	O
E)	Friday	O	O	O	O	O
F)	Saturday	O	O	O	O	O
G)	Sunday	O	O	O	O	O

Appendix E

Bone Density Study

MENSTRUAL HISTORY QUESTIONNAIRE

NAME:

BIRTHDATE:

TODAY'S DATE:

1. Have you ever had a period? Y or N (Circle one).

If yes, please complete the following:

2. I was __________ years old when I started my period.
3. My period began in __________ (month) of _______ (year).
4. My last period was _______ days ago.
5. Is there a chance that you could be pregnant? Y or N (Circle one).

Appendix F

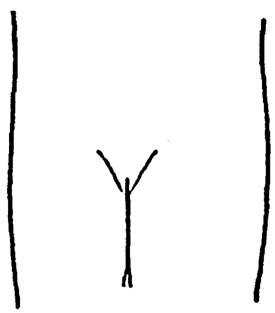
Self-Assessment of Maturity Status

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 themselves in words, so doctors have drawings of stages that all children go through. There are 5 drawings of pubic hair growth which are attached for you to look at.

We want to know how well you can select your stage of growth from the attached 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.

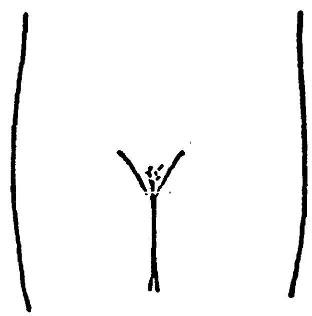
The drawings on this page show <u>different amounts of female pubic hair</u>.
Please look at each of the drawings and read the sentences under the drawings.
Then check the drawing that is <u>closest</u> to your stage of hair development.

Picture 1 ___



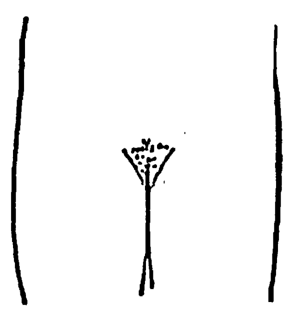
There is no pubic hair at all.

Picture 2 ___



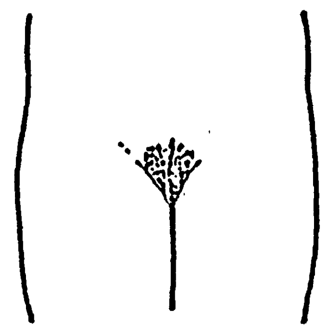
There is a small amount of long, lightly colored hair. This hair may be straight or a little curly

Picture 3



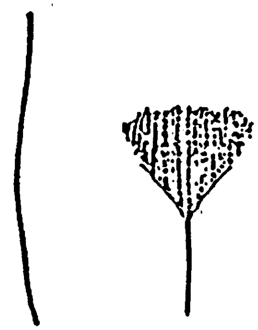
There is hair that is darker, curlier and thinly spread out to cover a somewhat larger area than in stage 2.

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.

Appendix G

LANDING Action	Notes	Magnitude x Body Wt.	Direction	Study	Notes
Heal Drops	no shoes	2.5-3.0	vertical	Bassey & Ramsdale, 1995	
Brisk Walk	adults	1.0		Cavanaugh & Cann, 1988	
	children	3.0		Nigg & Morlock, 1987	
	adults	3.0-5.0		Nigg, 1985	
				Nigg, 1988	
				Engsberg et al., 1991	
				Grimston et al., 1991	
Walk	barefoot	<1.0	vertical	reported by Nigg,1988	
	shoes	<1.0	vertical	"	
Running	toe	<1.0	vertical	"	force increases approximately
	heal	2.0-4.5	vertical	"	linearly as speed
Sprinting	spikes	3.0-5.0	vertical	"	increases
Gymnastics Landing	competition	6.0-7.0	vertical	"	
Backward Salto		9.0-10.0		"	
Volleyball Landing	block	2.5-4.0	vertical	"	
	spike	5.0-6.0	vertical	"	
Basketball Landing	rebound	4.0-6.0	vertical	"	
Diving-10 m tower	entry	15.0-25.0		"	
Boxing	punch	4.0-5.0		"	
Giant Swing	at hands	2.2		Neal et al.., 1995	
Asymmetric Bars	hip impact	7.0		reported by Nigg,1988	
Vertical Drop Landing					
0.5 meter ht.		3.0	vertical	Hyoku et al., 1984	reported in McNitt-Gray, 1994
2.0 meter ht.		12.0	vertical	Hyoku et al., 1984	reported in McNitt-Gray, 1994
0.32 meter ht.		4.2		McNitt-Gray, 1991	
0.72 meter ht.		9.1		McNitt-Gray, 1992	
1.28 meter ht.		11.0		McNitt-Gray, 1993	
Two-legged jumps	bare feet	2.0		Bassey & Ramsdale, 1994	on toes with flexed knees
Bckwrd 2/2 Salto	1 leg	8.8-14.4	vertical	Panzer et al, 1988	120 mm landing mat
		5.3-8.8	A-P	"	
		0.9-2.1	medio-ltrl	"	
		18.0	vertical	Panzer, 1987	
Horizontal Bar	dismount	8.2-11.6	vertical	Ozguven and Berme, 1988	
Jump landing	45 cm	5.0-7.0	vertical		no shoes, no matts
Tuck back Salto		6.0-14.0	vertical	McNitt-Gray et al., 1994	on a spring floor
		1.5-6.0	horizontal		
Layout back Salto		3.5-11.0	vertical	McNitt-Gray et al., 1994	on a spring floor
		0.5-2.5	horizontal		

Appendix G cont'd

TAKEOFFS Action	Notes	Magnitude x Body Wt.	Direction	Study	Notes
*Vertical Jump	takeoff	2.5-4.0		reported by Nigg, 1988	
Jump (d=3m/h=0.3m)	spikes	1.5-8.5	vertical	reported by Nigg, 1988	
	r. shoes	2.0-4.5	vertical	reported by Nigg, 1988	
Long Jump - females		3.8-10.0	vertical	reported by Nigg, 1988	
		2.5-5.0	AP		
		2.0-6.5	medio-ltrl		
Long Jump - males		5.0-11.5	vertical	reported by Nigg, 1988	
		4.5-7.0	AP		
		2.0-5.0	medio-ltrl		
Triple Jump	hop	8.0-10.0	vertical	reported by Nigg, 1988	
	step	8.5-12.5	vertical	reported by Nigg, 1988	
	jump	7.0-12.0	vertical	reported by Nigg, 1988	
High Jump		4.5-8.5	vertical	reported by Nigg, 1988	
		3.5-5.5	horizontal		
*Soccer - support leg		2.0-3.0		reported by Nigg, 1988	
*Ice Hockey	push	1.5-2.5		reported by Nigg, 1988	
*Cross Country Skiing	push	2.0 - 3.0		reported by Nigg, 1988	
*Ski Jump		1.5-3.0		reported by Nigg, 1988	
*Giant Swings	on rings	7.5 - 9.5		reported by Nigg, 1988	
		6.5 - 9.2		Bruggemann, 1987	
Giant Swings	females	6.0		Bruggemann, 1994	
*Trampoline		5.0-7.0		reported by Nigg, 1988	
Double Backward Salto	2 footed	16.0	vertical	Bruggemann, 1987	from roundoff
		0.6-2.6	horizontal		
Running Forward Salto		9.0	vertical		no damping mat
		2.5	horizontal		
Forward Russian Salto		13.6		[a]Miller and Nissinen, 1987	no mat
Frwrd Handspring Vault	hand push	1.5-1.6	vertical	[a]Richter et al., 1993	one hand
Frwrd/Hand- Spring /Roundoff	front leg	1.7		reported by Bruggemann, 1994	
One Leg Takeoff	back leg	1.3			
	hand push	3.0	vertical	[a]Kassat, 1974	
		1.0	horizontal		
Pommel Horse				[a]Markolf et al., 1990	
frontal scissors + flairs		2.0			
double leg circles		1.1			
backward support		2.0			
Tuck Backward Salto		5.5-16.5	vertical	McNitt-Gray et al., 1994	on a spring floor
		2.0-4.5	horizontal		
Layout Backward Salto		6.0-15.0	vertical	McNitt-Gray et al., 1994	on a spring floor
		2.5-4.5	horizontal		
Tuck Double Back Salto		7.5-13.0	vertical	McNitt-Gray et al., 1994	on a spring floor
		2.5-4.5	horizontal		

*measured as an active force but included here as no impact force data was available. It is important to note that active forces are generally smaller than impact forces

[a] reported in Bruggerman, 1994

Appendix H

Results of ANCOVA comparing BMC between gymnasts and controls using height and weight as covariates.

Site	df	F	p<
Total Body BMC	1,59	44.463	0.001
AP Lumbar Spine BMC	1,59	24.432	0.001
Proximal Femur BMC	1,59	38.055	0.001
Femoral Neck BMC	1,59	16.403	0.001
Intertrochanter BMC	1,59	38.214	0.001
Trochanter BMC	1,59	13.208	0.001