BONE AND MUSCLE MEASURES IN ADOLESCENT MALE CROSS-COUNTRY SKIERS

THE RELATIONSHIP BETWEEN BONE AND MUSCLE MEASURES IN ELITE ADOLESCENT MALE CROSS-COUNTRY SKIERS COMPARED TO NORMALLY ACTIVE MATCHED CONTROLS

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ABSTRACT

Exercise associated muscle induced bone strain has potential osteogenic effects that may increase skeletal density, bone cross-sectional area and structural strength. Whether the effects of exercise and the muscle-bone relation are similar in weight bearing and non-weight bearing bones remains to be determined. This study compared bone density, geometry and biomechanical properties, and bone and muscle cross-sectional areas of 13 elite adolescent male cross-country skiers with height, weight, age and maturity matched non-athletic controls. Total bone mineral density (BMD_{TOT}), and trabecular bone mineral density and total bone cross-sectional area (CSA_{TOT}) were measured at the distal 4% of the radius (DR) of the dominant (D) and non-dominant (ND) arms, and tibia (DT) using peripheral quantitative computed tomography (pQCT); BMD_{TOT}, CSA_{TOT}, cortical BMD, cortical thickness (CrtTH) and area (CSA_{CORT}), stress-strain index polar, x, y, polar moment of inertia, axial moment of inertia, and muscle cross-sectional area (mCSA) were measured at the 66 % length of the proximal tibia (PT) and proximal radius (PR) of the D and ND arms. Whole body BMD, whole body bone area, and hip areal bone mineral density were measured using dual energy X-ray absorptiometry (DXA). Speed of sound along the bone was measured using quantitative ultrasound (QUS) at the 1/3 DR and PT. There were no differences between the skiers and controls for any of the descriptive measures, however, there was a trend ($p=0.06$) for skiers to have lower percent body fat than controls. There were no differences between skiers and controls for the bone outcome measures using pQCT, DXA or QUS, except for CrtTH at the PT which was significantly higher in skiers (5.42 ± 0.25mm, $p=0.03$) than controls (5.18 ± 0.28mm). Cross-country skiers had increased CrtTH at the PT suggesting little differential effect of mechanical loading on bone density, geometry or biomechanical properties associated with skiing.

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TABLE OF CONTENTS

List of Appendices

List of Figures

List of Tables

INTRODUCTION

The ultimate goal of the research examining the influence of exercise on bone is to develop treatment and prevention strategies for osteoporosis (6, 10, 49, 61, 88, 90, 115) and to determine which sports or exercises are osteogenic. It is a well known fact that 1 in 4 women will suffer from osteoporosis after the age of 50, however, what is not as commonly known is that 1 in 8 males over the age of 50 will also be afflicted with osteoporosis (16). Considering, that by the year 2041, 25 % of the population will be over the age of 65 (16), osteoporosis is becoming a condition of much greater concern. Within the next few years, strategies must be developed to fight this disease and reduce its incidence. Before these strategies can be developed one must first understand the processes of bone modeling and remodeling, as well as the current state of the literature on the relationship between bone and exercise.

Bone Remodeling

Genetics accounts for approximately 60-80% of variance within bone measures, while the other 20-40% is explained by environmental factors (5, 22). These environmental factors include nutrition (especially dietary calcium and vitamin D), and weight bearing exercise (5). Therefore, it is these environmental factors that are of greatest importance for research since these are the modifiable behaviors that could improve bone status and prevent osteoporosis. To further understand the mechanisms by which these environmental factors affect bone properties, there must be an understanding of how bone can be influenced by diet and, more importantly for this research, exercise.

Bone is a dynamic tissue constantly undergoing modeling and remodeling (118). Bone turn over is stimulated by both external and internal loads placed on the skeleton (52). By definition, bone modeling is the process by which osteoblasts lay down new bone resulting in bone growth by increased mineralization and changes in bone size (33, 55). Remodeling, by contrast, involves the breakdown of bone by osteoclasts, followed by the formation/replacement of bone by osteoblasts (33, 55). Although it is known that the process of modeling and remodeling are stimulated by mechanical loading (20, 31, 32, 33, 52, 55, 100, 118, 121), the signaling pathway/mechanism is still under debate (31, 60, 82). This pathway is thought to be a feedback mechanism where mechanical loads are sensed by an intrinsic signaling receptor within bone that elicits a skeletal adaptive response to the perturbing stimulus (31). Somehow, these mechanical signals, causing the deformation of bone, are converted into biochemical stimuli which control bone remodeling (by osteoblast and osteoclast function), likely through some form of hormonal control (65).

Under normal physiological conditions and with fully functioning feedback mechanisms the skeleton will usually maintain an adequate amount of bone mass and with mechanical loading can potentially reach a state of "over adequate" adaptation but will rarely reach a state of inadequacy (32). The processes of modeling and remodeling are responsible for the changes in bone architecture (i.e. size, shape and bone mineral content distribution) as a result of mechanical loading (36, 60). The most important variables affecting bone strength are bone mass, the size and shape/distribution of mineral within the bone, bone length, and the presence of microdamage (38, 47, 94, 116).

The sites of bone modeling and remodeling of interest are the endosteal and periosteal surfaces of the bone (36, 73, 85). Within adolescent males, the majority of bone accrued during growth is on the periosteal surface until around the age of 20 years (85, 105). After the age of 30, mechanical loading no longer stimulates an increase in bone, but helps in the regulation of bone gain/loss (33, 61, 62).

In theory, bone attempts to reach an optimal mechanical structure to prevent damage (e.g. fracture), however, whether this state is ever reached is questionable (121). Many theories exist about the bone modeling/remodeling process but the question still remains unanswered as to how exactly this process occurs. Researchers are in agreement about the concept that bone responds to mechanical loads placed on the skeleton through ground reaction forces and/or muscle contractile forces, however, the process of adaptation is the point of contention. Wolff argued that any adaptation that occurs to bone can be predicted through mathematical equations, and Frost provides a much more complex explanation about the process (31). Frost (31) believes that bone will adapt in unit mechanical properties and in the architecture/location of bone materials in direct response to loads placed on the bone, with an interaction likely existing between these two factors. Therefore, when analyzing the response of bone to a loading stimulus, the material (mineral content and density), geometric (cross-sectional area) and biomechanical components must be measured. The bone material properties along with the bone geometry are important determinants of bone strength (55). The geometry of the bone either resists or prevents the mechanical loads placed on the bone (55) and if the load is of sufficient magnitude, the bone will respond to the mechanical load. In response to loading, there will be an increase in material properties (i.e. increased mineral content) and geometry (i.e. increased bone diameter as a result of endosteal resorption and periosteal apposition) (55). These changes result in the bone being able to withstand a higher magnitude of loading before failure occurs (55). Frost's Mechanostat theory is based on the idea that bone will respond to an error, thereby "turning on" either bone growth, modeling or remodeling through the feedback mechanism (32, 33, 34). In order for bone adaptation (material and/or architectural) to occur and the feedback mechanism to be "turned on", the load placed on the bone must exceed a minimum effective strain (MES) (31, 32).

Three levels of strains have been defined: 1. normal strains that do not exceed the MES with no bone adaptation, 2. strains that are above the MES, due mostly to physical activity, that cause an adaptive response within bone, and 3. trivial strains that do not place enough load on the bone to cause adaptation or maintenance of current bone status and usually result in bone loss (e.g. spaceflight) (31). As long as strains are above the MES an adaptation will occur, but if the strain becomes habitual and falls below the MES, the bone will no longer adapt (31, 34, 36, 39, 65). The MES threshold will change/adjust based on the activity level of the individual (32). Loads which exceed the MES cause microdamage to the bone and stimulate bone modeling/remodeling processes resulting in bone adaptation (34-38, 62). If a load falls within the MES range (normal range) remodeling will repair the damage without any increase in bone measures (39). If the mechanical loads are too high and occur suddenly, the microdamage caused to the bone cannot be repaired and overuse injury to the bone will result (37). The balance within the remodeling process for bone adaptation is between the damage done to the bone and the subsequent repair of that damage (37, 56). Figure 1 provides a schematic representation of the Mechanostat theory contributing to the understanding of bone's response to an exercise stimulus. The factors, other than mechanical loading, that influence the MES response include nutrition, hormones, biochemical messengers, disease states, genetics and toxic agents (32, 33). Overall, it is the mechanical loads placed on bone during exercise that are thought to be responsible for adaptation.

Understanding the biomechanics of bone is also very important in determining the influence of different factors on bones' response to mechanical loading. From a biomechanical view point the bone can be described by its elastic (spring/rigidity of the bone) and plastic (permanent deformation) components (116). Any mechanical load placed on the bone will cause deformation of the elastic intermolecular bonds that resist the loading forces which stimulate the process of bone adaptation (35). This deformation of bone is measured by strain which is defined as the percent change in the length of the bone or the amount of deformation of the bone when a load is placed on it (116). A load-deformation curve represents the relationship between the load placed on the bone and the amount of deformation of either the plastic or elastic components (116). The stress on the bone is the force per unit area and it can be measured under either tensile, compressive or shear conditions (116). A bone is weaker in tension compared to compression (116); tension occurs on the convex side of a bending bone while compression occurs on the concave side. Mechanical loads placed on the bone cause the tension and compression which results in changes to the elastic and plastic components,

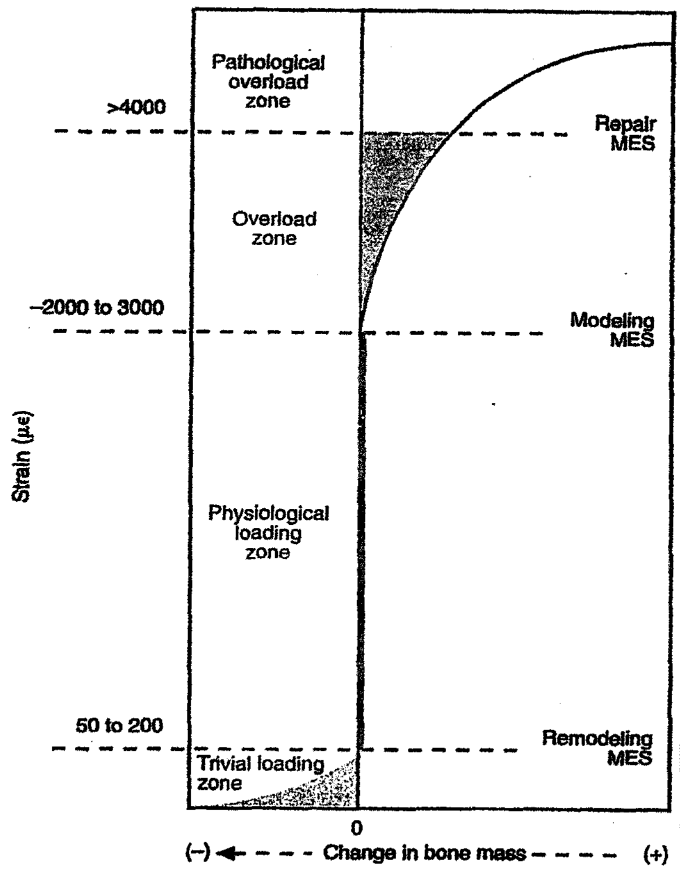


Figure 1: Schematic representation of Frost's Mechanostat Theory. During times of disuse (e.g. bed rest or spaceflight) the skeleton will be in the trivial loading zone. Everyday activities such as walking, are sufficient to keep the skeleton in the physiological loading zone. If sufficient, the magnitude and frequency of loads placed on the skeleton during physical activity will place the skeleton within the overload zone resulting in differential adaptation in bone. When the magnitude and frequency of the loads are too high, the skeleton will be in the physiological overload zone and injury may result.

with adaptation occurring as a result of the microdamage to the plastic components. The strength of the bone, and its ability to resist deformation, is reflected in its size and shape, and the material within it (73). For exercise, the question is whether or not the loading condition places sufficient forces on the bone to cause deformation and therefore adaptation. Also important within exercise is the belief that the magnitude of the force is the most important determinant of mechanical load stimulation of bone adaptation with lesser importance ascribed to loading frequency (32, 33, 34, 59, 61, 62, 113, 120). Recent studies, however, indicate that the frequency of loading may also impact on the adaptation response of bone by altering the sensitivity of the cellular mechanisms and product expression.

The stimulus of mechanical loading on the skeleton required for proper bone development begins in the womb with muscle contractile forces (5, 20). What is important to skeletal health is the continued mechanical loading of physical activity, especially during growth (5, 33, 39, 60, 65). Peak bone mass can only be achieved if individuals participate in weight bearing and muscle strengthening exercise during childhood and adolescents (5). By maximizing peak bone mass through physical activity/mechanical loading, an individual is helping to prevent osteoporosis later in life (60). Turner (118) emphasizes three rules for bone adaptation as a result of mechanical loading: 1. dynamic loading stimulates bone adaptation, better than static loading, 2. short duration mechanical loading is more effective at stimulating bone adaptation compared to longer duration activities, 3. bone is more responsive to novel mechanical loading regimes, rather than to states of routine loading. The most important factors of the mechanical loading stimulus to promote adaptation appear to be the magnitude of the load and the number of loading cycles (20, 34, 62, 65). However, some believe that the distribution of the strain is also important for bone formation (65) suggesting the importance of how the load is placed on the bone for adaptation to occur.

Bone is thought to adapt to daily repeated dynamic loads or strains rather than loads that are infrequent (34). For the majority of individuals, the mechanical loading placed on their skeleton is only sufficient to maintain their mineral status within the normal range (38). Further, the positive benefits of mechanical loading on bone mass can only be maintained if the stimulus remains (65). If a tissue like bone falls into a state of disuse there will a resultant decrease in bone mass (39). For an individual who participates in regular physical activity, the mechanical loads placed on the bone may cause beneficial adaptations and it is this adaptation that is of interest to researchers. The most important changes as a result of physical activity are those to bone mass and architecture (39, 52, 60, 99) because these factors are important to bone strength.

The mechanical loads placed on the bone as a result of exercise are either muscle contractile forces or ground reaction forces. The mechanical loading of bone by muscle contractile forces are very important for bone health, especially during periods of disuse (e.g. bed rest) (5, 38, 39). These muscle contractile forces place high mechanical loads on the bone because of the poor biomechanical advantage of the human musculo-skeletal system, and result in high contractile forces producing movement (39). The increase in bone mass in certain athlete populations demonstrates the skeleton's ability to adapt to supra physiological (above MES) strain magnitudes/mechanical loading conditions (99). Unfortunately the best type of exercise to promote skeletal health is still not known, but what is known is that any changes seen in bone as a result of physical activity are limited to sites within the skeleton that were placed under mechanical loading during the exercise

(60, 112). This site specific effect suggests a locally controlled mechanism for the stimulation/regulation of bone remodeling (82).

When studying the effects of exercise on bone there are a few important factors that need to be taken into consideration. The size and shape of the bone are reflective of the mechanical loads placed upon it (34), therefore, any changes seen in bone following training can be attributed to an adaptation to the increased mechanical loading. If using a cross-sectional study design, then any differences in size and shape of the bone between two groups can be attributed to the exercise. For this model to be viable there are the assumptions that no difference would exist if the athlete group did not participate in the sport and that no other factors (e.g. diet) are different between the groups.

Another important variable within the study of bone's adaptation to exercise is the approximately 4 to 8 month lag between the overloading mechanical strain placed on the bone and the adaptation as a result of bone modeling, and a 3 to 4 month lag for bone remodeling (35, 36, 38, 39, 82). If this delay in bone adaptation to the stimulus is not taken into consideration, then the differences as a result of exercise may not be seen between groups. For example, in a study of 6 months duration with increasing magnitude of strain, if the final testing for bone is done at the end of the 6 months, any difference seen will be a result of what was done at 2-3 months of training. Unfortunately each sport must be studied individually to assess whether or not the mechanical loading placed on the skeleton during that sport is sufficient to result in bone adaptation. In a cross-sectional study design it is important to study bone during the time of maximal adaptation. For cross-country skiing this takes place in the spring following the competitive season.

Self-selection bias can also provide a source of error within a cross-sectional design because athletes may have larger and stronger bones which select them to success in sport. Therefore, it may not be surprising that athletes have higher bone density, geometry and biomechanics compared to controls.

Review on Exercise and Bone

Studies have found that physical activity has a positive effect on bone during adolescence (8, 27, 40, 59, 61, 66, 68, 107, 120) and could be beneficial in the prevention of osteoporosis. Exercise places mechanical loads on the bone, which facilitates proper/optimal bone development (20, 103). Without normal mechanical loading, bones will only develop between 30 and 50% of their potential bone mass (119). This review will focus on exercise during the first three decades of life, since this is the time in which peak bone mass is attained (27, 111), and examine strategies for prevention of osteoporosis rather than treatment of the disease. By optimizing peak bone mass, osteoporosis may be prevented (6, 30, 40, 66, 68, 77) since the amount of bone acquired during the two years surrounding peak rate of accrual is thought to be equal to the amount lost during adulthood (70). Therefore adolescence provides the optimal time for altering bone mass and geometry since 90% of bone mineral content is accumulated during this time (76). The late teen years are especially important for reaching peak bone mass within a physically fit population (6). Studying the effects of exercise on bone is especially important considering that physical activity in addition to dietary calcium is one of the two most critical modifiable variables during growth that influence bone (27, 30, 77, 107). Maintenance of calcium stores within the body is vital to skeletal health and optimizing the effects of physical activity on bone (47). Vitamin D is also very important for skeletal health (83). When examining the influence of different types of exercise/physical activity on bone, it is important to examine both intervention and athlete model studies.

Intervention Studies

Intervention studies provide knowledge about the specific effect of a training stimulus on bone over time. This model allows for more control over what is done with the participants and allows for randomization of individuals into either intervention or control groups in an attempt to eliminate self-selection bias based on skeletal characteristics. Three basic types of intervention studies have been done to investigate the effects of exercise on bone in children: those that have incorporated jump training protocols, resistance training protocols, and protocols that include a variety of exercises. Also within this section, two population-based studies will be reviewed.

Jump training protocols have been the most widely studied training modality in the growing population. Studies have been done on children and adolescents ranging from 6 to 15 years of age, and Tanner stages 1 to 3 (40, 49, 53, 70). Variation exists within the protocols, with interventions lasting 10 to 20 minutes, 2 or 3 times per week for between 7 to 9 months (40, 49, 53, 70). These programs incorporated a wide variety of jumps including jumping jacks, box jumps, hopping and lunge jumps (40, 49, 53, 70). Jumpers were found to have higher bone mineral content (BMC) and bone area at the femoral neck, and higher BMC and bone mineral density (BMD) at the lumbar spine (40), higher BMC and areal BMD (aBMD) at the lumbar spine and femoral neck (70), and higher BMC at the lumber spine and femoral neck (49), and leg (53). Although some studies found differences at the lumbar spine (49, 53) others did not (40). This discrepancy between studies has been explained by the possible attenuation of forces before reaching the spine (70).

Unfortunately the positive effects of the jump training protocols on bone measures are not consistent and are influenced by both gender and maturational status. In the study by Heinonen et al. (49) only the premenarcheal jumpers were found to have higher BMC than the controls, while no difference between groups was seen for the postmenarcheal group. However, premenarcheal girls were also found to have higher BMC increases as a result of the training compared to the postmenarcheal girls. The effect of maturational status may be due to the hormonal profiles with a hormone-exercise interaction (70) and the peak BMC velocity which occurs around the same time as peak height velocity (77).

Fuchs and Snow (41) are the only group to have done a follow-up study to determine if the effects of their jump training study (40) were still present after seven months of detraining. Differences in BMC and bone area at the femoral neck were maintained; however, there was no longer a difference at the lumbar spine (41).

Although this was a relatively short duration for follow-up, it does suggest that the positive effects of the jump training protocol persist for several months. Longer follow-up studies need to be done to determine the true long-term effects of this training protocol on bone.

Two studies were reviewed that used resistance training as the intervention method with adolescent females. In these studies the age range of the participants was 14 to 18 years. In the study by Nichols, Sanborn and Love (87) participants were randomly assigned to either training or control groups. Whereas, in the study by Blimkie et al. (13), the girls were matched for age, body mass and level of physical activity before being randomly assigned into either group. The protocols consisted of 9 to 12 repetitions of 13 to 15 exercises for 2 to 4 sets. The protocol by Blimkie et al. (13) lasted only 26 weeks compared to the 15 month protocol by Nichols et al. (87). Differences in BMD were only seen in the study by Nichols et al. (87) where the resistance trained females were found to have higher BMD at the femoral neck compared to baseline; no differences existed between the trained and control participants at other sites. The possible reasons for not finding differences in these studies are discussed below in the limitations of the study design.

The third type of intervention study design incorporated a variety of activities into the exercise prescription. The protocols included activities such as weight training, soccer, Australian rules football, modern dance, gymnastics and other sports and games (14, 79, 109, 125). The sessions were done 3 to 4 times per week for 30 to 45 minutes each time, with the intervention lasting anywhere from 8 months to 4 years (14, 79, 109, 125). This type of intervention was implemented with children from 9 to 16 years of age (14, 79, 109, 125). BMC was found to be higher in the exercisers at total body, femoral neck, greater trochanter, lumbar spine and femoral midshaft (125). The exercisers were also found to have higher BMD at the total body, lumbar spine, legs, arms, pelvis, femoral neck and proximal femur (79), and higher aBMD at the total body, lumbar spine and legs (14). After the four-year intervention, femoral neck BMC, aBMD and volumetric BMD were found to be higher in the exercise group compared to controls (109). Therefore even combinations of exercises have a positive effect on bone.

Population-based studies have examined the relationship between current or past physical activity on measures of BMD or BMC. The Saskatchewan study assessed level of physical activity through a questionnaire, however, it did not quantify the amount of physical activity for the children (7). Despite the lack of quantification, the most physically active males, (those in the top quartile) but not females were found to have higher BMC at the total body and lumbar spine at the age of peak bone mineral content velocity, and the femoral neck at one year following peak bone mineral content velocity (7). This gender difference cannot be attributed to either hormonal difference or physical activity level since the amount of physical activity of each gender was not defined. The Iowa study used accelerometer data in combination with a questionnaire to assess the physical activity levels of their participants (54). Physical activity was found to be positively correlated to BMC and BMD values of the children in the study (54). Assuming that the participants in the Iowa study were a representative group of children from this population, this study provides more compelling evidence of the association between the level of physical activity and bone health than the findings from the Saskatchewan Bone Accrual Study (7).

Before making any final conclusions about the influence of these interventions on bone, the limitations of this study design must be considered. One of the major limitations is the duration of the intervention protocols; the studies lasted anywhere from 26 weeks to 4 years and may explain some of the discrepancy among findings. The study by Blimkie et al. (13) which did not show differences within the resistance-trained females compared to control may be a result of the short duration of the study. Attrition rate is also a limiting factor for the study by Nichols et al. (87) that did not find positive results. This may be a result of insufficient participants, and thus statistical power, in each group by the end of the study to determine differences. The timing of the last bone measurement may also have limited the ability to see differences in the training model studies. If the last bone measurement is taken at the completion of the study, then any differences seen would be a result of training done several month prior, due to the bone remodeling transient (55). Considering that the highest magnitude of loading is done in the last stage of the training protocol, then the changes to bone as a result of training will not as yet be seen when the last bone measures are taken at the end of the study.

The inconsistency in training protocols is another limitation of the intervention method of study in general, and not of any study in particular. The intervention studies that combine a number of different activities do not allow for the activity or activities that are causing the osteogenic effect to be isolated, although they do provide a more interesting training protocol for children which may maintain their interest longer (40).

Limiting the interventions to one activity will help determine which activity is having an effect on bone and lead to a prescription or guidelines for the general population sooner.

Technology is a limiting factor in both the intervention and athlete model designs. Dual energy X-ray absorptiometry (DXA) provides a good assessment of BMD and BMC for each of the original scans (i.e. total body, hip and lumbar spine). However, researchers often perform regional analyses from the original scans to make comparisons between groups. Using this assessment has some major limitations, because differences between groups are usually relatively small and when regional analyses are used, the precision of the measurement is decreased. This may impact on whether or not differences are found between groups. The possibility also exists that in studies that did not find changes with DXA, differences may have been found if other technologies such as peripheral quantitative computed tomography (pQCT) had been used. The pQCT scan takes a cross-sectional picture of the bone and can assess if bone geometry as well as bone density changes. The dual photon absorptiometry used by Blimkie et al. (13) is less precise than DXA and could account for the reason that differences were not seen with that resistance training protocol.

Athlete Model Studies

Athlete model studies provide a unique opportunity to study the effects of extreme levels of exercise inherent in specific sports on bone. However, to make the connection between the sport and the positive effects on bone, one must assume that the athletes do not self select into the sport based on their skeletal characteristics. In this model, the differences seen in bone measures in athletes are presumed to be the result of the forces and loading that the skeleton undergoes during their participation in the sport.

Gymnastics is the most widely studied sport for its potential osteogenic effects. Studies have been done on gymnasts who range in age from 7 to 19 years, to one study that included a group of retired gymnasts aged 18 to 35 (8, 21, 25, 26, 67). The gymnasts were training a minimum of 14 hours per week up to 36 hours per week and were matched with inactive controls (8, 21, 25, 26, 67). Findings from theses studies show that gymnasts had higher aBMD at the femoral neck and trochanter, and higher bone mineral apparent density (BMAD) at the total body, femoral neck and lumbar spine (25). Also, higher BMD of the total body (21, 26), lumbar spine, and femoral neck (26, 110) has been reported. As well, gymnasts were found by Bass et al. (8) to have higher aBMD of the total body, spine, leg and arm, and higher bone mass and apparent volumetric density of lumbar spine and femoral midshaft.

Bass et al. (8) provided a unique piece of the puzzle when she and her colleagues included a group of retired gymnasts in their study to examine the possible long-term effect of gymnastics training on BMC and BMD. Retired gymnasts were found to have higher BMD at the total body, femoral neck, Ward's triangle, trochanter, lumbar spine and arms and legs when compared to controls of the same age (8). This study demonstrated the potential long-term benefits of gymnastics training on bone measures, but, due to the cross-sectional design and not knowing the differences while they were younger, the long-term effects can only be postulated. Only a longitudinal study that follows gymnasts from competition years through retirement can provide the exact long-term effects of the loading on bone. It can still be concluded, however, that gymnastics is a sport with potentially positive effects on bone at load bearing sites throughout the skeleton.

Two articles were reviewed that studied the effect of hockey on bone mineral density. Both studies were done on hockey players who were 15.9 +/- 0.3 years of age and Tanner stage 3 or above (89, 91). The hockey players trained approximately 10 hours per week and were compared to an inactive group of males matched for age, weight and pubertal status (89, 91). The findings of the study showed that the hockey players had higher BMD at humerus, femur, proximal femur and tibial tuberosity. No differences were seen for the total body, lumbar spine or skull BMD (89, 91). It is interesting to note that hockey players were only found to have higher BMD at the tibial tuberosity when those players suffering from Osgood-Schlatter were excluded from the analysis (91). Also, the excluded players had significantly lower BMD at the tibial tuberosity when compared to the 'healthy' players (89). It would be difficult to make firm conclusions that hockey does confer positive skeletal benefits in players from the two studies, because based on the authors and the subject description, both studies appear to be examining the same group of players. However, differences were seen in BMD suggesting that hockey does have some osteogenic benefit.

Several studies have reported the effects of volleyball on bone sites throughout the body. The studies were done on males and females ranging in age from 19 to 26 years (3, 4, 18, 26). The level of competitive status ranged from university to the elite professional level; training hours ranged from 8 to 30 hours per week (3, 4, 18, 26). The study by Alfredson et al. (3) found female volleyball players to have higher BMD at the total body, lumbar spine, femoral neck, Ward's triangle, greater trochanter, both arms and non-dominant femur. In another study by Alfredson et al. (4) female volleyball players were found to have higher BMC than controls over a one-year period only at the proximal humerus. Calbet et al. (18) found that male elite volleyball players had higher BMD at lumbar spine, femoral neck, intertrochanteric region, greater trochanter, Ward's triangle, spine, pelvis, right arm, and right and left leg. BMC values were also higher than controls for the femoral neck, greater trochanter, spine, pelvis, and right leg (18). The study by Fehling et al. (26) compared volleyball players not only to controls but also to gymnasts and swimmers; they found volleyball players to have higher BMD at the lumbar spine, femoral neck, Ward's triangle, and total body compared to swimmers and controls. However, gymnasts were found to have higher BMD of the arms compared to volleyball players (26). Based on the results of these studies it can be concluded that volleyball is a sport with a positive impact on BMC and BMD in individuals in their third decade of life.

A study by Bennell et al. (10) took a different approach to the elite athlete model study by following a group of athletes for a 12-month period. They examined the BMD and BMC differences between groups and how it changed over the length of the study. The study consisted of three groups of male and female participants; a power sport group (sprinters, hurdlers and jumpers), middle and long distance runners, and a control group (10). All participants were between 17 and 26 years of age; all athletes trained a minimum of 11 hours per week (10). Both the female power athletes and runners were found to have significantly larger changes over the year in total body BMC, and upper limb, lumbar spine and femur BMD compared to controls (10). Total body BMC was found to be higher in male power athletes and runners compared to controls along with lumbar spine, femur and tibia/fibula BMC (10). The male power athletes were also found to have a significantly larger increase in lumbar spine from baseline compared to the endurance runners (10). This study provided some unique data by following the changes in BMC and BMD over a year of training in these athletes. From this study we can conclude that power track and field events, and middle and long distance running have positive effects of BMD and BMC in males and females. In a multi-sport analysis of adolescent female swimmers, runners, triathletes, cyclists and controls, higher BMD was found amongst the runners at load bearing sites (24). These findings emphasize the theory that weight bearing/high-impact sport is best for promoting osteogensis.

Soccer has also been studied for its possible osteogenic effects by Karlsson et al. (59) and Alfredson, Nordström and Lorentzon (2). Both male and female soccer players were studied ranging in age from 17 to 35 years, and training between six and twelve hours a week on average. Female soccer players were found to have higher BMD at the lumbar spine, femoral neck and Ward's triangle. The study by Karlsson et al (59) found that male soccer players had higher BMD at the total body, legs, trunk, pelvis, lumbar spine, femoral neck, Ward's triangle and trochanteric regions. The study by Karlsson et al. (59) was the only study reviewed that quantified the number of hours of the sport required to find a difference compared to controls. Karlsson et al. (59) concluded that greater than six hours a week of soccer are required to elicit osteogenic benefits. The higher BMD values are attributed to the compressive, shear and bending forces experienced during soccer as a result of the high acceleration/deceleration and rapid changes in direction (2). From these studies it can be concluded that soccer does have positive effects on bone density.

The one study examining the effects of cross-country skiing on bone measures focused on 16 year old females (92). DXA was used to assess BMD and BMAD between the athlete and control groups (92). Findings showed skiers to have higher BMD at the left and right humerus, left diaphysis of the humerus, femoral neck, femoral diaphysis and greater trochanter, and higher BMAD at the femoral neck (92). A major limitation of these findings is that only a single full body scan was done with a regional analysis follow-up. This approach is not sensitive enough to make accurate regional comparisons from such a large scan area. More sensitive measures need to be done before cross-country skiing can be included in the list of sports with osteogenic benefits.

Several studies have examined bone density and geometry measures of tennis players (17, 45, 57, 67). An interesting finding from these studies, is the apparent differences in bone size, BMD and BMC between the dominant and non-dominant arms of the players and no side to side differences among controls (17, 45, 57). Although one study only found differences between tennis players and controls in measures of bone geometry, the researchers emphasize the importance of this finding by noting that an increase in size may result in higher bone strength/a higher force before failure occurs (i.e. higher force before fracture) (45). These results provide justification for the study of side to side differences in other sports where unilateral or bilateral loads are placed on the arms, for example in the sports of volley-ball or cross-country skiing.

Other research has been done to examine the relationship between sports and bone measures, however, to include all sports in this review would not be realistic. The sports found to have a positive influence on BMD and/or BMC include powerlifting (115), basketball (67), squash, aerobic dance, and speed skating (48). Not all sports have been found to have positive effects on BMC and BMD; swimmers and water polo players were not found to have higher BMD when compared to controls (26, 67, 110). In these studies, swimmers and water polo players were compared to inactive controls and athletes from various sports including running, gymnastics, tennis and volleyball. There are some possible reasons why differences may not have been seen in these groups and it cannot be concluded that these sports are not good for bones. In the only other study (other than on gymnasts) that examined the long-term effects of exercise on bone, no difference was found between the retired soccer players and control groups (58).

The limitations of cross-sectional and athlete model study designs must be considered before making final conclusions about the benefits of a sport on bone. As discussed within the intervention method limitations, technology provides one of the major limitations on knowing the full extent of the influence of sport on bone. This is likely present in swimmers and water polo players who may experience positive effects on bone through changes in cross-sectional area without any changes in bone density. Another limitation to the athlete model is the inability to quantify the exact amount of physical activity required to elicit the changes in bone density. Karlsson et al. (57) made an attempt at quantifying the hours of physical activity required to see differences when they concluded that with six hours of soccer playing, differences in BMD were apparent between athletes and controls. The hours of sport required to see changes in bone is important when trying to generalize the findings to something that is applicable to the general population, since the ultimate goal of this research is to develop effective exercise programs for osteoporosis prevention and optimization of skeletal health.

The main conclusion from these studies is that impact-loading sports provide some positive effects on bone. However, the effect on bone is site specific and depends on the mechanical loading pattern of the sport. Differences in athletes compared to controls were only seen in weight bearing locations except in gymnasts, volleyball players, and cross-country skiers where loads are also placed on the upper extremities. One study showed possible long-term benefits of gymnastics training on the skeleton in retired athletes (8), however, it is not known if possible lasting effects on bone are to be expected from all sports.

Cross-country Skiing

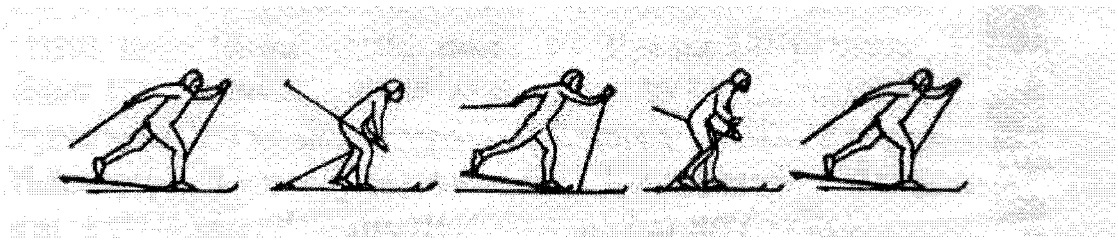
Cross-country skiing has been practiced for approximately 4000 years, with its beginnings as a mode of transportation (23). Many advances in the sport both in equipment and technique have brought it to its current prominence (23). There are two major techniques in cross-country skiing, skating and classical, with both training and competition split relatively equally between the two techniques (92). Cross-country skiing is a weight bearing sport and therefore has potential osteogenic effects on bone. From a biomechanical perspective, an additional unique aspect of cross-country skiing is that most of the large muscle groups within both the upper and lower body are used (78, 123) which also gives the sport the potential for whole body beneficial skeletal effects.

Before a biomechanical critique can be done there must be a basic understanding of the sport. The classical technique is comprised of a sub-set of more specific skills which include diagonal striding, double poling and kick double poling techniques. The diagonal stride involves opposite hand and leg movements with the skis pointed forward in the track; for example while the right arm and left leg are in the push/kick phase, the left arm and right leg are in the recovery phase (Figure 2A). In double poling there is a simultaneous pole plant with both poles followed by the trunk bending forward while the arms follow through; the legs do not contribute to the forward propulsion. Kick double poling is the same as the double poling in technique except that during the arm recovery phase there is a kick by one of the legs (usually the legs alternate, however, some skiers will kick with the same leg with every stride). The skating technique can be further broken down into one-skate, two-skate and offset approaches (Figure 2B). The one skate approach is the most used skating technique within racing as it is the fastest; for this technique the legs perform a "skating" action and the arms are used for poling with every kick. In the two skate technique, both legs are performing the skating action, however the arms only pole with every other kick (i.e. the arms will only pole while the right or left leg are pushing). The offset skating technique is used for climbing steep hills and is similar to the two-skate approach in that the arms only pole on one side, however, the timing and positioning are changed; the poles are planted at the same time as the foot with the arm on the side that the leg is pushing higher up the hill (reaching) while the other arm is down closer to the body.

The typical preparation schedule for a cross-country skier will involve high volume training at low intensity during the summer months, followed by an increase in speed/intensity training during the pre-competition phase (42). During the competitive season, the training shifts to high intensity with interval training coupled with a decrease in exercise volume (42). Athletes will go through a taper phase prior to major events, especially for high level competitions (42). This higher intensity training during the competitive season could potentially have a more beneficial effect on bone because forces placed on the bone may be greater during this time. Due to the nature of the training, skiers are able to increase their VO2max between 1-3 ml/kg/min every year between 15 to 20 years of age, while individuals in the general population reach their peak value around 8 to 10 years of age (102). During a typical race, the distance is split evenly between uphill, downhill and level terrain, however approximately 50% of the total time of a race is spent on the uphill sections (101).

With no jarring or pivoting during skiing, it is relatively low risk activity for orthopedic injury (78). The most common injuries include medial collateral ligament and anterior cruciate ligament sprains, injury to the meniscus, ankle sprains, ulnar collateral ligament sprain, acromial-clavicular joint sprain, hallux rigidus and sesamoid inflammation in the foot (78). Another study reported that cross-country skiing may lead to anterior endplate lesions in the thoracolumbar and lumbar spine regions in adolescents who train and compete at a relatively intense level (96).

A



B

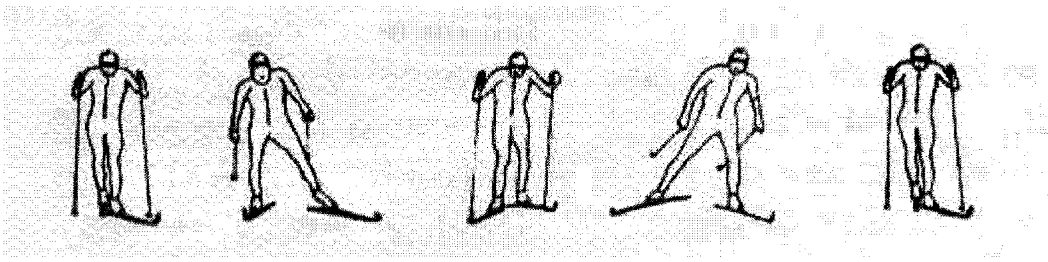


Figure 2: Schematic illustration of the two basic techniques in cross-country skiing; A: classical technique, B: skate technique (the illustration is of the one-skate technique since it is the most commonly used in racing). (12).

Some sports are characterized by typical body types, for example you rarely see a 6-foot tall gymnast; however, there is no typical body type for cross-country skiers. One study analyzed the influence of body mass on performance in an attempt to determine the "ideal" body type for the sport (11). The findings showed that heavier skiers have an advantage on the downhill and flat sections of the course while the lighter skiers are at an advantage on the uphill sections; the researchers concluded that factors other than body weight influence performance (11). Although body weight may not be important for performance, it has been shown to have positive effects on bone (55). Factors other than mass that affect skiing performance include gravity, friction, aerodynamic or hydrodynamic lift and drag, and centripetal force; all of these factors will influence the biomechanics of skiing (29). Unfortunately, no studies have examined the influence of body composition (i.e. muscularity) or strength on cross-country ski performance. If the assumption was made that more elite cross-country skiers have more muscle and are stronger, then differential adaptation in bone would be expected in these elite skiers as a result of higher muscle contractile forces.

In the Amsterdam Growth and Health longitudinal study (61) cross-country skiing was only given an osteogenic peak strain score of 1. Other sports that scored 1 were jogging and ballroom dancing, whereas skipping received a score of 3. The score given to each sport is based on the ground reaction forces placed on the body during the sport; a score of 1 corresponds with ground reaction forces of between 1 and 2 times body weight (63). The classification of the ground reaction forces by Kemper during skiing correspond with the forces reported earlier by Pierce and colleagues (93).

A few studies (74, 93, 106) have measured the forces during skiing for both the classical and skating techniques; however, analysis has not been performed for all techniques within the two broader technique categories. Poling forces during diagonal striding and marathon skating have been reported to be around 17% of body weight (93), however during skating, the poling forces are approximately two to four times higher (51, 106). Of interest, especially considering the contra-lateral limb bone differences within racket sport athletes (17, 45) and volleyball players (18), are the significant differences reported in poling forces between dominant and non-dominant arms during the two-skate technique (74, 106). This difference could potentially influence bone adaptations if the force differences are great enough to elicit differential responses like those seen within tennis players (17, 45, 57). Other factors affecting poling forces during skiing were grade of the hill, with an increased poling force as the grade of the hill increased (75, 64) and grip during the classical technique, with higher poling forces reported when skiing with poor grip during diagonal stride (64).

Poling contributes between 31-66% of the propulsive forces (9, 50, 73, 106), however, this value will change depending on terrain (72). When reported as power, the arms have been thought to contribute between 10 and 30% of the overall power (46). As noted earlier, the amount of force produced by poling is also dependent on the technique, and this may account for the variability in poling power reported in the literature. During summer training, athletes will use roller skis to train on roads. Poling forces on the hard asphalt surface are much higher and this increases the risk for injury. Research is currently being done to design a pole to decrease ground reaction forces placed on the arm (95). Although this may reduce the risk for injury, decreasing the ground reaction force on the arm may attenuate the potential osteogenic effects of these forces.

The legs provide 30 times more force than the arms with 69% of the propulsive force coming from the lower limbs (9). Some have suggested higher kicking forces during the classical technique (51), however, there is not a sufficient amount of data to support this theory. One study does report that during classical skiing, skiers only use between 10 to 20% of their maximal muscle strength (124). The forces produced by the legs during skating are reported to range between 1.2 and 1.6 times body weight (106). Unfortunately there is not much data regarding leg forces during skiing, likely due to methodological issues related to accurate measurements. Interestingly, terrain has been found to influence the amount of time within a stride that the force is applied, with a higher portion of time within a stride spent applying force on uphill terrain (12). The only conclusion that can be drawn from the literature is that the legs provide the majority of the propulsive forces during skiing (74).

Some of the limitations of the force measurements by Pierce (93) are that the measurements are limited to the classical and marathon skating techniques so that no true force measurements are available for the skating technique. It has been reported that poling forces are higher during the skating technique (124), but unfortunately no specific measurements were given. Other limitations within the force measurements during skiing include the different phases of the technique cycle (glide, preload and kick) and the multidirectional nature of the kick (64, 106). Even the kick wax used during classical skiing will affect the force measurements (64). And when measuring forces during skiing a three dimensional model must be used (106). A potentially confounding factor within these force measurements is the recent advances in equipment, since the time of these earlier force measurement studies. What will not change, however, with equipment and technique, are the relative contributions of upper and lower body muscle forces during skiing. Therefore, cross-country skiing still mechanically loads the skeleton of the upper and lower body and has potential for whole body osteogenic effects.

Without the ability to actually measure the forces on the bone it is unknown whether the bone is placed under tensile or bending stress. It is likely that during skiing there is a combination of both types of stresses being placed on the bone. Bending is likely contributing more to the forces placed on the bone than tensile stress due to the nature of the sport, since muscle contractile forces elicit mostly bending stress in human bones. To determine if the mechanical loading during cross-country skiing is sufficient to cause adaptation to the bone, a study must be done examining bone properties within skiers.

Purpose

The primary purpose of this study was to investigate the association between lower body weight-bearing and upper body muscle contractile forces on skeletal adaptations in adolescent male cross-country skiers compared to normo-active controls. A secondary purpose was to investigate the muscle-bone relationships between weight-bearing and non-weight-bearing regions of the skeleton and the possible influence or interaction with training status.

An adolescent male population was chosen because not much research has been done within this population and therefore, not much is known about bone development within this group. With a large number of boys within this demographic being highly active at a highly competitive level, this provides a large sample base population.

Hypotheses

1. The weight-bearing and muscular loads placed on the lower body appendicular skeleton during cross-country skiing will be associated with greater bone adaptation in density, geometry and biomechanical properties in skiers compared to controls.
2. The higher arm muscular forces in skiers will be associated with greater upper body skeletal adaptation in density, geometry and biomechanical properties in skiers compared to controls.
3. Unilateral dominance in arm usage during skiing will be associated with greater bone adaptation in density, geometry and biomechanical properties in the dominant vs. non-dominant arms in skiers, and between dominant arms in skiers and controls.

METHODOLOGY

This research project received ethical approval from McMaster Research Ethics Board. All participants were informed of testing procedures and consent was obtained from all participants, as well as from a legal guardian of those under the age of 18 years.

Elite cross-country skiers (n=15) and normo-active controls (n=15) were recruited to participate in the study. The sample size was calculated based on a power estimate using means and standard deviations for bone measures reported in a similar study of female cross-country skiers (92). Unfortunately 2 skiers dropped out due to injury/previous commitments reducing the number of skiers participating in the study to 13. All skiers raced on the provincial circuit during the racing season preceeding testing and achieved a minimum average point value of 80 on the provincial points scale. Points are calculated based on the average times of the first three finishers in the category. Six of the 13 skiers also participated at the national junior championships as members of the provincial team. Controls were recruited from friends or family of the other study participants, colleagues and researcher. Inclusion criteria for skiers and controls were: adolescent males between 16 and 19 years of age and Tanner stages 4 or 5. Individuals with a metabolic disorder affecting bone, and for controls, participation in cross-country skiing at any time were criteria for exclusion. One skier was Tanner stage 3, however, with the limited number of skiers, the decision was made to include his data in the study.

Testing of cross-country skiers took place between one and a half and three and a half months after the end of the competitive season. The timing of the testing ensures that measures of bone will reflect the adaptation to peak training loading during the cross-country skiing season. The need for the delay in testing after the competitive season is due to the bone-remodeling transient (35, 36, 38, 39, 82). Controls were tested during the fall and winter.

All testing took place at McMaster University, either at in the Department of Nuclear Medicine, Hamilton Health Sciences or in the Department of Kinesiology, the Ivor Wynne Centre. Testing lasted approximately two and a half to three hours. Three different methods for assessing bone parameters were used, quantitative ultrasound (QUS), dual-energy X-ray absorptiometry (DXA), and peripheral quantitative computed tomography (pQCT). Strength was assessed by handgrip dynamometer, Biodex and force plate. Physical activity (PA), and diet and lifestyle factors were assessed by questionnaire.

Primary Measurements- Bone Assessment Techniques

QUS

QUS measures the speed of sound (SOS) in the bone and has been found to be a predictor of osteoporotic fracture risk (108). Some of the advantages of QUS are that it does not expose participants to ionizing radiation, it does not cost as much as other methods (55) and it is relatively non-invasive (28). At the radius and tibia, the SOS is measured for cortical bone. Although it is thought that the SOS provides measures of bone qualitative and quantitative properties (28) and/or microarchitecture, what QUS is truly measuring remains unknown (55). Some believe that the sound waves traveling in the bone provide information about the mechanical properties of the bone (i.e. stiffness and mass density) (15).

All testing was completed using the 7000P model of the Sunlight Omnisense, and the 2.0 version of the software (Sunlight Medical Ltd. Rehovot, Israeal). A quality control scan was done at the beginning of each day to ensure that the QUS was measuring accurately and to calibrate the device for room temperature. All measures with the QUS were done using the CM probe (largest probe). Participant information was entered into the computer so that scan results could be accessed at a later date. Information entered into the computer included name, date of birth and participant number.

Measurements were done for both radii for all participants: scanning order was recorded manually for the radial measures because there is no function within the QUS to differentiate between arms (left/right). The measurement site was found by having the participant rest his elbow on a flat surface and extending the arm up in the air (perpendicular to surface) with the wrist straight and the palm facing the participant. The end of the tape measure was placed under the elbow and a measurement was taken from the base of the elbow to the tip of the middle finger, ensuring that the wrist remained straight. The length was multiplied by 2/3 to obtain the measurement for the distal site on the radius (Figure 3A). A mark was made on the arm at this site using a white eyeliner pencil. The arm was then allowed to rest horizontally on a table and the mark was extended over the entire radius at this point as a guide for the measurement.

Participants rested the arm to be measured on a board with a small cushion under the wrist and the arm semi-pronated so that that radius was located superiorly at the "top" of the arm. The participants held onto a bottle of ultrasound gel during testing to ensure appropriate arm positioning. Ultrasound gel was placed on the probe and on the arm of the participant. The probe was then placed on the arm and the foot pedal was pressed to start the measurement. The probe was moved slowly across the radius (first away from and then towards the researcher); an indicator tone reflecting transmission quality was maintained as constant as possible throughout the measurement sequence. The passes with the probe were continued until the sound stopped and the measurement was complete. The measurement procedure was repeated a minimum of two times, or until three trials were completed with acceptable technical comparability. The measurement process was repeated on the other arm.

The tibial measurement of QUS was only done on the dominant leg of the participant; leg dominance was established by asking participants which leg they would kick a soccer ball with. This measurement site was found by having the participant bend his knee at approximately a 90-degree angle while seated in a chair. The measuring tape was placed under the heel on the medial side of the dominant leg. The first measurement was taken at the middle of the medial malleolus and the second at the joint line at the top of the tibia. Tibial length was calculated by subtracting the height of the malleolus from the height of the tibial joint line. The length of the tibia was multiplied by 2/3 to obtain the 66% site of the tibia (the height of the malleolus was added to this value to obtain the height of the measurement from the floor) (Figure 3B). A mark was made on the tibial

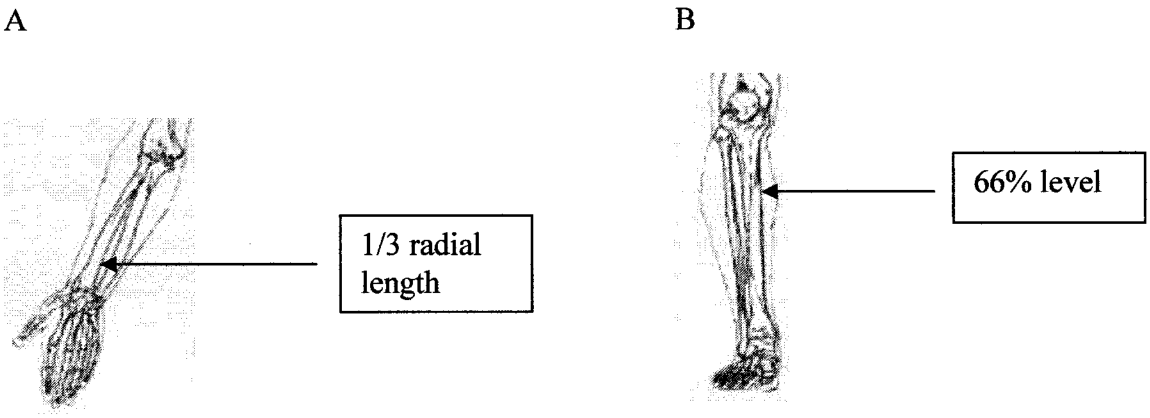


Figure 3: Schematic of Quantitative Ultrasound measurement sites for A: the radius, and B: the tibia.

surface at this location and extended over the entire superior surface of the tibia. Another mark was made at this location over the tibialis anterior muscle, for the site of the pQCT measurement (see pQCT methods section). The midshaft tibia protocol for QUS was selected to do this measurement because it is the manufacturers's reference site on the tibia. However, for the purpose of this thesis and to minimize radiation exposure and to align sites for both QUS and pQCT measurements, the 66% length of the tibia was used rather than the manufacturer's recommended 50% site. Ultrasound gel was placed on the tibia so that the marker line was in the middle of the area being measured. The probe was placed on the leg and the foot pedal was pressed to start the measurement. The probe was moved across the tibia maintaining tone transmission quality until the trial was completed. This was repeated a minimum of two times or until three trials that were technically comparable were obtained.

DXA

Dual energy X-ray absorptiometry (DXA) is a body composition technology based on a two compartment model of bone and non-bone tissue (55). The two compartments are differentiated by X-ray beams of distinct energy levels (55). It is the attenuation of these X-rays through the body that allow for the calculation of the various outcome measures. Bone measures obtained from DXA include bone mineral content (BMC) and areal bone mineral density (aBMD) (55). Because the scan is two dimensional (anterior-posterior image) only, a measure of areal density can be obtained, not true volumetric density. Due to the nature of the technology, assessment of fat and lean body mass is also possible (114). DXA allows low dose radiation scans making it appropriate for use within a pediatric population with relatively low risk (114). The Hologic QDR-4500A (Hologic Inc. USA) located in Nuclear Medicine at Hamilton Health Sciences was used for all DXA measurements.

A quality control (QC) scan of the lumbar spine phantom was done at the start of every day and a whole body phantom scan once per week to ensure measurement accuracy of the equipment. Scans cannot be performed until the daily or weekly QC scans are completed.

For all scans the participants wore clothing that did not contain metal. Subjects were also asked to remove all metal jewelry. If participants were dressed in clothing that contained metal they were asked to change into a hospital gown. Any metal worn during the scan will result in falsely high readings (43).

The whole body (WB) scan was performed by having the participant lie on the DXA measurement platform (Figure 4). The body was positioned so that all body parts were within the black line around the platform that indicates the acceptable scan area. The arms were positioned away from the body to allow for separate regional analysis. The legs were positioned approximately shoulder width apart to ensure that they could also be separated during analysis. The scan took approximately three minutes; during this time the participant was asked not to move or speak, and to breathe normally. To analyze the

scan, the body was segmented into arms, legs, head, trunk and spine regions. Arms were separated at the humeral head; legs were separated by bisecting the femoral neck (to ensure the pelvis was within the trunk measurement); the head was separated by placing a line at the base of the skull; the spine was separated by placing lines vertically on either side of spine and another line at the level of L4; the pelvis was separated at the top of the hip.

A separate scan was also taken of the dominant hip (determination of leg dominance as discussed in QUS section) of all participants (Figure 4). For this scan, the participant remained on the measurement platform lying supine. For comfort, the participants were given a pillow for their head. To position the hip correctly a board was placed under the

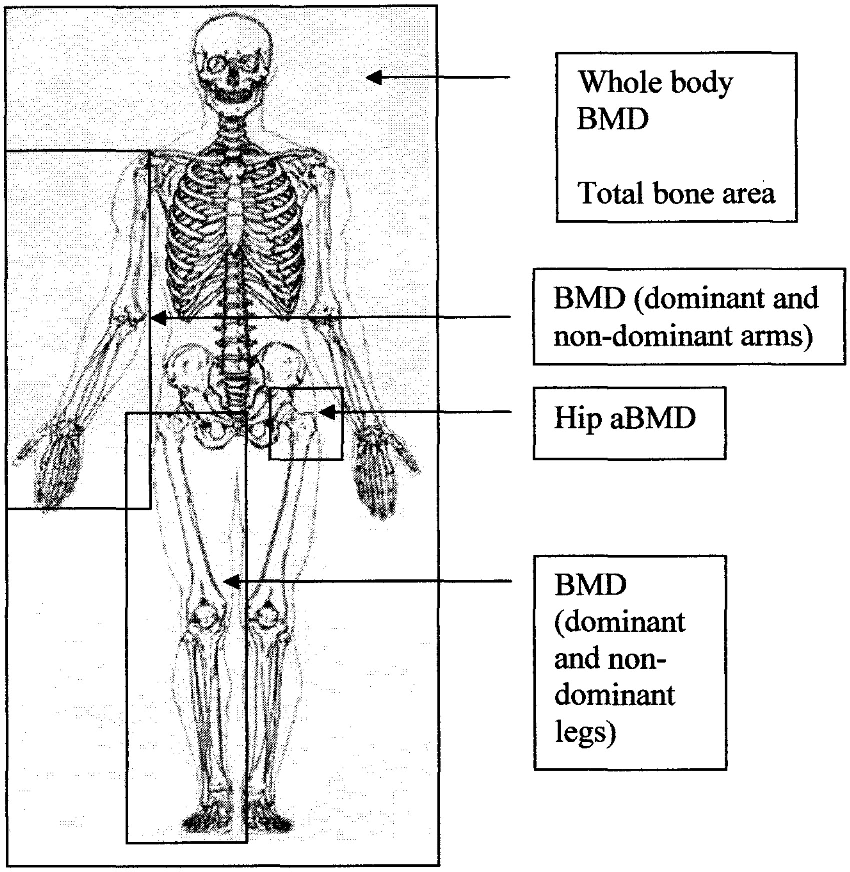


Figure 4: Schematic illustration of DXA measurement sites for the whole body, hip, arms and legs.

legs of the participant. The leg of the hip being measured was then lifted and internally rotated to expose the lesser trochanter, and a Velcro strap was placed around the foot and attached to the board to maintain this position. The board was then adjusted so that the femur was positioned parallel to the bed. The laser was used to position the measurement arm of the DXA over the hip of the participant. The image appeared on the screen of the computer so that if the position of the scan was not correct, the measurement arm could be adjusted before the scan was completed. After the completion of the scan, the hip was analyzed by adjusting the scan region of interest and the orientation of the boxes and lines that separated areas of interest for the hip. DXA scans were performed on only 13 of the 15 controls due equipment malfunction on the test date. Coefficients of variation (CV) in DXA measurements (separate scans) in this age groups have been reported to range between 0.9% (86) and 1.5% (6) in the literature. Reproducibility of regional measures of BMD from the whole body scans are usually ≤ 4.1% (CV) (89, 91).

pQCT

Peripheral quantitative computed tomography (pQCT) provides an excellent method for measuring bone properties as it not only gives a measurement of mineral quantity (i.e. BMC and BMD), but also its architectural (i.e. CSA) and biomechanical features (38, 94, 105). In fact a significant correlation has been found between the failure of bone to a specific load and the prediction of the load according to pQCT measures (94). pQCT is also based on attenuation of X-rays through the tissue; although it is limited principally to cross-sectional measurements of the extremities. The cross-sectional images also allow for the separation and quantification of both trabecular and cortical bone (44). With the pQCT device, the true volumetric density of bone can be measured (44, 55).

The XCT 2000 pQCT (Stratec) was used for measurements in the present study. All scans were completed and analyzed using the XCT550 version of the software. The pQCT allows for cross-sectional images to be made at different sites along the arm (radius) and leg (tibia) for bone and muscle measurements. The advantage of the pQCT is that it allows for the separation of cortical and trabecular bone mineral along with measurements of total bone mineral content and volume. Determination of BMD, BMC and bone area can be made along with measures of bone biomechanical properties. Measures of muscle cross-sectional area can also be done at proximal sites, however, no separation can be made between specific muscles of the limb. The pQCT technique is based on low dose radiation passing through the limb with the attenuation of the x-rays giving an indication of the amount of bone mineral and bone area. A quality assurance (QA) scan was performed at the beginning of each measurement day to ensure measurement accuracy of the device. Scans could not be performed until a QA scan was done. The cone phantom was used to perform the QA scan. The quality assurance (QA) program starts with an AP view of the phantom and then performs scans at five different sites along its length. All scans must fall within normal limits for the QA to be successful; if not successful the QA must be performed again until the scan is successful.

For each participant, subject name, date of birth, gender, and identification code were entered into the computer to ensure that all individual scans could be located at a later date for analysis. Also entered was the side (right or left) of the scan and the length of the bone being scanned (length measurements are described below). The measurement masks set up for this study included the radius at the 4% and 66% level with a scout view (SV) (Radius 4% 66% with SV), the tibia at the 4% level with a SV (Tibia 4% with SV), and the muscle measurement without a SV which was done at the 66% level of the tibia (Muscle Measurement no SV). A measurement mask allows for all parameters for the scan to be entered into the software before the scan begins: parameters include device position (e.g. 4% of length), scanning speed (a slower scan speed was used for muscle measurements because better resolution could be obtained, however, it is also associated with a higher radiation dose), resolution (as defined by voxel size), and whether or not a SV would be used. The SV feature allows for the automatic alignment of the measurement sites by taking an AP scan of the distal bone (radius/ulna for the arm and the tibia/fibula for the leg) and a reference line positioned at specific anatomical landmark. Separate measurement masks were set up for the 4% and 66% levels of the tibia because the tibia was too long to allow for measurements to be taken without repositioning of the limb within the machine.

Measurements were done at the 4% and 66% distal sites for both radii of the dominant and non-dominant arms, and the tibia of the dominant leg. Scans done at the 4% distal site of the bone provide a measurement of the total and trabecular bone, while scans at the distal 66% level of the bone provide measurements of total and cortical bone. Although there is a thin layer of cortical bone at the 4% level, the resolution of the pQCT is not sensitive enough to provide an accurate measurement of cortical bone at this site.

The distal tibia measurement was taken at the 4% level using a SV. The length of the tibia was measured as the distance between the middle of the medial malleolus and the joint line of the knee (palpated at the top of the tibia). The leg was placed in the pQCT scanner and secured with a Velcro strap and clasp. The measurement arm was moved down to the ankle just distal to the end of the tibia and the SV was performed. After the SV was performed the reference line was positioned so that it bisected the middle of the distal end of the tibia and the scan was performed.

The same measurement location was used for the 66% tibia as was previously described for the QUS tibial measurement. The height of the malleolus from the floor was subtracted from the height of the joint line of the knee to obtain the length of the tibia. The 66% length of the tibia was calculated and then added to the height of the malleolus and a mark was made on the tibia at this height (height from floor) (Figure 5A). A scout view could not be used for this measurement because of the length of the tibia. The XCT 2000 only has a 220 mm range. The machine was manually positioned at the measurement site (as marked on the skin with eye pencil).

Measurements were done on both the dominant and non-dominant arms with the pQCT to allow for side to side comparisons of bone measures. Radial length was calculated by asking participants to place their arms on a desk, with the forearm supinated and pointing up in the air (perpendicular to the desk) and measuring from the desk surface (elbow) to the distal radius. The distal radius was found by palpation. The researcher realizes that the length measured is actually that for ulnar length; however, this is the recommended method used to measure radial length in the literature (104). The arm was positioned so that it was straight out from body on the medial side and went straight into the pQCT. The arm of the pQCT was moved into position so that it was just distal to the distal end of the radius and the SV was performed. The reference line was positioned so that it bisected the medial edge of the distal radius; the scans of the 4% and 66% radius were then completed (see Figure 5B). The protocol was repeated on the opposite arm. The pQCT measures allow for differentiation between the left and right sides.

All scans were examined to ensure that participants did not move during the procedure and that they were of sufficient quality to be analyzed. If a scan did not meet the accepted standards, it was repeated.

For data analysis, the pQCT software program is opened as before, but without the need to perform a QA scan. Once the menu comes up at the beginning of the "XCT550" operation software, the "Analyze" menu is selected and then advanced to the "select patient" prompt. The participant can be found by name, ID, patient number, birth or first name. After the patient file is located, the scans done on that patient can be selected for analysis.

The outcome measures from pQCT include BMD, BMC, bone cross-sectional area, cortical thickness, and muscle cross-sectional area. The cross-sectional moment of inertia is used to measure the bending stress of the bone and the polar moment of inertia is the sum of two cross-sectional moments of inertia (116). The stress strain index (SSI) measures within the polar, X and Y directions and provides a measure of bone mechanical strength (97).

Bone Analysis Procedures

A region of interest (ROI) box was placed over the bone of interest; the radius for the 4% and 66% measurements on the dominant and non-dominant arms, and the tibia for the 4% and 66% measurements. Once the bone was selected, the data was incorporated into a computational loop for automatic analysis with preset outcome variables. For the

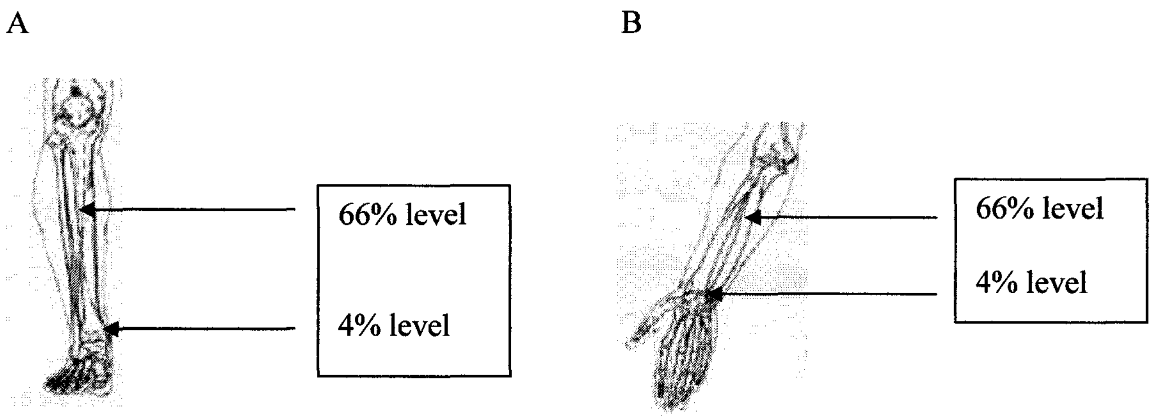


Figure 5: Schematic illustration of pQCT measurements sites of the 4% and 66% tibia (Figure 5A), and 4% and 66% radius (Figure 5B).

4% scans of the radius and tibia that were used for total bone analysis, the threshold was set to 280 mg/mm^3. For trabecular bone analysis at the 4% level, the threshold was set at 169 mg/mm^3, with the inner 45% of the bone area identified as the area of interest. For measurements at the 66% level for the radius and tibia, the threshold was set at 711 mg/mm^3 to assess the total and cortical bone measures. Incomplete data sets are used for some variables as there were errors in the measurement procedures.

The reproducibility of bone cross-sectional area, total BMD and trabecular BMD at the 4% radial level is reported to be 1.40%, 1.49% and 0.82% respectively, in the literature (84). At the 66% level of the radius, the reproducibility of total area, cortical area and BMD as 1.41%, 0.95% and 0.95% respectively (85). The estimated short-term error for measures of bone area was reported to be less than 1% at the 66% level of the tibia (98).

Muscle Analysis by pQCT

Muscle analysis was done at the 66% sites for the dominant and non-dominant arms, and the dominant leg. The ROI was set over the entire scan (to include muscle, fat, and both bones). For the 66% tibia, a manufacturer provided macro was used to analyze the parameters with the preset thresholds, filters and areas. The muscle macro did not work on four of the 66% tibia scans; in these cases manual analysis was performed. Manual analysis was done for the 66% radius scans. During manual analysis, four separate reconstruction scans were generated to obtain total area, bone area, cortical area, and muscle and bone areas combined (98). The total bone area and cortical bone area values obtained from this analysis included the radius and ulna for the arm scans, and the tibia and fibula for the dominant leg scan. To obtain the muscle and bone areas, the cancellous bone function was used with an area of 99.9% (the computer would not accept 100%), threshold of 40 mg/mm^3, contour mode 3, peel mode 1 and filter F03F04 (98). For total area, the cancellous bone analysis function was used with an area of 99.9%, threshold of –53 mg/mm^3, contour mode 3 and peel mode 1 (98). For bone area, the cancellous bone analysis was used with a threshold of 280 mg/mm^3, area of 99.9%, contour mode 1 and peel mode 1 (98). Cortical bone area was obtained by using the cortical bone analysis function with a threshold of 711 and contour mode 1 (98). These thresholds, areas, contour and peel modes, and filters were determined by what the preset muscle macro used for automatic analysis. When analyzing the muscle and bone area values, the filter was sometimes changed to F03F05 and/or the threshold changed to eliminate all fat from the scan to obtain an area of only muscle and bone. The cortical CSA to muscle CSA calculation was performed using the cortical cross-sectional area of the bone of interest at the measurement site (i.e. radius or tibia) (104). The short term error for muscle measurements at the 66% level of the tibia has been reported in the literature as 1.15% (98). There are no reported reliability or reproducibility data for muscle measurements of the arm.

Secondary Measurements

Biodex

Biodex (System 3, Biodex Medical Systems, USA) measurements were performed to assess flexion and extension strength of the dominant leg. Participants' name, age, weight and identification code were entered into the software so that the results could be obtained at a later time. The participants were seated on the Biodex dynamometer and straps were placed across their hips and shoulders, and across the testing leg to ensure that participants could not move and the muscles of the leg were isolated. During testing, participants were also asked to hold the handles on the side of the dynamometer. Four different measurements were taken of leg flexion and extension; isometric strength at a knee angle of 120 degrees, isokinetic strength at 60 deg/s, 90 deg/s and 300 deg/s. Encouragement for maximal effort was provided to each participant during the testing.

The isometric leg strength test was completed first for all of the participants, eliminating the possibility of the isokinetic strength testing causing fatigue. The protocol required participants to complete three sets of five seconds of maximal leg extension, followed by five seconds of rest, and then five seconds of maximal leg flexion, with each set separated by ten seconds of rest. Approximately three minutes of rest was given to participants before proceeding to the isokinetic strength testing. The outcome measures from the isometric strength protocol included peak torque, maximum average peak torque, and maximum average peak torque relative to body weight for extension and flexion as well as the ratio of agonist and antagonist strength.

The participants remained seated on the Biodex dynamometer between testing protocols. While participants were resting, the researcher reselected the participant and selected the isokinetic testing protocol. The isokinetic speeds were randomized so that there was no effect of fatigue due to previous testing at other speeds on results. Three different protocols were entered into the software that were identical except for the order of the speeds (60, 90 and 300 deg/s). The protocol required participants to complete one set of five maximal kicks at each speed. Approximately one minute of rest was given between each testing speed. Before the isokinetic strength testing was started, the range of motion was set to ensure that participants did not injure themselves (by allowing them to move only within their range of motion). The outcome measures for each speed for the isokinetic strength testing included peak torque, peak torque relative to body weight, the maximum total work for the repetitions, average power, the maximum average peak torque for extension and flexion, and the range of motion and the agonist, antagonist strength ratio.

Handgrip Dynamometer

A standard handgrip dynamometer (Steoelting Co., Chicago, USA) was used for measuring both dominant and non-dominant grip strength of the participants. The dynamometer was placed in the hand of the participant and the bar for the fingers was adjusted so that it went across the interphalangeal joint when the fingers were gripping the dynamometer. Once adjusted correctly for each participant the task was explained; participants were instructed to hold the dynamometer in the specified hand away from the body with the forearm pronated, and to squeeze as fast and as hard as possible while not moving the upper body (a demonstration of correct technique was provided by the researcher). Measurements of dominant and non-dominant handgrip strength were taken by alternating hands until three trials on each hand were completed. Results of each trial were recorded and then averaged to determine grip strength, in kilograms, for each hand.

Force Platform

A counter-movement jump was performed on a custom built force platform to assess whole body muscle power. This type of jump was chosen because it closely mimics the movement done during the kicking phase in both classical and skating skiing techniques. A description and demonstration of the jump was given to each participant and then each participant was given an opportunity to practice the jump twice before the criteria tests were performed. If the hands did not remain on the hips during the jump then the jump was repeated. The counter-movement jump was completed by having participants stand on the force platform with body weight equally distributed on the two halves of the force plate. Participants then performed the jump by bending at the knees in a continuous motion down to approximately a 90 degree angle and then immediately jumping upwards with maximal effort. Weight was taken before each jump because there was slight variability within this measure and power outcome measures were normalized relative to weight. Subjects were instructed to make the jump as explosively as possible. Between each jump, the force plate was reinitialized to zero, the start point for data collection. The force plate was also reinitialized if the weight did not fall within +/- 0.02 kg on repeated trials. The outcome measures included power normalized to body weight (W/kg), absolute power (kW), absolute force (N), and speed (m/s). The results for all three jumps were averaged to obtain the final values.

Height and Weight

Participants stood in socked feet against a wall and height was measured using a standard stadiometer. Measurements were taken at the end of a deep inhalation with the subjects looking straight forward. Measurements were taken to the closest 0.1 cm.

To measure weight, participants stood on a balance scale in shorts, a t-shirt and socked feet. Measurement was taken to the closest 0.1kg.

Tanner Staging Assessment

Participants were provided (in an envelope) with figures depicting the 5 stages of pubic hair development as described by Tanner (Appendix A) and asked to go to the bathroom to place a check mark beside the stage that most represented them. To maintain comfort level, the assessment results remained in an envelope until after the completion of testing and the participant had left.

Modifiable Physical Activity Questionnaire

All participants completed the Modifiable Activity Questionnaire for adolescents (Appendix B) to quantify the amount of physical activity (PA) completed within the last year (1). Questions requested the number of hours of physical activity per day, the types of activities (sports) and physical activity levels during different months of the year. The average total weekly hours for each sport/activity was calculate using the formula (1):

$$\text{PA (h/wk)} = \text{(mo)} \times \text{(4.3 wk/mo)} \times \text{(d/wk)} \times \text{(min/d)} \div \text{(60 min/h)} \div \text{(52 wk/yr)}$$

The sum of weekly hours was calculated to get the total average hours per week of physical activity.

For the skiers, the number of training hours and competition hours were included in the daily activity score. Because much of the training for skiing is completed by cross-training during the off-season, it is not possible to separate out total training hours for the year. However, because the analysis is completed for each sport/activity separately, the average number of hours spent cross-country skiing each week can be calculated (includes both hours training and competition). The calculation was done by using the equation:

Time skiing (h/wk) = (d/wk) x (min/d) ÷ (60 min/h)

Lifestyle Questionnaire

All participants completed a lifestyle questionnaire (Appendix C) to assess nutritional status. The questionnaire contained questions about food frequency (e.g. number of times per day, week or month items such as milk and cheese were consumed), and calcium and multivitamin supplementation.. Dietary calcium values were calculated by examining the types (e.g. milk, yogurt, cheese) and the frequency (e.g. 1-2 times per day) of foods consumed, and calculating the percent of the skiers or controls that reported eating the food; these percentages were then compared between groups.

Statistical Analysis

Independent t-tests were used to determine between group differences for descriptive and physical characteristics (age, height, weight, percent body fat, lean tissue mass, Tanner stage, physical activity), dietary (calcium and vitamin D), pQCT (total density, total area, trabecular density, cortical density, cortical area, cortical thickness), DXA (whole body BMD, total bone area, dominant and non-dominant leg BMD, hip aBMD), QUS (SOS at the dominant and non-dominant radius, and tibia), forceplate (relative power, absolute power, absolute force, speed), grip strength, isometric (peak torque, maximum average peak torque, maximum average peak torque relative to body weight for flexion and extension, agonist/antagonist ratio) and isokinetic (peak torque, peak torque relative to body weight, the maximum total work for the repetitions, average power, the maximum average peak torque for extension and flexion, and the range of motion and the agonist, antagonist strength ratio) leg strength measures. A 2-way ANOVA was used to examine group (skier vs. control) by condition interaction for weight-bearing (leg) vs. non-weight-bearing (arm) bone outcomes, and dominant vs. non-dominant arm bone outcomes. Significance level was set at $p \leq 0.05$ for all analyses. Pearson-product moment correlation analysis was used to examine the relationship between bone density and geometry measures, and muscle cross-sectional area. STATISTICA analysis software (version 5, 1997 edition) was used for all calculations.

Power calculations were performed using the Power Calculator on the UCLA website: calculators.stat.ucla.edu/powercalc/. The power calculation used to determine the number of participants required for the current study used the means and standard deviations of significant findings from the study by Petterson and collegues (92) that studied bone outcome measures in adolescent female cross-country skiers. Power calculations performed on the data from the current study were completed in the same manner; the means and standard deviations of each group for the bone outcome measures of interest were entered into the power calculator to determine the number of participants required to find a significant difference between the groups. A significance level of $p \leq 0.05$, and a power of 0.8 was used for all power calculations.

RESULTS

Descriptive and Physical Characteristics.

There were no differences between cross-country skiers and controls for age, height, weight, Tanner stage, or lean tissue mass (see Table 1). However there was a trend for lower percent body fat for skiers (p=0.06).

Table 1: Descriptive and physical characteristics of skiers (n=13) and controls (n=15).

Descriptive	Skiers		Controls		
Measure	Mean	SD	Mean	SD	p-value
Age (years)	17.3	1.1	17.9	1.7	0.317
Height (cm)	177.1	4.1	179.2	8.1	0.413
Weight (kg)	70.2	8.3	74.8	12.5	0.261
% Body Fat	12.4	4.3	16.8	7.0	0.062
Lean Tissue (kg)	55.7	55.9	55.8	66.7	0.970
Tanner Stage	4.8	0.6	4.5	0.5	0.163
Physical Activity (h/wk)	11.3	3.9	5.7	3.4	0.0006*
Time Skiing (h/wk)	8.3	3.1	N/A	N/A	N/A

*significantly different between groups, p<0.001

QUS

There were no differences between skiers and controls in speed of sound at the dominant radius, non-dominant radius, or tibia (Figure 6).

DXA

No differences were found between skiers and controls for whole body bone mineral density (Figure 7A), total bone area (Figure 7B), dominant leg bone density, non-dominant leg bone density(Figure 7C), and total hip areal bone mineral density (Figure 7D).

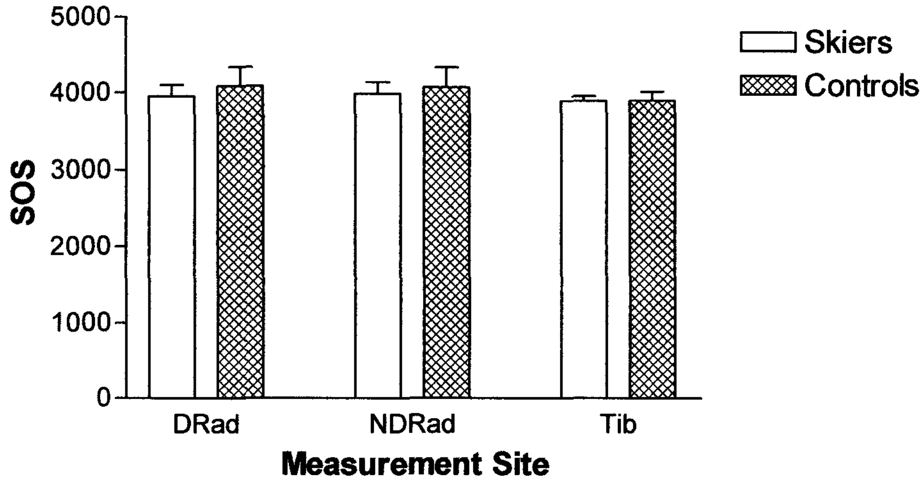


Figure 6: Speed of sound (SOS) at the distal radius of the dominant (DRad) and non-dominant (NDRad) radii, and the proximal dominant tibia (Tib) of the skiers and controls.

PQCT

There were no differences between skiers and controls in total bone density, trabecular bone density, or total bone area at the 4% radius of the dominant and non-dominant arm, or at the 4% dominant tibia (Figure 8). Likewise, there were no differences for any of the measures of bone density (Figure 9), geometry (Figure 10) or biomechanical properties (Figure 11, 13) between skiers and controls at the 66% radius of the dominant and non-dominant arms, or, with the exception of mean cortical thickness ($p=0.02$; higher in skiers), for the density (Figure 9), geometry (Figure 10) or biomechanical properties (Figure 12, 13) at the 66% dominant tibia.

There were no differences in muscle area (Figure 14A) or the bone to muscle area ratio (Figure 14D) between skiers and controls at the 66% radius of the dominant and non- dominant arm, or at the 66% level of the tibia.

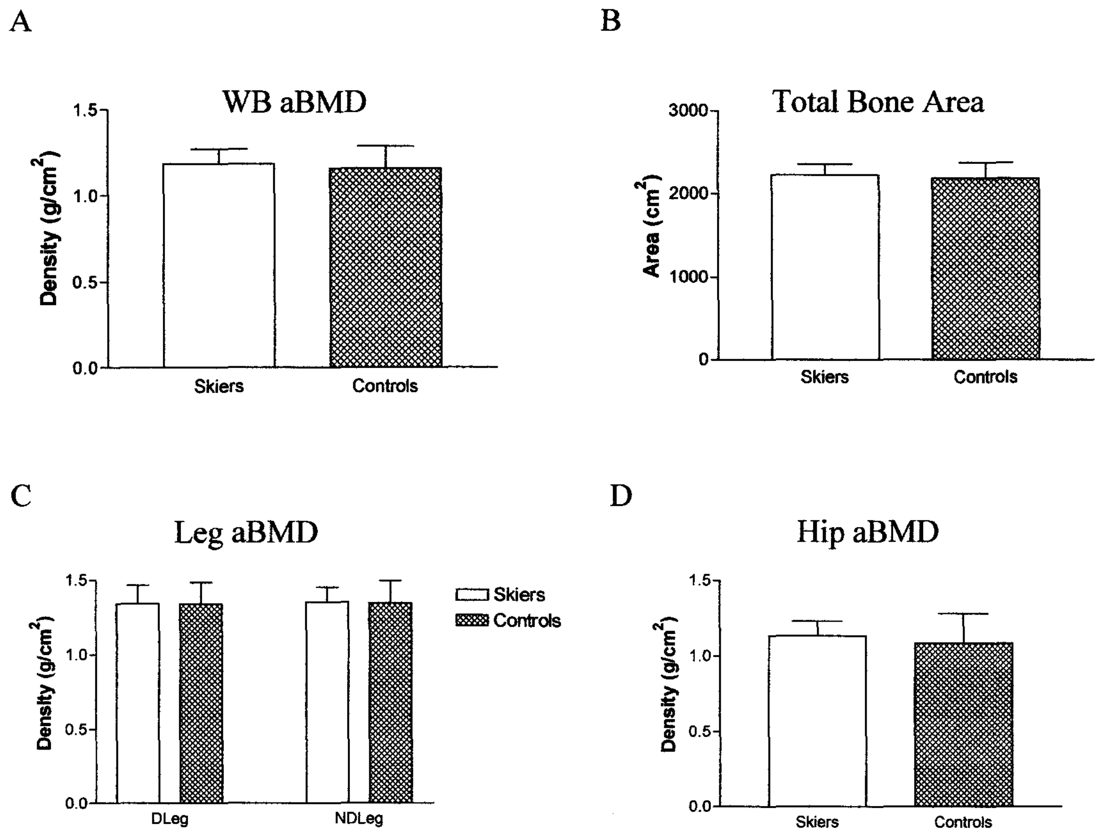


Figure 7: A: Whole body bone mineral density of the skiers and controls. B: Total bone area of the skiers and controls. C: Bone mineral density of the dominant (DLeg) and non-dominant (NDLeg) legs of the skiers and controls. D: Dominant hip areal bone mineral density of the skiers and controls.

For the dominant radius, skiers had a significantly lower fat area (p=0.03) (Figure 14B) and fat to muscle area ratio (p=0.02) (Figure 14C) compared to controls. There were no differences between skiers and controls for fat area (Figure 14B) or the fat to muscle area ratio (Figure 14C) at the non-dominant radius. At the 66% tibia site, skiers had a significantly lower fat to muscle area ratio (p=0.03) (Figure 14C), and there was a trend (p=0.07) for skiers to have a lower fat area compared to controls (Figure 14B).

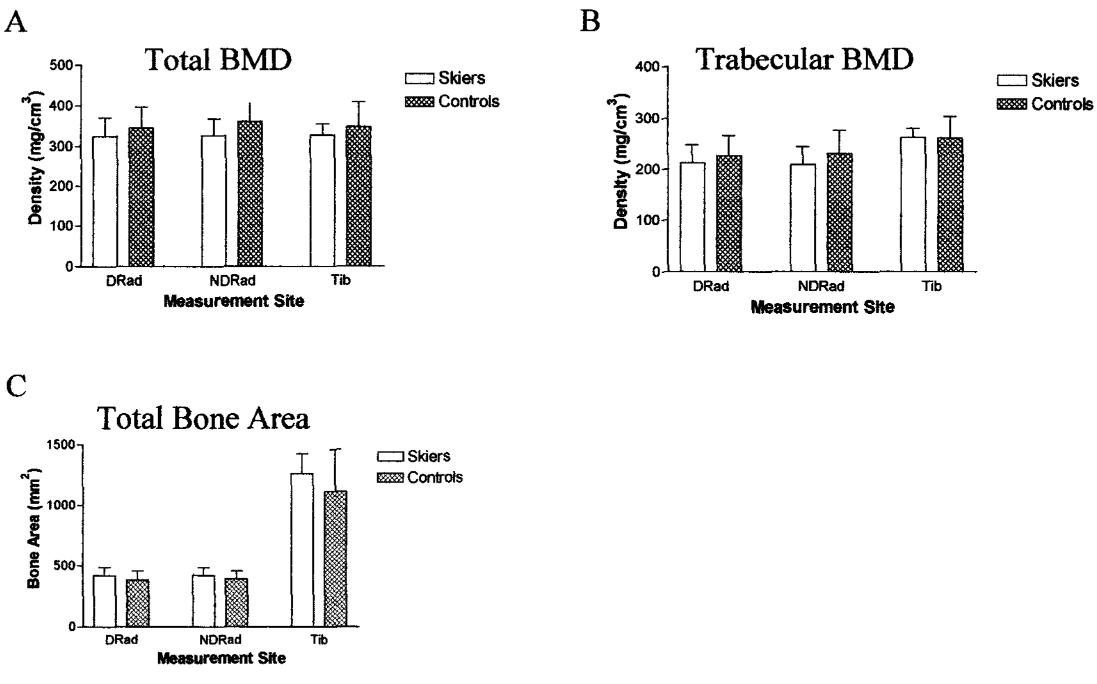


Figure 8: A: Total bone density for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib). B: Trabecular bone density for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib). C: Total bone area for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia of the skiers and controls at the 4% level.

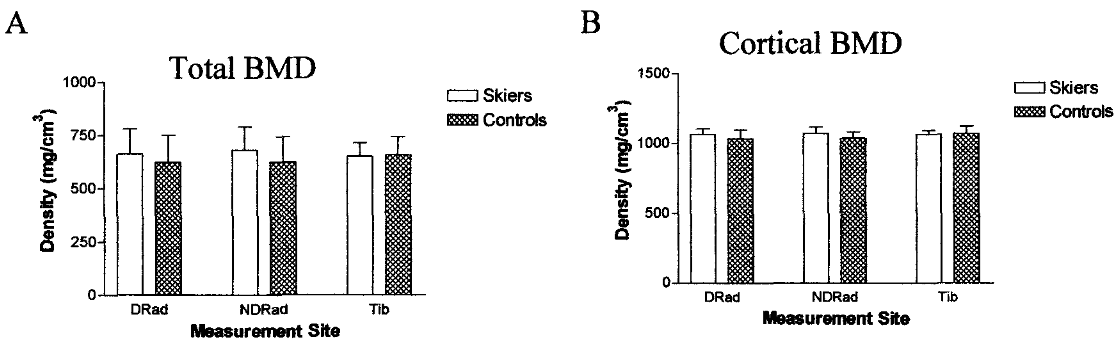


Figure 9: A: Total bone density of the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib). B: Cortical bone density for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib) of the skiers and controls at the 66% level.

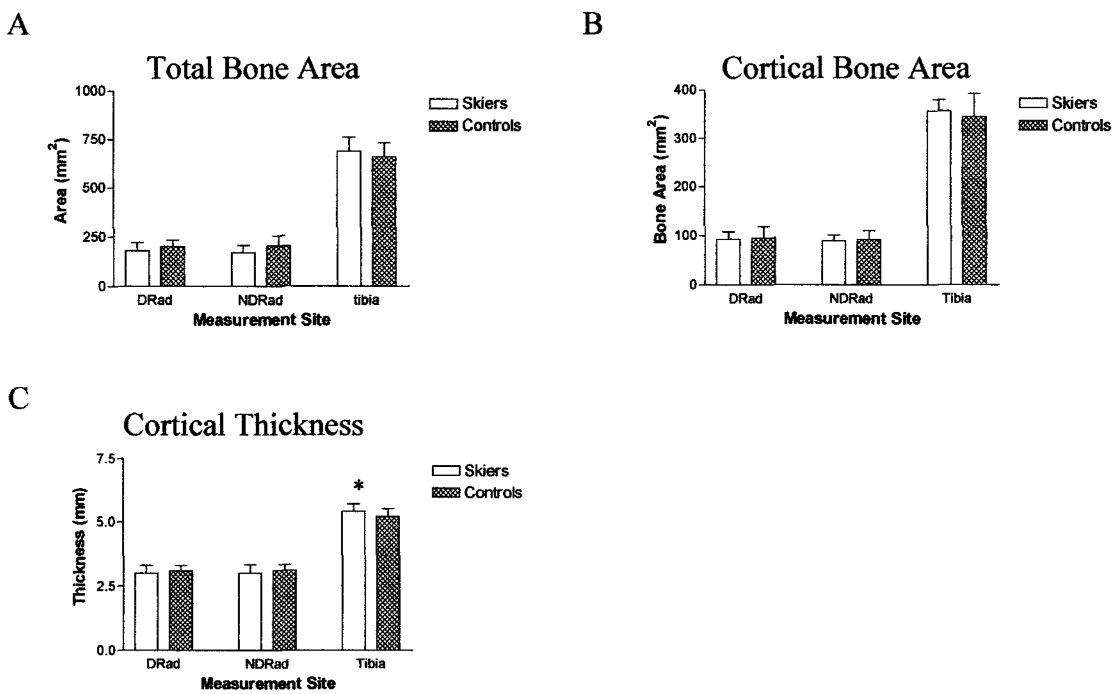
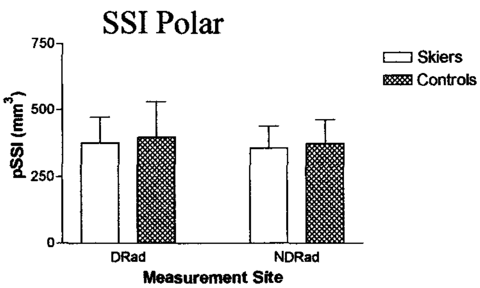


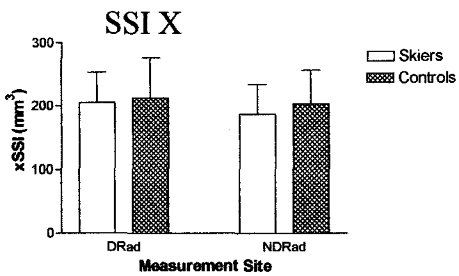
Figure 10: A: Total bone area for the domiant (DRad) and non-dominant (NDRad) radii, and the dominant tibia. B: Cortical bone area for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia. C: Cortical thickness for the dominant (DRad)

and non-dominant (NDRad) radii, and the dominant tibia of the skiers and controls at the 66% level. (*significantly different between groups, p<0.05).

A



B



C

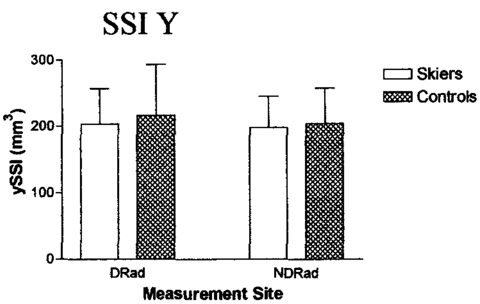


Figure 11: Stress Strain Index (SSI) of the skiers and controls at the 66% level, A: in the Polar direction for the dominant (DRad) and non-dominant (NDRad) radii. B: in the X direction for the dominant (DRad) and non-dominant (NDRad) radii. C: in the Y direction for the dominant (DRad) and non-dominant (NDRad) radii.

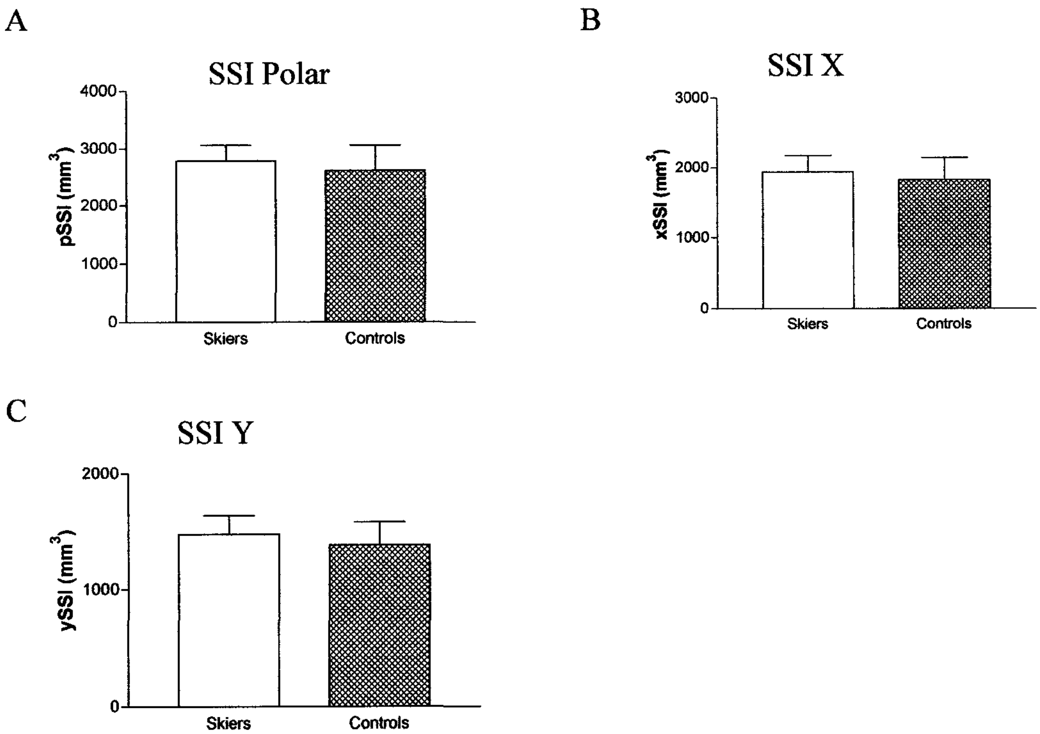


Figure 12: Polar stress strain index (pSSI) of the skiers and controls at the 66% level, A: in the Polar direction for the dominant tibia. B: in the X direction for the dominant tibia. C: in the Y direction for the dominant tibia.

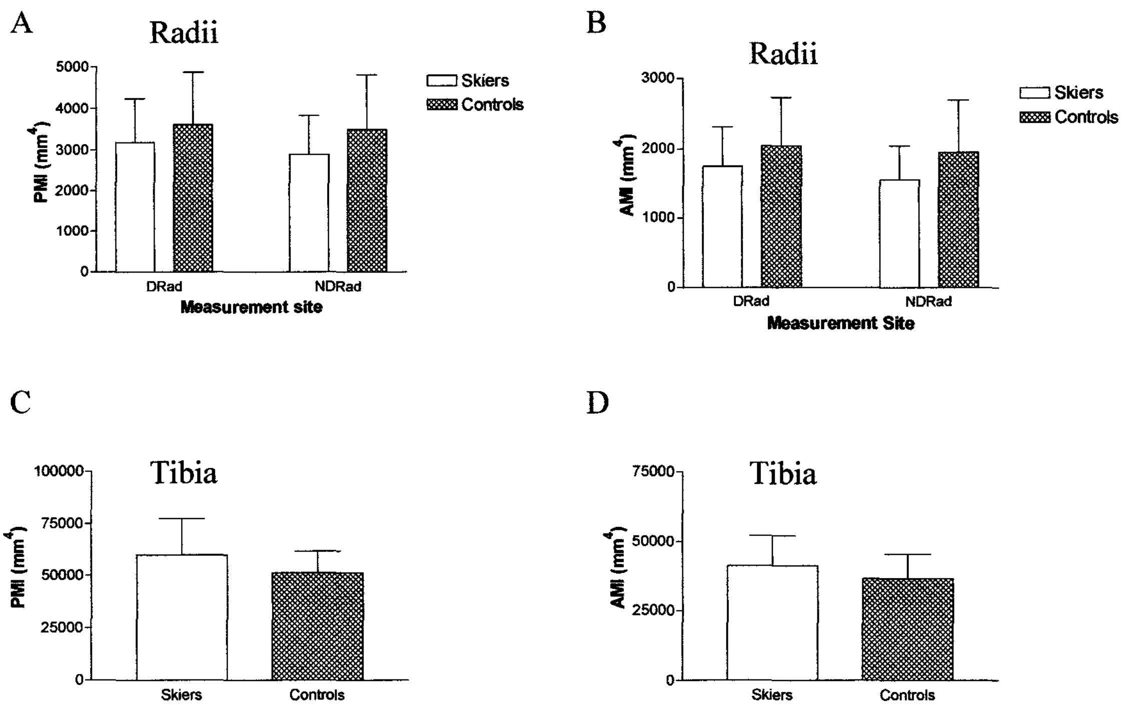


Figure 13: A: Polar moment of inertia (PMI) for the dominant (DRad) and non-dominant (NDRad) radii. B: Axial moment of inertia (AMI) for the dominant (DRad) and non-dominant (NDRad) radii. C: Polar moment of inertia (PMI) for the dominant tibia. D: Axial moment of inertia (AMI) for the dominant tibia of the skiers and controls at the 66% level.

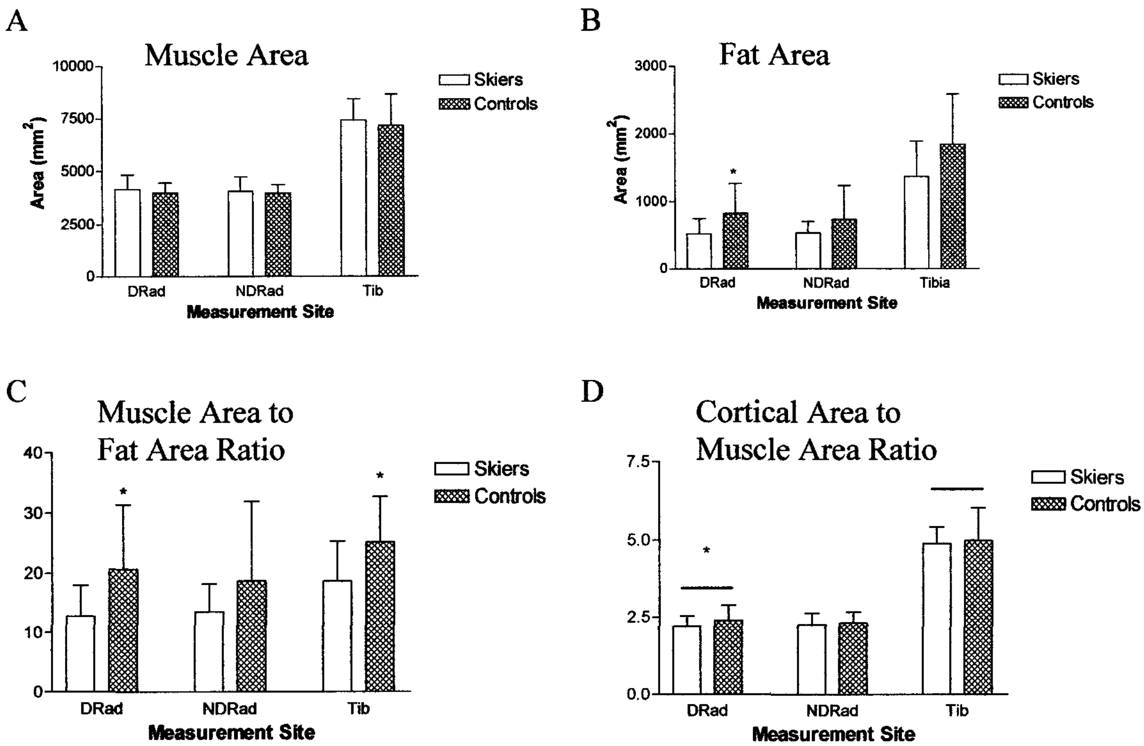


Figure 14: A: Muscle cross-sectional area for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib). B: Fat cross-sectional area for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib). C: Ratio of fat to muscle area for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib). D: Ratio of bone to muscle area for the dominant (DRad) and non-dominant (NDRad) radii, and the dominant tibia (Tib) for the skiers and controls at the 66% level. (*significantly different at $p<0.05$).

Strength Measures

There were no differences between skiers and control for force platform measures of power relative to body weight, or absolute power and speed (Table 2). Skiers had significantly higher jumping forces ($p<0.001$) during the counter movement jump compared to controls (Table 2). There were no differences in grip strength between skiers and controls for either the dominant or non-dominant arms (Table 3).

No differences were found for leg isometric peak torque, maximum average peak torque, maximum average peak torque relative to body weight, or the agonist/antagonist strength ratio between skiers and controls (Table 4).

Likewise, there were no differences between skiers and controls for isokinetic leg extension peak torque, peak torque relative to body weight, maximal repetition total work, average power, or maximum average peak torque measured at 60 deg/s (Table 5). For leg flexion measures at 60deg/s there were no differences between skiers and controls for peak torque, maximum repetition total work, or maximum average peak torque (Table 5); however, skiers had significantly higher values for leg flexion peak torque relative to body weight ($p=0.02$), average power ($p=0.03$), and the agonist/antagonist strength ratio ($p=0.001$) compared to controls (Table 5) at this specific contraction velocity.

There were no differences between skiers and controls for isokinetic (90deg/s) leg extension peak torque, peak torque relative to body weight, maximal repetition total work, average power, or maximum average peak torque (Table 6). Likewise, no differences were found between skiers and controls at 90deg/s isokinetic leg flexion for peak torque, maximum repetition total work, or maximum average peak torque (Table 6). However, differences were found between skiers and controls for peak torque relative to body weight for leg flexion ($p=0.03$), average power for leg flexion ($p=0.05$) and the agonist/antagonist ratio ($p=0.01$) with skiers having higher values compared to controls (Table 6).

Table 2: Relative power, force, speed and power during counter movement jumps in skiers and controls.

Measure	Skiers		Controls		
	Mean	SD	Mean	SD	p-value
Power (W/kg)	47.06	4.60	46.34	5.79	0.721
Force (kN)	2.77	0.65	1.52	0.21	<0.001
Speed (m/s)	2.64	0.14	2.61	0.22	0.648
Power (kW)	3.36	0.55	3.39	0.51	0.874

Table 3: Grip strength in kilograms of skiers and controls for the dominant and non-dominant hands.

Measure	Skiers		Control		
	Mean	SD	Mean	SD	p-value
Dom Hand (kg)	52.0	9.3	46.9	11.2	0.205
Non-Dom Hand (kg)	50.0	8.9	46.4	8.4	0.287

At 300deg/s no differences were found between groups for leg extension or flexion peak torque relative to body weight, maximum repetition total work, average power, maximum average peak torque or flexion peak torque (Table 7). Controls had significantly ($p=0.02$) higher peak torque leg extension strength compared to skiers at a speed of 300deg/s (Table 7). The agonist/antagonist strength ratio was significantly higher in skiers compared to controls ($p=0.01$) at the 300deg/s speed (Table 7).

Table 4: Measures of peak torque (Peak TQ), maximum average peak torque (Max Avg Peak TQ), maximum average peak torque relative to body weight (Max Avg Peak TQ BW), and the agonist to antagonist ratio (Ag/Antag) during isometric leg extension at 120 degrees of knee flexion in skiers and controls.

MEASURE		Skiers		Controls		
		Mean	SD	Mean	SD	p-value
Peak TQ (N•m)	Extension	168.0	36.9	191.4	63.9	0.328
	Flexion	118.0	26.1	116.0	29.5	0.870
Max Avg Peak	Extension	159.5	37.8	176.0	58.5	0.460
TQ (N•m)	Flexion	110.2	23.9	109.3	27.5	0.936
Max Avg Peak	Extension	236.1	49.1	238.6	64.8	0.922
TQ BW (%)	Flexion	162.0	25.1	150.9	38.2	0.449
Ag/Antag		71.4	15.6	63.6	14.0	0.215

Table 5: Measures of peak torque (Peak TQ), peak torque relative to body weight (Peak TQ BW), maximum repetition total work (Max Rep Tot Work), average power (Avg Power), maximum average peak torque (Max Avg Peak TQ), and the agonist to antagonist ratio (Ag/Antag) during isokinetic leg flexion/extension exercise at 60deg/s in skiers and controls.

MEASURE		Skier		Control		
		Mean	SD	Mean	SD	p-value
Peak Torque	Extension	178.2	33.5	186.8	36.2	0.570
(N•m)	Flexion	121.5	30.7	102.2	27.0	0.123
Peak TQ BW	Extension	263.4	38.6	258.4	51.3	0.804
(%)	Flexion	178.3	34.7	140.8	34.6	0.018*
Max Rep Tot	Extension	132.7	25.0	153.8	37.4	0.150
Work (J)	Flexion	114.8	35.4	91.0	29.7	0.091
Avg Power	Extension	97.4	15.8	104.7	30.4	0.515
(N)	Flexion	84.4	26.4	62.8	20.1	0.034*
Max Avg Peak	Extension	150.8	18.4	150.7	47.6	0.994
TQ (N•m)	Flexion	110.3	30.1	88.1	26.7	0.074
Ag/Antag		68.5	14.0	54.2	4.0	0.001*

*significantly different at $p<0.05$

Table 6: Measures of peak torque (Peak TQ), peak torque relative to body weight (Peak TQ BW), maximum repetition total work (Max Rep Tot Work), average power (Avg Power), maximum average peak torque (Max Avg Peak TQ), and the agonist to antagonist ratio (Ag/Antag) during isokinetic knee flexion/extension exercise at 90deg/s in skiers and controls.

MEASURE		Skier		Control		
		Mean	SD	Mean	SD	p-value
Peak Torque	Extension	157.5	28.8	163.1	27.4	0.634
(N•m)	Flexion	109.3	27.4	94.9	20.4	0.156
Peak TQ BW	Extension	233.3	37.2	224.5	34.3	0.560
(%)	Flexion	160.8	33.8	130.8	27.4	0.026*
Max Rep Tot	Extension	126.2	25.0	142.0	28.7	0.185
Work (J)	Flexion	103.8	31.6	87.0	24.0	0.154
Avg Power (N)	Extension	130.6	23.8	138.1	31.5	0.546
	Flexion	111.0	38.1	84.7	24.1	0.049*
Max Avg Peak	Extension	141.9	26.8	141.9	30.4	0.992
TQ (N•m)	Flexion	101.8	29.7	84.2	21.3	0.105
Ag/Antag		69.5	14.8	58.0	5.4	0.011*

* significantly different at p<0.05

Table 7: Measures of peak torque (Peak TQ), peak torque relative to body weight (Peak TQ BW), maximum repetition total work (Max Rep Tot Work), average power (Avg Power), maximum average peak torque (Max Avg Peak TQ), and the agonist to antagonist ratio (Ag/Antag) during isokinetic knee flexion/extension exercise at 300deg/s in skiers and controls.

MEASURE		Skier Mean	SD	Control Mean	SD	p-value
Peak Torque	Extension	88.6	18.0	121.2	34.0	0.020*
(N•M)	Flexion	88.9	22.4	92.0	33.9	0.818
Peak TQ BW	Extension	131.6	21.5	166.3	46.9	0.062
(%)	Flexion	131.9	29.4	124.9	41.4	0.678
Max Rep Tot	Extension	65.5	15.9	76.2	17.5	0.165
Work (J)	Flexion	60.0	18.3	53.6	15.7	0.388
Avg Power	Extension	150.1	25.5	163.3	38.6	0.395
(N)	Flexion	140.9	52.0	112.2	55.3	0.241
Max Avg Peak	Extension	75.4	14.9	97.4	30.7	0.071
TQ (N•M)	Flexion	74.1	17.2	72.6	21.1	0.868
Ag/Antag		101.8	23.8	76.5	18.1	0.009*

*significantly different at $p<0.05$

Muscle and Bone Relationships

Data were combined for both groups since there were no differences in muscle area, bone density or bone area between skiers and controls. Significant correlations were found between muscle area and total bone mineral content at the 66% level of the dominant radius ($r=0.52$), non-dominant radius ($r=0.51$) and tibia ($r=0.51$), and between muscle area and total bone area at the non-dominant radius ($r=0.43$) and tibia ($r=0.51$). Muscle area was significantly correlated with cortical bone mineral content (BMC) at the dominant radius (r=0.44) and the non-dominant radius (r=0.44), and cortical bone area at the dominant radius (r=0.49), non-dominant radius (r=0.48) and tibia (r=0.48) (Table 8). No other relationships were found between the muscle area and measures of bone material properties or bone geometry (Table 8).

Weight Bearing vs. Non-weight Bearing Bone Density Contrasts

Trabecular bone mineral density at the 4% tibia was significantly higher ($p=0.001$) than trabecular bone mineral density at the 4% dominant radius (Table 9). No other differences were found between weight bearing and non-weight bearing sites for total bone mineral density at the 4% or 66% sites, or for cortical bone mineral density (Table 9). No differences were found between skiers and controls for any of the bone density measures (Table 9). However, the cortical CSA to muscle CSA ratio is significantly lower at the radius compared to the tibia ($p<0.01$) (Figure 14D); data was collapsed between groups for this comparison as there were no between group differences.

Dominant vs. Non-dominant Arm Bone Mineral Contrasts

Cortical bone mineral content was significantly higher in the dominant arm compared to the non-dominant arm (Table 10). No side to side differences were found for trabecular bone mineral content or total bone mineral content at the 4% or 66% levels (Table 10). No interaction was found between groups or condition for bone measures and arm dominance (Table 10).

Dietary Factors- Calcium and Vitamin D

Based on the reported frequency of consumption of calcium containing foods (i.e. milk, yogurt, cheese, cottage cheese, sour cream and ice cream/milk), there were no differences between skiers and controls. Only two skiers and one control reported the use of a multivitamin supplement. Similarly, only one control reported taking a calcium supplement, however, the control also reported only taking the supplement once a month. Unfortunately a large portion of vitamin D comes from the sun, therefore, it is not possible to accurately quantify and compare this variable between groups.

Table 8: Correlations between total bone mineral content (Tot BMC), total bone mineral density (Tot BMD), total area, cortical bone mineral content (Cort BMC), cortical bone mineral density (Cort BMD), cortical area (Cort Area), and cortical thickness (Cort thick) with muscle area at the dominant radius (DOM RAD), non-dominant radius (NDOM RAD) and dominant tibia.

Measure	DOM RAD	NDOM RAD	TIBIA
Tot BMC	0.52*	0.51*	0.51*
Tot BMD	0.11	-0.11	-0.04
Tot Area	0.30	0.43*	0.51*
Cort BMC	0.44*	0.44*	0.38
Cort BMD	0.07	0.03	-0.16
Cort Area	0.49*	0.48*	0.48*
Cort thick	0.30	0.39	0.35

*significantly different from 0

Table 9: P-values for differences in total bone (Tot BMD) and trabecular bone mineral density (Trab BMD) at the 4% site, and total bone (Tot BMD) and cortical bone mineral density (Cort BMD) at the 66% site in weight bearing (dominant tibia) versus non-weight bearing (dominant radius) limbs.

Bone Measure	Group	Arm vs Leg	Interaction
Tot BMD 4%	0.240	0.677	0.981
Trab BMD 4%	0.623	<0.001*	0.287
Tot BMD 66%	0.734	0.828	0.401
Cort BMD 66%	0.645	0.114	0.114

*significantly different at $p<0.05$, higher in the tibia

Table 10: P-values for differences in total bone (Tot BMC), and trabecular bone mineral content (Trab BMC) at the 4% site, and total bone (Tot BMC) and cortical bone mineral content (Cort BMC) at the 66% site between dominant (DOM) and non-dominant (NDOM) arms of the participants.

Measure	Group	DOM/NDOM	Interaction
Tot BMC 4%	0.755	0.698	0.352
Trab BMC 4%	0.913	0.917	0.781
Tot BMC 66%	0.099	0.225	0.593
Cort BMC 66%	0.547	0.018*	0.241

*significantly different at $p<0.05$, higher in dominant arm

DISCUSSION

Influence of Cross-country Skiing on Bone Outcome Measures

Only one difference between cross-country skiers and controls was reported for the bone outcome measures for the present study, suggesting that the mechanical forces, whether external or internal, placed on the skeleton during cross-country skiing were not sufficient to cause differential adaptation in bone. In addition, the fact that no differences were found in the height, weight, percent body fat, lean tissue mass, Tanner stage and age between the skiers and controls supports the finding that mechanical loading during skiing was probably not above the normal physiological range to elicit significant skeletal adaptations. Cortical thickness at the 66% site of the tibia was the sole bone outcome measure to differ between skiers and controls. This difference may be attributed to differing levels of physical activity as this was the sole descriptive characteristic in the study to differ between groups. Alternatively, since these contrasts were not adjusted for multiple comparisons, it is also possible that this sole difference between groups could simply be explained by chance.

When this study is compared to the study of adolescent female cross-country skiers (92) similarities are found in age, stage of maturation and training hours; however, the results of the studies are very different. Female cross-country skiers had higher BMD at the left and right humerus, left humerus diaphysis, femoral neck, femoral diaphysis and greater trochanter, and BMAD at the femoral neck when compared to controls. In the present study, no differences were found in any of the DXA bone measures between skiers and controls. In the study of female cross-country skiers, only one DXA scan was performed on each participant and then regional analysis was performed; however, this regional analysis may not have provided an accurate or sensitive enough measure of bone outcomes for comparison. So although there were no differences in the present study, the measurement methods were more sensitive. The differences found in bone measures in female cross-country skiers (92) may also be attributed to larger differences in activity levels between the skiers and control participants. The activity levels of the female controls may have been much lower than the activity level of the male controls in the present study since adolescent females tend to be much less active than males. The inactive female controls were participating in less than 2.5 hours of physical activity per week (92), whereas in the current study the inactive controls participated, on average in 5.7 hours of physical activity per week.

It has been suggested that more than 6 hours a week of mechanical loading is required before differences will be seen in bone measures (59). When comparing the reported levels of physical activity between the skier and control groups, this difference is found to be only 5.4 hours. This raises the question as to whether or not the differences in level of physical activity were, although statistically different, physiologically sufficient to cause differences in bone. If a less active control group had been used, then it is possible that more differences in bone measures may have been found.

The only difference found within the pQCT bone measures of the skiers and the controls was a significantly higher mean cortical thickness at the 66% tibia of the skiers. The age of the participants does correspond with a critical time within the lifespan for developing bone mass (6) and more specifically this measurement has been reported to have large increases between the ages of 13 and 18 years (85). This fact could account for why this was the only site where a between group difference was found within the bone measures. However, other factors must be taken into consideration before any conclusions can be drawn. The cortical thickness was calculated by mean cortical thickness rather than the circular ring model. The mean cortical thickness measurement derives thickness by calculating the distance between the inner and outer edges of the cortical shell. The circular ring model assumes that the tibia is perfectly round when subtracting the inner edge of the cortical shell from the outer edge. Unfortunately no difference was found between skiers and controls for cortical thickness based on the circular ring model (data reported in Appendix D). The discrepancy in these findings raises the question of the significant difference being a result of statistical error. This theory is supported by the low statistical power (0.39) associated with the significant difference in mean cortical thickness.

Bone adaptation to mechanical loading (20, 31, 32, 33, 52, 55, 121, 118, 100) can be a result of either muscle contractile forces or ground reaction forces acting on the skeleton. Although not measured directly in this study, skiers tend to have a high proportion of slow twitch fibers, which produce weaker contractions, than fast twitch fibers (102). This could potentially explain why no differences in bone measures were found between the skiers and controls; the muscle contractile forces were probably not of sufficient magnitude to cause an adaptation within bone. It could then be concluded that the forces placed on the skeleton during skiing were all within the normal MES range.

The leg muscle strength and power measures indicate that the skiers produced higher forces during the counter movement jump, and had higher peak torque relative to body weight and average power for leg flexion at 60 and 90deg/s than controls. However, no differences were found between the skiers and controls during isometric leg strength assessment. Further, when strength was measured at a kicking speed of 300deg/s the controls were found to have higher peak torque during extension. The few differences in leg muscle strength at relatively non-specific slow contraction speeds and lack of differences in forearm strength between groups support the finding that muscle forces were not sufficiently different between groups to elicit differences in bone outcome measures between the skiers and controls in the present study. These results are in agreement with the literature which shows correlations between leg strength and bone mineral density within adolescent male populations (90), and the theory that muscle force is very important for bone health (38).

Higher than normal bone measures have been reported for males sprinters and endurance runners (10), tennis players (17, 45), powerlifters (115), hockey players (89, 91), soccer players (59), and volleyball players (18). Based on the classification by Kemper and colleagues, these sports have peak strain ratings of 2 or 3 (only volleyball had a rating of 3), suggesting ground reaction forces between 2 to 4 (for peak strain score of 2) or more than 4 (peak strain score of 3) times body weight (61, 63). The ground reaction forces at the lower legs of skiers were reported as only being between 1.2 and 2 times body weight (63, 106). Skiers in the present study were likely not producing high enough forces to cause adaptation to the bone, at least not at a high enough magnitude to cause large adaptation within bone. High impact loading is also thought to be better for inducing changes in bone measures than low impact loading (113). The fact that cross-country skiing is considered a low impact sport, supports the findings of this study whereby no differences were found between skiers and controls.

Although the arms experience ground reaction forces as a result of poling, the poling forces also appear to be insufficient to cause adaptation of bone in the present study. No differences were evident between the skiers and controls for any of the bone measures at either measurement site (4% and 66% levels) in the arms. However, trabecular bone density in the tibia was higher than in the dominant radius at the 4% or 66% level. This suggests that the ground reaction and/or muscle contractile forces in the tibia were sufficiently higher than those in the arm to cause a differential effect for this potentially more sensitive bone outcome measure. However, it would appear as though an adaptation in bone geometry accounts for the different magnitudes of mechanical loading. These results are consistent with a study done in soccer players where no differences were seen in non-weight bearing sites between athletes and controls but differences were found in weight bearing sites (59). If poling forces (ground reaction force and muscle force) were higher in cross-country skiing, there would be potential for greater bone differentiation between groups, evident even in the arms. A more timely and sensitive assessment of the effects of poling forces on bone measures in the arm would be accomplished by performing the measurements after the summer and fall training, following this period of high volume of roller skiing. Roller skiing produces much higher poling forces, because the poles are planted in pavement which is a much harder surface (95).

Similar to the pQCT results for bone, no differences were found between the groups for bone density measures using DXA for the whole body or hip scans. DXA may not have been a sensitive enough technique to find differences between the groups. However, using BMAD with DXA allows for the reduction in the error caused in BMD measures as a result of bone size (86). Other studies have found differences between athlete groups using DXA measures (10, 26, 57), including a study done on female cross-country skiers (92). Considering the number of studies that have found differences using DXA, it is much more likely that the mechanical loading was not sufficient in the present study to cause a significant adaptation to bone. Alternatively, the difference between our study of males and the previous study of cross-country female skiers may be attributed to an exercise training-sex interaction. The possibility of a sex difference in responsiveness to training among adolescents has not been investigated and warrants further follow-up.

Muscle-Bone Relationships

Interestingly, no differences were found for muscle cross-sectional area at either the forearm or tibia between skiers and controls. As well, the muscle-bone area ratios were similar between the two groups. Unfortunately very little research has been done examining muscle cross-sectional area and the bone-muscle area ratio within athletes using the pQCT method of measurement. However, muscle cross-sectional area has been reported to be positively associated with bone geometry, more specifically cortical bone area (98). If muscle area is a surrogate measure of local muscle force and is an important determinant of bone adaptation then these findings support this theory, as only one bone measure was found to be different between the skiers and controls in this study. Positive correlations were found between muscle area and the bone measures of BMC, cortical BMC, and cortical bone area. The correlation between muscle area and cortical area at the tibia is consistent with findings from other studies (98), however, the other relationships have not been reported in the literature. Muscle area measures were only correlated with bone measures at the 66% site as this was the location of the muscle area measurement. Taken together, these findings confirm a general putative relationship between muscle and selected bone outcomes, but also suggest that the muscle force involved in cross-country skiing is not sufficiently different from controls to alter this relationship or to differentiate bone outcomes in skiers. The findings of this study then, are generally consistent with the literature which finds significant correlations between selected bone geometry measures and muscle force (98, 103, 104) and with the underlying premise of the strain threshold hypothesis postulated by the Mechanostat theory (32, 33).

The ratio of cortical CSA to muscle CSA was significantly lower at radius compared to the tibia suggesting regional variations in the muscle bone relationship between weight-bearing and non-weight-bearing sites. This calculation was done using the cortical area of only the radius or tibia, consistent with the method used by Schoenau and colleagues (104). However, if the cortical area of the second bone (ulna or fibula, in the arm or leg, respectively) was included in the calculation of bone area, as in the method used by Rittweger and colleagues (98), the difference in the bone to muscle ratio between weight-bearing and non-weight bearing sites is eliminated. Therefore, according to the second method of calculation of the muscle-bone relationship, there is a universal or invariable relationship between muscle and bone areas that appears independent of skeletal site. This finding suggests not only the potential importance of the muscle-bone relationship but also the importance of the method used to calculate this ratio as it could drastically impact the interpretation of results. The comparison of the muscle-bone relationship between weight-bearing and non-weight-bearing sites is a unique finding from this study, as the author is not aware of any other study to have reported this relationship within the same population.

Influence of Arm Dominance on Bone Outcome Measures

Differences have been found in bone measures between dominant and non-dominant arms of male racket sport athletes (17, 45) and volleyball players (17). These results combined with the reports of higher poling forces in the dominant arm of cross-country skiers (74,106) would anticipate differences between the dominant and non-dominant arm measures of the skiers in the present study. However, this was not the case, as no differences were seen for any of the bone measures at either the 4% or 66% radius sites between the dominant and non-dominant arms of the skiers. Therefore, it is likely that the difference in force production between the arms was not sufficient to cause any adaptation in bone in the present study. These results are consistent with another study in cross-country skiers that reported no difference in arm bone measures among the athletes but did report significant differences in the controls (92). Forearm strength, as measured by grip strength, did not differ between the skiers and controls; this data is consistent with the finding of no differences in muscle area between the two groups at the radius, and supports the hypothesis that muscle forces were not sufficiently high or different between arms to elicit significant skeletal adaptations at this site in the present study.

The fat area of the dominant radius was significantly lower in the skiers compared to controls and a trend for lower fat area was also found at the proximal tibia in the skiers. As well, the fat to muscle area ratio was found to be significantly lower in skiers in the dominant radius and tibia. These results are consistent with the trend for lower percent body fat within the skiers. Also, the lower overall body fat percent and regional areal distribution among skiers may reflect preferential utilization of fat as fuel for this predominantly aerobic activity. As well, based on the bone outcome measures, the muscle contractile forces were low suggesting a lower activity intensity and therefore, a higher proportion of fat used as fuel.

Dietary Influences

Calcium and Vitamin D are two important nutrients in the diet having an impact on bone (5), and must be taken into consideration when examining bone outcome differences associated with exercise. In the present study, there were no differences in the frequency of consumption of calcium containing foods between the skiers and controls, eliminating the confounding effect that dietary calcium could have on the bone outcome measures. Unfortunately, providing an accurate quantification of Vitamin D status for comparison between the skiers and controls was difficult since it not only comes from the diet, but is also synthesized in the body as a result of sunlight exposure. Although skiers were spending more time exposed to sunlight as a result of their training, the reduced daylight hours in the winter and limited skin exposure may not have been enough to result in significantly different amounts of Vitamin D between the skiers and controls.

Limitations

The study was limited by access to high level skiers, mostly due to the location of the testing (only one skier lived within the Hamilton area). The study design also provided some limitation to data interpretation. With a cross-sectional design such as was used in this study, it is assumed that any difference between groups is a result of the physical activity, if all other potentially confounding variables are similar. In the present study, since no differences were found in these putative confounding variables due to careful matching, then the assumption is that observed differences may be attributed to differences in physical activity level.

The limited findings and interpretation of the data in this study suggest that cross-country skiing does not provide sufficient enhanced mechanical loading to elicit differential bone adaptations compared to controls. Unfortunately, the activity level of some of the control participants may have masked potential differences between groups, since although none of the controls competed in skiing, some were still relatively active. If the control participants were truly inactive, then it is possible that more differences may have been found. The best way to control for such a limitation would be to use a repeated measures longitudinal study design where baseline measures could have been taken and differences over a season (training and competing) could have been assessed in both the skiers and control participants. Unfortunately the second study design is much more labor intensive, expensive and logistically difficult to undertake, especially with the dispersion of the elite skiers geographically around the region. Also, with the longitudinal design there is risk of participant dropout.

Another major limitation of the current study design was the lack of control for seasonal variations in bone measures. Unfortunately, due to complications with recruitment of controls, testing of the controls did not take place until the fall and winter following the testing of the skiers. Individuals tend to be more active during the summer months because of nicer weather, therefore, controls were potentially more active during the summer than winter and their skeletons would have been adapting to this increased mechanical loading producing higher values than if tested in the spring.

Although the only significant difference between the skiers and controls was the cortical thickness at the 66% tibia, the average values for the bone outcome measures of the skiers tended to be consistently higher than those of controls. In fact, at the 4% dominant and non-dominant radii, the average total bone areas were higher in the skiers. At the 66% dominant and non-dominant radii, the average cortical density and total density were also higher; in addition at the non-dominant radius the average cortical thickness was higher in the skiers. Similarly, the total bone area and trabecular density were higher at the 4% tibia of the skiers. Total area, cortical area, SSI polar, X and Y and polar and axial moments of inertia measurements at 66% tibia were also higher in skiers compared to controls. The average DXA measures of whole body BMD, total bone area, both dominant and non-dominant leg BMD, and hip aBMD were also higher in skiers compared to controls. When power calculations were performed, at an alpha of 0.05 and a beta of 0.8, it was determined that the study would require between 31 and 371 skiers and between 31 and 495 control participants to detect statistically significant differences. Interestingly, if the number of participants had been increased to 75 (a 5 fold increase), the number of significant findings would have increased from one to eight and likely a trend for three more measures, all within the pQCT data. However the number of participants would have needed to be increased to at least 200 per group to have any significant findings with the DXA measures and that would only have lead to one significant finding. With 200 participants per group there would have been significant differences in 15 variables with the pQCT measures. These findings illustrate the better sensitivity of the pQCT for measuring smaller regional differences between groups compared to DXA. Unfortunately the feasibility of testing this number of participants within such a specialized group would have been difficult, considering the number of cross-country skiers competing at the required level.

CONCLUSION

The only difference seen between the skiers and controls was the mean cortical thickness at the 66% tibia length. Although no other differences were seen, cross-country skiing can be listed as an exercise that is not harmful to skeletal development/attainment of peak bone mass. The results also support the importance of weight bearing conditions for bone adaptation to occur, since differences were seen in BMD between the arms and legs of the participants. More research is needed to exclude cross-country skiing as a non-osteogenic sport.

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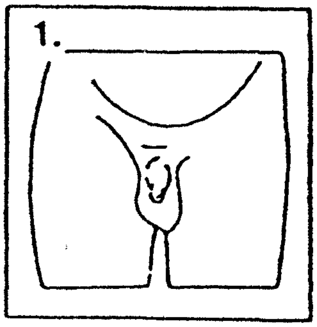
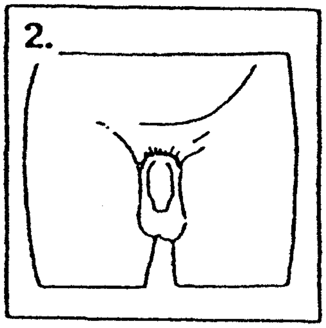
Appendix A- Tanner Stage of Maturation Assessment

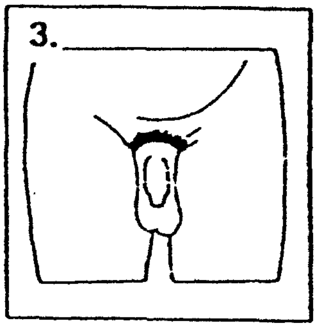
- Please look at the Pubic Hair only in these pictures.
- Please put a tick in the box that looks most like you now.

No hairs

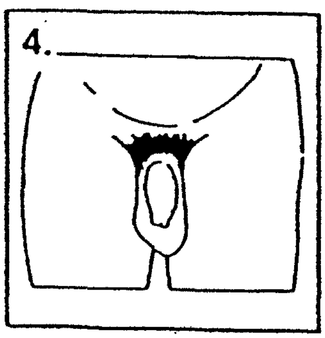




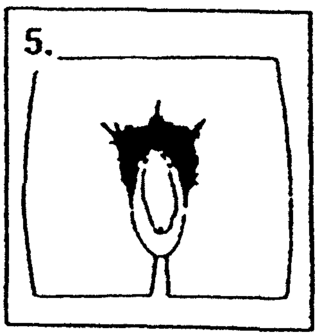
Very little hair



Quite a lot of hair



The hair has not spread over the thighs



The hair has spread over the thighs

Appendix B- Modifiable Physical Activity Questionnaire

Modifiable Activity Questionnaire for Adolescents

DATE________ NAME__________________ ID __ __ __ __

SCHOOL ______________ CLASS

1. How many times in the past 14 days have you done at least 20 minutes of exercise hard enough to make you breathe heavily and make your heart beat fast? (Hard exercise includes, for example, playing basketball, jogging, or fast bicycling; include time in physical education class)

   ( ) None
   ( ) 1 to 2 days
   ( ) 3 to 5 days
   ( ) 6 to 8 days
   ( ) 9 or more days

2. How many times in the past 14 days have you done at least 20 minutes of light exercise that was not hard enough to make you breathe heavily and make your heart beat fast? (Light exercise includes playing basketball, walking or slow bicycling; include time in physical education class)

   ( ) None
   ( ) 1 to 2 days
   ( ) 3 to 5 days
   ( ) 6 to 8 days
   ( ) 9 or more days

3. During a normal week how many hours a day do you watch television and videos, or play computer or video games before or after school?

   ( ) None
   ( ) 1 hour or less
   ( ) 2 to 3 hours
   ( ) 4 to 5 hours
   ( ) 6 or more hours

4. During the past 12 months, how many team or individual sports or activities did you participate in on a competitive level, such as varsity or junior varsity sports, intramurals, or out-of-school programs.

   ( ) None
   ( ) 1 activity
   ( ) 2 activities
   ( ) 3 activities
   ( ) 4 or more activities

   What activities did you compete in?

   ____
   ____
   ____
   ____
   ____
   ____

PAST YEAR LEISURE-TIME PHYSICAL ACTIVITY

Check all activities that you did at least 10 times in the **PAST YEAR**. Do not include time spent in school physical education classes. Make sure you include all sport teams that you participated in during the Last year.

Aerobics
Band/Drill Team
Baseball
Basketball
Bicycling
Bowling
Cheerleading
Dance Class
Football
Garden/Yard Work

Gymnastics
Hiking
Ice Skating
Roller Skating
Running for Exercise
Skateboarding
Snow Skiing
Soccer
Softball
Street Hockey

Swimming (Laps)
Tennis
Volleyball
Water Skiing
Weight Training (Competitive)
Wrestling
Others:
____
____
____

List each activity that you checked above in the "Activity" box below.
Check the months you did each activity and then estimate the amount of time spent in each activity.

Activity	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Months per Year	Days Per Week	Minutes Per Day

96

Appendix C- Lifestyle Questionnaire

Where were you born? ______________________________

Where were you parents born? Mother ____________________

Father ____________________

LIFESTYLE INFORMATION -DIET

During your childhood (from birth to present) how often did you eat/drink the following foods?

.				Frequency			
Food	Never	1-2 Times Daily	3+ Times Daily	1-2 Times Weekly	3+ Times Weekly	1-2 Times Month	3+ Times Month
Alcohol	☐	☐	☐	☐	☐	☐	☐
Tea/Coffee	☐	☐	☐	☐	☐	☐	☐
Cola/Pop	☐	☐	☐	☐	☐	☐	☐
Milk	☐	☐	☐	☐	☐	☐	☐
Yogurt	☐	☐	☐	☐	☐	☐	☐
Cheese	☐	☐	☐	☐	☐	☐	☐
Cottage Cheese	☐	☐	☐	☐	☐	☐	☐
Pizza w Cheese	☐	☐	☐	☐	☐	☐	☐
Sour Cream	☐	☐	☐	☐	☐	☐	☐
Ice Cream/Milk	☐	☐	☐	☐	☐	☐	☐
Beans	☐	☐	☐	☐	☐	☐	☐
Beets	☐	☐	☐	☐	☐	☐	☐
Broccoli	☐	☐	☐	☐	☐	☐	☐
Red Meat	☐	☐	☐	☐	☐	☐	☐
White Meat	☐	☐	☐	☐	☐	☐	☐
Foul eg. Chicken	☐	☐	☐	☐	☐	☐	☐
Shell Fish	☐	☐	☐	☐	☐	☐	☐
Fish	☐	☐	☐	☐	☐	☐	☐
Organ Meat	☐	☐	☐	☐	☐	☐	☐

Do you eat a special diet? yes ☐ no ☐

If yes, please specify the type of diet:

Vegetarian ☐

Low sodium ☐

Low cholesterol ☐

Other (please specify)____

Do you take a calcium supplement? yes ☐ no ☐

If yes, how many times a day do you take it? _____times/day

What is the name of the supplement?

How many milligrams of calcium does it contain? ________mgs.

Do you take a multivitamin supplement? yes ☐ no ☐

If yes, how many times a day do you take it? _______times/day

What is the name of the supplement?__________

How many milligrams of calcium does it contain?_______mgs.

Do you take any of the following antacid: on a daily basis?

Rolaids, Tums yes ☐ no ☐

If yes, how many times a day does she take it? _______.times/day

Do you take a bran or fiber supplement? yes ☐ no ☐

If yes, how many times a day do you take it? ________times/day

What is the name of the supplement?___________________

How many grams of fiber does it contain? gm/serving.

Approximately how many hours do you spend watching television or playing video/computer games each day?

____________ average hours per day from Monday-Friday

____________ average hours per day on Saturday and Sunday

Please provide any other comments regarding your lifestyle or physical activity which you think we should know.about:____

____

____

____

How do you usually get to and from school/work?

Fall and spring: Walk ☐ Bike ☐ Car ☐ Bus ☐

other:__________________________________

Winter: Walk ☐ Bike ☐ Car ☐ Bus ☐

other:__________________________________

How far is it from home to your school/work? ______ kilometers.

Do you usually come home for lunch? yes ☐ no ☐

How do you usually get to and from school/work at lunch and after school/work ?

Fall and Spring: Walk ☐ Bike ☐ Car ☐ Bus ☐

other:__________________________________

Winter: Walk ☐ Bike ☐ Car ☐ Bus ☐

other:____________________________________

After eating lunch, what type of activity, if any, do you do?______________________________________

How long is your lunch breaks? __________minutes.

Do you take Physical Education at school? yes ☐ no ☐

How many times per week do you have Physical Education classes? _______times per week.

How long are Physical Education classes usually? _________minutes.

MEDICAL HISTORY AND STATUS

Have you ever been treated for any of the following conditions? [hyper = excess; hypo = deficiency]

food allergies	yes ☐ no ☐	asthma	yes ☐ no ☐
other allergies	yes ☐ no ☐	kidney disease	yes ☐ no ☐
back pain	yes ☐ no ☐	liver problems	yes ☐ no ☐
.SCOliosiS	yes ☐ no ☐	gastrointestinal disease	yes ☐ no ☐
epilepsy	yes ☐ no ☐	muscular dystrophy	yes ☐ no ☐
osteoporosis	yes ☐ no ☐	osteoarthritis	yes ☐ no ☐
rheumatoid arthritis	yes ☐ no ☐	anemia	yes ☐ no ☐
diabetes	yes ☐ no ☐	excess urinary calcium	yes ☐ no ☐
malabsorption	yes ☐ no ☐	excess blood calcium	yes ☐ no ☐
hyperparathyroid	yes ☐ no ☐	hypothyroidism	yes ☐ no ☐
hyperthyroidism	yes ☐ no ☐	hypoparathyroid	yes ☐ no ☐

other (specify):____

Have you ever had a bone scan or a diagnostic X-ray in the last year? yes ☐ no ☐

If yes, what body part was X-rayed? yes ☐ no ☐

Have you ever had a fractured bone? yes ☐ no ☐

If yes, please indicate which bone(s) was/were fractured and when the fractures occurred.

1st fracture: body part __________mo___________ yr__________

2nd fracture: body part __________mo___________ yr__________

3rd fracture: body part __________mo___________ yr__________

Have you ever been hospitalized or confined to bed for any reason, or had a limb immobilized (e.g. arm in a cast) for 21 days or longer? yes ☐ no ☐

If yes, list the condition, approximate date it occurred, and the length of time you were hospitalized or immobolized.

	Injury type	Date of Injury	Time Immobolized
e.g.	wrist fracture	July, 1982	6 weeks
	____________	____________	____________
	____________	____________	____________
	____________	____________	____________
	____________	____________	____________

Is there a history of wrist, hip, or spine fractures in your family? yes ☐ no ☐

If Yes, indicate who was affected:

☐ mother ☐ father

☐ maternal grandmother ☐ paternal grandmother

☐ maternal grandfather ☐ paternal grandfather .

Is there a history of osteoporosis in your family? yes ☐ no ☐

If Yes, indicate who was affected

☐ mother ☐ father

☐ maternal grandmother ☐ paternal grandmother

☐ maternal grandfather ☐ paternal grandfather .

Is there a history of any other bone disease in your family? yes ☐ no ☐

If Yes, please indicate the family member(s) affected:

1________________________

2________________________

What is the name of the condition(s) affecting this family member?

1________________________

2________________________

Appendix D- Consent Form

McMaster
University
Health Sciences

INFORMATION AND CONSENT/ASSENT TO PARTICIPATE IN RESEARCH

You are being asked to participate in a research study being conducted at the Department of Kinesiology at McMaster University, Hamilton by Dr. Blimkie and Amy Mark MSc. Candidate.

Purpose of the Study:

To examine the influence of loads experienced during cross-country skiing on skeletal development.

Procedures:

This study consists of a single testing session that will last approximately two hours. During this time four different tests will be conducted, three types of scan for bone assessment and one jump test to assess leg muscle power. Before starting testing measurement of height and weight will be taken.

The first set of tests will be taken using the pQCT scanner, a small X-ray machine that will provide images of the bones in your forearm and leg. For this scan you will be required to place your limb in a small cylinder and keep the limb motionless for approximately 4 minutes (per scan) while the scan is done. Five different scans will be taken using the pQCT, two on each arm and one of the leg.

The second scan is similar to the first one because it also takes an image of the bone using X-rays. The device being using is call DEXA; you will be required to lay motionless for about 4 minutes (per scan) on a table while the devices take the scan. During the scan the device will move over top of your body to take the image. The first scan will take an image of you whole body while the second scan will take an image of your hip.

The third test that will be done is using a quantitative ultrasound machine that will send high frequency sound waves through your arm or leg. Two measures will be taken with this device, one of the arm and one of the leg. Ultrasound gel will be applied to the skin for the scan while the probe moves across the limb (similar to tests done on pregnant women).

The final test will be done on a force plate that will assess your maximum power during jumping. The procedure involves a five-minute warm up and then 3 practice jumps that will increase in effort followed by 2 maximal effort jump trials on the force plate platform.

As an inducement (incentive) for your participation in the study, you will have the opportunity to undergo maximal oxygen uptake (VO_2max) testing. The test consists of up to 6 stages on a treadmill with an increase in treadmill speed and incline with each stage (each stage lasts 3 minutes). You are not required to complete this testing to be included as a participant in this study.

Potential Risks:

The ultrasound measures of bone have no known health risks or discomfort associated with the measures. Both of the X-ray devices (pQCT and DEXA) involve safe and low doses of radiation (approximately one third of the typical radiation of a chest X-ray and about the same amount of radiation received in a return trans-continental air flight) and are used extensively with individuals of all ages. During the muscle power testing you may experience some short-term muscle fatigue, however, you will recover with rest within a few seconds. If you choose to have VO_2max testing done you may experience some muscle fatigue that will go away within a few minutes after completing the test.

Benefits:

As a participant in the study you will have the opportunity to learn about you bone density, total percentage of body fat and the relation ship between your muscle strength and bone health. Your participation will allow further understanding within the scientific community about the relationship between exercise and bone health.

Confidentiality:

All of the data from the study will be kept confidential and stored in offices and one computer that only the investigators have access to. The results of the study may be published in a scientific journal making the results public, however no reference will be make of your name or to you so that you will remain anonymous as a participant in the study. At the end of the study you will be provided with your own results as well as those of the group if you are interested.

Participation and Withdrawal:

It is your choice whether or not you would like o participate in this study and if you do volunteer for this study you may also withdraw from the study at any time without consequences of any kind. As a participant you may also request the removal of your data from the study and refuse to answer questions you do not feel comfortable answering while still remaining in the study. If circumstances arise which warrant you to be removed from the study, the investigators reserve the right to request this.

Rights of Research Participants:

As a participant you may withdraw your consent and discontinue participation at any point in the study. As a participant you are not waiving any legal claims, right or remedies by participating in this research study. This study has been reviewed by and has received ethics clearance from the Hamilton Sciences Corporation/McMaster University Research Ethics Board. If you have any questions regarding your rights as a research participant, you may contact the Hamilton Health Sciences Patient Relations Specialists at (905) 521-2100 x75240.

INFORMATION:

If you have any questions or concerns about the study or participation, please contact Amy Mark at (905) 525-9140 x27390, markae@mcmaster.ca, or Dr. Blimkie at (905) 525-9140 x24702.

I UNDERSTAND THE INFORMATION PROVIDED FOR THIS STUDY AS DESCRIBED HEREIN. MY QUESTIONS HAVE BEEN ANSWERED TO MY SATISFACTION, AND I AGREE TO PARTICIPATE IN THIS STUDY. I HAVE RECEIVED A SIGNED COPY OF THIS FORM.

Name of participant	Signature of participant	Date
Name of guardian	Signature of guardian	Date

INVESTIGATOR:
In my judgment the participant is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent and participate in this research study.

Signature of Investigator	Date

Appendix E- Raw data for measures analyzed

DESCRIPTIVE DATA

	Age (years)	Height (cm)	Weight (kg)	Percent Body Fat	Lean Tissue (g)	Tanner Stage	Physical Activity (h/wk)
skier	19.603	182.0	77.7	13.2	62554.8	5	8.47
skier	18.041	182.7	60.3	6.5	51240.9	5	10.74
skier	16.628	178.5	85.4	16.1	65419	5	11.85
skier	16.362	169.0	58.4	11.0	47610.7	4	7.73
skier	19.553	176.1	72.0	6.4	61026.3	5	17.63
skier	17.587	174.2	69.1	12.0	55627.1	5	16.79
skier	18.849	176.1	63.2	10.4	50778.9	5	16.00
skier	18.644	180.3	73.1	21.1	52312.3	5	8.64
skier	16.088	175.7	69.6	11.7	55177.2	5	6.36
skier	16.931	171.6	58.9	9.6	47569.9	3	9.57
skier	17.595	175.7	71.2	9.8	57808.2	5	7.44
skier	17.691	176.3	79.5	18.3	58622.6	5	15.96
skier	17.047	184.7	74.0	14.5	57989.1	5	10.21
control	20.184	187.5	79.5			5	13.69
control	19.97	185.5	66.0			5	4.33
control	17.348	194.5	95.0	18.2	70131.2	5	
control	16.58	170.8	74.1	22.7	51664.8	5	4.80
control	20.515	179.2	81.0	17.0	58154.2	4	3.10
control	19.80	171.7	54.5	9.8	44258.8	5	5.75
control	19.312	177.2	95.4	28.6	62376.5	4	2.27
control	17.973	183.5	71.0	12.2	57582.7	5	7.15
control	16.43	172.8	80.0	25.1	53257.2	4	7.52
control	17.403	184.0	59.5	9.1	47767.5	4	2.48
control	17.775	186.5	77.6	17.4	57001.5	4	8.19
control	16.099	175.3	71.0	17.5	53937.6	4	5.09
control	16.195	163.8	59.1	7.6	50822.4	4	8.68
control	15.06	183.5	69.1	8.8	57320.3	4	
control	17.452	173.0	89.9	24.3	60641.4	5	1.32

QUS- SOS

	domrad	ndomrad	tib
skier	4330	4320	3958
skier	3832	3886	3839
skier	3959	4051	3883
skier	3959	3860	3983
skier	4042	4063	3930
skier	4022	4108	3816
skier	3873	3882	3850
skier	3874	3951	3895
skier	3988	4060	3872
skier	3766	3737	3833
skier	3825	3986	3942
skier	4053	4060	3939
skier	3789	3776	3791
control	4009	4002	4013
control	4016	4061	3989
control	4110	4019	3927
control	3910	4023	3879
control	4313	4328	4025
control	4555	4511	3976
control	4391	4067	3826
control	4235	4261	3935
control	3907	3953	3842
control	4020	4028	3997
control	3962	3935	3898
control	3794	3774	3583
control	3801	3824	3877
control	3798	3620	3772
control	4453	4589	3812
avg skier	3947.1	3980.0	3887.0
SD skier	150.3	155.7	59.9
avg control	4084.9	4066.3	3890.1
SD control	248.6	261.9	115.4

RAW DATA FOR DXA BONE MEASURES

Participant	WB BMD	Total Area	Dleg BMD	NDleg BMD	Hip aBMD	WB BMC	hip BMC
1	1.20	2426.85	1.30	1.35	1.12	2908.98	49.06
2	1.24	2151.63	1.33	1.34	1.25	2669.96	43.00
3	1.20	2255.72	1.40	1.50	1.09	2713.10	44.46
4	1.05	2043.60	1.25	1.19	1.05	2153.49	40.57
5	1.25	2356.27	1.39	1.47	1.20	2952.11	47.25
6	1.06	2109.84	1.24	1.20	1.01	2225.92	42.21
7	1.28	2156.76	1.37	1.38	1.28	2754.75	41.57
8	1.19	2159.12	1.47	1.46	1.14	2578.16	41.48
9	1.10	2211.96	1.23	1.20	0.94	2439.45	36.61
10	1.09	2083.03	1.32	1.23	1.08	2259.85	41.12
11	1.26	2281.75	1.40	1.45	1.22	2868.46	46.62
12	1.18	2259.67	1.36	1.28	1.10	2657.50	49.05
13	1.30	2469.03	1.39	1.54	1.24	3210.13	56.10
3	1.39	2659.38	1.61	1.67	1.44	3693.60	56.96
4	1.19	2069.92	1.37	1.38	1.11	2457.50	38.60
5	1.30	2283.35	1.55	1.49	1.33	2972.50	48.80
6	1.02	1936.42	1.11	1.12	0.72	1966.40	24.49
7	1.13	2281.02	1.35	1.34	1.11	2568.90	39.15
8	1.00	2164.99	1.18	1.16	0.81	2169.50	33.08
9	1.05	1993.08	1.29	1.31	1.01	2095.00	36.51
10	1.12	2121.53	1.23	1.25	0.93	2377.90	34.36
11	1.31	2366.40	1.46	1.41	1.25	3104.30	56.03
12	1.23	2179.74	1.37	1.47	1.11	2671.90	39.90
13	1.04	1974.84	1.27	1.23	1.01	2062.70	38.40
14	1.07	2140.93	1.23	1.26	1.04	2285.30	36.51
15	1.24	2244.54	1.40	1.42	1.22	2786.10	42.76
	p=0.5712	p=0.5180	p=0.9809	p=0.9106	p=0.4287	p=0.5791	p=0.1633
Skier avg	1.18	2228.09	1.34	1.35	1.13	2645.53	44.55
Skier StDev	0.08	130.27	0.07	0.12	0.10	311.32	5.02
Control avg	1.16	2185.86	1.34	1.35	1.08	2554.74	40.43
Control StDev	0.13	192.09	0.14	0.15	0.20	491.79	9.02

Fem neckBMD	Fem neckBMC	Fem neck A	TrochBMD	TrochBMC	TrochA	InterBMD
0.97	5.47	5.65	0.90	12.54	13.94	1.28
1.18	5.66	4.82	1.05	12.62	12.07	1.40
0.96	5.67	5.88	0.87	10.58	12.19	1.24
1.01	4.95	4.90	0.90	9.73	10.77	1.13
1.10	6.04	5.48	0.91	11.05	12.12	1.39
0.81	4.79	5.91	0.79	11.23	14.27	1.22
1.07	5.69	5.33	1.05	11.44	10.91	1.50
1.07	5.75	5.36	0.91	11.93	13.10	1.33
0.75	4.77	6.37	0.77	10.10	13.16	1.13
0.96	5.24	5.43	0.89	10.91	11.40	1.22
1.01	5.92	5.89	0.94	12.00	12.76	1.46
0.99	5.69	5.77	0.84	10.89	12.99	1.26
1.06	6.14	5.78	1.10	22.39	20.41	1.44
1.40	8.05	5.74	1.17	16.88	14.48	1.66
1.14	3.99	3.50	0.85	8.90	10.53	1.23
1.14	7.54	6.61	1.08	15.96	14.82	1.65
0.64	3.56	5.60	0.60	8.04	13.38	0.87
1.01	5.33	5.30	0.97	11.36	11.65	1.22
0.77	4.83	6.27	0.65	9.29	14.28	0.94
0.92	5.17	5.61	0.86	8.30	9.63	1.10
0.92	4.69	5.10	0.72	8.50	11.74	1.05
1.17	6.64	5.70	1.01	12.66	12.53	1.37
1.13	5.85	5.16	0.92	12.47	13.50	1.24
0.91	4.47	4.90	0.85	10.67	12.56	1.13
0.91	4.85	5.34	0.87	11.18	12.80	1.21
1.06	6.02	5.68	0.98	12.07	12.29	1.44
p=0.8309	p=0.8771	p=0.5107	p=0.5924	p=0.4757	p=0.5745	p=0.3779
1.00	5.52	5.58	0.92	12.11	13.08	1.31
0.11	0.45	0.43	0.10	3.21	2.44	0.12
1.01	5.46	5.42	0.89	11.25	12.63	1.24
0.20	1.33	0.74	0.16	2.80	1.52	0.24

InterBMC	InterA	Wards BMD	Wards BMC	Wards A	Dom Arm	Non-Dom Arm
31.05	24.21	0.93	1.06	1.15	0.86	0.84
24.71	17.60	1.22	1.37	1.12	0.90	0.88
28.21	22.82	0.88	0.98	1.12	0.81	0.79
25.89	22.83	1.11	1.42	1.28	0.71	0.71
30.16	21.66	1.02	1.16	1.14	0.86	0.85
26.18	21.51	0.70	0.79	1.12	0.79	0.74
24.43	16.32	1.04	1.18	1.14	0.84	0.80
23.80	17.96	1.09	1.39	1.28	0.76	0.80
21.74	19.30	0.65	0.72	1.10	0.81	0.77
25.70	21.10	0.96	1.23	1.28	0.74	0.77
28.70	19.64	0.94	1.00	1.06	0.87	0.82
32.47	25.87	0.94	1.20	1.27	0.83	0.79
27.57	19.18	1.12	1.44	1.28	0.94	0.95
32.02	19.31	1.40	1.61	1.15	0.95	0.93
25.71	20.85	1.04	1.04	1.01	0.81	0.82
25.30	15.29	1.11	1.10	1.00	0.92	0.87
12.89	14.89	0.54	0.59	1.10	0.73	0.73
22.47	18.39	1.07	1.33	1.25	0.81	0.83
18.97	20.11	0.65	0.72	1.10	0.73	0.71
23.05	20.98	0.90	1.13	1.26	0.71	0.71
21.17	20.24	0.86	0.97	1.13	0.81	0.80
36.73	26.74	1.30	1.64	1.26		
21.58	17.44	1.07	1.35	1.26	0.77	0.79
23.26	20.61	0.78	0.87	1.11	0.66	0.69
20.48	16.99	0.83	0.92	1.11	0.77	0.77
24.67	17.12	0.94	1.02	1.08	0.85	0.83
p=0.0883	p=0.1707	p=0.9102	p=0.6486	p=0.2561		
26.97	20.77	0.97	1.15	1.18	0.82	0.81
3.09	2.76	0.16	0.23	0.08	0.06	0.06
23.72	19.15	0.96	1.10	1.14	0.79	0.79
5.84	3.07	0.24	0.31	0.09	0.08	0.07

pQCT at 4% DOMINANT RADIUS

	TOT_CNT	TOT_DEN	TRAB_CN	TRAB_DEI	TOT_A	TRAB_A
skier	159.70	326.10	43.08	195.60	489.75	220.25
skier	130.68	332.90	39.16	221.90	392.50	176.50
skier	127.03	369.30	32.08	207.30	344.00	154.75
skier	111.63	299.10	36.37	216.80	373.25	167.75
skier	156.96	317.30	42.46	190.80	494.75	222.50
skier	97.32	275.10	25.37	159.60	353.75	159.00
skier	155.17	353.50	54.84	277.60	439.00	197.50
skier	119.96	371.70	34.56	238.30	322.75	145.00
skier	136.03	280.50	38.09	174.70	485.00	218.00
skier	153.47	410.30	45.12	268.10	374.00	168.25
skier	119.47	321.60	31.52	188.70	371.50	167.00
skier	163.11	324.10	55.64	245.90	503.25	226.25
skier		238.30		184.40	502.30	226.00
control	162.92	376.90	37.61	193.40	432.25	194.50
control	139.56	379.50	39.91	241.50	367.75	165.25
control	176.83	349.00	54.04	237.00	506.75	228.00
control	101.94	389.50	31.07	263.90	261.75	117.75
control	155.94	386.90	45.67	252.00	403.00	181.25
control	114.83	306.00	29.90	177.20	375.25	168.75
control	137.58	401.10	42.51	275.60	343.00	154.25
control	127.37	253.20	30.50	134.80	503.00	226.25
control	122.24	302.40	43.38	238.70	404.25	181.75
control	136.36	401.10	35.69	233.70	340.00	152.75
control	167.13	384.90	49.76	254.90	434.25	195.25
control	399.94	323.10	30.29	252.60	338.50	152.25
control	99.61	294.30	46.37	199.00	397.00	178.50
control	147.14	253.10			259.80	
control		370.60				
	p=0.3637	p=0.2886	p=0.9742	p=0.3509	p=0.2071	p=0.3385
skier avg	135.88	324.60	39.86	213.05	418.91	188.37
skier SD	21.61	45.66	9.06	36.03	68.17	30.68
con avg	156.39	344.77	39.75	227.25	383.33	176.65
con SD	73.87	51.93	8.02	39.97	74.12	30.47

pQCT DOMINANT RADIUS AT 66% LEVEL

Participant	TOT_CNT	TOT_DEN	TOT_A	CRT_CNT	CRT_DEN	CRT_A	CRT_THK_C
skier	134.19	610	220	114.33	1071	106.75	2.364
skier	106.13	825.9	128.5	108.27	1102	98.25	3.292
skier	103.19	641.9	160.75	89.22	1052.7	84.75	2.235
skier	105.03	718.2	146.25	92.04	1054.9	87.25	2.489
skier	147.04	620.4	237	120.32	1050.8	114.5	2.441
skier	103.82	615.2	168.75	84.45	1042.6	81	2.044
skier	112.27	665.3	168.75	97.24	1062.7	91.5	2.37
skier	98.26	798.8	123	89.99	1128.4	79.75	2.547
skier	118.88	455	261.25	77.93	1015.3	76.75	1.456
skier	88.13	466.9	188.75	62.35	978	63.75	1.443
skier	123.1	681	180.75	109.61	1069.4	102.5	2.594
skier	132.14	829.7	159.25	119.32	1128.3	105.75	2.993
skier	135.29	682.4	198.25	121.82	1082.8	112.5	2.719
control	147.16	600.7	245	119.86	1033.2	116	2.423
control	115.86	468.6	247.25	86.24	1017.6	84.75	1.679
control	159.29	682.9	233.25	133.82	1060	126.25	2.781
control	121.98	642	190	104.05	1061.8	98	2.365
control	135.13	893.4	151.25	124.18	1139.3	109	3.271
control	114.84	515	223	81.24	1034.9	78.5	1.643
control	132.21	690.4	191.5	102.67	996.8	103	2.5
control	102.47	480.5	213.25	68.32	1001	68.25	1.445
control	105.96	739.7	143.25	92.95	1068.4	87	2.521
control	109.57	594.7	184.25	95.67	1084.1	88.25	2.13
control	175.97	754.4	233.25	158.44	1100.3	144	3.287
control	82.91	429.6	193	44.31	886.2	50	1.091
control	101.59	540.4	188	74.01	939.9	78.75	1.839
control	122.49	669.4	183	104.88	1051.4	99.75	2.484
	p=0.3939	p=0.3757	p=0.1331	p=0.9930	p=0.1575	p=0.8035	p=0.5189
	115.959	662.362	180.096	98.992	1064.531	92.692	2.384
	17.371	117.469	40.779	18.369	41.599	15.420	0.523
	123.388	621.550	201.375	99.331	1033.921	95.107	2.247
	24.827	128.886	32.399	29.048	64.672	24.181	0.651

CRT_THK	RX_CM_W	RY_CM_W	RP_CM_W
3.244	268.643	301.252	522.504
2.616	201.561	186.664	331.387
2.848	196.859	162.641	345.609
2.778	155.953	169.764	304.411
3.309	292.751	298.734	553.808
3.115	188.693	172.278	295.793
2.914	182.361	212.458	369.741
2.543	137.912	156.388	268.503
3.543	193.822	178.869	353.577
3.052	136.986	123.291	231.792
2.949	233.641	227.99	425.366
3.072	220.591	198.603	373.534
3.062	257.81	253.947	489.035
3.502	294.005	303.226	559.211
3.331	214.716	187.854	369.868
3.371	280.815	354.755	602.955
3.046	222.337	218.001	411.851
2.661	182.801	216.035	336.935
3.212	161.859	186.408	328.826
3.089	206.599	177.312	358.984
3.195	169.726	148.343	287.356
2.761	165.942	170.96	279.546
3.045	218.265	220.116	412.058
3.333	358.881	376.679	685.507
3.08	108.887	110.486	201.071
3.09	169.003	146.197	301.628
2.974	223.171	213.844	396.543
p=0.2135	0.737342724	0.61719483	0.650790071
3.003	205.199	203.298	374.235
0.276	48.405	54.159	98.160
3.121	212.643	216.444	395.167
0.230	63.906	77.697	134.766

pQCT at 4% NON-DOMINANT RADIUS

	TOT_CNT	TOT_DEN	TRAB_CNT	TRAB_DEN	TOT_A	TRAB_A
skier	153.7	341.7	34.5	170.7	449.8	202.3
skier	138.8	297.0	45.3	215.3	467.3	210.3
skier	137.3	347.3	37.3	210.1	395.3	177.8
skier	103.1	277.6	30.7	183.6	371.5	167.0
skier	174.7	364.1	47.1	218.3	479.8	215.8
skier	105.8	262.9	29.6	163.6	402.5	181.0
skier	132.6	381.2	42.1	269.1	347.8	156.3
skier	124.5	368.2	36.4	239.4	338.0	152.0
skier	137.4	291.6	37.5	176.7	471.3	212.0
skier	108.0	265.9	33.4	182.9	406.3	182.8
skier	162.6	368.7	50.4	254.1	441.0	198.3
skier	112.6	342.6	27.0	183.0	328.8	147.8
skier	181.1	331.4	62.6	254.7	546.5	245.8
control	161.7	356.6	36.5	179.1	453.5	204.0
control	132.0	368.9	37.8	235.3	357.8	160.8
control	187.3	378.8	56.2	252.8	494.3	222.3
control	111.9	437.6	32.7	284.3	255.8	115.0
control	169.7	407.4	50.3	268.7	416.5	187.3
control	110.2	292.6	28.3	167.3	376.5	169.3
control	136.8	377.5	45.1	276.6	362.3	163.0
control	119.8	265.7	28.9	142.6	451.0	202.8
control	120.9	297.2	43.0	234.7	406.8	183.0
control	128.2	400.0	32.0	222.1	320.5	144.0
control	157.8	382.0	47.5	255.9	413.0	185.8
control	139.7	379.7	43.3	261.9	368.0	165.5
p-value	0.74	0.07	0.87	0.18	0.27	0.27
skier avg	136.3	326.2	39.5	209.3	418.9	188.4
skier SD	25.9	41.9	9.8	35.8	64.2	28.9
cont avg	139.7	362.0	40.1	231.8	389.6	175.2
cont SD	24.4	51.2	8.9	45.8	64.3	28.9

pQCT NON-DOMINANT RADIUS AT 66% LEVEL

	TOT_CNT	TOT_DEN	TOT_A	CRT_CNT	CRT_DEN	CRT_A	CRT_THK
skier	134.9	631.2	213.8	114.2	1070.1	106.8	2.4
skier	119.2	857.4	139.0	109.7	1111.1	98.8	3.1
skier	104.7	725.7	144.3	91.8	1096.2	83.8	2.4
skier	90.1	713.7	126.3	85.1	1064.2	80.0	2.5
skier	130.0	688.5	188.8	114.9	1107.4	103.8	2.6
skier	101.3	645.4	157.0	86.5	1042.3	83.0	2.2
skier	101.4	681.8	148.8	90.3	1097.9	82.3	2.3
skier	99.7	818.9	121.8	90.3	1146.3	78.8	2.5
skier	118.9	516.0	230.5	83.9	1025.9	81.8	1.7
skier	92.7	503.6	184.0	71.9	971.9	74.0	1.7
skier	115.6	652.2	177.3	102.8	1081.6	95.0	2.4
skier	123.3	817.7	150.8	100.6	1090.6	92.3	2.6
skier	137.0	585.4	234.0	110.5	1023.3	108.0	2.3
control	161.5	576.9	280.0	125.7	1041.0	120.8	2.3
control	109.6	471.9	232.3	79.9	1014.8	78.8	1.6
control	156.6	511.0	306.5	103.3	995.9	103.8	1.8
control	116.9	686.5	170.3	101.7	1081.6	94.0	2.4
control	140.0	859.1	163.0	120.1	1111.9	108.0	3.0
control	109.5	533.0	205.5	79.1	1061.8	74.5	1.6
control	121.8	722.7	168.5	96.1	1003.6	95.8	2.5
control	107.4	497.7	215.8	74.1	988.0	75.0	1.6
control	98.5	756.1	130.3	89.3	1088.8	82.0	2.5
control	116.4	549.9	211.8	84.5	1055.8	80.0	1.7
control	169.3	721.9	234.5	132.6	1060.7	125.0	2.7
control	91.7	564.2	162.5	66.5	949.7	70.0	1.8
control	114.4	654.9	174.8	99.0	1039.2	95.3	2.4
p-value	0.18	0.22	0.06	0.99	0.07	0.65	0.26
skier avg	113.0	679.8	170.5	96.3	1071.4	89.8	2.4
skier SD	15.8	109.7	37.8	13.5	46.1	11.5	0.4
cont avg	124.1	623.5	204.3	96.3	1037.9	92.5	2.2
cont SD	24.8	118.4	50.3	20.3	45.8	17.9	0.5

CRT_THK	RX_CM_W	RY_CM_W	RP_CM_W	IX_CRT_A	IP_CM_W
3.3	290.1	242.7	481.5	2406.2	4360.1
2.8	172.9	177.0	330.0	1217.5	2362.6
2.8	166.5	162.3	304.4	1376.2	2303.3
2.7	143.6	151.6	270.8	1168.9	1915.0
3.1	238.0	257.1	463.9	1916.0	3970.1
3.0	168.1	181.7	339.6	1400.5	2448.6
2.8	160.0	193.3	324.0	1228.9	2472.8
2.5	132.5	161.2	276.2	838.6	1842.3
3.3	161.7	255.5	377.4	1880.8	3707.5
3.0	159.5	143.7	265.0	1464.2	2489.4
3.1	209.7	215.3	395.3	1731.7	3187.3
	169.7	147.3	274.7	1153.6	2060.0
3.8	259.4	283.3	506.0	2438.9	4483.5
3.6	310.0	330.5	543.7	3469.6	6415.7
3.3	210.7	176.0	361.6	2194.8	3656.1
	264.2	259.9	478.5	3173.7	5631.4
3.1	193.1	186.9	367.3	1586.8	2850.7
3.0	136.7	222.2	321.2	1031.9	2846.2
3.1	180.9	158.7	301.1	1742.7	2965.6
2.9	185.7	187.7	354.3	1615.9	2800.7
3.2	185.4	202.4	319.5	1890.8	3195.2
2.7	148.2	157.8	286.3	1081.1	1988.7
3.1	183.2	190.3	323.3	1689.0	3273.5
	286.7	264.3	536.4	2605.0	4683.8
3.0	149.3	126.8	267.1	1370.6	2007.3
3.0	209.7	193.3	379.2	1970.2	3127.0
0.40	0.42	0.75	0.61	0.12	0.19
3.0	187.0	197.8	354.5	1555.5	2892.5
0.3	47.7	47.8	84.2	490.0	936.0
3.1	203.4	204.4	372.3	1955.5	3495.5
0.2	53.4	53.9	91.0	740.9	1319.4

pQCT at 4% LEVEL DOMINANT TIBIA

	TOT_CNT	TOT_DEN	TRAB_CN	TRAB_DEI	TOT_A	TRAB_A
skier	399.9	277.9	158.1	244.2	1438.9	647.4
skier	336.4	348.4	105.3	242.4	965.6	434.4
skier	413.9	324.6	146.1	254.6	1274.9	573.6
skier	458.6	338.0	175.5	287.4	1357.0	610.6
skier	465.2	337.8	169.6	273.7	1377.1	619.7
skier	372.6	318.1	142.0	269.5	1171.4	527.0
skier	435.0	362.0	153.0	282.9	1201.6	540.6
skier	427.6	347.9	155.2	280.6	1229.3	553.1
skier	423.8	282.1	161.0	238.2	1502.2	676.0
skier	382.8	332.0	135.4	260.9	1153.3	518.9
skier	392.0	366.0	133.8	277.8	1070.9	481.8
skier	374.7	322.5	125.8	240.7	1161.9	522.7
skier	466.5	311.2	181.6	269.2	1499.0	674.6
control	472.5	368.2	157.2	272.3	1283.3	577.3
control	386.6	376.2	124.7	269.8	1027.5	462.3
control	691.5	372.0	285.2	341.0	1858.8	836.3
control	351.1	475.8	102.6	309.2	738.0	332.0
control	475.9	430.3	151.5	304.4	1106.0	497.5
control	280.5	278.3	87.8	193.6	1007.8	453.3
control	403.7	349.6	145.2	279.5	1154.8	519.5
control	376.0	257.5	137.5	209.3	1460.3	657.0
control	322.0	283.9	118.8	232.8	1134.0	510.3
control	333.0	324.3	119.5	258.6	1027.0	462.0
control	424.3	337.4	156.3	276.3	1257.8	565.8
control	111.2	399.6	32.1	256.7	278.3	125.0
control	311.3	327.8	92.8	217.2	949.5	427.3
control	354.9	263.4	131.1	216.2	1347.3	606.3
control	404.1	377.3	142.0	294.7	1071.0	481.8
p-value	0.38	0.30	0.29	0.93	0.17	0.17
skier avg	411.5	328.3	149.4	263.2	1261.8	567.7
skier SD	39.7	26.9	21.2	17.5	165.0	74.3
cont avg	379.9	348.1	132.3	262.1	1113.4	500.9
cont SD	123.0	62.0	53.5	41.8	345.9	155.7

pQCT DOMINANT TIBIA AT 66% LEVEL

	TOT_CNT	TOT_DEN	TOT_A	CRT_CNT	CRT_DEN	CRT_A	CRT_THK	CRT_THK
skier	456.8	573.8	796.2	375.7	1046.3	359.0	4.1	5.9
skier	419.5	643.9	651.5	349.0	1058.7	329.6	4.3	5.3
skier	373.3	645.2	578.6	383.3	1065.8	359.7	5.2	5.0
skier	465.8	642.3	725.1	407.1	1085.5	375.0	4.6	5.4
skier	465.0	597.0	778.9	369.6	1020.4	362.2	4.2	5.6
skier	462.5	719.8	642.6	406.4	1100.4	369.3	5.0	5.2
skier	460.5	663.1	694.4	382.4	1046.5	365.4	4.6	5.3
skier	431.2	684.7	629.8	369.8	1088.2	339.8	4.6	5.2
skier	389.5	506.3	769.3	310.9	1014.2	306.6	3.5	5.8
skier	449.9	747.0	602.2	401.3	1086.7	369.3	5.2	5.6
skier	452.1	681.2	663.7	397.9	1090.7	364.8	4.8	5.3
skier	501.6	686.2	730.9	425.4	1082.5	393.0	4.9	5.6
control	445.9	872.6	511.0	427.7	1166.9	366.5	6.0	4.5
control	417.1	668.1	624.3	362.9	1107.2	327.8	4.4	4.9
control	545.6	761.2	716.8	495.1	1117.7	443.0	5.8	5.2
control	455.3	573.1	794.5	385.8	1089.1	354.3	4.1	5.4
control	480.0	738.2	650.2	430.7	1110.5	387.8	5.2	5.2
control	341.2	570.8	597.8	289.5	1092.6	265.0	3.5	5.1
control	428.6	663.8	645.8	344.7	1014.3	339.8	4.5	5.1
control	371.4	562.4	660.5	305.7	1054.5	289.9	3.6	5.2
control	378.4	636.4	594.6	328.9	1059.5	310.4	4.2	5.2
control	376.7	635.7	592.6	317.4	1117.1	284.2	3.8	5.2
control	467.4	650.3	718.7	401.0	1074.8	373.1	4.6	5.5
control	488.7	647.5	754.8	398.6	1045.4	381.3	4.6	5.5
control	387.0	605.4	639.3	327.1	1003.3	326.0	4.3	4.9
control	404.6	569.0	711.0	328.7	952.8	345.0	4.3	5.5
control	472.6	711.4	664.3	412.2	1055.8	390.4	5.2	5.3
p-value	0.48	0.78	0.29	0.55	0.76	0.42	0.84	0.03
skier avg	444.0	649.2	688.6	381.6	1065.5	357.8	4.6	5.4
skier SD	35.5	65.6	71.7	30.5	28.5	22.7	0.5	0.3
cont avg	430.7	657.7	658.4	370.4	1070.8	345.6	4.5	5.2
cont SD	55.3	85.3	72.3	57.2	53.6	47.2	0.7	0.3