AN ABSTRACT OF THE DISSERTATION OF

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Osteoporosis is characterized by low bone mineral density (BMD), bone fragility, and an increased risk of osteoporotic fracture. The disease is systemic in nature but potential solutions include exercises prescriptions that target the clinically relevant sites of osteoporosis (hip and spine) to improve bone mass. The aim of this dissertation was to determine if atypical loading and load magnitude increased bone mass at the hip and spine, respectively, in young athletic women. The first study sought to determine if six months of uncustomary loading in the form of a "hip drop", increased BMD at the hip in young women (n=39, aged 20.2 ± 1.3 years). The hip drop applied a direct side impact to the right greater trochanter, the left hip was the control. The second study compared the spine BMD response after six months of rowing training in experienced (n=16, aged 21.2 ± 1.2 years) and novice rowers (n=19, aged 19.5 ± 0.8 years) with a control group (n=14, aged 19.2 ± 1.6 years). Bone mineral density at the hip and spine were measured in

the first and second studies, respectively. Results from the first study showed a significant difference in BMD between hips at the femoral neck but there were no side-to-side differences at the greater trochanter or the total hip. The second study revealed that six months of rowing training increased spine BMD in the experienced rowers (2.1%) but not in the novices (-0.05%).

Specific Loading Protocols to Promote Bone Mineral Density in Young Women

By

Jane A. LaRiviere

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Jane A. LaRiviere, Author

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How does one justly acknowledge a decade? There are countless people at Oregon State University and beyond who at one time or another were faced with me looking at them….and yes, probably needing something. I am and continue to be awed by the selflessness with which people offered their wisdom, time, humor, insight, advice and support.

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CONTRIBUTION OF AUTHORS

Dr. W.C. "Toby" Hayes is the third author for the manuscript entitled "Atraumatic side impact loading of the greater trochanter for increasing bone mineral density in young woman." Dr. Hayes was instrumental in the development of the hip drop model and he provided expertise in the editing of the manuscript.

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DEDICATION

I dedicate this dissertation to my grandmothers Alice Adams (1908-1997) and Delia LaRiviere (1910-1998). Tough but gentle women who lived out loud and who were impervious to the standards of their day.

SPECIFIC LOADING PROTOCOLS TO PROMOTE BONE MINERAL DENSITY IN YOUNG WOMEN

CHAPTER 1

INTRODUCTION

Osteoporosis is a disease characterized by low bone mass, bone fragility and an increased risk of fracture. An estimated 10 million Americans suffer from osteoporosis and 80% are postmenopausal Caucasian women (Watts, 2001). Of the approximately 1.5 million osteoporosis-related fractures reported each year, over half are vertebral fractures and about 300,000 are hip fractures (World Health Organization, technical report, 1994). In women, bone loss associated with aging begins about a decade after skeletal maturity and averages 1% per year there after (Melton et al., 1997). Bone loss is accelerated during menopause and the average woman can lose 20% of her bone mass between the ages of 40 and 70 years (Watts, 2001). Low bone mass at the hip and spine increase the risk of fracture at these sites (Melton et al., 1993; Cummings et al., 1993). The health implications associated with women who suffer hip fractures are well documented; 10 to 20% die within the first year from complications directly associated with the fracture or from an existing underlying disease, 50% never regain independence and 25% require nursing home care. Less well known is that over the long term, increased rates of mortality after vertebral fractures are just as great (Watts, 2001). In addition to lifestyle challenges, over $13 billion is spent each year caring for patients with osteoporosis-related problems and as the mean age of the world's population increases, the costs will continue to rise (Melton et al., 1997; Ray et al., 1997).

Peak bone mass and osteoporosis-related fracture prevention

Bone mineral density is a major determinant of fracture risk (Hui, Slemenda, Johmson, 1988) and bone mass accumulated prior to the onset of age-related bone loss will determine bone health later in life (NIH consensus conference, 2001). In other words, the more bone you "stockpile" prior to peak bone mass, the more bone you can afford to lose during the unavoidable aging process. Some researchers believe that peak bone mass is reached shortly after the cessation of longitudinal growth (Theintz, Buchs, Rizzoli, Slosman et al., 1992), others believe that bone tissue continues to accumulate into the third decade of life (Recker et al., 1992). Regardless, genetics play the predominant role in the attainment of peak bone mass. However, to maximize or improve your genetic predisposition, secondary factors such as adequate nutrition, normal levels of reproductive hormones and weight bearing exercise can exert a strong influence on peak bone mass. Of these secondary factors, mechanical loading has been reported to independently improve bone mass (Snow-Harter et al., 1992). Thus, increased mechanical loading may be an important non-pharmaceutical strategy to stockpile bone prior to reaching peak bone mass and reduce the risk of osteoporosis-related fractures later in life.

Skeletal bone mass and the effects of weight-bearing exercise

Regular weight bearing exercise is key to achieving and maintaining optimal bone mass. This is evident during periods of forced unloading such as from prolonged bed rest or space flight, where bone is lost, especially in the weight bearing bones (Baldwin, White, Arnaud et al., 1996; Krolner and Toft, 1983). However, there is some uncertainty regarding the type and dose of loading necessary to improve bone mass. For example, weight training has increased bone mass in some cohorts of pre-menopausal women (Snow-Harter et al., 1992; Lohman et al., 1995), but not in others (Heinonen et al., 1996b; Rockwell et al., 1990; Vuori et al., 1994) and to date, there are few standardized protocols to address this issue. One difficulty is the inclusion of a variety of exercises in prospective designs, for example, aerobics plus jumping or aerobics plus weight-training (Bassey and Ramsdale, 1994; Friedlander et al., 1995). This blanket approach makes it difficult to partition out the dose-response for specific exercises and loads in order to assess the efficacy of various loading protocols. Adherence to the principle of specificity, where only one type of exercise is evaluated and the dose factors are controlled, will help define loading regimens for bone that are consistently osteogenic and in the long term, reduce the number of osteoporosis-related fractures.

Association of bone mass and weight-bearing exercise in cross-sectional designs

Cross-sectional designs support the premise that people who engage in regular physical activity have higher bone mass than those that do not. The positive association between increased mechanical loading and BMD is particularly evident in athletes. The data show that athletes have higher bone mass than their non-athletic counterparts and that athletes who participate in high magnitude loading activities such as gymnastics have higher bone mass than athletes whose activity is non-weight bearing, such as swimming (Fehling et al., 1995; Robinson et al., 1995)). Fehling et al. (1995) compared female athletes from sports with different loading patterns. They found that volleyball players and gymnasts exhibited significantly greater bone mass at the femoral neck and lumbar spine than did swimmers and controls. Robinson and associates (1995) compared collegiate female athletes who participated in high versus low impact sports. They found that gymnasts had significantly greater bone mass at the femoral neck and lumbar spine than distance runners and controls, despite a similar prevalence of menstrual irregularities. Robinson et al. (1995) concluded that the high magnitude forces associated with gymnastics training had a powerful osteogenic effect that appeared to counteract the negative side effects of low circulating estrogen and amenorrhea. Other cross-sectional reports show that the benefits of loading are site-specific. Tennis and squash players exhibit higher BMD in their playing arm than in their non-playing arm (Huddleson, Rockwell, Kuland and Harrison, 1980; Haapasalo et al. 1994). Further, Slemenda and Johnson (1993) have reported that young female figure skaters, whose activity loads the lower, but not the upper body, exhibited greater BMD in the lower body compared to controls but that group differences vanished when the upper body sites were compared. In summary, cross sectional studies support that long-term participation in load bearing activity is beneficial to bone mass, but athletes participating in certain activities do not achieve greater bone mass. The difference appears to be explained by the specificity and intensity of the load-bearing environment.

Prospective exercise trials for increasing bone mass

Exercise intervention studies have the advantage of accounting for the biological process of bone turnover and thus enable researchers to make inferences with respect to loading environments and BMD. Clinically, load-bearing exercise has been shown to improve bone mass at the lumbar spine (Lohmann et al., 1995; Snow-Harter et al., 1992; Snow et al., 2001) and the hip (Bassey and Ramsdale, 1994; Heinonen et al., 1996a). The types of exercise utilized in these exercise protocols suggest that high magnitude forces (Snow et al., 2001; Taaffe et al., 1997) and activities associated with high loading rates, such as jump training (Bassey and Ramsdale, 1994; Heinonen et al., 1995, 1996; Winters and Snow, 2000), best increase hip BMD in pre-menopausal women and that load magnitude is more osteogenic than load repetition. However, there are relatively few exercise studies in humans to support this theory (Snow et al., 2001; Taaffe et al., 1995; Robinson et al., 1995). Specifically, Bassey and Ramsdale (1994) reported a 3.4%

increase in BMD at the trochanter but not the femoral neck or the spine in pre-menopausal women following 6 months performing 50 jumps per day most days of the week. In young women athletes, Taaffe et al. (1997) showed that over a similar training period, gymnasts significantly increased bone mass compared with swimmers and runners at the femoral neck and lumbar spine. In this study the gymnasts had high initial BMD values and 30% of the gymnasts reported menstrual abnormalities. The authors concluded that the high magnitude and high rates of loading, characteristic of gymnastics training resulted in high BMD values and this adaptation could be protective against age-related losses later in life. Prospective studies provide evidence that bone mass is optimized to best resist the forces to which it most often encounters, such as the high impact loading associated with gymnastics. Conversely, there appears to be a minimum environmental load necessary to stimulate BMD changes because the high volume, repetitious training associated with elite running and swimming have not been shown to initiate protective changes in BMD in young women (Taaffe et al., 1997).

The importance of load magnitude and specificity in exercise protocols for increasing bone mass

The higher than normal BMD values observed in people who participate in high intensity activities such as gymnastics have led investigators to focus on force magnitude as the key element in bone promotion. And thus, recent investigations have sought to increase peak forces at the hip and spine by the addition of weighted vests during exercise and various jump training protocols (Shaw and Snow, 1998; Witzke and Snow, 2000). To date, the results of these protocols have been equivocal and it is difficult to conclude that increasing the intensity of conventional type activities corresponds with an increase in bone mass. The weighted vests and jump protocols undoubtedly increase the magnitude of the force delivered to the target bone but the conventional direction of loading may not alter the strain distribution within the bone. If the mechanisms responsible for bone adaptation are regulated by the strain differentials, as some believe (Lanyon, 1996) then it follows that a more novel load configuration might provide a stimulus for bone formation. The importance of creating a unique loading environment where the forces associated with loading produce atypical strains within the target bone is not well understood. Although, Kohrt et al. (1997) has reported that in older women, uncustomary exercise (rowing and weight training) increased BMD at the lumbar spine to a similar extent as customary exercise (walking and stairs) but with lower force magnitudes and rates of loading.

In addition, it is well documented that bone tissue adheres to the principle of specificity whereby form follows function. If the intent of researchers is to identify means of reducing osteoporosis-related fractures then conventionally administered exercise interventions (i.e. activities of daily living), may simply be adapting the bone to conditions that rarely result in fracture. In fact, hip fractures seldom occur during normal activity, but instead are most commonly associated with a fall (Hayes et al., 1993). Therefore, an alternative and potentially more productive approach might be to encourage bone adaptation and thus resistance to fractures for the specific loading conditions known to be associated with most hip fractures (Carter et al., 1998). The use of such atypical loading conditions to impart specific resistance to fracture in the loading mode under which fracture most often occurs has not been attempted previously.

Statement of purpose

To reduce the number of osteoporosis-related fractures aggressive preventative measures must be explored. Increasing bone mass in young women prior to the onset of bone loss (aged 20-30 years) may provide a strategy for combating bone loss associated with aging and menopause. In an effort to contribute to future exercise prescriptions designed to increase bone mass and decrease the risk of osteoporotic fractures, we examined two different loading environments specific to the hip and lumbar spine in a group of collegiate female athletes (n = 39, aged 20.2±1.3 years). In order to identify training principles that increase bone mass it is necessary to regulate the type, intensity and duration (repetition) of exercise. In the first study, we developed a unique loading regime, the "hip drop", that applied a direct impact of approximately two times body weight to the greater trochanter in a direction perpendicular to the long axis of the femur. Based on evidence that bone responds to loading in a site-specific manner (Haapasalo et al., 1994), it is plausible that an atraumatic side impact might increase bone density at the hip in a manner that imparts resistance to fracture loads. Thus, we conducted an exercise intervention study where the subjects performed 90 "hip drops" per week for six-months. The use of such atypical loading to impart specific resistance to fracture in the loading mode under which fracture most often occurs had not been attempted previously. Specific to this design, we asked the following research questions: 1) Does atraumatic side impact, applied to the hip in a loading configuration comparable to a fall, increase hip BMD? In addition, soft tissue overlying the greater trochanter has been shown to attenuate force from side impacts (Robinovitch et al., 1995). To address this issue, our second research question was: 2) Does the bone response depend on the thickness of soft tissue overlying the greater trochanter?

As part of the previous study the same cohort of athletes then served as a model for developing exercise prescriptions for decreasing vertebral osteoporosis. Rowing is highly specific to the spine and the vertebral column is thought to incur the greatest loads (Morris et al., 2000). The subjects were homogeneous in terms of overall activity, outside activity and anthropometric measures, differing only in rowing experience. Our aim was to examine six months of rowing training on lumbar spine BMD in competitive female athletes, whom were members of a collegiate rowing team. The team was comprised of 16 athletes with an average of 26 ± 10 months of rowing experience and 19 novice athletes who at the onset of the study had been rowing for only 3 months. Specific to this design we asked the following research question: Is the bone response at the spine from rowing training different in experienced versus novice rowers.

CHAPTER 2

ATRAUMATIC SIDE IMPACT LOADING OF THE GREATER TROCHANTER FOR INCREASING BONE MINERAL DENSITY IN YOUNG WOMEN

Jane A. LaRiviere, Christine M. Snow and W.C. Hayes

Abstract

Previous attempts to increase hip bone mineral density (BMD) have used loading modes that reflect activities of normal daily living such as walking, running and jumping. However, the hip seldom fractures under these conditions. Instead, ninety percent of hip fractures occur from falls. Falling to the side and landing on the greater trochanter raise the risk of fracture 6- and 20- fold, respectively. Given the critical role that side impact loading plays in hip fracture etiology, we hypothesized that an atraumatic side impact loading protocol might be used to increase the fracture resistance of the hip in its dominant failure mode. To explore this approach, we studied the effects of an atraumatic side impact on hip BMD in young women (n = 39, aged 20.2±1.3 years). Using a within subjects design, hip drops were performed from a left side-lying position such that the hips were lifted 10 cm from the floor and then released to impact on the wooden surface, directly on the greater trochanter. The right hip served as the control. This side impact loading was performed 3 times/week, 30 repetitions per session for six months. BMD of the hip (femoral neck, trochanter, total hip) and trochanteric soft tissue thickness were assessed by DXA at baseline and 6 months. Average ground reaction forces for the hip drops were two times body weight. In repeated measures analysis of variance (ANOVA) there was a significant group by time interaction, suggesting a small (1.2%) but significant (p = 0.02) difference in femoral neck BMD between the left and right sides after six months of hip drops. BMD at the trochanter and total hip were not significantly different between sides. There was no association between trochanteric soft tissue thickness and bone response at any region of the hip. The role of moderate intensity, side impact loading in osteoporosis-related fracture prevention warrants further exploration.

Key Words: Atypical loading - Side impact - Hip Drop - Bone Mineral Density - Osteoporosis - Hip fracture

Introduction

The structural competence of bone deteriorates with reduced bone mass, resulting in an increased susceptibility to fracture. Currently, there are more than 300,000 hip fractures in the United States annually that carry an estimated $8.7 billion in economic cost (29). Structural testing of cadaveric hips has shown that bone mineral density (BMD) is a robust and independent predictor of bone fracture load, explaining up to 85% of the variance in bone strength (14). In Caucasian women 65-84 years of age, at least 90% of hip fractures are associated with low bone mineral density (24). Thus, increasing BMD at the hip is an important preventive strategy for reducing hip fractures. Furthermore, augmenting hip BMD in premenopausal women may help combat the bone loss associated with aging and menopause.

Mechanical loading is a proven osteogenic stimulus. However, the type, intensity and frequency of skeletal loading required to improve BMD is poorly understood. Clinical reports suggest that to increase BMD, one or more of the following components of loading be present: 1) high magnitude forces; 2) high loading rates; and 3) diverse loading environments (20). High magnitude forces have been shown to increase BMD at the hip (18,32,36,38). Activities associated with high loading rates, such as jump training, have increased hip BMD in pre-menopausal women (1,2,15,16,40). Least understood is the importance of creating a unique loading environment where the forces associated with loading produce atypical strains within the target bone. At the hip, bone mass and architecture are thought to be optimized so as to best resist those loads to which it is most often subjected, such as the forces associated with weight bearing (42). To build bone, recent interventions have used exercise protocols designed to increase peak forces at the hip, e.g., the addition of weighted vests during exercise and various jump training protocols (35,41). However, limiting such high intensity exercise protocols to loading associated with the activities of daily living may simply be adapting the bone to conditions that rarely result in fracture. An alternative and potentially more productive approach might be to encourage bone adaptation and thus resistance to fracture for the specific loading conditions known to be associated with most hip fractures (6). Ninety percent of hip fractures occur from a fall; landing on the greater trochanter raises the risk of hip fracture more than 20-fold (13). The use of such atypical loading conditions to impart specific resistance to fracture in the loading mode under which fracture most often occurs has not been attempted previously.

Our aim was to examine the effect of six months of side impact loading on hip BMD in young women. We developed a unique loading regime, the “hip drop”, that applied a direct impact of approximately two times body weight to the greater trochanter in a direction perpendicular to the long axis of the femur. Based on evidence that bone responds to loading in a site-specific manner (12), it is plausible that an atraumatic side impact might increase bone density at the hip in a manner that imparts resistance to fracture loads. Specific to this design, we asked the following research question: 1) Does atraumatic side impact, applied to the hip in a loading configuration comparable to a fall, increase hip BMD? In addition, soft tissue overlying the greater trochanter has been shown to attenuate force from side impacts (30). To address this issue, our second research question was: 2) Does the bone response depend on the thickness of soft tissue overlying the greater trochanter?

Methods and Materials

Subjects

Women between the ages of 18 and 23 were recruited from the Oregon State University rowing team. Exclusion criteria included: 1) the existence of conditions known to affect bone metabolism (e.g. uncontrolled diabetes); 2) injuries that would inhibit the performance of a hip drop; and 3) medications known to affect bone (e.g. steroid-derived asthma medication). Of 47 potential participants, one subject was excluded due to a pre-existing injury. During the study seven subjects discontinued the intervention when they left the team for personal reasons. Thirty-nine women completed the study and of those four subjects reported pain from hip drop performance and were instructed to take a day off. One subject required three sessions for recovery. Five subjects reported bruising but did not miss any sessions due to this complaint. The crew athletes practiced six days per week. The duration of each training session was approximately two hours. The majority of total training time (85 - 90 %) was spent rowing on the water, on the rowing ergometer or in the rowing tank. Approximately five minutes of each session was allotted to the hip drop experiments. All subjects were eumenorrheic (10-12 menstrual cycles/year) and reported having regular cycles during the six month intervention. Five subjects reported taking birth control pills. Caloric consumption and calcium intake per day were assessed based on average food intake over the previous year by the Block Food Frequency Questionnaire, a previously validated frequency-amount questionnaire used by the National Cancer Institute (4). Caloric intake averaged 1950 ± 548 kcal/day. The mean calcium intake was 1330 mg/day, which is above the recommended daily allowance of 1200 mg/day for women of this age (27). Height, weight and soft tissue thickness over the greater trochanter were measured at baseline and six months and did not change significantly during the intervention (Table 2.1). The Oregon State University Institutional Review Board approved this study and all subjects gave written informed consent.

Table 2.1. Subject characteristics at baseline and 6-months (N = 39)

	Baseline (Mean ± SD)	6-months (Mean ± SD)
Age (years)	19.6 ± 1.3	20.2 ± 1.3
Height (cm)	172.0 ± 8.3	172.0 ± 8.3
Weight (kg)	73.6 ± 10.1	71.8 ± 14.5
Right Hip Soft Tissue (mm)	53.8 ± 12.3	53.4 ± 11.1
Left Hip Soft Tissue (mm)	52.9 ± 12.5	52.8 ± 11.3
Right Femoral Neck BMD T-Score (%)	115.5 ± 12.6	
Left Femoral Neck BMD T-Score (%)	115.1 ± 12.2	
Right Trochanter BMD T-Score (%)	112.1 ± 11.4	
Left Trochanter BMD T-Score (%)	113.5 ± 12.7	

Intervention

For this within-subject design, the left hip was the test hip and the right hip served as the control. Prior to baseline testing, all subjects participated in several practice sessions and received performance feedback. The subjects were considered trained when the hip drop was performed in a consistent and repeatable manner. Subjects began in a side-lying position so that the left greater trochanter was in contact with the floor. The upper body rested on the left elbow and the right hand was positioned in front of the body for balance and for assisting in lifting the hips off the ground. The pelvis was raised 10 cm off the ground and then dropped vertically to the floor, impacting the greater trochanter. Subjects were instructed to drop freely for maximum impact. To ensure standard performance, a 10 cm block was slid under the test hip and removed prior to the drop. Each subject performed 30 hip drops three times a week for 6 months. Each session lasted less than 60 seconds. Prior to conducting the six-month experiment, a pilot project to evaluate the safety of the hip drop loading condition was conducted. Seventeen women participated in ten-weeks of hip drops performed three times a week. Repetitions were gradually increased up to 30 per session so that 90 hip drops were performed per week. The pilot work confirmed that young active women could tolerate this type of loading without injury or chronic discomfort.

Measurements

Bone mineral density (g/cm^2) was measured by dual-energy X-ray absorptiometry (DXA)(QDR-1000/W, Hologic Inc. Waltham, MA) for the left and right proximal femora at baseline and six months. The coefficient of variation (CV) in our laboratory is <1.0% for the proximal hip.

The soft tissue overlying the greater trochanter was determined using a specific DXA technique (22). The subject was positioned supine on the densitometer. The box size for the hip scan was increased to accommodate hip girth and the X-ray pencil beam was then positioned 1 cm from the most lateral aspect of the hip. A cardboard block was positioned under the beam at the start point of the scan to differentiate between the skin/air interface. Measurement was obtained by counting the number of pixels (1 pixel = 1.006 mm) between the greater trochanter and skin surface.

Ground reaction forces from the hip drops were recorded for each subject using a Kistler model 9281B force plate (Kistler Instrumente AG, Winterthur, Switzerland). The force plate was connected to an electronic amplifier unit. Output signals were sampled at 500 Hz using a data acquisition board and personal computer. The force plate was triggered by the investigator prior to each hip drop. A one-centimeter thick piece of artificial turf (All-Pro, Dallas, TX) was placed over the force plate and the subject was positioned so that the greater trochanter impacted the center of the forceplate. Vertical ground reaction forces were collected for each subject. Hip drops were performed in a consecutive manner and four impacts were recorded.

Statistical Analyses

All data were screened for normality, linearity and homoscedasticity prior to the analysis. Repeated measures analysis of variance (ANOVA) were used to evaluate changes in BMD between sides at the femoral neck, trochanter and total hip after six months of hip drops. Pearson correlation coefficients were used to measure the associations between bone response, soft tissue thickness and ground reaction force data. For each hip site, paired t-tests were used to compare the post-intervention percent change in bone to zero. All statistical analyses were performed using SPSS for Windows software (SPSS, Chicago, Ill). Power analyses revealed that with more than 30 subjects, the study provided greater than 77% statistical probability to detect a 3% change in BMD at a significance level of $p < 0.05$.

Results

The repeated measures ANOVA resulted in a statistical difference between sides at the femoral neck BMD ($p = 0.02$; Table 2.2, Figure 2.1). Specifically, femoral neck BMD increased 0.66% at the test hip and decreased -0.66% at the control hip. However, the percent changes were not significantly different from zero ($p>0.10$). There were no significant differences in BMD between the control and test hips at the trochanter ($p = 0.40$) or total hip ($p = 0.76$).

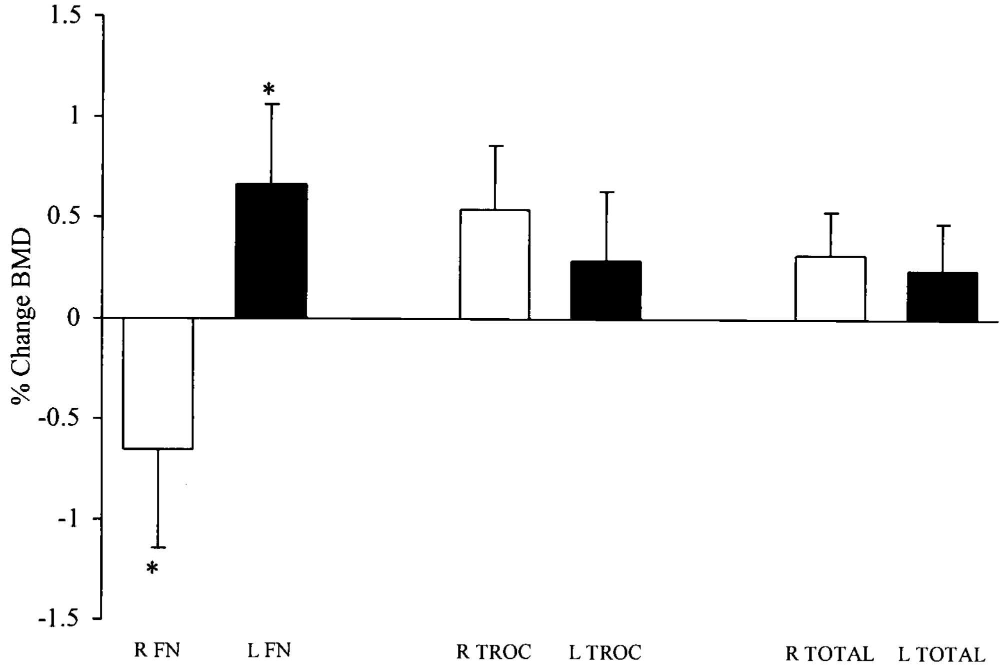
The bone response was not dependent on thickness of soft tissue overlying the left hip ($r = -0.12$, $p = 0.49$), nor were there significant associations between peak ground reaction forces and percent change in BMD at the left femoral neck site ($r = 0.00$, $p = 0.99$).

Table 2.2. Bone mineral densities pre and post intervention for the left and right hip sites (g/cm^2)

	Left Hip (test)			Right Hip (control)		
	Baseline	6 months	% change	Baseline	6 months	% change
Total Hip	1.041	1.043	+0.239	1.037	1.040	+0.315
Trochanter	0.800	0.801	+0.288	0.790	0.794	+0.539
Femoral Neck	0.973	0.979	+0.664[a]	0.991	0.983	-0.656[a]

[a] significant difference between the left and right sides at the femoral neck ($P = 0.02$)

Figure 2.1. Percent change between left and right femoral neck, trochanter and total hip (Mean ± SE)



* significant difference between left and right femoral necks (p=0.02)

Discussion

Our primary aim was to determine the effect of atraumatic side impact loading on hip BMD in young women. Secondary to this goal we sought to determine if the bone response was dependent on the thickness of soft tissue overlying the greater trochanter. We report that side impact loading applied in the form of a "hip drop' resulted in a statistical difference in BMD between hips at the femoral neck. However, the reported changes are close to our laboratory's DXA machine error and thus, the clinical relevance of these changes is questionable. In addition, there were no changes at the trochanter or total hip sites. Furthermore, thickness of soft tissue overlying the greater trochanter was not associated with the magnitude of bone response.

This study has several strengths. It is unique in that it is the first effort designed to add bone in a way that potentially reinforces the hip against the loads that cause hip fracture. The "hip drop" loading configuration allowed us to investigate the effects of an impact loading condition on hip BMD, independent of the potentially osteogenic forces associated with muscular contractions (19). Previous interventions have relied on protocols associated with upright or weight-bearing activities. Additional strengths are the short time required to execute 30 repetitions of hip drops (< 60 s in duration/session) and, unlike other interventions, hip drops avoid the use of special or expensive equipment. Also, the within-subject design provided a method to control for the genetic and environmental determinants of BMD (17,18,39). Finally, the study design created an environment to encourage compliance where all subjects performed the hip drops together and participated in the same type and intensity of physical activity outside of the intervention. Of the 3120 possible sessions for hip drops, only 74 were missed due to absence from practice and/or injury. Thus, compliance was 97.3%. Other prospective bone studies have reported low compliance rates and participation in outside activity as confounding variables (37,41).

It is important also to note the limitations of our study. First, six months is a relatively short intervention period to expect significant increases in BMD, as it may take up to six months to complete one bone remodeling cycle (23). Future side impact loading protocols should be at least 12 months in duration to include additional remodeling cycles and enhance the potential for a bone response. Second, in comparison to other investigations, relatively few repetitions were performed (15,40). We used 90 repetitions per week compared to up to 200 repetitions per week by others (15). However, the number of repetitions we used were based on tolerance exhibited by the subjects and on the premise that the atypical nature of the load may be more important to bone accretion than the number of repetitions (11,20,33,34). A third limitation is that we may not have overloaded the bone sufficiently to result in a maximum osteogenic response. The vertical ground reaction forces that we measured in all subjects (n=39) ranged from 726 N – 2640 N (mean 1473 ± 384 N), with the forces varying as expected with subject weight, exact drop height, trochanteric soft tissue thickness, and the ability of the subjects to relax at impact. Our loads are in agreement with those of Robinovich et al. (1991), who used a pelvis release apparatus to estimate the loads delivered to the greater trochanter from side falls at different heights. They estimated that from heights between 10 – 70 cm hip impact forces ranged from 2000 N – 5600 N. In addition, our loads are well below the in-vitro failure loads for younger subjects reported by Courtney et al. (1994). To determine fracture strength of the proximal hip, cadaveric femurs (aged 30.0 ± 11.9 years) were loaded in a direction and rate similar to a side fall from standing height. Measured fracture loads averaged 8000 N ± 1500 N. Thus, the hip drop impact to the greater trochanter averaged less than 25% of the failure load reported in young cadaveric femurs. Given this finding, it is possible that the hip drop loading protocol did not sufficiently overload the bone to stimulate bone accretion at all regions of the hip (11).

Finally, a fourth limitation is the method used to assess soft tissue thickness over the greater trochanter (22). The measure was obtained while the subjects were lying supine on the bone densitometer. Thus, due to displacement of soft tissue, it is plausible that our measures systematically overestimated the actual soft tissue thickness between the greater trochanter and the floor at contact. A better soft tissue assessment may be to use the lateral imaging techniques available from DXA (Hologic, Inc) to measure the space between the greater trochanter and floor in a side lying position.

With respect to our findings on soft tissues, in ex vivo hip impact experiments performed on cadaver femora, Robinovitch et al (1995) reported that an increase in soft tissue thickness over the greater trochanter from 8 mm to 42.5 mm resulted in a reduction of the peak impact force from 6420 N to 4050 N. Since average trochanteric soft tissue thickness for subjects in our study was 52 millimeters (range: 25-82 mm), the actual impact load rendered at the hip may have been significantly less than the measured ground reaction forces. This may, in part, explain the weak bone response at the femoral neck and the lack of response at other hip sites.

It is of interest to compare the osteogenic response to our side impact loading protocol with those of previous studies that have been based on variations on activities of daily living. Other loading protocols have shown that the bone response at the hip is not consistent across all regions (1,15,18,21,40). We expected the direct side impacts to the greater trochanter to increase bone density at both the trochanteric and femoral neck regions, but only observed a small response at the femoral neck. It is possible that the stresses imparted by this loading configuration were highest at the femoral neck. Previous studies have reported region-specific differences from mechanical loading at the hip. For example, jumping increases bone mineral density at the trochanter but not the femoral neck (1,40), and in the femoral neck but not the trochanter (15). Specifically, in women aged 35-45 years, Heinonen et al. (1996) showed a 1.6% increase in femoral neck BMD after performing 100-200 jumps three times a week for 18 months. Winters and Snow (2000) reported an increase of 2.6% in trochanteric BMD after women (aged 30-45 years) performed about 100 jumps three times a week for 12 months. There is no clear explanation for these differences in results. However, in addition to jumping, the subjects in these prospective trials participated in either aerobics or lower body resistance training, thus it is difficult to partition out the effects of jumping alone. Also, it is important to note that the younger women in our study may not have reached peak bone mass and were most likely still accumulating bone tissue. This observation may account for the trend of non-significant increases in BMD observed at all hip sites except the right femoral neck.

There is a plethora of research describing load magnitude, impact and rate of force application for walking, running and jumping. Comparatively, ground reaction forces from hip drops were of moderate intensity (1.5 - 3.6 BW), and thus lower than landing from a jump height of 0.3 meters (4.5 BW) (28), higher than those observed in walking (1.0 – 1.5 BW) and similar to those in running (2.0 – 2.9 BW) (26). Another kinetic variable used to compare impacts is time to peak force or rate of force application. In our laboratory, we have shown that jumping from a height of 60 cm results in a peak force of 8 times body weight, with the time to peak force averaging 0.034 seconds (3). This is equivalent to a rate of force application of 235 body weights per second. By comparison, peak forces for walking and running reportedly range from 1-3 times body weight and the time to peak force range from 0.1-0.03 seconds (5,10). This is equivalent to a rate of force application of 10-80 body weights per second. Comparatively, hip drops produced moderate ground reaction forces with an average time to peak force of 0.03 seconds. Thus, the loading rates and the rate of force application for hip drops (60 BW/second) are comparable to the loading rates recorded in walking and slow running.

Although the subjects in this study were crew athletes, it is unlikely their activity influenced hip BMD. First, rowing has not been shown to benefit any skeletal site other than the spine (8,25,43,44). Second, Cavanagh et al. (1992) reported that peak loads at the foot in running were five times greater than in rowing (1628 N vs 307 N, respectively). Since running has not been shown to increase hip bone mass in premenopausal women it is unlikely that rowing would have elicited a bone response in our subjects.

The hip drop protocol used in this study has several advantages over other forms of mechanical loading (e.g. exercise) reported to increase bone mass. First, compared to traditional exercise programs, hip drops are not physically taxing and take only minutes to perform. Second, unlike strength training protocols, no expensive equipment is needed. Finally, hip drops can be performed anywhere. Thus, in terms of a realistic lifestyle intervention, "hip drops" may provide brief moderate intensity loading easily performed at home. It is important to note however, that the method used in this study requires muscle strength to raise the hips off the ground from a side-lying position. While this was not difficult for young subjects, it may prove challenging for an older population. Thus, if this protocol proves more osteogenic in future work, it might be possible to develop an apparatus for the elderly that delivers a direct load to the trochanter by specialized instrumentation (6).

References

1. Bassey EJ, Ramsdale SJ (1994) Increase in femoral bone density in young women following high impact exercise. Osteoporos Int 4:72-75

2. Bassey EJ, Rothwell MC, Littlewood JJ, Pye DW (1998) Pre- and postmenopausal women have different bone mineral density responses to the same high-impact exercise. J Bone Miner Res 13:1805-1813

3. Bauer JJ, Fuchs RK, Smith GA, Snow CM (2001) Quantifying force magnitude and loading rate from drop landings that induce osteogenesis. J Appl Biomech 17:142-152

4. Block G (1989) Human dietary assessment: Methods and issues. Prev Med 18:653-660

5. Breit GA, Whelan RT (1997) Prediction of human gait parameters from temporal measures of foot-ground contact. Med Sci Sports Exerc 29:540-547

6. Carter DR, Beaupre GS, Hayes WC (1998) Increasing bone fracture resistance by repeated application of low magnitude forces resembling trauma forces. U.S. Patent 5,752,925

7. Cavanagh PR, Davis BL, Miller TA (1992) A biomechanical perspective on exercise countermeasures for long term spaceflight. Aviat Space Environ Med 63:482-485

8. Cohen B, Millet PJ, Mist B, Laskey MA, Rushton N (1995) Effect of exercise training programme on bone mineral density in novice college rowers. Br J Sports Med 29:85-88

9. Courtney AC, Wachtel EF, Myers ER, Hayes WC (1994) Effects of loading rate on strength of the proximal femur. Calcif Tissue Int 55:53-58

10. Crossley K, Bennell KL, Wrigley T, Oakes BW (1999) Ground reaction forces, bone characteristics, and tibial stress fracture in male runners. Med Sci Sports Exerc 31:1088-1093

11. Frost HM (1992) The role of changes in mechanical usage set points in the pathogenesis of osteoporosis. J Bone Miner Res 7:253-261

12. Haapasalo H, Kannus P, Sievanen H, Heinonen A, Oja P, Vuori I (1994) Long-term unilateral loading and bone mineral density and contentinfemale squash players. Calcif Tissue Int 54:2 49-255

13. Hayes WC, Myers ER, Morris JN, Gerhart TN, Yett HS, Lipsitz LA (1993) Impact near the hip dominates fracture risk in elderly nursing home residents who fall. Calcif Tissue Int 52:192-198

14. Hayes WC, Myers ER, Robinovitch SN, Van Den Kroonenberg A, Courtney AC, McMahon TA (1996) Etiology and prevention of age-related hip fractures. Bone 18:77S-86S

15. Heinonen A, Kannus P, Sievanen H, Oja P, Pasanen M, Rinne M, Uusi-Rasi K, Vuori I (1996) Randomized controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. Lancet 348:1343-1347

16. Heinonen A, Oja P, Kannus P, Sievanen H, Haapasalo H, Manttari A, Vuori I (1995) Bone mineral density in female athletes representing sports with different loading characteristics of the skeleton. Bone 17:197-203

17. Heinonen A, Sievanen H, Kannus P, Oja P, Vuori I (1996) Effects of unilateral strength training and detraining on bone mineral mass and estimated mechanical characteristics of the upper limb bones in young women. J Bone Miner Res 11:490-501

18. Kerr D, Morton A, Dick I, Prince R (1996) Exercise effects on bone mass in postmenopausal women-are site-specific and load-dependent. J Bone Miner Res 11:218-225

19. Kohrt WM, Ehsani AA, Birge SJ Jr (1997) Effects of exercise involving predominantly either joint-reaction forces on bone mineral density in older women. J Bone Miner Res 12:1253-1261

20. Lanyon LE (1996) Using functional loading to influence bone mass and architecture: Objectives, mechanisms, and the relationship with estrogen of the mechanically adaptive process in bone. Bone 18:37S-43S

21. Lohman T, Going S, Pamenter R, Hall M, Boyden T, Houtkooper L, Ritenbaugh C, Bare L, Hill A, Aickin M (1995) Effects of resistance training on regional and total bone mineral density in premenopuasal women: A randomized prospective study. J Bone Miner Res 10:1015-1024

22. Maitland LA, Myers ER, Hipp JA, Hayes WC, Greenspan SL (1993) Read my hips: measuring trochanteric soft tissue thickness. Calcif Tissue Int 52:85-89

23. Marcus R (1998) Editorial. Exercise: Moving in the right direction. J Bone Miner Res 13:1793-1796

24. Melton LJ III, Thamer M, Ray NF, Chan CH, Chesnut CH, Einhorn TA, Johnston CC, Raisz LG, Silverman SL, Siris ES (1997) Fractures attributable to osteoporosis: report from the national osteoporosis foundation. J Bone Miner Res 12:16-23

25. Morris FL, Payne WR, Wark JD (1999) The impact of intense training on endogenous estrogen and progesterone concentrations and bone mineral acquisition in adolescent rowers. Osteoporos Int 10:361-368

26. Nilsson J, Thorstensson A (1989) Ground reaction forces at different speeds of human walking and running. Acta Physiol Scand 136:217-227

27. NIH Consensus Development Panel (2001) Osteoporosis prevention, diagnosis, and therapy. JAMA 285:785-795

28. Prapavessis H, McNair PJ (1999) Effects of instruction in jumping technique and experience jumping on ground reaction forces. J Orthop Sports Phys Therapy 29:352-356

29. Ray NF, Chan JK, Thamer M, Melton LJ (1997) Medical expenditures for the treatment of osteoporotic fractures in the United States in 1995: Report from the national osteoporosis foundation. J Bone Miner Res 12:24-35

30. Robinovitch SN, McMahon TA, Hayes WC (1995) Force attenuation in trochanteric soft tissues during impact from a fall. J Orthop Res 13:956-963

31. Robinovitch SN, Hayes WC, McMahon TA (1991) Prediction of femoral impact forces in falls on the hip. J Biomech Eng 113:366-374

32. Robinson TL, Snow-Harter C, Taafe DR, Gillis D, Shaw J, Marcus R (1995) Gymnasts exhibit higher bone mass than runners despite similar prevalence of amenorrhea and oligomenorrhea. J Bone Miner Res 10:26-35

33. Rubin CT, Lanyon LE (1985) Regulation of bone mass by mechanical strain magnitude. The effect of strain magnitude. Calcif Tissue Int 37:411-417

34. Rubin CT, Lanyon LE (1984) Regulation of bone formation by applied dynamic loads. J Bone Joint Surg Am 66:397-402

35. Shaw JM, Snow CM (1998) Weighted vest exercise improves indices of fall risk in older women. J Gerontol 53:M53-M58

36. Snow CM, Williams DP, LaRiviere J, Fuchs RK, Robinson TL (2001) Bone gains and losses following seasonal training and detraining in gymnasts. Calcif Tissue Int 69:7-12

37. Snow-Harter C, Bouxsein ML, Lewis BT, Carter DR, Marcus R (1992) Effects of resistance and endurance exercise on bone mineral status of young women: A randomized exercise intervention trial. J Bone Miner Res 7:761-769

38. Taaffe DR, Robinson TL, Snow CM, Marcus R (1997) High-impact exercise promotes bone gain in well-trained female athletes. J Bone Miner Res 12:255-260

39. Vouri I, Heinonen A, Sievänen H, Kannus P, Pasanen M, Oja P (1994) Effects of unilateral strength training and detraining on bone mineral density and content in young women: A study of mechanical loading and deloading on human bones. Calcif Tissue Int 55:59-67

40. Winters KM, Snow C.M (2000) Detraining reverses positive effects of exercise on the musculoskeletal system in premenopausal women. J Bone Miner Res 15:2495-2503

41. Witzke KA, Snow CM (2000) Effects of plyometric jump training on bone mass in adolescent girls. Med Sci Sports Exerc 32:1051-1057

42. Wolff J (1892) Das Gestez der Transformation der Knochen. Hirchwald, Verlag von August., Ed. Berlin

43. Wolman RL, Clark P, McNally E, Harries M, Reeve, J (1990) Menstrual state and exercise as determinants of spinal trabecular bone density in female athletes. BMJ 301:516-518

44. Wolman RL, Faulman L, Clark P, Hesp R, Harries MG (1991) Different training patterns and bone mineral density of the femoral shaft in elite, female athletes. Ann Rheum Dis 50:487-489

CHAPTER 3

SPINE BMD INCREASES IN EXPERIENCED BUT NOT NOVICE COLLEGIATE FEMALE ROWERS

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Abstract

Exercise is beneficial to bone, yet prescriptions for augmenting bone mass at the spine remain elusive. In order to develop an exercise prescription for building bone density, it is first necessary to identify exercises that target clinically relevant fractures sites and then determine the dose (load magnitude, load cycles, duration) required to stimulate bone accretion at different ages. There is evidence that rowing exercise targets the spine, but the dose of exercise required to build bone is poorly understood. To further explore this topic, we studied the bone response at the spine in female collegiate rowers (n=16, experienced, n=19, novices) after a six month competitive season. At the onset of the observational period the experienced athletes had been rowing of 26 ± 10 months whereas the novices athletes been rowing for 3 months. During the season, all rowers participated in the same training program and took approximately the same number of strokes per training session (1000-1200 repetitions). Thus, we compared the spine BMD of experienced rowers (aged 21.2 ± 1.2 years) and novice rowers (aged 19.5 ± 0.8 years) to each other and to a group of normally active controls (n = 14, aged 19.2 ± 1.6 years). BMD was assessed by DXA at baseline and following the competitive season. After six months of rowing there was a significant difference between rowing groups at the lumbar spine (p=0.03). The experienced rowers demonstrated a greater percent increase in spine BMD than the novice rowers (2.14 ± 2.5% vs -0.05 ± 2.4%). Since repetitions/session were consistent between rowing groups, the greater response at the lumbar spine in experienced rowers versus

novice rowers suggests that, in order to increase spine BMD over a short time period in young adult women, a minimum effective load magnitude is required.

Key Words: Osteoporosis - Bone Mass - Load Magnitude - Exercise

Introduction

Osteoporosis is a disease characterized by low bone mass, bone fragility and an increased risk of fracture. Vertebral fractures are the most common of all the osteoporosis-related fractures, with 750,000 cases reported each year (16). Since higher bone density is protective against vertebral fractures, strategies to build spine bone mineral density (BMD) may reduce fracture incidence (4). Exercise is one non-pharmaceutical strategy to increase spine bone density, but the type of exercise that targets the spine is yet to be identified.

Clinical reports suggest that load magnitude is more osteogenic than load repetition, yet there are few exercise studies in humans to support this theory (9,12,14,15). In order to study this hypothesis, the exercise must target the site measured and the repetitions and intensity (load magnitude) should be controlled. Rowing is highly specific to the spine and the vertebral column is thought to incur the greatest loads (7). In fact, in cross-sectional reports, young women who participate in rowing training have higher spine BMD than non-rowers (7,18). And, in limited longitudinal studies, adolescent girls and college-aged men have shown spine BMD increases as a result of rowing training (3,6).

Our aim was to examine the potentially different bone response at the spine in novice and experienced crew athletes after six months of rowing training. All women were members of the Oregon State University women's rowing team. For comparison, spine BMD of the rowers was compared with that of a normally-active control group measured over a similar time period. Specific to this design, we asked the following research question: Is the bone response at the spine after a six month competitive season different in experienced vs. novice rowers? We expected the experienced rowers to generate higher loads at the spine during the observational period and thus, hypothesized that experienced rowers would have significantly greater changes in BMD at the spine than the novice rowers.

Methods and Materials

Subjects

Women between the ages of 18 and 23 were recruited from the Oregon State University rowing team and the general student body. Exclusion criteria included: 1) the existence of conditions known to affect bone metabolism (e.g. uncontrolled diabetes); 2) injuries that would inhibit rowing performance; and 3) medications known to affect bone (e.g. steroid-derived asthma medication). Of the 43 athletes on the Oregon State University women's rowing team, one subject was excluded due to a pre-existing back injury. During the study, seven rowers discontinued the intervention when they left the team for personal reasons and thus the team evaluated in this study was comprised of 19 first year novice rowers (aged 19.5 ± 0.8 years) with 3 months of rowing experience and 16 experienced rowers (aged 21.2 ± 1.2 years) with 26 ± 10 months of rowing experience. For comparison, we used data from a control group recruited for a previous study in our laboratory (9). The 14 non-rowing controls (aged 19.2 ± 1.6 years) were normally-active college women and their spine measurements were assessed with the same spine protocol as the rowers (DXA, Hologic QDR/1000-W, Waltham, MA), however the time between scans for rowers and controls was six and seven months, respectively. The Oregon State University Institutional Review Board approved the study and all subjects gave written informed consent.

Rowing Training

During the observation period, all rowers participated in eight training sessions per week. Of the eight sessions, six were spent rowing on the water or on the rowing ergometer and two were spent cross-training that consisted of running, weight training and stretching. The duration of each training session was approximately 90 minutes for rowing and 45 minutes for cross-training and thus, the majority of total training time (83%) was spent rowing. On average, during each rowing session, the athletes took 1000-1200 repetitions (strokes) per session for a total of 6000 repetitions per week, regardless of experience level. During the observational period there were 5158 potential rowing sessions, of which 120 were missed due to absence from practice and thus compliance was 97.6%.

Assessments

All subjects completed the Oregon State University Bone Research Laboratory Health History Questionnaire. For the rowers, caloric consumption and calcium intake per day were assessed based on average food intake over the previous year by the Block Food Frequency Questionnaire, a previously validated frequency-amount questionnaire used by the National Cancer Institute (1). Controls completed 3-day diet records. Rowers and controls were eumenorrheic (10-12 menstrual cycles/year) and reported having regular cycles during the entire observational period. Five rowers (three experienced and two novices) but no controls reported taking birth control pills during the study. Mean calcium intake for rowers met the recommended intake of 1200 mg/day for women of this age but that of the control group did not (Table 3.1)(8).

Bone mass measurements

For rowers, bone mineral density was assessed at the end of November and early June whereas controls were assessed at the end of October and May. Spine bone mineral density (g/cm^2) was measured by dual-energy X-ray absorptiometry (DXA)(QDR-1000/W, Hologic Inc. Waltham, MA). The in-house coefficient of variation for the spine is $\leq 1.0\%$.

Rowing measurements

Rowing performance was assessed on a Concept 2 rowing ergometer (Concept 2, Model C, Morrisville, VT.). All rowers performed timed 2000 and 6000-meter tests once per month on separate days in January, February and March.

Statistical Analyses

Means and standard deviations were computed by standard statistical techniques. Prior to the analysis the data were screened for normality, linearity, equal variances and homogeneity of regression slopes for the covariate. An analysis of covariance (ANCOVA) was conducted to determine the effects of group membership on the difference between the pre- and post-test spine BMD values when controlling for body mass index (BMI). Body mass index was controlled for in the analysis because the groups differed at baseline (Table 3.1). Separate repeated measures ANOVA's were used to assess the differences between novice and experienced rowers on the 2000 and 6000-meter timed ergometer tests. All statistical analyses were performed with SPSS for Windows software, version 9.0 (SPSS, Inc., Chicago, IL).

Table 3.1. Subject characteristics at baseline and follow-up (Mean ± SD)

	Experienced Rowers (N = 16)		Novice Rowers (N = 19)		Control Group (N = 18)	
	Pre-training	6-months	Pre-training	6-months	Pre-training	7-months
	X ± SD	X ± SD	X ± SD	X ± SD	X ± SD	X ± SD
Characteristic						
Age (years)	21.2 ± 1.2[a]		19.5 ± 0.8		19.3 ± 1.5	
Training (months)	26 ± 10		3 ± 0		0	
Calcium Intake (mg)	1277 ± 560[c]		1418 ± 507[c]		816 ± 246[d]	
Body Mass Index (BMI)	25.3 ± 2.4	25.5 ± 2.0	24.4 ± 1.9	24.3 ± 2.0	21.8 ± 2.5[b]	22.3 ±2.6
Spine BMD (g/cm^2)	1.104 ± 0.13	1.126 ± 0.12	1.148 ± 0.09	1.147 ± 0.10	1.114 ± 0.12	1.123 ± 0.13
% Change Spine BMD		2.14 ± 2.53[e]		-0.05 ± 2.37		0.73 ± 1.28
Spine BMD T-Score (%)	105.3 ± 10.6		106.9 ± 9.2		103.6 ± 11.3	

[a] Experienced rowers different from novice rowers and controls (P=0.001)

[b] Controls different from rowers (P=0.01)

[c] Block Food Frequency Questionnaire (Block, 1989)

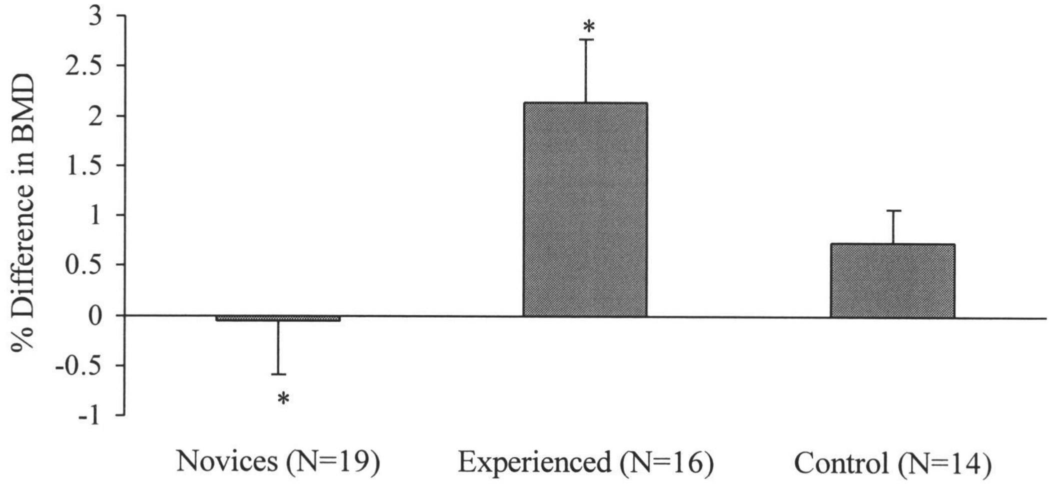
[d] 3-day diet record

[e] Experienced different from novices (P=0.03)

Results

The ANCOVA adjusted for BMI revealed significant group difference in spine BMD (p=0.03). In pairwise comparisons, experienced rowers demonstrated a significant increase in spine BMD compared to novice rowers (p=0.01)(Figure 3.1). There were no pairwise differences at the spine between the controls and either the experienced (p=0.58) or novice rowers (p=0.10). In repeated measures ANOVA, the 2000 meter and 6000 meter ergometer times for the experienced rowers were significantly different than the novice rowers in each month (p=0.0001) (Figures 3.2, 3.3). Specifically, the experienced athletes demonstrated better performance than the novice rowers for the 2000 meter and 6000 meter ergomoter tests at all time points (January, February and March).

Figure 3.1. Percent difference in spine BMD between groups (mean ± SE).



* experienced rowers significantly different than novices (P=0.01)

Figure 3.2. 2000 meter ergometer test scores (Mean ± SE), experienced (N=16) significantly better than novices (N=19) for all tests (p=0.0001)

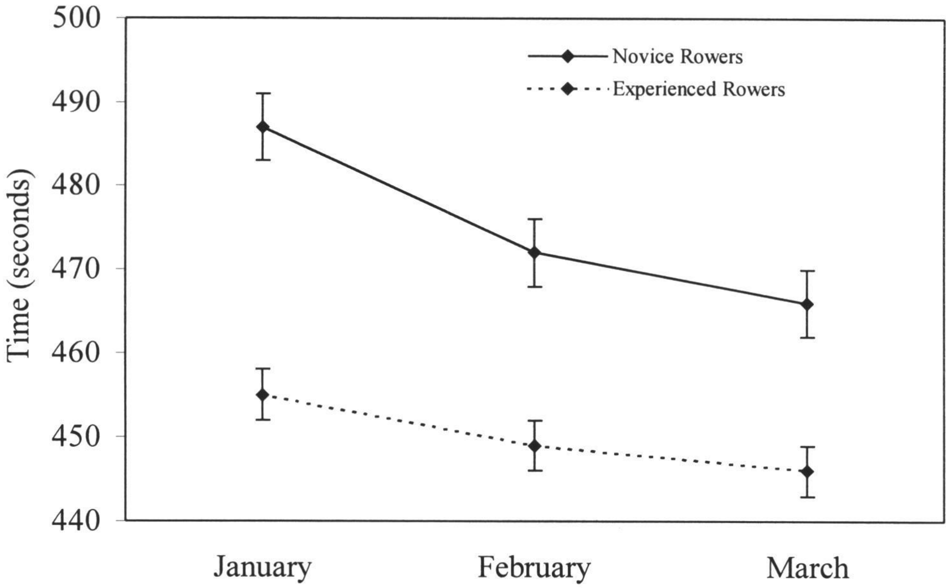
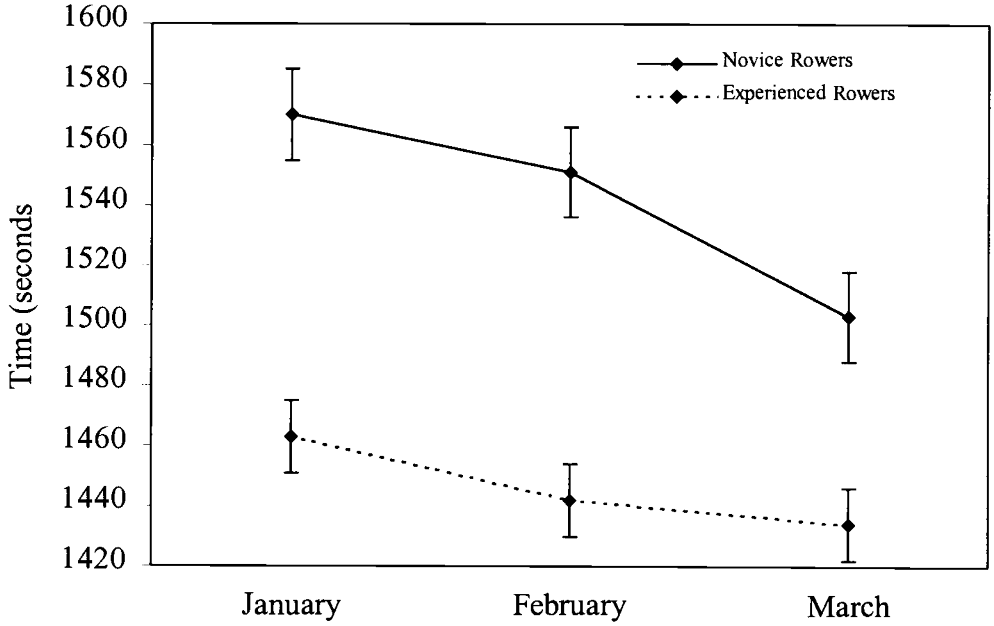


Figure 3.3. 6000 meter ergometer test scores (Mean ± SE), experienced (N=16) significantly better than novices (N=19) for all tests (p=0.0001)



Discussion

Our primary aim was to determine whether spine BMD differs in novice and experienced women rowers after six months of rowing training. We report that lumbar BMD increased significantly more in experienced rowers than the novice rowers. Specifically, experienced rowers demonstrated a 2.14% increase in spine bone density whereas the changes observed in the novice rowers and the controls were not greater than the in-house precision error for DXA spine measurements.

This study has several strengths. First, we compared the response of the spine to rowing in two similar groups of female athletes. All rowers participated in the same type and duration of training, took a similar number of strokes (repetitions) each session and participated in the same day-to-day workouts. Due to the time required for team membership, participation in outside activities known to influence bone mass was minimal. In addition, due to the study design compliance was high at 97.6%. Other prospective studies have reported low compliance rates and also participation in outside activity as confounding variables (13,17). Also, the conclusion of the observational period coincided with the end of the competitive racing season and thus included a progressive overload from training as team members prepared for the conference championships.

It is important to note limitations. Due to the study design, participation was limited to members of the Oregon State women's rowing team, thus it was not a randomized exercise intervention. However, our results provide a first step in developing a model to study the effects of rowing training as a strategy to build vertebral BMD in adults. Second, the control group had been recruited for an earlier study conducted in our laboratory (9) and thus were not measured over the same observational period as the rowers. However, since there were anthropometric differences at baseline between the rowing groups and the control group, we controlled for this difference by adjusting for initial BMI in the analysis. Third, we did not quantify the lumbar compressive or shear forces in the rowing groups nor did we count the exact number of repetitions required to complete the ergometer tests. However, the rowers took an average of 28-30 strokes per minute for the 2000-meter test and 26-28 strokes per minute for the 6000-meter test. In addition, the novice and experienced rowers did not differ significantly in height and because of this presumably had a similar stroke length. Given the same number of strokes and the same length of stroke, the only way to cover the same distance faster is to apply more force. Since the experienced rowers were significantly faster on all tests it follows that they also generated more force than the novice rowers. Lastly, six months is a relatively short intervention period to expect significant increases in BMD, as up to six months may be required to complete one bone remodeling cycle (5). It is possible that the forces produced by the novice rowers were not high enough early in the study to sufficiently overload the bone. A longer intervention would include more remodeling cycles and improve the potential for a bone response in the novice group.

Cross-sectional data report that rowers have higher lumbar BMD than non-rowing controls. Morris et al. (2000) compared BMD values of 14 female rowers (aged 19.7 ± 1.6 years) with 14 female matched controls. All rowers had been training for a minimum of three years and were rowing at least five times per week. They found that the rowers had greater lumbar spine BMD but were not different than the controls at the other sites measured. Smith and Rutherford (1993) compared total body and spine BMD in male athletes compared to controls. The cohort was comprised of 12 rowers (aged 20.8 ± 2.4 years) who trained on average 25 hours per week, 8 triathletes (aged 29.1 ± 5.4 years) who trained 20 hours per week and 13 non-exercising controls (aged 21.7 ± 3.6 years). Results revealed that the rowers had higher BMD at the spine and total body than both the triathletes and the controls. Wolman et al. (1990) compared bone density in women athletes and found that, despite a similar prevalence of menstrual irregularities, national team lightweight rowers (aged 25.1 ± 3.5 years) had significantly higher lumbar BMD than both elite runners (aged 25.9 ± 2.7 years) and professional dancers (aged 22.7 ± 3.8 years). While these studies support that rowing targets the spine, they do not provide information relative to load magnitude and the effect of rowing on spine BMD over time.

Two longitudinal studies have reported the benefits of rowing on the lumbar spine and our study corroborates these findings in college-aged women (3,6). Morris et al. (1999) showed that, in adolescent girls aged 14-15 years, 18 months of rowing training resulted in a significant 6.2% increase in lumbar spine BMD compared to a 1.1% increase in the control group. In that study, the girls participated in three to five on-water rowing sessions and three land-based training sessions per week. Cohen et al. (1995) showed a 2.9% increase in lumbar BMD in 17 male novice college oarsmen after seven months of rowing compared with eight aged-match controls. Training included eight hours of rowing, one hour of weight training and one hour of running per week. It is likely that the collegiate men were stronger at baseline than the novice women in our study and thus, able to generate greater forces at the spine earlier in their intervention.

In rowing, to maximize the propulsive effect of the oar, the back extensors must transfer the forces generated by the legs to the oar handle. However, the power transfer and resulting forces to the spine require good coordination between the legs, back and arms (Boland and Hosea, 1994). The degree to which the lower extremity forces are transmitted to the oar depend on the technical skill of the rower and thus, it is possible that the skill level of the rower may influence the loads delivered to the spine (2). Rowing can produce lumbar compressive forces of seven times body weight (10). In elite lightweight women rowers Morris et al (2000) used inverse dynamics and an instrumented rowing ergometer to estimate the compressive force on the lumbar spine during a race simulation. They calculated the average lumbar compressive force to be 4.6 X body weight. The rowers had been training for a minimum of three years and rowed at least five times per week. Although we do not have force data for our rowers, we assessed the power differences between novice and experienced rowers by analyzing results from standard race simulation rowing ergometer tests (Concept 2, Model C, Morrisville, VT). The Concept 2 ergometer provides a variety of performance parameters including a Watts (W) output that is a linear measure of power. The faster a given distance is rowed the greater the power. As part of normal training all rowers were tested in January, February and March over two different distances performed on different days (Figures 3.2, 3.3). The time difference between novice and experienced rowers is small, however, there is a trend towards the novices improving relative to the experienced rowers as training progressed. And, the Concept II formula for Watts,

$$W = ((\text{Meters rowed per second})^3 * 2.8),$$

where 2.8 is a manufacturer machine constant, indicates that velocity is not linearly related to power applied. In fact, increasing velocity by two times would require eight times more power. Thus, small differences in time reflect a larger difference in power between the novice and experienced rowers. Based on the ergometer results we believe that the forces generated by the experienced rowers over the full six-month trial were greater than the forces generated by the novices and that the higher magnitude loading resulted in the observed BMD differences.

Our results support the theory that, for a similar number of repetitions there is a minimum effective load magnitude that promotes osteogenesis, given normal to high initial spine BMD. Our results may provide preliminary data from which to develop a exercise prescription for reducing vertebral osteoporosis.

References

1. Block, G. Human dietary assessment: Methods and issues. Prev Med 18:653-660; 1989.

2. Boland, A.L., and Hosea, T.M. Injuries in rowing. In: *Clinical Practice of Sports Injury Prevention and Care.* P. A. F. H. Renstrom (Ed.) Cambridge, MA: Blackwell Scientific Publications, 1994, pp. 624-632.

3. Cohen, B., Millet, P.J., Mist, B., Laskey, M.A., and Rushton, N. Effect of exercise training programme on bone mineral density in novice college rowers. Br J Sports Med 29:85-88; 1995.

4. Cummings, S.R., Black, D.M., and Nevitt, M.C. Bone density at various sites for prediction of hip fractures. Lancet 341:72-75; 1993

5. Marcus, R. Editorial. Exercise: Moving in the right direction. J Bone Miner Res 13:1793-1796; 1998.

6. Morris, F.L., Payne, W.R., and Wark, J.D. The impact of intense training on endogenous estrogen and progesterone concentrations and bone mineral acquisition in adolescent rowers. Osteoporos Int 10:361-368; 1999.

7. Morris, F.L., Smith, R.M., Payne, W.R., Galloway, M.A., and Wark, J.D. Compressive and shear forces generated in the lumbar spine of female rowers. Int J Sports Med 21:518-523; 2000.

8. NIH Consensus Development Panel. Osteoporosis prevention, diagnosis, and therapy. JAMA 285:785-795; 2001.

9. Robinson, T.L., Snow-Harter, C., Taafe, D.R., Gillis, D., Shaw, J., and Marcus, R. Gymnasts exhibit higher bone mass than runners despite similar prevalence of amenorrhea and oligomenorrhea. J Bone Miner Res 10:26-35; 1995.

10. Saal, J.S., and Hosea, T.M. Rowing. In: *The Spine in Sport.* R. G. Watkins (Ed.) St. Louis, Missouri: Mosby, 1996, pp. 578-591.

11. Smith, R. and Rutherford, O.M. Spine and total body bone mineral density and serum testosterone levels in male athletes. Eur J Appl Physiol 67:330-334, 1993.

12. Snow, C.M., Williams, D.P., LaRiviere, J., Fuchs, R.K., Robinson, T.L. Bone gains and losses following seasonal training and detraining in gymnasts. Calcif Tissue Int 69:7-12, 2001.

13. Snow-Harter, C., Bouxsein, M.L., Lewis, B.T., Carter, D.R., and Marcus, R. Effects of resistance and endurance exercise on bone mineral status of young women: A randomized exercise intervention trial. J Bone Miner Res 7:761-769; 1992.

14. Taaffe, D.R., Robinson, T.L., Snow, C.M., and Marcus, R. High-impact exercise promotes bone gain in well-trained female athletes. J Bone Miner Res 12:255-260; 1997.

15. Taaffe, D.R., Snow-Harter, C.M., Connolly, D.A., Robinson, T.L., Brown, M.D., and Marcus, R. Differential effects of swimming versus weight-bearing activity on bone mineral status of eumenorrheic athletes. J Bone Miner Res 10:586-592; 1995.

16. Watts, N.B. Osteoporotic vertebral fractures. © 2001 American Association of Neurological Surgeons. Neurosurg Focus 10(4); 2001.

17. Witzke, K.A. and Snow, C.M. Effects of plyometric jump training on bone mass in adolescent girls. Med Sci Sports Exerc 32:1051-1057; 2000.

18. Wolman, R.L., Clark, P., McNally, E., Harries, M., and Reeve, J. Menstrual state and exercise as determinants of spinal trabecular bone density in female athletes. BMJ 301:516-518; 1990.

CONCLUSION

The primary mechanical function of bone is to maintain load-bearing capacity. In diseases such as osteoporosis, this capacity is compromised. Reduced bone mass, increased skeletal fragility and susceptibility to fracture characterize osteoporosis and in women, estrogen deficiency and advancing age are the most common causes. Osteoporosis is a major public health problem. In the United States, 10 million people suffer from osteoporosis and 18 million more have lower than normal bone mass. One-third of women over the age of 50 meet the criteria for osteoporosis and after the age of 80 years, 70% of women have osteoporosis (Melton, 1995). However, it is important to note that bone loss associated with estrogen deficiency and aging does not always result in osteoporosis. In fact, one of the most protective factors for lifelong skeletal health is peak bone mass. After completion of longitudinal growth, bone continues to accumulate until the third decade of life (Recker et al., 1992). The more bone mass a person attains early in life the better protection against the inevitable reductions in bone density later in life. Since peak bone mass is a major determinant of lifetime fracture risk, improving bone mass in young women may reduce osteoporosis-related fractures. It is therefore important to identify aggressive strategies to attain greater bone mass in young women.

The attainment and maintenance of peak bone mass depends on genetics, adequate nutrition, normal reproductive hormone function and exercise (NIH, 2000). Exercise is a proven non-pharmaceutical strategy to increase bone density. However, the type, intensity and frequency of skeletal loading required to improve BMD is poorly understood. There is evidence that high magnitude forces and high loading rates best stimulate bone adaptation, however the "dose response" observed in gymnastics training and other high intensity activities has minimal practical application for the general population. Therefore, it is necessary to investigate alternative loading configurations and identify potential relationships amongst the components of loading. For example, can a moderate load applied in an atypical direction elicit a similar response at the hip as a larger load applied in a direction that patterns the activities of daily living, such as jumping?

The aim of our study was to provide preliminary data from which to develop alternative exercise prescriptions that improve bone mass in young women and reduce the risk of osteoporosis-related fractures at the hip and spine later in life. First, we hypothesized that atypical side impact loading would specifically increase the fracture resistance of the hip in its dominant failure mode. Second, we sought to determine if load magnitude influenced spine BMD in young women when repetitions were similar.

In the "Hip Drop" study our results revealed a significant difference between the test and control hip at the femoral neck. Specifically, the test hip increased 0.6% and the control hip decreased 0.6%. Although our data reached significance the practical implications are unknown. First, a 0.66% change is in the range of our DXA machine error and thus may not reflect an actual change in the femoral neck. Second, if indeed there were small changes we do not know the structural consequences of a 0.66% change. In future work it would be appropriate to examine hip geometry to determine if compensatory restructuring has occurred. In light of these observations, our training program was specifically designed to include only one exercise, with a controlled dose (repetitions) and a known force estimate. Despite our marginal results, this study provides a specific exercise prescription from which to build on. For example, modifying the weekly dose from three to five days per week or increasing the length of the design to one year may provide more substantive results. Also, it may be possible to design a device that mechanically loads the hip. This device would remove the performance demands of the current hip drop model and may provide a bone stimulus at the hip in the frail elderly. We designed this alternative and potentially more productive approach to encourage bone adaptation for the specific loading conditions known to be associated with most hip fractures. Given the existing evidence for site-specific bone adaptation from loading and the lack of substantial research in this area, further study is warranted.

In the second study our results showed that experienced but not novice rowers increased spine BMD following six months of rowing training. The experienced rowers were significantly better in several sport specific rowing tests. The rowing stroke targets the spine and we believe that the experience rowers were able to generate larger forces at the spine than the novice rowers. Since repetitions and training sessions were consistent between rowing groups, the greater response at the lumbar spine in experienced rowers versus novice rowers suggests that, in order to increase spine BMD over a short time period in young adult women, a minimum effective load magnitude is required. Our results support other longitudinal data that show rowing to be beneficial to the spine, however, our data provides evidence that a minimum force must be generated before rowing is osteogenic at the spine.

There is strong evidence that life long bone health depends on the amount of bone accumulated prior to age of 30 years. After that the opportunity to increase bone mass diminishes and unavoidable bone loss begins to occur. In adulthood, the more bone you have the more bone you can afford to lose. Thus, measures taken to increase bone mass early in life will, to an extent, prevent osteoporosis-related fractures later in life. Similarly, the protective benefits of exercise to maintain bone later in life are dependent on a commitment to long-term mechanical loading. In both the young and old, the best methods for positively affecting bone mass from loading are still being explored. With this in mind, aggressive preventative measures to build and/or maintain bone mass, such as the atypical loading protocol presented here, must continue to be defined, examined and tested.

BIBLIOGRAPHY

Baldwin, K.M., White, T.P., Arnaud, S.B., Edgerton, V.R., Kraemer, W.J., Kram, R., Raab-Cullen, D., and Snow, C. Musculoskeletal adaptations to weightlessness and development of countermeasures. Med Sci Sports Exerc 28:1247-1253; 1996.

Bassey, E.J. and Ramsdale, S.J. Increase in femoral bone density in young women following high impact exercise. Osteoporos Int 4:72-75; 1994.

Bassey, E.J., Rothwell, M.C., Littlewood, J.J., and Pye, D.W. Pre- and postmenopausal women have different bone mineral density responses to the same high-impact exercise. J Bone Miner Res 13:1805-1813; 1998.

Bauer, J.J., Fuchs, R.K., Smith, G.A., and Snow, C.M. Quantifying force magnitude and loading rate from drop landings that induce osteogenesis. J Appl Biomech 17:142-152; 2001.

Block, G. Human dietary assessment: Methods and issues. Prev Med 18:653-660; 1989.

Boland, A.L., and Hosea, T.M. Injuries in rowing. In: *Clinical Practice of Sports Injury Prevention and Care.* P. A. F. H. Renstrom (Ed.) Cambridge, MA: Blackwell Scientific Publications, 1994, pp. 624-632.

Breit, G.A. and Whelan, R.T. Prediction of human gait parameters from temporal measures of foot-ground contact. Med Sci Sports Exerc 29:540-547; 1997.

Carter, D.R., Beaupre, G.S., and Hayes, W.C. Increasing bone fracture resistance by repeated application of low magnitude forces resembling trauma forces. U.S. Patent 5,752,925, 1998.

Cavanagh, P.R., Davis, B.L., and Miller, T.A. A biomechanical perspective on exercise countermeasures for long term spaceflight. Aviat Space Environ Med 63:482-485; 1992.

Cohen, B., Millet, P.J., Mist, B., Laskey, M.A., and Rushton, N. Effect of exercise training programme on bone mineral density in novice college rowers. Br J Sports Med 29:85-88; 1995.

Courtney, A.C., Wachtel, E.F., Myers, E.R., and Hayes, WC. Effects of loading rate on strength of the proximal femur. Calcif Tissue Int 55:53-58; 1994.

Crossley, K., Bennell, K.L., Wrigley, T., and Oakes, B.W. Ground reaction forces, bone characteristics, and tibial stress fracture in male runners. Med Sci Sports Exerc 31:1088-1093; 1999.

Cummings, S.R., Black, D.M., and Nevitt, M.C. Bone density at various sites for prediction of hip fractures. Lancet 341:72-75; 1993

Dalsky, G.P., Stocke, K.S., Ehsani, A.A., Slatopolsky, E., Lee, W.C., and Berg, S.J. Weight-bearing exercise training and lumbar bone mineral content in postmenopausal women. Ann Intern Med. 108:824-828, 1988

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

Friedlander, A.L., Genant, H.K., Sadowsky, S., Byl, N.N., Gluer, C.C. A two year program of aerobics and weight training enhances bone mineral density of young women. J Bone Min Research. 10:547-585, 1995.

Frost, H.M. The role of changes in mechanical usage set points in the pathogenesis of osteoporosis. J Bone Miner Res 7:253-261; 1992.

Haapasalo, H., Kannus, P., Sievanen, H., Heinonen, A., Oja, P., and Vuori, I. Long-term unilateral loading and bone mineral density and content in female squash players. Calcif Tissue Int 54:2 49-255; 1994.

Hayes, W.C., Myers, E.R., Morris, J.N., Gerhart, T.N., Yett, H.S., and Lipsitz, L.A. Impact near the hip dominates fracture risk in elderly nursing home residents who fall. Calcif Tissue Int 52:192-198; 1993.

Hayes, W.C., Myers, E.R., Robinovitch, S.N., Van Den Kroonenberg, A., Courtney, A.C., and McMahon, T.A. Etiology and prevention of age-related hip fractures. Bone 18:77S-86S; 1996.

Heinonen, A., Kannus, P., Sievanen, H., Oja, P., Pasanen, M., Rinne, M., Uusi-Rasi, K., and Vuori, I. Randomized controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. Lancet 348:1343-1347; 1996.

Heinonen, A., Oja, P., Kannus, P., Sievanen, H., Haapasalo, H., Manttari, A., and Vuori, I. Bone mineral density in female athletes representing sports with different loading characteristics of the skeleton. Bone 17:197-203; 1995.

Heinonen, A., Sievanen, H., Kannus, P., Oja, P., and Vuori, I. Effects of unilateral strength training and detraining on bone mineral mass and estimated mechanical characteristics of the upper limb bones in young women. J Bone Miner Res 11:490-501; 1996.

Huddleston, A.L., Rockwell, D., Kuland, D.N., and Harrison, R.B. Bone mass in lifetime tennis athletes. JAMA. 244:1107-1109, 1980.

Hui, S.L., Slemenda, C.W., and Johnston, C.C. Age and bone mass as predictors of fracture in a prospective study. J Clin Invest 81:1804-1809; 1988

Kerr, D., Morton, A., Dick, I., and Prince, R. Exercise effects on bone mass in postmenopausal women-are site-specific and load-dependent. J Bone Miner Res 11:218-225; 1996.

Kohrt, W.M., Ehsani, A.A., and Birge, S.J. Jr. Effects of exercise involving predominantly either joint-reaction forces on bone mineral density in older women. J Bone Miner Res 12:1253-1261; 1997.

Krolner, B., and Toft, B. Vertebral bone loss: an unheeded side effect of therapeutic bed rest. Clin Sci 64:537-540; 1983

Lanyon, L.E. Using functional loading to influence bone mass and architecture: Objectives, mechanisms, and the relationship with estrogen of the mechanically adaptive process in bone. Bone 18:37S-43S; 1996.

Lohman, T., Going, S., Pamenter, R., Hall, M., Boyden, T., Houtkooper, L., Ritenbaugh, C., Bare, L., Hill, A., and Aickin, M. Effects of resistance training on regional and total bone mineral density in premenopuasal women: A randomized prospective study. J Bone Miner Res 10:1015-1024; 1995.

Maitland, L.A., Myers, E.R., Hipp, J.A., Hayes, W.C., and Greenspan, S.L. Read my hips: measuring trochanteric soft tissue thickness. Calcif Tissue Int 52:85-89; 1993.

Marcus, R. Editorial. Exercise: Moving in the right direction. J Bone Miner Res 13:1793-1796; 1998.

Melton, L.J. III., Atkinson, E.J., O'Fallon, W.M., Wahner, H.W., and Riggs, B.L. Long-term fracture prediction by bone mineral assessed at different skeletal sites. J Bone Miner Res 10:1227-1233; 1993.

Melton, L.J. III., Thamer, M., Ray, N.F., Chan, C.H., Chesnut, C.H., Einhorn, T.A., Johnston, C.C., Raisz, L.G., Silverman, S.L., and Siris, E.S. Fractures attributable to osteoporosis: report from the national osteoporosis foundation. J Bone Miner Res 12:16-23; 1997.

Morris, F.L., Payne, W.R., and Wark, J.D. The impact of intense training on endogenous estrogen and progesterone concentrations and bone mineral acquisition in adolescent rowers. Osteoporos Int 10:361-368; 1999.

Morris, F.L., Smith, R.M., Payne, W.R., Galloway, M.A., and Wark, J.D. Compressive and shear forces generated in the lumbar spine of female rowers. Int J Sports Med 21:518-523; 2000.

Nilsson, J., and Thorstensson, A. Ground reaction forces at different speeds of human walking and running. Acta Physiol Scand 136:217-227; 1989.

NIH Consensus Development Panel. Osteoporosis prevention, diagnosis, and therapy. JAMA 285:785-795; 2001.

Prapavessis, H., and McNair, P.J. Effects of instruction in jumping technique and experience jumping on ground reaction forces. J Orthop Sports Phys Therapy 29:352-356; 1999.

Ray, N.F., Chan, J.K., Thamer, M., and Melton, L.J. Medical expenditures for the treatment of osteoporotic fractures in the United States in 1995: Report from the national osteoporosis foundation. J Bone Miner Res 12:24-35; 1997.

Recker, R.R., Davies, M., Hinder, S.M., Heaney, R.P., Stegman, M.R., Kimmel, D.B. Bone mass gain in adult young women JAMA 268:2403-2408; 1992

Robinovitch, S.N., McMahon, T.A., and Hayes, W.C. Force attenuation in trochanteric soft tissues during impact from a fall. J Orthop Res 13:956-963; 1995.

Robinovitch, S.N., Hayes, W.C., and McMahon, T.A. Prediction of femoral impact forces in falls on the hip. J Biomech Eng 113:366-374; 1991.

Robinson, T.L., Snow-Harter, C., Taafe, D.R., Gillis, D., Shaw, J., and Marcus, R. Gymnasts exhibit higher bone mass than runners despite similar prevalence of amenorrhea and oligomenorrhea. J Bone Miner Res 10:26-35; 1995.

Rockwell, J.C., Sorenson, A.M., Baker, S., Leahey, D., Stock, J.L., Michaels, J., Baran, D.T. Weight training decreases vertebral bone density in premenopausal women: a prospective study. J Endocrin Metab 71:988-993; 1990.

Rubin, C.T. and Lanyon, L.E. Regulation of bone mass by mechanical strain magnitude. The effect of strain magnitude. Calcif Tissue Int 37:411-417; 1985.

Rubin, C.T. and Lanyon, L.E. Regulation of bone formation by applied dynamic loads. J Bone Joint Surg Am 66:397-402; 1984.

Saal, J.S., and Hosea, T.M. Rowing. In: *The Spine in Sport.* R. G. Watkins (Ed.) St. Louis, Missouri: Mosby, 1996, pp. 578-591.

Smith, R., and Rutherford, O.M. Spine and total body bone mineral density and serum testosterone levels in male athletes. Eur J Appl Physiol 67:330-334, 1993.

Shaw, J.M. and Snow, C.M. Weighted vest exercise improves indices of fall risk in older women. J Gerontol 53:M53-M58; 1998.

Slemenda, C., and Johnston, C.C. High impact activities in young women: site-specific bone mass effects among female figure skaters. Bone Miner. 20:125-132, 1993

Snow, C.M., Williams, D.P., LaRiviere, J., Fuchs, R.K., Robinson, T.L. Bone gains and losses following seasonal training and detraining in gymnasts. Calcif Tissue Int 69:7-12, 2001.

Snow-Harter, C., Bouxsein, M.L., Lewis, B.T., Carter, D.R., and Marcus, R. Effects of resistance and endurance exercise on bone mineral status of young women: A randomized exercise intervention trial. J Bone Miner Res 7:761-769; 1992.

Taaffe, D.R., Robinson, T.L., Snow, C.M., and Marcus, R. High-impact exercise promotes bone gain in well-trained female athletes. J Bone Miner Res 12:255-260; 1997.

Taaffe, D.R., Snow-Harter, C.M., Connolly, D.A., Robinson, T.L., Brown, M.D., and Marcus, R. Differential effects of swimming versus weight-bearing activity on bone mineral status of eumenorrheic athletes. J Bone Miner Res 10:586-592; 1995.

Theintz, G., Buchs, B., Rizzoli, R., Slosman, D., Clavien, H., Sizonenko, P.C. and Bonjour, J.P. Longitudinal monitoring of bone mass accumulation in healthy adolescents: evidence for a marked reduction after 16 years of age at the levels of lumbar spine and femoral neck in female subjects. J Clin Endocrinol. Metab 75:1060-1065; 1992

Vouri, I., Heinonen, A., Sievänen, H., Kannus, P., Pasanen, M., and Oja, P. Effects of unilateral strength training and detraining on bone mineral density and content in young women: A study of mechanical loading and deloading on human bones. Calcif Tissue Int 55:59-67; 1994.

Watts, N.B. Osteoporotic vertebral fractures. © 2001 American Association of Neurological Surgeons. Neurosurg Focus 10(4); 2001.

Winters K.M. and Snow C.M. Detraining reverses positive effects of exercise on the musculoskeletal system in premenopausal women. J Bone Miner Res 15:2495-2503; 2000.

Witzke, K.A. and Snow, C.M. Effects of plyometric jump training on bone mass in adolescent girls. Med Sci Sports Exerc 32:1051-1057; 2000.

Wolff, J. Das Gestez der Transformation der Knochen. Hirchwald, Verlag von August., Ed. Berlin, 1892.

Wolman, R.L., Clark, P., McNally, E., Harries, M., and Reeve, J. Menstrual state and exercise as determinants of spinal trabecular bone density in female athletes. BMJ 301:516-518; 1990.

Wolman, R.L., Faulman, L., Clark, P., Hesp, R., and Harries, M.G. Different training patterns and bone mineral density of the femoral shaft in elite, female athletes. Ann Rheum Dis 50:487-489; 1991.

World Health Organization. Assessment of fracture risk and its application to screening for osteoporosis. WHO technical report series 843. Geneva: WHO, 1994.

APPENDICES

APPENDIX A

Informed Consent

A. **ATYPICAL BONE LOADING FOR INCREASING BONE MASS**

B. **Investigators.** Christine Snow, Ph.D., Associate Professor, Department of Exercise and Sport Science 737-6788; Jane LaRiviere, MS. 737-2827

C. **Purpose.** Bone loss during aging and periods of reduced weight bearing, as in bed rest and spaceflight, increases susceptibility to osteoporosis and fracture. Mechanical loading of the skeleton through exercise is a positive stimulus for increasing bone mass yet there are no studies in women during the premenopausal years that show increased bone in the hip, a primary fracture site. Results from our work to date have demonstrated that athletes who perform jumping and falling (gymnasts and wrestlers) have very high bone mass at the hip. This program, using hip drops, mimics the falling activities of athletics and is expected to build bone at the hip, thus reduce susceptibility to hip fracture. This one-year study involves 6 months of hip drops and 6 months of detraining which will provide information on the effect of specific, uncustomary loading on bone, evaluate the forces on bone from the activity, and to evaluate the effects of detraining.

D. **Procedures:** I have been invited to participate in this study. It has been explained to me that it's purpose is to determine if special exercises designed to increase the loads on my skeleton will have a positive effect on hip bone mineral density. I have been selected as a subject because I am a healthy, normally menstruating, pre-menopausal woman between the ages of 18 and 45 years old. I am within 20% of my normal body weight and am able to participate in a physical activity program. I am not pregnant, do not smoke, consume more than 2 alcoholic drinks per day, do not have a condition (i.e. diabetes) that would affect bone metabolism, and do not take medications know to affect my bones (i.e. synthroid, prednisone, or steroid-derived asthma medications). In addition, I am currently not involved in regular high impact activities such as gymnastics, basketball, or volleyball.

E. **Exercises.** I understand that I will be performing hip drops, in which I will lift my hip 4 inches from a side-lying position, then drop, relaxed, onto a padded surface. I understand that I will be instructed at OSU on how to perform the hip drops on a force plate to help me maximize loads at the hip. I will then perform the hip drops three times/week with supervision.

F. **Questionnaires.** I understand that I will be asked to complete a food frequency questionnaire, which will be used to assess my calcium intake over the past year. Based upon these results, I will be asked to supplement my diet with the amount of calcium necessary to bring my daily intake up to the Recommended Dietary Allowance of 1000 mg/day, either using calcium tablets or dietary sources. The calcium intake is set at 1000 mg/day because this is the intake recommended by the National Osteoporosis Foundation (NOF) and the investigator wants to ensure that I have the necessary "building blocks" for bone mineral development.

G. **Ongoing assessments of bone mineral density and body composition.** I understand that my bone mass (whole body, left and right hips, spine) and body composition will be assessed every 6-months using a bone densitometer (DXA). My right hip will be the control hip and the bone mineral density (BMD) change will be compared with the change in BMD of the loaded hip. DXA delivers very low dose x-ray. The amount of radiation I will be exposed to in this study is less than that which I would encounter from natural background radiation when flying in an airplane across the country.

H. **Foreseeable risks or discomforts.** I understand that during the training and testing sessions, every attempt will be made to ensure my safety and comfort. If I experience any injury or complications as a result of my participation, I should notify the researcher as soon as possible so that appropriate safety measures may be taken. While there are some risks associated with the hip drop activity, adjustments in the protocol (reducing height of drop and/or number of repetitions) will be made to accommodate my individual needs.

I. **Benefits from the research.** Benefits of participation include knowledge of bone, muscle and fat mass, and changes over time, as well as participation in an important study to define strategies for prevention of osteoporosis.

J. **Confidentiality.** I understand that as a subject in this study, my confidentiality will be maintained at all times using a number coding system. No one except the researchers will have knowledge of my participation or the results of my test, without my prior consent. I understand that the results of this study may be presented and published, but that no reference will be made as to my identity.

K. **Voluntary Participation.** I understand that my participation in this study is strictly voluntary, and that I may withdraw my participation at any time, without the loss of benefits.

L. **Compensation for injury.** I understand that Oregon State University does not provide a research subject with compensation or medical treatment in the event a subject is injured as a result of participation in a research project.

M. **If I have questions.** If I have any questions or concerns about the research I may contact the researchers, Jane LaRiviere (737-2827) or Christine Snow (737-6788), at any time during the study.

N. **Understanding and Compliance.** My signature below indicates that I have read and understand the conditions described above. I give my informed and voluntary consent to participate in the study.

Participant's Signature ______________________ Date __________

Investigator's Signature ______________________ Date __________

APPENDIX B

OREGON STATE UNIVERSITY BONE RESEARCH LABORATORY

Health History Questionnaire

____ ____________________
Last name First name Middle Date of birth

______________________________ ______________________________
Address, street City, State

____________________ ____________________________________
phone work/home Occupation and/or sports team

Weight ________pounds Height ____ft_____inches M F (circle one)

Please list your present medications and dosages
(include birth control pills/vitamins):

____

****

PAST HISTORY (Check if yes) Have you ever had?		FAMILY HISTORY (Check if yes) Have your grandparents, parents or siblings had?	
High cholesterol	___	Diabetes	___
Rheumatic fever	___	Heart attacks	___
Heart murmur	___	High blood pressure	___
High blood pressure	___	High cholesterol	___
Heart trouble	___	Congenital heart disease	___
Disease of arteries	___	Heart operations	___
Varicose veins	___		
Lung disease	___	Other____________________	
Operations	___		
Back injury	___	____________________	
Other musculoskeletal injury or problems	___	Date of last medical exam? __________	
Epilepsy	___		
		Physician:____________________	

If yes to any of the above, please explain

Which describes your racial/ethnic identify? (Please check all that apply)

___ White, European American, Non Hispanic ___ North African or North African American
___ Asian, Asian American ___ Pacific Islander
___ Black, African American, Non Hispanic ___Hispanic of Latino American
___ Middle Eastern or Middle Eastern American ___ American Indian or Alaskan Native
___ If none of the above choices apply to you, please use your own description:

____

___ Decline to respond

PRESENT SYMPTOMS REVIEW (Check if yes)
Have you recently had?

Chest pain ___ Other______________________________
Shortness of breath ___
Heart palpitations ___
Cough on exertion ___
Coughing blood ___
Back pain ___
Painful, stiff or swollen joints ___

HEALTH HABITS

Smoking	YES	NO		
Do you smoke?	___	___		
Cigarettes	___		How many/day? _______	How many years? _____
Cigar	___		How many/day? _______	How many years? _____
Pipe	___		Times/day? _______	How many years? _____

If you have quit smoking, when did you quit? _____ How many yrs did you smoke? ___

Alcohol Consumption
Do you drink alcohol daily? Y N (circle one) If yes, how many drinks/week? ______

Consumption of calcium-rich daily products
How many 8 oz glasses of milk do you drink per day? _____per week? ____
How many servings of cheese (1 oz) do you eat per day? _____per week? ____
How many servings of yogurt (1 cup) do you eat per week?_____

Body Weight
What was your weight 1 month ago? _____ What was your weight 2 months ago? _____

Cola Beverages
How many cola beverages do you drink daily? ___________
How many years have you been drinking cola beverages on a regular basis? ______

Activity History

I. In high school, would you describe yourself as:

___ active ___ moderately active ___not active (please check one)

Were your activities predominately swimming or cycling? (if yes, circle one)

II. Since high school, would you describe yourself as:
___ active ___ moderately active ___not active (please check one)

Were your activities predominately swimming or cycling? (if yes, circle one)

OSTEOPOROSIS RISK FACTORS

Please circle true or false for the following. If you think a statement may apply to you but are not sure, place a question mark (?) by that statement.

1. true false I have a history of rheumatoid arthritis.
2. true false I have been treated with cortisone or similar drugs.
3. true false I have a close relative with osteoporosis.
4. true false I have a history of an overactive thyroid gland.
5. true false I have a history of overactive parathyroid gland.
6. true false I have a history of alcoholism.
7. true false I have a history of chronic liver disease.
8. true false I have a history of multiple myeloma.
9. true false I have a history of the blood tumor, leukemia.
10. true false I have a history of stomach ulcers.
11. true false I have lactase deficiency (inability to digest milk).
12. true false Some of my stomach has been surgically removed.
13. true false I take anabolic steroids now or have in the past.
14. true false I avoid milk and other dairy products.
15. true false I usually eat meat at least twice a day.
16. true false I drink more than 2 cups of coffee or tea daily.
17. true false On average, I drink 2 or more soft drinks daily.
18. true false I have about 3 or more alcoholic beverages daily.
19. true false I follow a vegetarian diet and have so for years.
20. true false I am not very physically active most of the time.
21. true false I have lost more than 1 inch in height.
22. true false I take or have taken thyroid hormone pills.
23. true false I took phenobarbitol or dilantin for over a year.
24. true false I use Maalox or Mylanta antacids frequently.
25. true false I have taken furosamide (Lasix) for over one year.
26. true false I have been treated with lithium for over one year.
27. true false I have been treated with chemotherapy for cancer.
28. true false I take or have taken cyclosporin A (Sandimmune).
29. true false I have received an organ transplant (kidney, etc.).
30. true false I have had trouble with anorexia nervosa or bulimia.

(Women only)

35. true false I lost my period for a year or more before it came back.
36. true false I have had irregular menstrual periods.
37. true false My menstrual period did not begin until after age 16.
39. true false I have a medical history of endometriosis.
40. true false I lost my periods when I was exercising heavily.
41. true false I have had both ovaries surgically removed.
42. true false I have breast fed a baby for one month or more.
43. true false I take tamoxifin as treatment for breast cancer..
44. true false I went through menopause before age 50.
45. true false I have gone through menopause (change of life).
46. true false I have received estrogen treatment after menopause.

If you take estrogen, for how many years? ________
How many children have you given birth to? ____________
What was the date of your last menstrual period?____________________

APPENDIX C

Dissertation Proposal

Atypical Loading for Increasing Bone Mass

Introduction

There are currently 300,000 hip fractures in this country annually which carry an estimated $8.6 billion economic cost. A robust and independent predictor of hip fracture risk is bone mass. Bone mineral density (BMD) explains as much as 85% of the variance associated with the ability to withstand an applied load (Njeh et al., 1997). In Caucasian women 65-84 years of age 90% of proximal hip fractures are associated with low bone mass (Melton et al., 1997). Thus, increasing bone mass at the hip is an important preventive strategy.

There is evidence that the human skeleton responds to increased mechanical loading by increasing bone mass. Furthermore, adaptations are site specific. For example tennis and squash players exhibit higher BMD in the playing arm than in the non-playing arm (Huddleson et al., 1980; Haapasalo et al. 1994). Slemenda and Johnson (1993) have reported that young female figure skaters, whose activity loads the lower, but not the upper body, exhibit greater BMD in the lower body compared to controls but that group differences vanished when the upper body sites were compared. In 1995, Robinson and co-workers compared collegiate female athletes who participated in high versus low impact sports. They found gymnasts had significantly greater bone mass at the femoral neck and lumbar spine than did distance runners and controls, despite a similar prevalence of menstrual irregularities. Thus they concluded that high magnitude forces to the skeleton from gymnastics training had a powerful osteogenic effect that appeared to counteract the increased bone resorption from low circulating estrogen that accompanies amenorrhea. Fehling and associates (1995) compared female athletes from sports with different loading patterns. They found that volleyball players and gymnasts exhibited significantly greater bone mass at the femoral neck and lumbar spine than did swimmers and controls. In addition, the gymnasts had significantly greater arm BMD than did the volleyball players. These data suggest that high magnitude forces have a positive effect on bone mass and that the response is specific to the site that is loaded.

Longitudinal data have also shown that high magnitude forces have a significant and positive effect on bone mass. In a six month jumping trial, Bassey and Ramsdale (1994) reported a significant increase of 3.4% in bone mass at the greater trochanter.

Certain types of mechanical loading appear to be more osteogenic than others (Taaffe et al., 1997). However, few investigators have attempted to quantify the load magnitudes in human subjects and to our knowledge no one has attempted to apply a direct impact to the hip.

This investigation proposes to evaluate the effect of uncustomary loading on hip bone mineral density. Previous intervention trials have included running, aerobics and jumping all of which have loaded the femur vertically along the long axis of the bone (Robinson et al.,1995; Bassey and Ramsdale, 1994; Bennell et al.,1997; Friedlander et al., 1995). In contrast, the experimental load or 'hip drop' in the proposed longitudinal design is atypical in that the impact is applied directly to the greater trochanter of the hip, perpendicular to the long axis of the femur. In preliminary work we have shown that wrestlers who repeatedly load their hips in uncustomary patterns, have significantly higher bone mass at the hip than normal. It is theorized that the load applied directly to the hip initiates a site-specific adaptive response that increases bone mass at this site. Furthermore, since falling to the side and landing directly on the greater trochanter increases the risk of hip fracture 6 fold, it is possible that mimicking a fall with this type of loading would add bone in a manner that would protect against hip fractures (Hayes et al., 1993). Thus, this proposal addresses the following research questions.

A. Research Questions

1. Does a direct load of moderate intensity on the greater trochanter of the hip promote osteogenesis in this region?

2. Do normal variations in the amount of soft tissue overlying the proximal femur attenuate osteogenesis at the hip?

B. Specific Aims

Aim 1: We intend to apply a side impact load called a 'hip drop' to the proximal femur. Pilot data showed that the hip drop load caused ground reaction forces (GRF) of between 2.5 and 4 X body weight (BW). Bassey and Ramsdale (1994) indicated that their jump protocol produced GRF's of at least 2 X BW. Heinonen et al. (1996) had subjects perform an aerobic jumping routine and reported GRF's of between 2.1 and 5.6 X BW. Given the unique nature of the hip drop we expect the load to be osteogenic. It is possible that the load transmitted by the hip drop will be higher in terms of physiological thresholds because the bone is not accustomed to this type of loading.

Hypothesis 1: Hip drops will increase bone mineral density at the greater trochanter and femoral neck of the proximal femur.

Aim 2: We intend to measure the amount of soft tissue overlying the hip and determine if the thickness of trochanteric soft tissue is inversely related to osteogenesis. Previous research has indicated that soft tissue overlying the greater trochanter attenuates the force applied to the hip with a side impact. Robinovich et al. (1995) conducted impact tests on trochanteric soft tissue samples taken from nine cadavers. The samples were positioned over a surrogate human pelvis and ranged in thickness from 8 to 45 mm with an average thickness of 24 mm. They found that during impact the soft tissue layer attenuated the peak femoral impact force by an average of 13%. It was estimated that the peak femoral impact force decreased at a rate of 70 N for each millimeter increase in soft tissue.

Hypothesis 2: As soft tissue overlying the hip increases, there is a corresponding decrease in bone mineral density.

C. Background and Significance

Epidemiology and Societal Costs. Each year in North America there are nearly 300,000 hip fractures and by the year 2050 this number is expected to double (Melton, 1993). Not only are hip fractures on the rise but the incidence of morbidity and the associated medical costs are startling. It is estimated that over $8.6 billion per annum is spent on hospital services, nursing home care and other expenses associated with hip fractures (Ray et al., 1997). Moreover, despite advancements in medical care, hip fracture sufferers often fail to return to their pre-fracture quality of life. The incidence of hip fractures will continue to increase as the percentage of elderly persons in the world grows. To address the potential epidemic of hip fractures aggressive preventive measures must be explored. Since hip BMD is a powerful predictor of hip fracture, increasing the amount of bone mass at the hip could be an important preventive strategy.

Bone Biomechanics Bone is a nonhomogeneous, anisotropic solid that has been shown to adapt to mechanical loading and unloading by altering its material (strength, stiffness, energy-absorbing capacity) and structural (architecture and geometry) properties (Kannus et al., 1996). Bone is lost during periods of disuse and reduced weight bearing, as in bed rest and space flight (Keller et al., 1991; Lueken et al., 1993). Conversely, bone mass has been shown to increased following participation in activities characterized by high magnitude forces (LaRiviere et al, 1995). Adding to this body of knowledge several researchers have concluded that creating versatile loading environments is important for bone health (Lanyon, 1996; Kannus et al., 1996), yet little is known regarding the bone response (material and structural) when loading occurs in a direction different from daily activities. To our knowledge there have been no longitudinal investigations studying the osteogenic effect of the uncustomary loading.

Structure and Function of Bone. The greater trochanter is comprised of approximately 70% trabecular bone and 30% cortical bone. The femoral neck is about 50% trabecular and 50% cortical bone. Long bones are better adapted to withstanding stresses along the axis of the bone than across the bone axis (anisotropic). Cortical bone has been shown to have greater resistance to compressive loading than tensile and transverse loading, however, compression loading has been shown to be more osteogenic than tensile and transverse loading. The major difference in trabecular bone is its increased porosity and metabolic activity. In addition, trabecular bone strength in compression is approximately the same as its strength in tension.

Animal Models. According to Lanyon (1996) dynamic functional strains stimulate the cells that maintain and adjust the skeletal architecture. The importance of strain regulation has been shown in animal studies in which: faster strain rates were more osteogenic than were slower strain rates (O'Conner et al., 1992); immobilization with only short periods of dynamic strain maintained bone mass (Rubin and Lanyon, 1984); bone formation increased with increasing strain magnitudes and different strain environments produce different bone formation responses (Rubin and Lanyon, 1985)

More recently, investigators have shown that in rat ulnas, daily periods of longitudinal (axial) loading within the physiological range have produced adaptive changes in both the bone mass and architecture (Mosley et al., 1997). At peak strain levels of -0.002 there was a reduction in the curvature of the bone accompanied by a reduction in bone formation. At peak strain levels of -0.004 there was a reduction in curvature accompanied by an increase in bone formation. It is interesting to note that only the higher of the two physiological strains was osteogenic. This could be due to the functional way the bone was loaded, with only the higher end strains being osteogenic. This is in contrast to the landmark studies by Rubin and Lanyon (1985), who showed bone formation with strain levels of -0.001 and as few as 36 consecutive 0.5 Hz cycles per day. However in the avian model, the physiological limits were established from strain gauge recordings taken while the birds were flapping their wings. It is likely that the compressive strains recorded in the immobilized and "loaded" wings was an **atypical** strain (loading) environment, which is potentially more osteogenic.

Human Models. Prospective exercise intervention trials have the advantage of accounting for the biological process of bone turnover. In pre-menopausal women a variety of different loading protocols and experimental designs have been performed. These range from weight training (Rockwell et al., 1990; Snow-Harter et al., 1992), aerobics (Smith et al., 1989), high and low impact exercises (Bassey and Ramsdale, 1994) and competitive athletics (Taaffe et al., 1997; Robinson et al, 1995). Uniting these studies is the desire to determine the types of activities that lead to bone accretion. Most have concluded that physical activity has a positive effect on bone mass. Few investigators have attempted to define the load magnitude of the exercises and there are no data that assess bone response from a load applied to the hip from a direction other than vertical.

Numerous loading protocols and activities have been examined and several studies have shown positive increases in bone mass at the lumber spine (Lohmann et al., 1995; Snow-Harter et al., 1992; Dalsky et al., 1988). However, until 1994 there were no reports of a positive response to exercise at the proximal femur. Bassey and Ramsdale (1994) showed a 3.4% increase in trochanteric BMD following 6 months of jumping. LaRiviere (1995) showed a 2% increase at the hip in gymnasts following a training season. It was concluded that the high magnitude forces experienced by the gymnasts were osteogenic. Based on these studies recent research has focused on increasing the magnitude of the load in the vertical direction, such as the addition of weighted vests used in conjunction with jumping protocols. However, limiting exercise regimens, designed to increase bone mass, to ever increasing vertical loads may be over looking other important mechanical parameters effecting bone mass. Further, increasing the performance demands by increasing the magnitudes of the vertical loads reduces the feasibility of implementing the exercise as a preventive strategy for maintaining hip BMD in general populations.

In addition, investigators have been using loading protocols in these interventions that are based on normal daily loading patterns. At the hip, fractures rarely occur spontaneously during normal activity, but instead are most commonly associated with a fall to the side directly on the greater trochanter (Hayes et al., 1993)

Gymnastics. Gymnasts regularly experience load magnitudes greater than physiological thresholds and despite a high prevalence of reproductive hormonal abnormalities, bone mass in gymnasts is significantly higher than normal, particularly at the hip (Robinson et al., 1995; Fehling et al., 1995; Taaffe et al., 1997). One explanation is that the magnitude of the strain, which results from landing, is able to counteract the hormonal deficiencies normally detrimental to the maintenance of healthy bone. However the typical training sessions of gymnasts differ depending on their event(s). Furthermore, they perform relatively few of their big tricks each session and the landing surfaces during training are heavily padded. One commonality is that all gymnasts fall, thus subject the skeleton to uncustomary loading and it is possible that these unique loading conditions are osteogenic.

Wrestling. Wrestlers experience far fewer high magnitude forces from vertical loading than gymnasts. A typical wrestling training session involves falls, typically on the hip to prevent landing on the stomach or back. We have shown that collegiate wrestlers have femoral neck BMD's 30% higher than normal collage aged men (To be presented at 1999 ACSM, BRL, Oregon State University). A possible explanation is the uncustomary loading environment routinely observed in wrestling training and competition promotes bone acquisition.

The commonalties between wrestlers and gymnasts include a higher than normal BMD at the hip and regular uncustomary loading. While both activities engender high force magnitudes in the body they are different in terms of direction of loading. Therefore, it is possible that the higher than normal hip BMD observed in wrestlers and gymnasts is due to their regular exposure to uncustomary loading. Whether the high BMD values observed in gymnasts is due more to falling on the hip than landing on the feet is unknown.

These data have led to the submission of a patent (Carter et al., 1998) to cover instrumentation to load the hip in an uncustomary horizontal direction. To date, the efficacy of this loading model has not been tested.

D. Preliminary Study

To evaluate the feasibility of conducting a hip drop study, 17 women participated in a 10-week hip drop investigation. The technique was explained to the women and they began performing 3 sets of 10 hip drops on the left side from a 10 cm height three times a week. In addition, hip drop ground reaction forces (GRF) were calculated from a force plate. The GRF's ranged between 2.5 and 4 X BW. No significant BMD findings were expected due to the short interval of the study but it was established that young active women could tolerate this type of loading protocol without injury or chronic discomfort.

E. Methods

Subjects: Fifty women athletes between the ages of 18 and 23 years, will be recruited from the Oregon State University Women's Crew. The exclusion criteria will be: 1) conditions known to affect bone metabolism (i.e. uncontrolled diabetes), 2) injuries that would prevent the proper performance of a hip drop, 3) medications known to effect bone (i.e. steroid-derived asthma medication). As crew athletes, all subjects will participate in the same training program. In all subjects the left hip will be the test hip and the right hip will serve as the control. To ensure proper technique, subjects will participate in several training sessions led by the investigator and will receive additional performance feedback from ground reaction forces generated by dropping on a force plate. The subjects will be considered trained when the hip drop can be performed in a repeatable manner, as judged by the investigator. The Oregon State University Institutional Review Board approved this study and all subjects will provide informed consent.

Menstrual, Dietary and Physical Activity Assessment. Questionnaires will be used to quantify menstrual status and dietary calcium intake.

Training. For Aim 1, the subjects will be trained as explained above to perform a consistent and repeatable hip impact. The subject will be positioned on their side so that their left greater trochanter is in contact with the floor. The upper body rests on the left elbow and the right hand was positioned in front of the body for balance and for assisting in lifting the hips off the ground. The subject begins the hip drop by raising their hips 10 cm off the ground and allowing the hips to drop vertically back to the ground, impacting the greater trochanter. The subject maintains a side lying position for the duration of the hip drop. To ensure that the quality of performance is maintained the hip drops will be performed with a partner. In between each hip drop one partner will slide a 10 cm measuring device under the test hip and removed it prior to the drop to assure that the standard hip drop height is reached.

Each subject will perform 30 hip drops three times a week for 6 months.

Measurements

Bone Measurement: Bone mineral density (g/cm^2) will be assessed at the proximal femur (greater trochanter and femoral neck) at baseline and six months using dual-energy X-ray absorptiometry on a QDR-1000/W (Hologic Inc. Waltham, MA). The coefficient of variation (CV) for hip BMD measures in our laboratory is <1.5%.

Soft Tissue Measurement. To measure the soft tissue overlying the greater trochanter we will use a technique introduced by Maitland et al. (1989). Maitland et al. (1989) compared trochanteric soft tissue thickness measured by ultrasound (US) to measures obtained by dual energy X-ray absorptiometry (DXA), hip circumference, body mass index, bioelectrical impedance and hip/waist circumference. They found that soft tissue assessment by DXA was significant and most strongly correlated with US trochanteric soft tissue measures ($r^2 = 0.815$, $P<0.0001$). They concluded that DXA provided a good measure of trochanteric soft tissue thickness and is much easier to use than US.

Trochanteric soft tissue will be obtained from the DXA hip scans obtained at baseline and six months. The subject will be positioned supine on the scanner bed. The X-ray pencil beam will be positioned 1 cm away from the most lateral aspect of the skin over the greater trochanter. A wooden block will be positioned under the beam at the start point of the scan to assist in differentiating the skin/air interface. Measurement is obtained by counting the number of pixels (1 pixel = 1.006 mm) between the greater trochanter and skin surface.

Data Analysis. Completely within 2 X 2 repeated measures ANOVA's will be used detect the difference between the experimental hip and the control hip for bone mineral density measurements obtained at baseline and 6 months.

Sample Size. Power calculations revealed that with an effect size of 3%, an alpha level of 0.05, a standard deviation of 0.075 and sample size of n = 30 the power to detect an interaction is 77%. To accounting for possible attrition a sample size of 48 was selected.

F. Literature Cited

Bassey, E.J. and Ramsdale, S.J. Increase in femoral bone density in young women following high impact exercise. Osteoporos Int 4:72-75; 1994.

Bennell, K.L., Malcolm, S.A., Khan, K.M., Thomas, S.A., Reid, S.J., Brukner, P.D., Ebeling, P.R., and Wark, J.D. Bone mass turnover in power athletes, endurance athletes, and controls: a 12-month longitudinal study. Bone 20:477-484; 1997.

Carter, D.R., Beaupre, G.S., and Hayes, W.C. Increasing bone fracture resistance by repeated application of low magnitude forces resembling trauma forces. U.S. Patent 5,752,925, 1998.

Dalsky, G.P., Stocke, K.S., Ehsani, A.A., Slatopolsky, E., Lee, W.C., and Berg, S.J. Weight-bearing exercise training and lumbar bone mineral content in postmenopausal women. Ann Intern Med 108:824-828; 1988.

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

Friedlander, A.L., Genant, H.K., Sadowsky, S., Byl, N.N., and Gluer, C.C. A two year program of aerobics and weight training enhances bone mineral density of young women. J Bone Min Res 10:547-585; 1995.

Haapasalo, H., Kannus, P., Sievanen, H., Heinonen, A., Oja, P., and Vuori, I. Long-term unilateral loading and bone mineral density and content in female squash players. Calcif Tissue Int 54:249-255; 1994.

Hayes, W.C., Myers, E.R., Morris, J.N., Gerhart, T.N., Yett, H.S., and Lipsitz, L.A. Impact near the hip dominates fracture risk in elderly nursing home residents who fall. Calcif Tissue Int 52:192-198; 1993.

Heinonen, A., Kannus, P., Sievanen, H., Oja, P., Pasanen, M., Rinne, M., Uusi-Rasi, K., and Vuori, I. Randomized controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. Lancet 348:1343-1347; 1996.

Huddleston, A.L., Rockwell, D., Kuland, D.N., and Harrison, R.B. Bone mass in lifetime tennis athletes. JAMA 244:1107-1109; 1980.

Kannus, P., Sievanen, H., and Vuori, I. Physical loading, exercise, and bone. Bone 18:S1-S3; 1996.

Keller, T.S., Strauss, A.M., and Szpalski, M. Prevention of bone loss and muscle atrophy during space flight. 42nd Congress of the International Astronautical Federation, October 1991, Montreal, Canada.

Lanyon, L.E. Using functional loading to influence bone mass and architecture: objectives, mechanisms, and the relationship with estrogen of the mechanically adaptive process in bone. Bone 18:37S-43S; 1996.

LaRiviere, J., Snow-Harter, C., and Robinson, T.L. Bone mass changes in female competitive gymnasts over two training seasons. Med Sci Sports Exer 27:S68; 1995.

Lohmann, T., Going, S., Pamenter, R., Hall, M., Boyden, T., Houtkooper, L., Rittenbaugh, C., Bare, L., Hill, A., and Aickin, M. Effects of resistance training on regional and total bone mineral density in premenopausal women: a randomized prospective study. J Bone Miner Res 10:1015-1024; 1995.

Lueken, S., Arnaud, S., Taylor, A., and Baylink, D. Changes in markers in bone formation and resorption in a bedrest model of weightlessness. J Bone Miner Res 8:1433-1438; 1993.

Maitland, L.A., Myers, E.R., Hipp, J.A., Hayes, W.C., and Greenspan, S.L. Read my hips: measuring trochanteric soft tissue thickness. Calcif Tissue Int 52:85-89; 1993.

Melton, L.J. Hip fractures: a worldwide problem today and tomorrow. Bone 14:S1-S8; 1993.

Melton, L.J., Thamer, M., Ray, N.F., Chan, C.H., Chesnut, C.H., Einhorn, T.A., Johnston, C.C., Raisz, L.G., Silverman, S.L., and Siris, E.S. Fractures attributable to osteoporosis: report from the national osteoporosis foundation. J Bone Miner Res 12:16-23; 1997.

Mosley, J.R., March, B.M., Lynch, J., and Lanyon, L.E. Strain magnitude related changes in whole bone architecture in growing rats. Bone 20:191-198; 1997

Njeh, C.F., Kuo, C.W., Langton, C.M., Atrah, H.I., and Boivin, C.M. Prediction of femoral bone strength using ultrasound velocity and BMD: an in vitro study. Osteoporos Int 7:471-477; 1997.

O'Conner, J.E., Lanyon, L.E., and Macfie, H. The influence of strain rate on adaptive bone remodeling. J Biomech 15:767-781; 1992.

Ray, N.F., Chan, J.K., Thamer, M., and Melton, L.J. Medical expenditures for the treatment of osteoporotic fractures in the United States in 1995: Report from the national osteoporosis foundation 12:24-35; 1997.

Robinovitch, S.N., McMahon, T.A., and Hayes, W.C. Force attenuation in trochanteric soft tissues during impact from a fall: J Orthopedic Res 13:956-963; 1995.

Robinson, T.L., Snow-Harter, C., Taafe, D.R., Gillis, D., Shaw, J., and Marcus, R. Gymnasts exhibit higher bone mass than runners despite similar prevalence of amenorrhea and oligomenorrhea. J Bone Miner Res 10:26-35; 1995.

Rockwell, J.C., Sorenson, A.M., Baker, S., Leahey, D., and Stock, J.L. Weight training decreases vertebral bone density in premenopausal women: a prospective study. J Clin Endocrinol Metab 71:988-993; 1990.

Rubin, C.T., and Lanyon, L.E. Regulation of bone mass by mechanical strain magnitude. The effect of strain magnitude. Calcif Tissue Int 37:411-417; 1985.

Rubin, C.T., and Lanyon, L.E. Regulation of bone formation by applied dynamic loads. J Bone Joint Surg 66:397-402; 1984.

Slemenda, C., and Johnston, C.C. High impact activities in young women: site-specific bone mass effects among female figure skaters. J Bone Miner Res 20:125-132; 1993.

Smith, E.L., Gilligan, C., McAdam, M., Ensign, C.P., and Smith, P.E. Deterring bone loss by exercise intervention in premenopausal and postmenopausal women. Calcif Tissue Int 44:312-321; 1989.

Snow-Harter, C., Bouxsein, M.L., Lewis, B.T., Carter, D.R., and Marcus, R. Effects of resistance and endurance exercise on bone mineral status of young women: a randomized exercise intervention trial. J Bone Miner Res 7:761-769; 1992.

Taafe, D.R., Robinson, T.L., Snow, C.M., and Marcus, R. High-impact exercise promotes bone gain in well-trained female athletes. J Bone Miner Res 12:255-260; 1997.

APPENDIX D

Chapter 2 – Raw Data

age1	age2	height	rfnbmd1	rtrbmd1	rtobmd1	rfnbmd2	rtrbmd2
18.3	18.8	180.3	0.899	0.87	1.015	0.881	0.856
18.3	18.8	167.6	0.9	0.763	0.998	0.92	0.789
20.8	21.3	172.7	1.175	0.883	1.174	1.122	0.884
22.2	22.7	165.1	1.026	0.788	1.112	1.012	0.78
18.8	19.3	179.1	1.056	0.792	1.079	1	0.791
22.7	23.2	182.9	0.835	0.74	0.933	0.847	0.768
18.8	19.3	165.1	1.157	0.949	1.214	1.158	0.959
18.4	18.9	165.1	1.032	0.766	1.023	1.023	0.749
19.4	19.9	172.7	1.05	0.898	1.102	1.011	0.922
20.1	20.6	158.8	0.926	0.777	0.972	0.929	0.783
18.4	18.9	175.3	1.086	0.651	1.006	1.049	0.654
18.6	19	152.4	0.951	0.661	0.891	0.977	0.634
20.2	20.7	177.8	1.066	0.749	1.036	1.106	0.759
18.4	18.9	176.5	1.008	0.746	1.032	1.021	0.766
19	19.5	182.9	0.972	0.797	1.012	0.98	0.815
18.7	19.2	174.0	1.027	0.839	1.074	0.952	0.821
18.9	19.4	175.3	0.822	0.774	0.956	0.839	0.769
19.3	19.8	172.7	1.038	0.827	1.056	1.043	0.83
19.6	20.1	175.3	1.094	0.759	1.077	1.096	0.786
19.3	19.8	160.0	1.043	0.802	1.088	1.037	0.813
21.2	21.7	172.7	1.092	0.904	1.146	1.085	0.897
18.9	19.4	177.8	0.988	0.825	1.043	1.008	0.844
18.2	18.7	180.3	1.044	0.855	1.109	0.939	0.841
21.6	22.1	175.3	1.001	0.785	1.028	0.991	0.794
21	21.5	175.3	0.96	0.712	0.993	0.944	0.729
20.7	21.2	177.2	1.126	0.777	1.067	1.128	0.797
19	19.5	180.3	1.146	0.834	1.109	1.117	0.822
19.9	20.4	162.6	0.992	0.787	1.026	0.987	0.791
18.7	19.2	177.8	0.898	0.689	0.92	0.917	0.683
19.4	19.9	181.6	0.98	0.789	1.072	1.015	0.781
21.7	22.2	172.7	0.895	0.787	1.001	0.873	0.759
19.5	20	172.7	0.892	0.746	1.024	0.885	0.768
20.9	21.4	177.8	1.152	0.958	1.252	1.197	0.973
18.2	18.7	172.7	0.877	0.765	1.056	0.856	0.756
18.7	19.2	155.0	0.728	0.602	0.77	0.737	0.596
20.9	21.4	175.3	1.032	0.917	1.079	1.033	0.941
19.9	20.4	160.0	1	0.77	1.047	0.98	0.79
21.9	22.3	177.8	0.826	0.661	0.892	0.814	0.67
19.1	19.6	152.4	0.857	0.814	0.977	0.834	0.819

rtobmd2	lfnbmd1	ltrbmd1	rtobmd1	lfnbmd2	ltrbmd2	ltobmd2	rsoftis1
1.013	0.92	0.943	1.06	0.925	0.935	1.059	26
1.019	0.904	0.749	1.003	0.925	0.764	1.031	58
1.188	1.126	0.858	1.179	1.115	0.875	1.18	57
1.117	0.949	0.747	1.055	0.963	0.761	1.062	73
1.065	1.034	0.844	1.071	1.092	0.86	1.102	49
0.954	0.783	0.718	0.863	0.807	0.736	0.877	51
1.207	1.151	1.021	1.263	1.101	0.985	1.227	60
1.043	0.993	0.761	1.038	1.017	0.766	1.049	67
1.1	0.985	0.909	1.08	0.984	0.913	1.09	67
0.985	0.871	0.8	0.957	0.874	0.809	0.95	41
1.006	0.913	0.635	0.931	0.95	0.637	0.923	76
0.879	0.976	0.709	0.941	0.967	0.71	0.938	40
1.047	1.062	0.778	1.051	1.075	0.785	1.056	52
1.048	0.973	0.771	1.048	0.974	0.763	1.046	68
1.007	0.993	0.84	1.07	0.994	0.872	1.081	45
1.052	0.977	0.855	1.072	0.962	0.859	1.056	65
0.967	0.818	0.788	0.978	0.87	0.789	0.995	48
1.051	1.007	0.785	1.018	1.039	0.787	1.017	36
1.096	1.063	0.787	1.092	1.048	0.81	1.115	69
1.093	1.009	0.809	1.101	1.098	0.822	1.125	38
1.153	1.134	0.929	1.187	1.118	0.881	1.15	56
1.047	0.976	0.831	1.032	0.996	0.836	1.048	71
1.074	1.002	0.851	1.15	0.981	0.849	1.136	62
1.039	0.979	0.833	1.039	0.995	0.843	1.05	50
0.995	0.924	0.73	0.99	0.916	0.727	0.979	40
1.086	1.108	0.784	1.071	1.101	0.791	1.062	48
1.082	1.13	0.856	1.122	1.133	0.835	1.102	56
1.057	1.015	0.748	1.008	1.025	0.773	1.018	50
0.919	0.891	0.671	0.94	0.878	0.67	0.942	50
1.074	1.05	0.822	1.101	1.072	0.865	1.135	70
0.992	0.911	0.768	0.992	0.899	0.751	0.995	41
1.033	0.952	0.818	1.066	0.969	0.836	1.076	57
1.265	1.145	1.007	1.297	1.127	0.999	1.318	68
1.048	0.836	0.732	1.011	0.826	0.719	1.008	56
0.766	0.742	0.555	0.766	0.745	0.555	0.759	36
1.1	1.002	0.909	1.078	0.984	0.883	1.07	60
1.042	0.93	0.779	1.007	0.928	0.764	1.001	38
0.886	0.809	0.679	0.912	0.812	0.663	0.904	47
0.992	0.889	0.789	0.965	0.887	0.776	0.966	45

rsoftis2	lsoftis1	lsoftis2	%chrfn	%chlfn	%chrtr	%chltr	%chrto
37	25	31	-2	0.543	-1.61	-0.848	-0.197
47	64	50	2.222	2.323	3.408	2.003	2.104
55	52	49	-4.51	-0.977	0.113	1.981	1.193
71	69	70	-1.36	1.475	-1.02	1.874	0.45
52	47	53	-5.3	5.609	-0.126	1.896	-1.297
56	42	50	1.437	3.065	3.784	2.507	2.251
49	58	46	0.086	-4.34	1.054	-3.53	-0.577
68	68	70	-0.872	2.417	-2.22	0.657	1.955
64	63	60	-3.71	-0.102	2.673	0.44	-0.181
44	41	42	0.324	0.344	0.772	1.125	1.337
71	82	78	-3.41	4.053	0.461	0.315	0
40	42	37	2.734	-0.922	-4.08	0.141	-1.347
53	51	53	6.226	0	1.198	3.018	1.062
70	69	69	1.984	0.103	2.681	-1.04	1.55
42	44	37	0.823	0.101	2.258	3.81	-0.494
60	65	62	-7.3	-1.54	-2.15	0.4678	-2.048
39	53	42	2.068	6.357	-0.646	0.1269	1.151
40	36	40	0.482	3.178	0.363	0.2548	-0.473
62	65	57	0.183	-1.41	3.557	2.922	1.764
34	32	38	-0.575	8.821	1.372	1.607	0.46
55	58	59	-0.641	-1.41	-0.774	-5.17	0.611
67	67	63	2.024	2.049	2.303	0.6017	0.384
54	60	59	-10.1	-2.1	-1.64	-0.235	-3.156
56	45	53	-0.999	1.634	1.146	1.2	1.07
39	36	39	-1.67	-0.866	2.388	-0.411	0.201
52	48	49	0.178	-0.632	2.574	0.8929	1.781
59	47	55	-2.53	0.265	-1.44	-2.45	-2.435
50	57	56	-0.504	0.985	0.508	3.342	3.021
50	46	50	2.116	-1.46	-0.871	-0.149	-0.109
71	63	64	3.571	2.095	-1.01	5.231	0.187
45	38	41	-2.46	-1.32	-3.56	-2.21	-0.899
66	56	65	-0.785	1.786	2.949	2.2	0.879
69	70	68	3.906	-1.57	1.566	-0.794	1.038
51	59	50	-2.39	-1.2	-1.18	-1.78	-0.758
40	39	42	1.236	0.404	-0.997	0	-0.519
59	57	63	0.097	-1.8	2.617	-2.86	1.946
38	46	46	-2	-0.215	2.597	-1.93	-0.478
49	45	46	-1.45	0.371	1.362	-2.36	-0.673
45	48	44	-2.68	-0.225	0.614	-1.65	1.535

%chlto	calories	calcium	grf1	grf2	grf3	grf4
-0.094	1729	1152	1520	1408	1420	1484
2.792	2456	1733	1356	1281	1367	1363
0.085	1858	1653	1935	1757	1841	1859
0.664	1591	821.2	2070	2014	1829	1868
2.894	2871	2506	1371	1487	1648	1655
1.622	2230	1002	1628	1764	1637	1610
-2.85	1044	747.8	1108	1334	1343	1209
1.06	2373	1639	1885	1530	1594	1578
0.926	1728	1491	1823	1638	1666	1806
-0.731	2609	1218	1375	1345	1191	1165
-0.859	1281	805	1720	1730	1700	1720
-0.319	2409	1606	791	717.8	764.2	739.7
0.476	2278	1264	1136	1722	1467	1500
-0.191	2364	1617	1169	1196	1382	1382
1.028	1951	1595	1441	1346	1267	1241
-1.493	2894	2260	1577	1682	1520	1723
1.738	2311	1259	2109	1934	1684	1909
-0.098	2423	1688	1350	1272	1426	1394
2.106	1429	599.5	1776	1576	1553	1568
2.18	1623	1421	993.7	1030	996.1	1123
-3.117	1087	520.3	1746	1773	1800	1723
1.55	1937	1473	1572	1565	1531	1416
-1.217	2064	2474	2851	2506	2592	2585
1.059	2091	2075	1306	1315	1378	1359
-1.111	2118	792.6	1757	1975	1588	1924
-0.84	3249	1651	1239	1180	1071	1007
-1.783	1322	941	2162	1931	1868	1803
0.992	2128	962.4	1133	1090	1282	1198
0.213	1177	658.1	1114	1061	966.8	1309
3.088	855.3	686.8	1926	1987	1821	1875
0.302	1892	1396	1311	1206	1614	1262
0.938	1556	1290	1593	1566	1393	1330
1.619	2311	2007	1470	1468	1264	1420
-0.297	1976	1627	1836	1821	1731	1648
-0.914	1189	765.9	731	737.7	748	825.6
-0.742	1795	1244	1535	1399	1681	1546
-0.596	2370	1335	811.8	894	715.6	900.3
-0.877	2045	999.6	1392	1148	1355	1133
0.104	1490	791	951.4	999.2	1098	893.3

APPENDIX E

Chapter 3 - Raw Data

rowtime	code	tscore	height	age	bmi1	bmi2
3	1	105	1.8	18.8	23.43	24.51
3	1	98	1.68	18.8	24.73	23.63
3	1	125	1.8	19.3	21.73	21.91
3	1	116	1.68	19.3	22.92	21.61
3	1	106	1.68	18.9	27.88	28.38
3	1	118	1.73	19.9	26.93	26.33
3	1	100	1.78	18.9	25	25.12
3	1	111	1.8	19.5	23.21	22.53
3	1	106	1.75	19.2	24.52	23.83
3	1	93	1.78	19.4	21.84	21.05
3	1	118	1.78	20.1	26.67	25.38
3	1	103	1.78	19.4	22.6	22.79
3	1	104	1.8	18.7	26.36	26.36
3	1	103	1.78	22.1	22.41	22.38
3	1	117	1.8	19.5	25.59	26.85
3	1	104	1.63	20.4	25.25	25.25
3	1	88	1.78	19.2	22.95	23.61
3	1	108	1.75	18.7	26.58	25.61
3	1	109	1.6	20.4	23.59	23.67
16	2	113	1.73	21.3	26.3	25.53
40	2	109	1.65	22.7	30.45	30.01
40	2	90	1.83	23.2	23.41	24.58
16	2	97	1.6	20.6	26.02	25.27
28	2	99	1.78	20.7	24.33	24.59
16	2	95	1.8	18.9	23.52	24.38
16	2	107	1.73	19.8	22.12	22.89
16	2	125	1.73	21.7	25.99	26.36
40	2	111	1.75	21.5	26.29	26.58
28	2	114	1.8	21.2	20.86	21.57
16	2	105	1.83	19.9	27.74	28.01
28	2	92	1.75	22.2	23.77	24.16
16	2	107	1.78	20	24.3	25
40	2	123	1.78	21.4	28.69	27.52
28	2	106	1.78	21.4	26.29	26.32
28	2	92	1.78	22.3	24.46	24.9
0	3	110	1.78	22.2	24.27	23.89
0	3	105	1.68	22.3	20.27	20.23
0	3	92	1.75	18.5	19.89	21.81
0	3	78	1.55	18.5	19.19	19.85
0	3	117	1.78	18.1	21.78	22.09
0	3	104	1.75	18.5	20.15	20.11
0	3	118	1.69	18	21.08	21.5
0	3	113	1.73	18.5	21.62	22.39
0	3	110	1.65	18.5	24.32	24.39

0	3	90	1.57	18.2	21.99	22.43
0	3	112	1.6	19.2	29.53	30.78
0	3	98	1.78	22.4	19	19.38
0	3	99	1.65	18.2	20.94	21.85
0	3	105	1.68	18.9	22.32	24.52

jan2k	feb2k	mar2k	jan6k	feb6k	mar6k
466.1	459	459	1470	1538	1538
494	481.8	470.1	1567	1552	1494
498.3	472.3	463.1	1565	1537	1508
516.7	472.4	464.2	1565	1575	1540
481.8	465.9	461.2	1554	1513	1486
478.1	456.7	447.9	1545	1462	1443
465.9	459.8	448.8	1494	1539	1446
516.4	502	491.4	1680	1680	1576
490.8	479.6	478.2	1604	1578	1540
481.6	466.7	458.4	1560	1560	1482
468.8	462.5	462.5	1548	1578	1492
519.5	496.8	488	1731	1659	1573
458.8	442.5	437.1	1494	1444	1427
465.1	447.7	445.9	1484	1454	1420
467.9	455.4	455.4	1477	1466	1432
496	471.8	464.9	1597	1547	1514
490.8	477.4	477.4	1579	1542	1496
488.1	475.3	463.1	1592	1538	1497
516.7	519	513.5	1706	1706	1655
452.7	442.4	443.9	1426	1403	1446
477.8	469.6	463.2	1508	1514	1501
437	436.7	433.6	1389	1376	1360
490	482.5	476.2	1592	1538	1559
446.4	435.9	438.2	1446	1402	1397
466.2	456.1	451.9	1467	1467	1463
465.7	463.2	458.3	1535	1490	1477
442.6	432.1	436.5	1415	1399	1383
441.4	430.4	433.3	1411	1403	1398
464	456.3	450.3	1482	1479	1461
453.7	443.1	447.3	1468	1445	1420
458.8	451.2	449.3	1433	1419	1419
460.5	454.6	454.6	1479	1464	1461
457.4	454	444	1508	1464	1445
434.1	435.8	426.4	1413	1398	1370
436.8	436.1	434.2	1420	1397	1383

lumbmd1	lumbmd2	diffbmd	%chlbmd	calcium
1.156	1.135	-0.021	-1.82	1152
1.024	1.061	0.037	3.61	1733
1.343	1.346	0.003	0.22	2506
1.239	1.247	0.008	0.65	747.8
1.113	1.142	0.029	2.61	1639
1.207	1.269	0.062	5.14	1491

1.093	1.079	-0.014	-1.28	805
1.199	1.195	-0.004	-0.33	1617
1.136	1.144	0.008	0.7	1595
1.023	1.008	-0.015	-1.47	2260
1.233	1.24	0.007	0.57	1688
1.11	1.109	-0.001	-0.09	1421
1.179	1.123	-0.056	-4.75	520.3
1.133	1.092	-0.041	-3.62	1473
1.293	1.266	-0.027	-2.09	792.6
1.071	1.092	0.021	1.96	1651
0.962	0.947	-0.015	-1.56	941
1.158	1.162	0.004	0.35	1290
1.141	1.144	0.003	0.26	1627
1.205	1.189	-0.016	-1.33	1653
1.079	1.154	0.075	6.95	821.2
0.938	0.953	0.015	1.6	1002
0.974	1.019	0.045	4.62	1218
1.01	1.042	0.032	3.17	1606
1.012	1.029	0.017	1.68	1264
1.115	1.15	0.035	3.14	1259
1.321	1.319	-0.002	-0.15	599.5
1.148	1.172	0.024	2.09	2474
1.187	1.205	0.018	1.52	2075
1.062	1.136	0.074	6.97	962.4
0.977	0.974	-0.003	-0.31	658.1
1.079	1.122	0.043	3.99	686.8
1.306	1.297	-0.009	-0.69	1396
1.277	1.286	0.009	0.7	2007
0.973	0.976	0.003	0.31	765.9
1.171	1.178	0.007	0.6	
1.115	1.116	0.001	0.09	
0.997	1.014	0.017	1.71	
0.841	0.828	-0.013	-1.55	
1.26	1.27	0.01	0.79	
1.123	1.156	0.033	2.94	
1.269	1.299	0.03	2.36	
1.22	1.23	0.01	0.82	
1.186	1.17	-0.016	-1.35	
0.966	0.982	0.016	1.66	
1.205	1.221	0.016	1.33	
1.045	1.039	-0.006	-0.57	
1.065	1.072	0.007	0.66	
1.138	1.146	0.008	0.7	