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Osteoporotic vertebral fractures are a common and costly public health problem with a high occurrence in older women due to menopausal-onset bone loss. Recent findings suggest that mechanical loading created by upper body resistance training can stimulate bone growth in the lumbar spine, reducing osteoporosis-related bone loss and associated fracture risk. However, there are little loading data on which to base an exercise-based osteoporosis prevention program. This study therefore determined how different combinations of upper and lower body resistance training exercises affected lumbar loading in middle-aged women. Kinematic and kinetic data were collected while 20 women, aged 37 to 50, performed bilateral biceps curls with 2.3 kg dumbbells, bodyweight squats, squats while wearing a 4.5 kg weighted vest, and a combined squat-plus-curl exercise. Using these data, peak compressive and anterior shear loads on L1 at the T12/L1 joint and on L5 at the L5/S1 joint were estimated using a biomechanical model and were compared between exercises. Combining the biceps curl with a squat produced significantly larger compressive loads at L5/S1 and larger anterior shear loads on L1 than when performing the biceps curl on its own. Static resistance in the form of the weighted vest created significantly larger compressive loads at L5/S1 (2002 ± 402 N) and larger anterior shear loads on L1 (682 ± 134 N) than did bodyweight squats. Contrary to our hypothesis, peak lumbar loads associated with adding dynamic resistance, in the form of the biceps curl, to a squat did not differ from those for bodyweight squats or for squats with the weighted vest. These results indicate that, for this population, adding static resistance to the upper body in the form of a weighted vest is the best choice, of the exercises studied, for inclusion in an exercised-based osteoporosis prevention program. However, for the low level of added resistance studied, the associated lumbar loads may not be sufficiently large to promote bone growth.

Effects of Combining of Upper and Lower Body Resistance Training on Lumbar Loading

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

Elizabeth R. Doran, Author

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

Effects of Combining of Upper and Lower Body Resistance Training on Lumbar Loading

Chapter 1 Introduction

Osteoporosis is a serious concern for older adults. It is defined as "a skeletal disorder characterized by compromised bone strength predisposing a person to an increased risk of fracture" (Siris et al., 2010). Osteoporosis occurs when the bone remodeling process becomes unbalanced, favoring osteoclast activity (bone resorption) over osteoblast activity (bone deposition). Clinically, osteoporosis is diagnosed using dual x-ray absorptiometry (DXA). A DXA-measured bone mineral density (BMD) that is 2.5 or more standard deviations below the average for a young woman is considered osteoporotic (Kanis, 2007).

Many factors, such as age, disuse, hormonal imbalances, nutritional deficiencies, alcohol abuse, smoking, and genetics can lead to osteoporosis (Iwaniec and Turner, 2008). One well-studied factor contributing to osteoporosis and fracture risk in women is the rapid bone loss caused by decreased estrogen levels associated with menopause (Cummings et al., 1998; Gennari et al., 1990; Khosla et al., 1997). Decreases in bone mass in postmenopausal women, combined with age-related sarcopenia and increased fall risk due to decreased postural stability, lead to dramatic increases in fracture risk for this population (Harvey et al., 2008). Estimates indicate that substantial costs can be attributed to osteoporotic fractures; the United States spent over $19 billion on osteoporotic fractures in 2005, and it was estimated that the costs will increase by 49% by the year 2025 (Burge et al., 2007). The most common form of osteoporotic fracture, accounting for 27% of total cases and 6% of total costs, is a vertebral fracture (Burge et al., 2007).

Although not as costly as hip fractures, vertebral fractures can be just as worrisome. An estimated 1.4 million, clinically-diagnosed, vertebral fractures occurred globally in 2000 and it is estimated that only one third of vertebral fractures come to clinical attention (Cooper et al., 1992; Delmas et al., 2005; Johnell and Kanis, 2006). A vertebral fracture can be relatively symptom free or can cause pain and disability that can last for years (Ross et al., 1994). Furthermore, individuals who have suffered a vertebral fracture tend to have characteristics that put them at increased risk of another fracture. Lindsay and colleagues found that women who suffer a vertebral fracture are five times more likely than women of the same age group to suffer a vertebral fracture within the following year (Lindsay et al., 2001). Results from the European Prospective Osteoporosis Study have also shown that the risk of a fracture within three vertebrae of an existing fracture is significantly greater than the risk of fracture in more distant vertebrae (Lunt et al., 2003). Multiple vertebral fractures can cause substantial decreases in quality of life, compromise mobility, and increase mortality risk (Kanis, 2007).

For women who develop osteoporosis of the spine, pharmaceutical and nutritional interventions attempt to minimize fracture risk by counteracting further loss of bone mineral content. Pharmaceutical interventions are the most common form of osteoporosis treatment; however, they have the limitation of being costly and regimented (Lindsay, 2008; Papapoulos, 2008). Nutritional supplementation does reduce rates of bone loss when combined with pharmaceutical treatment, but has not been found to correlate with spinal fracture risk (Dawson-Hughes, 2008; Ooms et al., 1995). A further disadvantage of these interventions is that they target bone mass but have no effect on fall risk.

Exercise training provides a promising alternative to these interventions: an integrative approach to preventing costly osteoporotic fractures by increasing bone and muscle mass through mechanical stimuli and decreasing fall risk through improvements in balance and coordination. Maintenance or improvements in BMD have been observed in exercising individuals in comparison to nonexercisers, potentially as the result of the mechanical loading, increased nutrient delivery, and/or hormonal changes caused by exercise (Borer, 2005). Of particular note, both anabolic and anticatabolic effects on bone in women have been found to result from low-volume, high-intensity training regimens that involve large joint reaction forces and/or large ground reaction forces (Engelke et al., 2006; Martyn-St James and Carroll, 2010; Winters-Stone and Snow, 2006). Furthermore, participation in activities involving large ground-reaction forces has been shown to correlate with increased bone mass at the most common and most costly sites of osteoporotic fracture, the spine and the hip (Guadalupe-Grau et al., 2009; Martyn-St James and Carroll, 2010). However, although training that involves large impact forces may be ideal for building higher peak bone mass in young adults, it often becomes impractical or inappropriate in older female populations.

Resistance training provides a means for women to decrease their future risk of osteoporotic fracture through improvements in both bone mass and muscular strength, without having to do jumping or plyometrics. Resistance training exercises can continue to be used as women age and still can be used post-menopause to target site-specific increases in bone mass. The reason resistance training is effective is because bone mass responds to physical activity in a “use it or lose it” manner, commonly known as Wolff’s Law (Wolff, 1892). Mechanical signaling at the cellular level, caused by repeated loading of a bone above normal physiological levels, leads to increased bone formation in the region of the applied stresses, as opposed to bone resorption and the suppression of bone formation with disuse (Lanyon, 1996; Leichter et al., 1989; Rubin and Lanyon, 1984).

Wolff's law would suggest that training that increases spinal loading would influence vertebral bone mass within the spine. Consistent with this, activities involving both upper body and lower body resistance, such as training done by rowers, appear to improve spine BMD (Morris et al., 2000), whereas training involving primarily lower body exercise seems to increase hip, but not spine, BMD (Winters and Snow, 2000). In a study conducted on premenopausal women by Winters-Stone and Snow (2006), the site-specific changes in bone mass differed depending on what type of resistance training exercises were performed. Participants who combined upper body resistance training, in the form of a bicep curl and/or an upright row, with lower body exercises, such as squats, as part of their exercise program showed an increase in the BMD of both the hip and spine. Conversely, women who performed lower body exercises without adding upper body resistance showed increases in the BMD of the hip but not the spine. Therefore, upper body resistance seems to be an essential component of improving spinal bone mass. By further understanding how resistance training exercises affect the lumbar vertebrae, it will be possible to design researched-based exercise programs to help reduce the risk of osteoporotic vertebral fracture.

It has been established that total body resistance training can be effective in increasing lumbar bone mass, and that greater core strength can reduce the incidence of vertebral fractures (Friedlander et al., 1995; Sinaki et al., 2002). However, little is known regarding the loads responsible for these improvements. Because the core musculature supports the vertebrae (McGill et al., 2003), increased core muscular strength and/or activation would increase the internal loading placed on the vertebrae for a particular movement. In what may be the only study that compared internal lumbar loads to bone mass, Morris et al. (2000) found that internal lumbar loads of 4.6 times body weight in compression were associated with higher lumbar bone mass than in controls. Exercises producing loading of this magnitude would thus be expected to affect spinal BMD, but smaller loads may also suffice. The International Osteoporosis Foundation recommends that, for maintaining bone health, postmenopausal women should perform resistance exercises at an intensity of 60%-80% of their 1 repetition maximum (International Osteoporosis Foundation, 2013). This recommendation is based on the Erlangen Fitness and Osteoporosis Prevention Study (EFOPS) by Kemmler and colleagues, who reported successful maintenance of BMD at the spine and hip over 12 years (Kemmler et al., 2004; Kemmler et al., 2012). However, the internal lumbar loads associated with the different resistance exercises used in EFOPS, or other similar programs have not been determined in this population. Quantifying internal loads for different types of resistance exercises would, importantly, make it possible to compare exercises' effectiveness at reducing the risk of a vertebral fracture.

Resistance training programs to reduce the risk of osteoporotic fractures should not only be effective, they should also be time efficient. The squat has been shown to be an effective exercise for maintaining hip BMD (Martyn-St James and Carroll, 2010) and can easily be performed while doing a variety of upper body exercises. Combining upper body resistance with a squat would thus save time and would most likely target not only utilization of upper extremity muscles but also greater utilization of the core muscles. Increased activation of the core musculature, together with any applied upper body load itself, should increase spinal loading, potentially stimulating improvements in bone mass. If upper body resistance and a squat exercise are to be combined to produce a time-efficient exercise that targets both hip and spine BMD, there is a need to measure the lumbar loading resulting from different types of upper body resistance so that the most effective osteoporosis prevention exercise might be identified or developed.

Types of upper body resistance may be divided into two broad categories: static and dynamic. Both static and dynamic upper body loading have been found to influence lumbar spine loading. As was noted earlier, dynamic compressive loads of 4.6 times body weight on the L4/L5 joint during rowing have been associated with high lumbar bone mass in elite female rowers relative to controls (Morris et al., 2000). It has also been found that static upper body loading in the form of a backpack or weighted vest increases lumbar loading during walking. Backpack loads of 15% and 30% of body weight resulted in an increase in lumbosacral (L5/S1) peak force of 26.7% and 64%, respectively, when compared to walking without a backpack (Goh et al., 1998). It has not been identified, however, whether dynamic versus static upper body loading of a given magnitude influences the load placed on the lumbar spine during a concurrent squat maneuver. Nor is it known whether performing a concurrent squat maneuver influences lumbar spine loading during an upper body resistance exercise. If adding a squat increases lumbar loading, this simple modification could be added to strength training programs to improve the effectiveness of upper body lifts loading the spine. It is also important to determine differences in lumbar loading that may exist between dynamic and static upper body resistance in this context in order to best develop resistance training programs targeting the prevention of osteoporotic vertebral fractures.

Problem Statement

The long-term goal of this research is to develop effective exercise intervention methods to prevent osteoporotic vertebral fractures. The objective of this study is to determine how different combinations of upper and lower body resistance training exercises affect lumbar loading in middle-aged women. Specifically, it will examine how adding upper body resistance to a squat maneuver and how adding a squat to an upper body resistance exercise influences lumbar loading in the participant population. The central hypothesis is that adding either static or dynamic upper body resistance to a squat will increase lumbar spine loading above levels observed when the exercises are performed separately. The rationale for pursuing this objective is that better understanding of the biomechanical loading to the lumbar spine caused by combined upper body and lower body resistance training can help practitioners develop exercise programs that target increased bone integrity at both the hip and the lumbar spine. I will test these hypotheses and objectives by addressing the following specific aims.

Aim 1: To compare lumbar loads during upper and lower body resistance exercises when performed simultaneously, as opposed to separately, by middle-aged women. Specifically, I hypothesize that, for a given amount of resistance, combining a bicep curl with a squat will produce larger lumbar loads than will either the standing bicep curl or the squat exercise performed by itself.

Aim 2: To compare the effects of different types of upper body resistance added to a squat on lumbar spine loading in middle-aged women. Specifically, I hypothesize that, for a given amount of upper body resistance, (a) static resistance in the form of a weighted vest will create larger lumbar loading than will squats with no added weight and (b) dynamic resistance in the form of a bicep curl will produce greater lumbar loading than will the static resistance.

Significance

Osteoporosis is a major global health concern, with spinal fractures being the most prevelant form of osteoporotic fracture (Burge et al., 2007). Some exercise programs to prevent osteoporotic facture have been found to be effective in augmenting and maintaining bone mass at both the hip and spine in premenopausal and postmenopausal women, respectively (Friedlander et al., 1995; Leichter et al., 1989; McNamara and Gunter, 2012; Bocalini et al., 2010). But the effectiveness of individual exercises, such as the ones included in these programs, has not been studied. In premenopausal women, Winters-Stone and Snow (2006) found that a program that included combined upper and lower body resistance training improved bone mineral density (BMD) of both the lumbar spine and hip, whereas lower body training without upper body involvement yielded improvements in BMD at the hip but not the spine. This suggests that upper body involvement is needed in a resistance training program in order for the program to have an effect on lumbar spine BMD. Furthermore, higher loads placed on the bone should result in greater relative increases in bone mass or better maintenance thereof (Ozcivici et al., 2010). In order to effectively develop exercises targeting strengthening of the lumbar vertebrae, it is important to determine what types of upper body loading provide the greatest osteogenic stimuli. Specifically, this study will evaluate two different upper body loading techniques (weighted vest and bicep curl) added to a squat and their relative utility as exercises to improve (or maintain) lumbar spine BMD in middle-aged women. The results are expected to establish that dynamic upper body lifting during a squat will load the lumbar spine to a greater extent than will static upper body loading. I also expect to find that performing upper and lower body resistance exercises together will load the lumbar spine to a greater extent than performing the exercises separately. This will help to identify the types of exercises that should be chosen or combined in an osteoporosis prevention program in order to place higher loading on the lumbar spine and, therefore, benefit lumbar bone mass.

Chapter 2 Literature Review

Overview

Osteoporosis is a skeletal disease characterized by fragile bones that are susceptible to fracture. Osteoporosis can be caused by many internal and external factors, such as old age, genetics, disuse, gonadal insufficiency, nutritional deficiencies, glucosteroid use, alcohol abuse, and smoking (Raisz, 2008). Osteoporotic fractures are a significant cause of morbidity and mortality in developed countries, and represent an economic burden of approximately $20 billion per year in the United States (Burge et al., 2007). The most common form of osteoporotic fracture is a vertebral fracture; an estimated 1.5 million vertebral compression fractures occur in the United States every year, at an annual cost of $746 million (Alexandru and So, 2012). With a steadily aging population and increasing life expectancy around the world, the number of osteoporotic fractures is expected to more than double by the year 2050 (Harvey et al., 2008). Elderly women are at higher risk than elderly men or younger women; and, one in three women over 50 years of age will suffer from an osteoporotic fracture (Melton et al., 2005). Decreases in bone mass due to lowering estrogen levels, combined with age-related declines in muscle strength and increased fall risk due to decreased postural stability, lead to dramatic increases in fracture risk for this population (Rubin et al., 2008).

The proposed study will focus on exercise-based prevention of osteoporotic fractures of the lumbar spine in middle-aged women. The lumbar spine experiences a greater proportion of bone loss than do other bones during menopause due to its high trabecular bone content (Old and Calvert, 2004). Twenty-five percent of all postmenopausal women in the United States will eventually suffer from an osteoporotic vertebral compression fracture during their lifetime and the likelihood increases to 40% in women who are 80 years or older (Old and Calvert, 2004).

Although not as costly as hip fractures, vertebral fractures can be just as worrisome. A vertebral fracture can cause pain and disability that can last for years. In addition, women who suffer a vertebral fracture have a 15% higher mortality rate than women of the same age who have not suffered a fracture (Old and Calvert, 2004). Unfortunately, people who suffer one vertebral fracture are more likely to suffer another one (Lindsay et al., 2001). Multiple vertebral fractures cause significant pain, height loss, decreased quality of life, the development of a dowager’s hump, and, in extreme cases, compromise breathing, balance, and mobility (Ross et al., 1994). Old and Calvert (2004) mention the following common complications of vertebral fractures: constipation, bowel obstruction, prolonged inactivity, deep venous thrombosis, increased osteoporosis, progressive muscle weakness, loss of independence, kyphosis and loss of height, crowding of internal organs, respiratory decrease-atelectasis, pneumonia, prolonged pain, low self-esteem, emotional and social problems, increased nursing home admissions, and mortality.

Current pharmaceutical and dietary interventions to prevent or delay bone loss work systemically. In other words, they promote overall increases in bone mass everywhere by delaying the removal of old bone in the skeleton. With spinal and hip fractures being the most common and debilitating forms of osteoporotic fracture, it would be ideal to create intervention methods specifically targeting these two areas and without drug side effects. Site-specific interventions can be used in combination with other intervention methods to further decrease fracture risk in fracture prone locations. Little research has been done into site-specific treatments, but exercises causing large joint reaction forces or large ground reaction forces, such as resistance training or jump training respectively, seem to be the most promising way to target spine and hip bone mass accrual and maintenance (Kemmler et al., 2011).

Purpose and Scope

The purpose of this literature review is to present a basic background to aid the reader in understanding the need for and methodology of the proposed study.
This review will achieve the following:

- Overview the pathogenesis and diagnosis of osteoporosis in postmenopausal women, with a specific emphasis on the lumbar spine;
- Discuss the strengths and weaknesses of current osteoporosis treatment methods and interventions;
- Explore why and how mechanical loading can lead to bone density improvements
- Introduce exercise as a promising intervention to maintain bone density of the lumbar spine;
- Explain the rationale for focusing on combined upper and lower body resistance training as an intervention method to target improvements or maintenance of lumbar spine bone mass;
- Discuss how lumbar spine loading can be measured and modeled;
- Conclude with a summary of key concepts and suggestions for future research.

Osteoporosis in Postmenopausal Women

Pathogenesis

In postmenopausal women, osteoporosis pathogenesis occurs because of accelerated bone loss caused by decreased levels of circulating sex hormones (Raisz, 2008). At the onset of menopause, women begin a 5-10 year rapid reduction in bone density. During this period, 20-30% of trabecular bone is lost, as well as 5-10% of cortical bone, due to a dramatic reduction in circulating estrogen (Khosla and Riggs, 2005). When present, estrogen functions to induce osteoblast formation and longevity and also suppresses the production of RANKL, a key factor causing osteoclast formation (Ross, 2008). When estrogen levels drop during menopause, a 90% increase in osteoclast activity, accompanied by only a 45% increase in osteoblast activity, results in net bone resorption (Drake and Khosla, 2008). After the initial decade of drastic decreases in bone density, with overall losses of about 10% taking place in the lumbar spine, women will continue to lose both cortical and trabecular bone but at a slower rate (Greendale et al., 2012).

Diagnosis

Osteoporosis is clinically diagnosed using DXA. Mineral content of bone, or BMC, is determined by the ratio between the amounts of energy absorbed by the bone tissue from a high and a low energy x-ray beam. Areal bone mineral density (BMD; expressed in g/cm^2) is used to compare a patient's results with a standard BMD. This measure provides a means to compare bone mineral content on a population level, but it must be noted that BMD numbers can be misleading and do not always reflect changes in bone integrity. Osteoporosis is defined as having a BMD that is 2.5 standard deviations below the average BMD of a 30-year-old. Osteopenia, pre-osteoporotic bone loss, is defined as a BMD 1 to 2.5 standard deviations below that of a 30-year-old.

Loss of bone mass during menopause does not necessarily lead to osteoporosis. A past or present lifestyle promoting accrual of healthy bone mass, or a genetic disposition to a high bone mass, may prevent BMD levels from dropping into the osteopenic or osteoporotic regions. Unfortunately, for many, age-related bone resorption does lead to osteoporosis and the associated osteoporotic fractures.

Factors Affecting Osteoporotic Fracture of the Lumbar Spine

The five lumbar vertebrae are the largest vertebrae of the spine. The lumbar vertebra is composed anteriorly of a large oval body, separated from the posterior vertebral arch by the vertebral foramen. The vertebral arch has two lateral transverse processes, two superior articular processes, and a central-posterior spinous process. The anterior column of the spine (i.e. the vertebral bodies and intervertebral disks) carries three quarters of the axial spinal load (Ferguson and Steffen, 2003). The vertebral body is composed primarily of trabecular bone, covered superiorly and inferiorly by a thin cortical endplate, 0.4-0.5 mm in thickness (Ferguson and Steffen, 2003). This shell only accounts for 10-15% of vertebral strength (Ferguson and

Steffen, 2003); its main purposes are to provide a smooth transition area to adjacent intervertebral disks and to transfer applied loads evenly to the underlying trabeculae. The trabeculae of the vertebral body produce most of a vertebra's resistance to compressive forces and, therefore, the integrity of trabecular (cancellous) bone is a key component of vertebral fracture prevention.

The high proportion of cancellous bone in vertebrae is the reason that they lose more bone than do other bones because of menopausal hormone changes; the high surface area of cancellous bone allows for greater effects of remodeling. The average stress to failure of a lumbar vertebral body, normalized to endplate cross-sectional area, ranges from 1 to 5 MPa (Ferguson and Steffen, 2003). However, the actual material properties, and therefore fracture risk, of the vertebral body vary depending on location. Trabeculae near the center of the vertebral body have been observed to be more plate-like and closer together, showing a higher strength, stiffness, and bone mineral density, than do the trabeculae closer to the peripheral anulus fibrosus, which tend to be thinner and more rod-like (Prakash et al., 2007). Bone accrues along lines of stress, protecting the vertebrae against fracture in the places it is usually stressed. Trabeculae tend to be oriented along the paths of principal axial forces associated with upright posture. The primary axial struts are reinforced by horizontal trabeculae near the endplates due to the transverse dispersion of force by the intervertebral disc (Prakash et al., 2007). Also, increased reinforcement of structures near the base of transverse processes are most likely the result of mechanically induced osteogenesis due to stresses associated with the facet joint and postural muscle pull. These differences in bone deposition influence trabecular size and shape in the vertebra, leading to non-homogeneous properties and weaker parts more prone to fracture.

In addition to the material properties that play a role in fracture risk of a vertebra, external loading, muscle force, and posture are also important. Muscles pulling across the lumbar vertebra to stabilize the region during performance of a physical task, such as a lift, apply internal loads on the joint of the spine. The total amount of loading experienced by a vertebra during such a task is a combination of the external loads on the body and the internal loads produced by muscle forces. In an erect standing posture, the vertebral body is loaded by the weight of the upper body and by muscle forces acting across the joint to maintain posture. The amount of loading may be proportional to the fracture risk. The mechanical loading of the vertebral body increases when the body mass moves anterior to the vertebra's sagittal axis of rotation. Flexion of the upper body has been found to result in as much as a ten-fold increase in compressive loading as compared to upright standing (Prakash et al., 2007). Over 92% of this increase in load is explained by co-contraction and muscle-derived extensor moments

(Prakash et al., 2007). Therefore, body position changes affect loading mostly due to increases in muscle pull across the joint. Hence, muscle force and external loading levels are important factors in osteoporotic fracture.

A healthy spine can resist fracture in hard falls or even during car accidents. The tolerance limit for compressive forces at the L5/S1 joint in non-pathological cadaveric spines has been estimated to be 4400 ± 1880 N, whereas shear loading tolerance appears to fall in the 750-1000 N range (Waters et al., 1993). Osteoporotic spines, however, are mechanically compromised and can fracture during the performance of trivial lifting tasks, rolling over in bed, and even during vigorous sneezing (Old and Calvert, 2004). Both wedge-type fractures (collapse of the anterior portion of the vertebral body) and burst-type fractures (collapse of the entire vertebral body) can occur. Most osteoporotic fractures of the lower spine occur in the region of T8-T12, at L1, and at L4 (Old and Calvert, 2004).

The high prevalence of these osteoporotic fractures has led to the development of many intervention methods to try to decrease the amount of bone loss in individuals in order to prevent osteoporotic fractures. Currently, the most common treatment methods for postmenopausal osteoporosis include both pharmaceutical and dietary interventions.

Common Treatment Methods for Osteoporosis

Pharmaceutical Interventions

Pharmaceutical interventions are the most common form of osteoporosis treatment. Treatment with estrogens (with or without progesterone), selective estrogen receceptor modulators (SERMs), bisphosphonates, or calcitonin have an antiresorptive effect on bone; they prevent bone loss by inhibiting osteoclast activity (Adami, 2008; Cosman and Greenspan, 2008; Lindsay, 2008; Papapoulos, 2008; Rizzoli, 2008). Delivery of Strontium Ranelate, Parathyroid Hormone (PTH), or a PTH derivative, such as Teriparatide, will have an anabolic effect on bone; these treatments stimulate osteoblasts to deposit osteoid and improve trabecular integrity (Kleerekoper, 2008).

Although many women are successfully treated for osteoporosis with medications, there are distinct limitations to this type of treatment. A major drawback is the cost of the pharmaceuticals. Additionally, the effectiveness of Estrogens and SERMs depend on strict adherence to a dosing regimen (Neer et al., 2001). Bisphosphonates, which can last in the bone tissue for up to five years, have been found to decrease bone quality and have been linked to necrosis of bone tissue (Ooms et al., 1995). PTH only stimulates bone growth on existing trabeculae (Papapoulos, 2008). Strontium ranelate is such a new treatment option that the long-term consequences are not entirely understood (Adami, 2008). All of these treatments, absent of other interventions, improve total-body bone mass, therefore they share the disadvantage of not being able to target bones with a higher susceptibility to fracture. Nevertheless, for those able to pay, pharmaceutical interventions can maintain bone mass above osteoporotic levels.

Dietary Interventions

An individual's diet can also influence bone mass. It is currently suggested that a daily intake of adequate vitamin D and calcium can prevent osteoporosis. Ooms et al. (1995) found that supplementing pharmaceuticals with Vitamin D does increase femoral neck bone mineral density. Because of findings like this, adequate intake of or supplementation with calcium and vitamin D are essential components of osteoporosis prevention methods and therapies (Dawson-Hughes, 2008).

Additional Influences on Bone Mass

Peak bone mass is reached in one's early 20s and is more or less maintained over the next three decades (Drake and Khosla, 2008). Incorporating daily physical activity that loads the skeleton and adequate nutrition during the first three decades of life can increase the peak levels of bone mass obtained by an individual (Bergmann et al., 2010). No longitudinal studies have been performed to date to show that this is preventative against osteoporosis later in life. However, it is logical to assume that when you start out with more bone, aging-related declines in bone mass will not produce as much concern.

Conclusions

Most patients concerned about bone loss have passed the point of being able to build a more robust skeleton. Therefore, present interventions have primarily been pharmaceutical in nature. Most drugs target osteoclasts, suppressing bone resorption. Unfortunately, maintaining bone mass through this mechanism can still lead to reduced integrity of the bone because of the diminishing physical strength of the non-resorbed aging bone. Drug treatments also fail to address other musculoskeletal “systemic level” problems such as muscle weakness, coordination difficulty, and associated fall risks that arise with aging. A treatment method that promotes bone formation and could improve musculoskeletal function, such as exercise, is an intriguing treatment option.

Bone Adaptations to Mechanical Loading

Bone tissue responds to physical activity in a “use it or lose it” type manner, commonly known as Wolff’s Law (Wolff, 1892). Repeated loading of a bone will lead to increased bone density in the regions of bone where the stresses are applied, whereas disuse leads to rapid resorption. Bone tissue responds to mechanical loading primarily by redirecting mesenchymal stem cells from adipocyte-directed differentiation to osteocyte-directed differentiation (Krause et al., 2008). Researchers have determined the important characteristics of loading necessary to elicit an osteogenic response and are beginning to understand how these responses are governed at the cellular level.

Important Loading Characteristics

To induce osteogenesis through mechanical loading, large dynamic loads or high-frequency, low-magnitude loads can be applied to bone (Ozcivici et al., 2010). Animal models have been useful in identifying mechanical properties that cause anabolic responses in bone. Among the findings of such studies is that the magnitude of applied loads seems to play an important role in bone remodeling. Greater dynamic strain due to an increased magnitude of dynamic loading leads to an increased anabolic response of bone, whereas static strain has been shown to be associated with catabolic responses (Ozcivici et al., 2010). Furthermore, too much strain will induce microdamage in the matrix and could compromise the integrity of the tissue. The strain rate produced by dynamic loading also plays a role in bone remodeling. Higher strain rates have been shown to produce greater adaptive responses on the periostial surface than do lower rates in mature bone (LaMothe et al., 2005). In addition, there appears to be an interaction between load magnitude, the frequency at which the load is applied, and the number of loading cycles on bone formation. Intermittent bouts of high stress, low frequency (1-3 Hz) and high strain (2,000-3,000 microstrain), can initiate an anabolic bone response (Ozcivici et al., 2010). However, low-magnitude, high-frequency signals (simulating muscle contractility) have also been shown to be anabolic to trabecular bone (Rubin et al., 2001). Furthermore, fewer loading cycles are needed as the microstrain increases to produce equivalent amounts of formation (Rubin et al., 2001). Interestingly, increased anabolic effects of mechanical loading have been found when additional rest is inserted between each loading cycle (Srinivasan et al., 2002). The bone deposition that occurs is in site-specific areas that protect against the applied stresses (Prakash et al., 2007). All these loading characteristics should be taken into account when developing an exercise program targeting bone mass improvements.

Cellular Level Mechanisms

Cell biologists are still trying to fully understand the cellular responses to the mechanical loading of bone. Strenuous activity will produce bone strains of 3000 microstrain, which translates to deformations on the order of Angstroms at the cellular level (Rubin and Lanyon, 1984). Although small in magnitude, these micro-scale mechanical signals have been found to have both anabolic and anti-catabolic effects on bone. As was noted, bone remodeling is sensitive to changes in strain magnitude, number of loading cycles, the distribution of loading, strain rate, and, perhaps, accelerations (Ozcivici et al., 2010). At the cellular level, these mechanical stressors decrease the rate of osteocyte apoptosis and have been found to direct mesenchymal stem cell differentiation in an osteoblast/osteocyte direction. The resultant osteogenesis then regulates osteoclast numbers through the expression of receptor activator of nuclear factor kappa-B ligand (RANKL) (Rubin et al., 2008).

The three-dimensional network of interconnected osteocytes within the bone matrix is thought to serve as an antenna for mechanical loading. The osteocyte network appears to have the capability of amplifying biomechanical stimuli (Rubin et al., 2008). Unfortunately, it is difficult to test this hypothesis in vivo and an in vitro reproduction of this microenvironment has yet to be developed. The observation that bone responds to deformities on the order of Angstroms points to the presence of a sensitive mechanoreceptor system. Multiple proposed mechanisms exist for this mechanoreceptive capability of bone tissue. Increased ion channel activity has been found to correspond with strain applied to osteocyte membranes (Rubin et al., 2008). Additionally, fluid shear and pressure have been linked to cytoskeletal mechanisms of signal transduction (Rubin et al., 2008). Mitogen-activated protein kinase (MAPK) activation by shear stress on endothelial cells lining bone vasculature are also thought to play an important role in osteo-mechanosensation (Rubin et al., 2008). Finally, osteocyte activation (measured by nitric oxide production, a parameter of bone cell activation) has been shown to increase with increased rate of fluid stress (Bacabac et al., 2004).

In conclusion, it is known that mechanical signaling can interrupt or affect almost any signaling cascade in the cell (cAMP, IP3, Calcium signaling, MAPK, etc.). Most likely, multiple types of mechanoreceptors in bone are responsible for integrating and coordinating the observed tissue responses to mechanical loading. Ultimately, the present research is aimed at using exercise interventions to place mechanical stresses on certain bones to utilize these cellular level mechanisms to induce bone deposition in sites prone to osteoporotic fracture.

Exercise as an Osteoporosis Treatment Option

The effects of mechanical stimuli observed at the cellular level are reflected by changes in bone mass (BMC and/or BMD) with exercise. As such, exercise training has the potential to provide a cheap and integrative approach to preventing costly osteoporotic fractures by increasing or maintaining bone mass. Kemmler and colleagues reported that their exercise program was effective in maintaining bone density at the spine and reducing bone loss at the hip in postmenopausal women (Kemmler et al., 2004; Kemmler et al., 2012). Also, participants in the Better Bones and Balance exercise program have been shown to have higher than average bone mass at the hip compared to an age-matched cohort (McNamara and Gunter, 2012). In addition to influencing bone mineral density, exercise can improve muscle function to potentially decrease fall risk through improved balance and strength. (Hourigan et al., 2008). As opposed to pharmaceutical and dietary interventions, exercise utilizes the activation of native mechano-signalling to induce lamellar bone formation through a process involving the entire bone remodeling cycle, thereby potentially limiting unwanted side-effects.

A factor that needs to be considered in using exercise training as a method to improve bone integrity is that the positive effects on bone mass tend to be local to the bones experiencing the hyperphysiological stresses. Sport or exercise that produces high joint contact forces within the lower extremity through jumping has been associated with increased bone mass of the hip but not the spine (Martyn-St James and Carroll, 2010; Winters-Stone and Snow, 2006). When daily exercisers include high magnitude resistance training that loads the upper body into their routine, increased BMD of the lumbar spine is observed as well (Martyn-St James and Carroll, 2010). Because hip and spinal fractures are common and costly in postmenopausal women, and exercise programs have been found to have both anabolic and anticatabolic effects on bone in these areas in this age group (Engelke et al., 2006), exercise could be used as a method to prevent osteoporosis and osteoporotic fracture.

Even though exercise may be useful in preventing osteoporosis, all types of osteogenic exercise may not be appropriate for all populations. Sports and plyometric training that stress the skeleton through large ground-reaction forces may be effective for building higher peak bone mass in younger adults, but this type of high impact training is likely inappropriate for most of the elderly female population because it may overload their musculoskeletal system. Resistance training produces high stresses on the skeleton through joint-reaction forces, and could be used in the postmenopausal population as an intervention against osteoporosis.

Resistance Training for Prevention of Osteoporosis

Resistance training is a type of exercise that middle-aged women are able to perform if they are looking to decrease their risk of osteoporotic fracture through exercise, specifically by maintaining BMD and improving muscular strength/coordination. In premenopausal women, both upper and lower body resistance training, in combination with jumping, have been found to provide site-specific reductions in bone loss (Winters-Stone and Snow, 2006). Similarly, in postmenopausal women, Pruitt , Kohrt , Bocalini, and colleagues found maintained BMD of the lumbar spine with resistance training (Bocalini et al., 2010; Kohrt et al., 1997; Pruitt et al., 1992). The twelve-year Erlangen Fitness and Osteoporosis Prevention Study failed to determine significant effects of exercise on “overall” fracture risk (p=.074) in postmenopausal women (Kemmler et al., 2011). But, they still found better maintenance of BMD at the lumbar spine with exercise: spine BMD changed -0.8% in the exercise group versus -4.0% in the control group (Kemmler et al., 2012). Therefore, the study furthered the evidence for the fracture prevention ability of exercise programs. Conflicting findings from Bemben, Chilibeck, and colleagues found no increases in BMD of the lumbar spine after resistance training interventions (Bemben et al., 2000; Chilibeck et al., 1996). Because many of these studies had similar exercise protocols, the conflicting findings may be accounted for by nonmechanical issues related to small sample sizes; as well as genetic factors, ethnicity, age, and diet, as all can play a role in varying responses to mechanical signals. Despite these conflicting findings, a meta-analysis found that high-magnitude resistance training had beneficial effects on lumbar BMD when combined with odd- or high-impact exercise (Martyn-St James and Carroll, 2010).

More specifically, research to date suggests that upper body resistance is important to include in a training program to target the lumbar spine. As evidence of this, Winters-Stone and Snow (2006) compared the effects of lower body exercise without upper body resistance training to effects of combined lower body exercise and upper body resistance training on BMD. Participants who combined upper body resistance exercises, such as a biceps curl, with a squat maneuver as part of their exercise program showed an increase in the BMD of both the hip and spine. Conversely, women who performed the squats without the bicep curls showed increases in the BMD of the hip but not the spine. While this evidence suggests that upper body resistance should be included in osteoporosis prevention programs, there is also a need to determine what type of upper body training is the most effective, in order to get the most benefits from the time and effort expended. One way to predict the effectiveness of the upper body resistance training exercises is to measure the loads placed on the spine, because tissue stresses elicit anabolic responses in bone at the cellular level. As was noted earlier, larger loads will elicit larger responses. Thus, if the spinal loads that result from different upper body resistance exercises are determined, the magnitudes of these loads could be used to determine which exercises might be most effective to use to prevent osteoporotic fracture.

Loading on the Spine During Resistance Training Exercise

There is an apparent gap in the research when it comes to measuring the loads generated on the lumbar spine when performing upper body resistance training exercises. It has been found that static upper body loading in the form of a backpack or weighted vest will increase lumbar loading during walking (Goh et al., 1998). Backback loads of 15% body weight (BW) increased L5/S1 loading by 27%, from 1.5 BW to 1.9 BW; a backpack weighing 30% BW increased L5/S1 loading by 64%, from 1.5 BW to 2.46 BW (Goh et al., 1998). In another study, of elite female rowers with high lumbar bone mass, Morris and colleagues found the compressive forces on the L4/L5 joint to be 4.6 times body weight during a simulated race on a stationary ergometer (Morris et al., 2000). This suggests that loading of this magnitude leads to improvements in bone mass. No known studies exist that determined the lumbar loading during a combined upper and lower body resistance training exercise. Furthermore, it has not been determined whether lumbar loading differs when performing upper and lower body exercises together versus separately. Combining upper and lower body resistance exercises may produce larger loads than when the exercises are performed separately. It is apparent from the above work that spinal loading that exceeds 5 BW is more than enough to elicit an anabolic response of vertebral bone; however, the minimum load needed is not known. It also seems that dynamic tasks (such as rowing) produce more spinal loading that a static upper body load (weighted vest). Higher loads should elicit greater anabolic responses in the bone. But, to date, there is little data off of which to base an exercise-based osteoporosis prevention program for the lumbar spine.

Measuring and Modeling Lumbar Loading

Measurement Techniques

The location of bone deep within the body makes it difficult to measure mechanical loading in vivo, especially in human subjects. Stresses and strains on bone can be estimated using strain gauges, analytical beam theory, finite element analysis, and more recently with digital image correlation (Sztefek et al., 2010). The approach to measuring loading is indirect and requires modeling. Possible sources of error are introduced when using a model to estimate forces on a particular joint. Therefore, it is important to carefully choose a model to achieve the desired measurements with an appropriate level of validity.

Modeling Biomechanical Forces

In order to determine what movements best provide mechanical stimulation to the vertebra, a method is needed to measure or estimate the loads placed on the lumbar vertebra during various exercises. As was noted, the mechanical forces experienced by joints during activity are difficult to record in vivo, especially in the spine of human subjects. However, there are numerous types of models available that use measurable inputs, such as ground reaction forces, kinematic inputs, and/or electromyography (EMG) recordings to predict the forces acting across a joint. In predicting the forces acting on the spine, both the external loading and the forces created by the muscles acting across the joint need to be considered. Stability of the spine and vertebral loading are governed by the coordination and coactivation of the postural muscles (McGill et al., 2003). The primary muscles involved, and that should be considered in predicting lumbar loading, are: the erector spinae, multifidus, semispinalis, quadrates lumborum, latissimus dorsi, external oblique, internal oblique and rectus abdominus. The complexity of dynamic body movement involving the interplay of many joints, muscles, and externally-applied forces has led to the development of many different models to estimate lumbar loading. These models use simplification, optimization, or EMG-assisted techniques to estimate muscle forces because the number of muscle forces across the joint exceed the number of equations of motion. These models fall into one of three categories: purely static, quasi-static, or dynamic.

Static models use the principles of static equilibrium to calculate the net force and torque acting at a joint of interest at a specific instant in time. The model then estimates the muscle forces needed to create that torque and uses these forces, together with the net force, to calculate the contact force at the joint. The Michigan Model is a simple example of a static model and can be used to estimate L5/S1 loading assuming a single erector spinae muscle (Chaffin and Anderson, 1991). This model is applicable when dealing with small accelerations.

Quasi-static models use inverse dynamics to calculate the net force and torque on the joint of interest over a particular time period or motion, taking into account the segmental accelerations. A quasi-static model then analyzes the resulting force and torque profile frame by frame over time to estimate the muscle activation patterns and joint contact force over the period of interest. A limitation of both static and quasi-static models is that they do not take into account the activation dynamics of a muscle. It takes time for a muscle to go from inactivity to creating force. In other words, the muscle force production over time should be continuous. With static and quasi-static models however, muscle forces are not constrained to this condition; the estimated muscle force can change from any value to another instantaneously. Therefore, static and quasi-static models are often not physiologically reasonable in estimating the muscle forces acting across a joint.

Dynamic models, such as OpenSim (http://opensim.stanford.edu/), do account for muscle activation dynamics. They can use a tracking algorithm to emulate a neural control system in reproducing a dynamic movement. In this type of modeling, muscle force depends on the current and previous neural control inputs to the muscle which, in turn, depend on previous movements of the joint. Hence, dynamic models potentially can produce more physiologically accurate results than can static or quasi-static models. Nevertheless, dynamic models are not true representations of muscle activation. Dynamic, as well as static, models have the disadvantage of underestimating muscle coactivation. Since coactivation of the trunk muscles to stabilize the lumbar spine is most likely prevalent during the exercises to be analyzed in the present study, both dynamic and static models could potentially underestimate loading of the vertebrae.

To overcome the limitations of coactivation underestimation, EMG-assisted models can be used. For example, Marras and colleagues developed a model in which muscle forces are computed from normalized EMG recordings using a relationship that depends on the muscle’s length, velocity, physiological cross-sectional area, and a gain factor that equates the net muscle moment with the resultant joint moment (Marras & Sommerich, 1991). From these muscle forces, spinal compression and shear are calculated based on the assumed anatomy and the resultant joint force. EMG-assisted models of the lumbar spine can include anywhere from 10-90 different muscles (Cholewicki and McGill, 1994; Granata and Marras, 1995a). At present, EMG is the preferred method for predicting spinal loading.

AnyBody Modeling System

For this study, we will use a generic, detailed, rigid-body model of the lumbar spine that was built using the AnyBody Modeling System (AnyBody Technology A/S, Aalborg, Denmark). This model is composed of seven rigid segments (pelvis, L1-L5 vertebrae, and thorax) with 18 degrees of freedom and 154 muscles (de Zee et al., 2007). The AnyBody software uses optimization algorithms to solve for the muscle and joint contact forces acting within the lumbar spine model, with the associated kinematics and external loads as input. The model generates the most efficient muscle activation pattern by optimizing a cost function such as minimizing the sum of the squared muscle stresses or minimizing maximum muscle stress. This quasi-static model was chosen because a static model is inappropriate for the dynamic tasks being tested, but the motion during these tasks is slow enough that rapid changes in muscle activation that require a dynamic model to model accurately will not occur. An EMG-assisted model will not be used because performing the maximal voluntary contractions needed to normalize the EMG would be inappropriate in the participant population to be tested, due to the associated risk of injury. Finally, despite its inherent limitations, the AnyBody lumbar spine model has been found to give comparable outputs to in vivo L4/L5 intradiscal pressure measurements (de Zee et al., 2007; Wilke et al., 2001), suggesting that its use is appropriate.

Summary

Osteoporotic fractures of the lumbar spine are a debilitating problem facing many older women. Current, common treatment methods using pharmaceuticals are costly and can have negative side effects. Exercise training in the form of resistance training is a possible alternative or supplement to pharmaceutical treatment for older women looking to decrease their risk of osteoporotic fracture through improvements in both BMD and muscular strength. Upper and lower body resistance training has been found to produce site-specific increases in bone and muscle mass. Bone mass responds to physical activity in a “use it or lose it” type manner, commonly known as Wolff’s Law. Repeated loading of a bone can lead to increased bone density in the region of bone to which the stresses are applied, if these stresses are large and/or rapidly-changing enough. Essentially, resistance training exercises could be tailored to target increases in bone density of the lumbar vertebra to help reduce the risk of vertebral fracture. In order to better develop these intervention programs, research must be conducted to identify the most efficient and effective exercises to include in training programs for preventing osteoporotic fractures.

Chapter 3 Methods

Participants

Twenty healthy women, aged 37-50 (mean ± SD age: 45.7 ± 3.5 years, height: 164.6 ± 6.2 cm, mass: 62.1 ± 9.8 kg), participated in this study. To qualify, participants had to be 35-50 years of age and had to report having participated in 20 minutes or more of moderate-to-high intensity physical activity on at least two days per week for the four weeks prior to participation in the study. Anyone who self-reported a condition that would cause the protocol to be difficult or painful, that would hinder her ability to perform the required tasks, or that might place her at elevated risk of injury was not allowed to participate. Self-reported histories of selected types of musculoskeletal, neurological, and cardiopulmonary conditions were specifically screened for, as was recent pregnancy, recent surgery, and the use of selected drugs or medications within the past 24 hours. For full inclusion criteria, please see the Physical Activity and Health History Questionnaire in Appendix B. The investigators determined eligibility from the questionnaire and through observations made during the warm-up. The Oregon State University Institutional Review Board approved this study and all participants gave written informed consent (Appendix A).

Instruments and Apparatuses

In order to obtain the estimated forces on the lumbar spine during the tasks under study, kinematic and ground reaction force data were collected and used as inputs for a biomechanical model. Kinematic data were measured at 60 Hz using a nine-camera motion capture system (Vicon, Los Angeles, CA). Simultaneously, ground reaction forces were sampled at 360 Hz from two force plates (Bertec, Columbus, OH) mounted flush with the floor.

Study Design

Participants performed a series of four resistance training exercises: a standing bicep curl (Curl), a squat (Squat), a squat with a weighted vest (Squat+Vest), and a squat with a bicep curl (Squat+Curl). The experiment was a repeated-measures design and the order in which the participants performed the exercises was counterbalanced.

Experimental Procedures

Data collection took place in the OSU Biomechanics Laboratory. On their arrival, and before any testing, participants gave their written informed consent to participate. They then completed the Physical Activity and Health History Questionnaire. Based on their answers, participants were allowed to perform the testing or were withdrawn from the study. Twenty-one women gave written informed consent to participate and 20 were eligible to participate.

Once their eligibility was confirmed, participants were asked to change into spandex shorts or short athletic shorts, a tank-top or sleeveless shirt, and their own athletic shoes. Participants then underwent a task-specific warm-up to familiarize them with the exercises to be performed and to prepare their muscles for the experimental trials. The warm-up consisted of the following:

1. A 3-minute walk.
2. A set of biceps curls while standing, with a 1 kg dumbbell in each hand.
3. A set of biceps curls while standing, with a 2.3 kg dumbbell in each hand.
4. A set of squats without added weight.
5. A set of squats while wearing a 4.5 kg weighted vest.
6. A set of the combined squat and biceps curl exercise, with a 2.3 kg dumbbell in each hand.

These exercises are described in detail below. All squats and curls were performed at a cadence of about 2 seconds/repetition, with a brief rest between repetitions and at least 1 minute of rest between sets. Exercises were explained and demonstrated to the participants and a simulated metronome was used to sound the desired cadence. The participant's form was monitored during each exercise and corrected by the investigators if necessary. Each warm-up set of squats and/or curls continued until the participant performed a total of 3 correct repetitions (based on the criteria described below) or until the first correct repetition she performed after her fourth repetition, whichever came first. If a participant had not been able to complete the warm-up exercises or had felt pain during the exercises, she would have been withdrawn from the study.

After the participant successfully completed the warm-up, she had a set of 27 small reflective markers attached to her skin or clothing using tape. Another four markers were attached to a headband that the particapant wore and three more were on a thin elastic strap that was attached around her trunk, above the waist. The markers were placed in the following locations:

- Head: four markers (right and left front of head; right and left back of head)
- Torso: six markers (C7; left, middle, and right torso, on the back at T10; body of the right scapula; clavicular notch)
- Arms: three markers each (shoulder; elbow; wrist)
- Pelvis: six markers (anterior and posterior iliac spines, iliac crests)

- Legs: four markers each (lateral femoral epicondyle; lateral thigh; lateral malleolus; lateral leg)
- Feet: two markers each (heel; 2nd metatarsal)

Two additional markers were placed on the back for the weighted vest trials and remained in place for the remainder of data collection.

To begin the data collection process, the partipant stood with one foot on each force plate in a known reference position, and a static trial was captured for two seconds. After all markers were identified in the static trial, the participant stood in the starting position for a squat exercise, with one foot on each of force plate, and the position of each foot was marked using masking tape. The participant was asked to return her feet to this same position for each experimental trial to follow. The participant then performed four sets of tasks in a counterbalanced order: Curl, Squat, Squat+Vest, and Squat+Curl. The following are descriptions for the proper completion of one repetition of each exercise.

1. *Curl*
   The participant was instructed to perform the biceps curl while standing with her feet in the marked positions and with her weight evenly balanced between both feet. A 2.3 kg (5 lb.) dumbbell was held in each hand. The participant was told to have her shoulders in their neutral positions, her elbows fully flexed, and her palms facing her body. The exercise began with an eccentric lowering of the dumbbells, in such a manner that arm movement was isolated to the elbow. When the elbows reached maximal extension, the direction of motion was reversed and the dumbbells were returned to their initial positions. The participant remained standing throughout the exercise.
2. *Squat*
   The participant stood with her feet in the marked positions, with her arms folded across her chest and her hands at her shoulders. A chair (seat height of approximately 43 cm) was located a distance of approximately half of the participant’s thigh lengh behind her heels. During the first part of the exercise, the participant lowered her hips backwards and towards the ground by flexing her hips, knees, and ankles. The participant was to lower her hips as far as she felt she safely could, without her hips going lower than her knees (i.e. without flexing her knees more than 90 degrees) or her buttocks touching the chair. She then returned to a standing position by extending her hips, knees, and ankles. The whole exercise was to occur in one continuous motion, with the left and right sides of the body moving

symmetrically. Throughout the exercise, the participant was to keep her weight approximately evenly balanced between both feet, her knees and shoulders behind the tips of her toes, her back straight, and her forearms against her chest.

3. *Squat+Vest*

   This exercise was identical to the bodyweight squat exercise, except the participant wore a weighted vest (Fitness by Cathe 10-Pound X-Vest, Altus Athletic Manufacturing, Altus, OK) during the exercise. The vest added 4.5 kg (10 lb.) to the upper body mass of the individual.
4. *Squat+Curl*

   The participant began this exercise in the same body position as the biceps curl exercise, with a 2.3 kg (5 lb.) dumbbell in each hand and her feet in the marked positions. The chair was behind the participant, as for the other squat exercises. During the first part of the exercise, the participant lowered the dumbbells by extending her elbows, as in the biceps curl exercise. At the same time, she lowered her hips backwards and towards the ground by flexing her hips, knees, and ankles, as in the bodyweight squat exercise. The participant was instructed to have the elbows reach full extension at about the same time that the hips reached their lowest point, namely as low as she felt she could safely lower them without touching the chair. She then returned to the starting position, arms and legs moving together such that the dumbbells reached her shoulders at about the same time that she returned to the upright standing position. The exercise was to occur in one continuous motion, with the left and right sides of the body moving symmetrically. The participant was instructed to keep her weight approximately evenly balanced between both feet, her knees and shoulders behind the tips of her toes, her back straight, and her upper arms near vertical throughout the exercise.

Participants performed five repetitions in a row of each exercise, with a brief pause (typically at least three seconds) between repetitions. Each repetition was a separate experimental trial, performed with a cadence of approximately one second for the downward phase and one second for the upward phase. A trial in which the participant was judged to have completed a repetition improperly was repeated, with a maximum of eight trials for each exercise. Feedback on form was given to participants after each trial. Kinematic and ground reaction force data was collected using the motion capture system and force plates during each experimental trial. At least two minutes of rest was provided between sets.

Finally, we measured the participant's body height and weight and obtained the following anthropometric measurements: foot length, ankle width, knee width, hip width, and arm width at the shoulder. Body height without shoes was measured using a stadiometer; body weight was measured using a standard scale; and the remaining anthropometric measurements were made using an anthropometer.

Data Analysis

In order to estimate lumbar loading during the Curl, Squat, Squat+Vest and Squat+Curl exercises, motion capture and ground reaction force data of the participant were input into a detailed rigid-body lumbar spine model within the AnyBody Modeling System (version 4.2.1, AnyBody Technology A/S, Aalborg, Denmark).

The AnyBody Modeling System software uses inverse dynamics and static optimization to compute the individual muscle forces, joint contact forces, and/or resultant joint forces and moments acting within the body. The lumbar spine model used for this study is a modified version of a standard model that was built using the AnyBody software and made available through their Managed Model Repository (version 1.2). The lumbar spine model is a detailed, 3-dimensional model that includes seven rigid segments (pelvis, L1-L5 vertebrae, and thorax) with 18 degrees of freedom (three at each joint), 154 muscles, and intervertebral disk stiffness (de Zee et al., 2007). The muscles are modeled as simple force generators for which muscle force is the product of a computed activation level (ranging from 0 – 1) and the muscle's maximum force. The maximum force of each muscle is assumed to be proportional to its physiological cross sectional area. The lumbar spine model is based on a person with a height of 1.75 m and a mass of 72 kg and assumes that muscles create a specific tension of 150 N/cm^2 at maximal activation. However, musculoskeletal geometry, segment inertial properties, and muscle strength are all scalable to the individual. This model has been verified to give comparable outputs to *in vivo* L4/L5 intradiscal pressure measurements (de Zee et al., 2007; Wilke et al., 2001).

For the present study, the standard lumbar spine model was modified to make the thorax the root segment instead of the pelvis. In addition, models of the two lower extremities, each consisting of three rigid segments (foot, leg, and thigh) having a total of nine degrees of freedom (three at each joint), were integrated with the lumbar spine model. The lower extremity model did not include muscles; instead, the segments were driven by resultant joint forces and torques at the ankle, knee, and hip joints of the model. Segment lengths were scaled to the participant's height, measured foot length, or pelvis width, as appropriate, with pelvis width derived based on Seidel et al. (1995). Segment masses and the inertial properties of the pelvis and lower extremity segments were computed based on de Leva (1996). The musculoskeletal geometry of the trunk and pelvis was then scaled based on segment length and mass, and muscle strength was scaled based on segment length, mass, and body fat percentage. Body fat percentage was estimated from the age and body mass index of the participant (Deurenberg et al., 1991).

For the computations, the motion capture and ground reaction force data were low-pass filtered using a fourth-order, zero-lag, Butterworth filter with a cut-off frequency of 5 Hz and 25 Hz, respectively. The motion capture data were then processed using BodyBuilder (Vicon, Los Angeles, CA) to find the location of joint centers, as well as marker positions in relation to the joint center locations. In this way, initial positions of the markers could be calculated and input to the AnyBody model. The BodyBuilder processing was also able to estimate the positions of occluded markers. When data were input into the AnyBody model, the software first optimized selected parameters of the model based on the motion capture data and computed the best-fit joint kinematics. AnyBody then completed an inverse dynamics analysis to calculate resultant joint forces and moments in the lower extremity, as well as muscle forces and joint reaction forces in the lumbar spine, from the ground reaction forces and optimized kinematics. In computing the muscle forces, the software used an optimization method that minimized:

$$\beta + \varepsilon \sum \sigma^2$$

at each sample of kinematic data, where β is the maximum muscle stress, ε is a weighting factor that was set at 0.001, and σ is each individual muscle stress.

The model output compressive, anteroposterior, and mediolateral forces at the six joints of the lumbar spine (T12/L1, L1/L2, L2/L3, L3/L4, L4/L5, and L5/S1) for each timepoint of an analyzed trial. The model also output the activity, as a proportion of maximum, of the most active muscle within the model at every timepoint. For the purposes of this study, only the T12/L1 and L5/S1 loading (compressive and anteroposterior shear forces) were analyzed. These specific lumbar joints were chosen for this analysis because the thoracolumbar and lower lumbar region are common sites of vertebral compression fracture (Babb and Carlson, 2006). Peak forces were obtained from the AnyBody output using MATLAB (MathWorks, Natick, MA) after plots of loading versus time were visually examined and apparent artifacts were removed. The first three correctly performed trials with complete data were used in the statistical analysis. Peak forces were averaged across like trials.

Statistics

One-way repeated-measures analysis of variance (ANOVA) was used to analyze the effect of the different exercises on the four dependent variables. The four dependent variables analyzed were peak compressive force on L5 at L5/S1, peak anterior shear force on L5 at L5/S1, peak compressive force on L1 at T12/L1, and peak anterior shear force on L1 at T12/L1. Exercise type (Curl, Squat, Squat+Vest, and Squat+Curl) was the within-subjects factor in the ANOVA. If significant differences in loading were found between exercises, post hoc tests comparing Curl to Squat+Curl, Squat to Squat+Vest, Squat to Squat+Curl, and Squat+Vest to Squat+Curl were conducted using paired t-tests with a Bonferroni correction. The level of significance for all analyses was set to $\alpha = 0.05$ and all analyses were performed using SPSS version 19 (IBM, Armonk, NY).

Based on the expected distribution of the means and a within-subject error of 471 N, derived from (Granata et al., 1999) it was initially estimated that a sample size of 20 participants would yield a power of 0.8 to detect differences between the means at $\alpha = 0.05$ (Keppel, 1991).

Chapter 4 Results

Lumbar loading for each exercise occurred in a pattern that was similar across vertebrae in the women who participated in this study. For all exercises, the lumbar level with the highest compressive loading was the L5/S1 joint, whereas the magnitude of the anteroposterior shear loads was greatest at T12/L1 (Figure 4.1). Additionally, the direction of the shear loading gradually changed across the different spinal levels. At T12/L1, there was an anterior shear force acting on the inferior vertebra and, at L5/S1, there was a posterior shear force acting on the inferior vertebra. In most trials of all three squatting exercises, the AnyBody model predicted that both peak compressive and peak anterior shear loads on L5 at L5/S1, as well as peak anterior shear on L1 at T12/L1, occurred near the lowest point of the squat, regardless of upper body resistance (Figure 4.2). Compressive force at T12/L1, however, was often greatest during standing, regardless of which exercise was performed. Some trials were characterized by noticeably larger forces during the rising phase of the squat than during the lowering phase, with the peak forces occurring in early-to-mid rising phase. During the Squat+Curl exercise, a bimodal force pattern was also sometimes seen, with one peak occurring late in the lowering phase and another occurring early in the rising phase. These two atypical patterns were both particularly evident in two of the participants. The timing of peak loading during the Curl exercise was consistent within participants, but less consistent between participants, with peak loading occurring variously near the beginning, middle, or end of the exercise. For all four exercises, peak loading tended to occur at or near the time of peak muscle activity within the lumbar spine model (Figure 4.2).

The ANOVA results indicated that there was a significant difference between exercises in the peak compressive force on L5 at the L5/S1 joint ($p < 0.001$), in the peak anterior shear force on L1 at the T12/L1 joint ($p < 0.001$), and in the peak compressive force on L1 at the T12/L1 joint ($p = 0.032$). No significant differences were found in the peak anterior shear force on L5 at L5/S1 ($p = 0.836$).

Post hoc testing revealed that, as compared to the Squat and Curl exercises performed separately, the combined Squat+Curl exercise only resulted in significantly greater peak loading of the lumbar spine than for the Curl exercise. Specifically, the Squat+Curl exercise produced 606 ± 372 N more peak compressive force on L5 at L5/S1 ($p < 0.001$) and 302 ± 128 N more peak anterior shear force on L1 at T12/L1 than did the Curl exercise ($p < 0.001$; Table 4.1). Peak compressive force on L1 at T12/L1 did not differ between the Squat+Curl and Curl exercises ($p = 0.061$). Similarly, peak compressive force on L5 at L5/S1, peak compressive force on L1 at T12/L1, and peak anterior shear force on L1 at T12/L1 did not differ between the Squat and Squat+Curl exercises ($p = 0.238$, 0.546, 0.338, respectively).

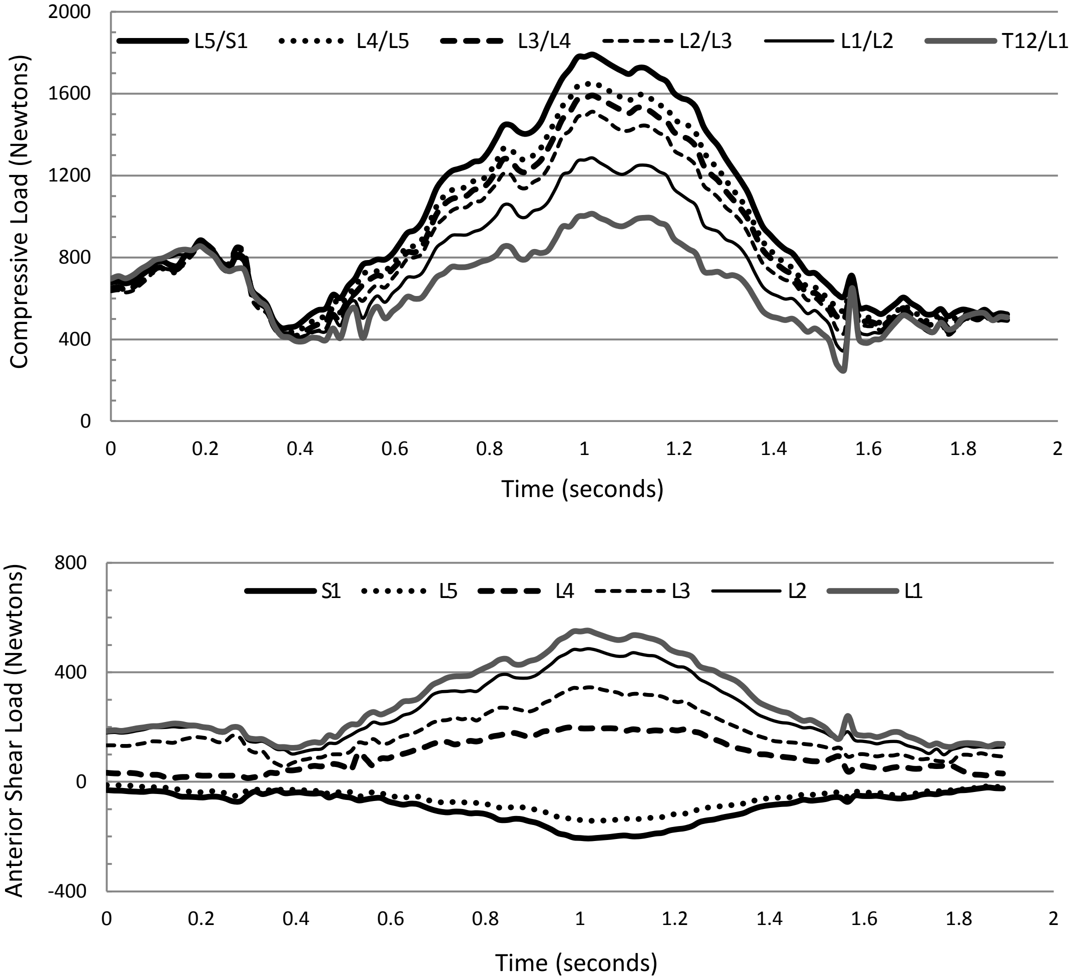

Figure 4.1 Compressive loads (top) and anterior shear loads on the superior face of the vertebra (bottom), as predicted by the AnyBody lumbar spine model, at each lumbar joint in a typical participant during a Squat+Vest task.

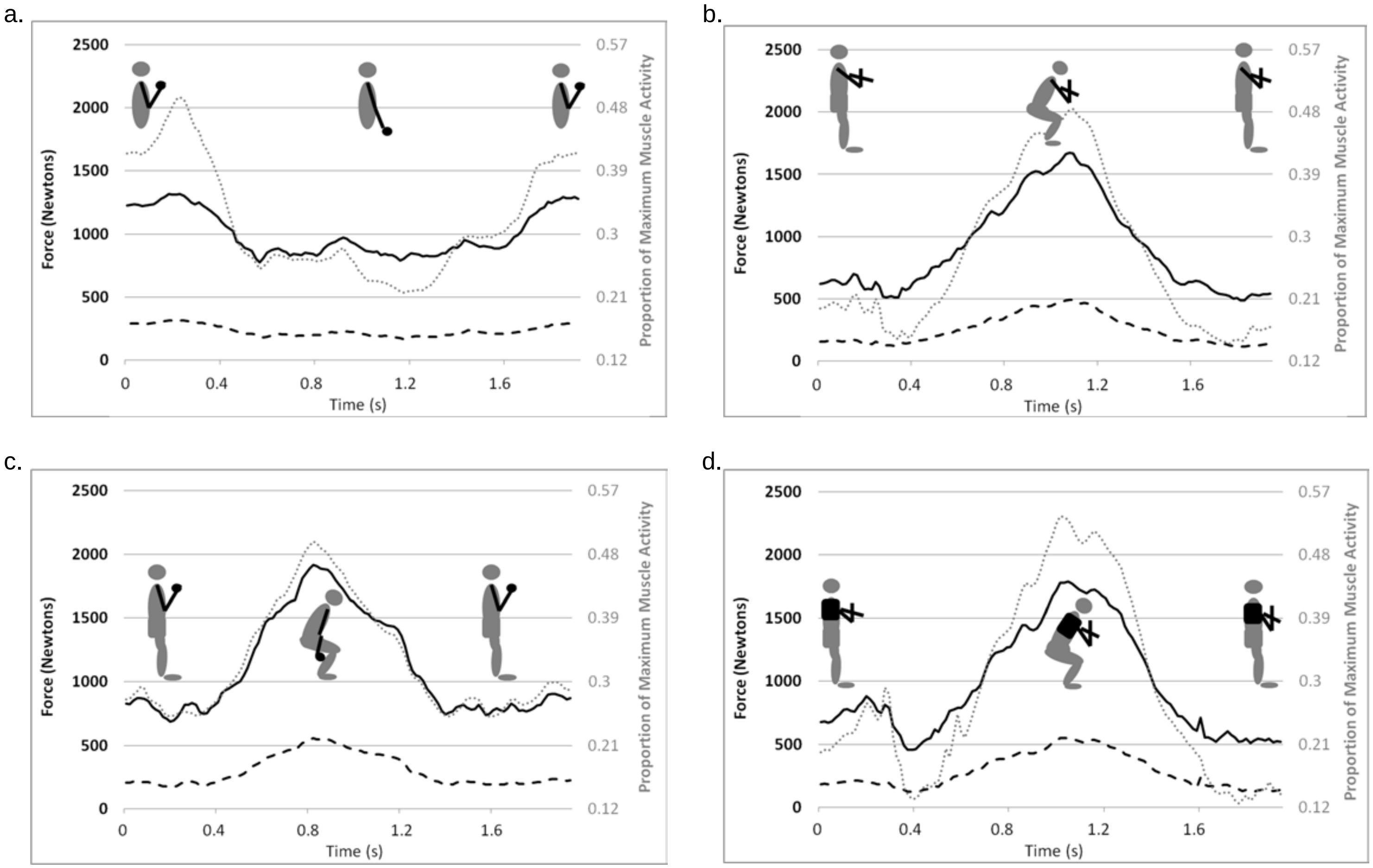

Figure 4.2 Predicted compressive loading on L5 at the L5/S1 joint (––), anterior shear loading on L1 at the T12/L1 joint (– –), and the activity, as a proportion of maximum, of the most active muscle within the model (·····) at each timepoint over the course of a typical repetition for the a) Curl exercise, b) Squat exercise, c) Squat+Curl exercise, and d) Squat+Vest exercise. The stick-figures show the approximate time when the participant started the lifting task, when she reached the deepest point of the squat and/or reached full extension of the curl, and when she completed the lifting task.

Table 4.1 Mean ± standard deviation of the predicted peak compressive and anterior shear loading on the L1 vertebral body at the T12/L1 joint and on the L5 vertebral body at the L5/S1 joint.

	L1 Loading (N)		**L5 Loading (N)**	
	Compressive	Shear	Compressive	Shear
Curl	1206 ± 402	326 ± 132	1285 ± 364	206 ± 83
Squat	1308 ± 389	610 ± 125	1835 ± 394	194 ± 90
Squat+Vest	1433 ± 426	682 ± 134*	2002 ± 402*	199 ± 95
Squat+Curl	1342 ± 329	628 ± 92†	1891 ± 348†	208 ± 77

***** Significantly different from Squat exercise ($p < 0.01$)
† Significantly different from Curl exercise ($p < 0.001$)
No comparisons of the Curl exercise to the Squat or Squat+Vest exercises were made in the post hoc testing.

Post hoc testing also revealed that adding 4.5 N of static upper body resistance, in the form of a weighted vest, to a squat exercise resulted in a significant increase in peak loading of the lumbar spine, whereas adding dynamic resistance of equivalent weight, in the form of a biceps curl, did not significantly change lumbar loading. Specifically, the Squat+Vest exercise produced 167 ± 245 N more peak compressive force on L5 at L5/S1 ($p = 0.007$) and 72 ± 108 N more peak anterior shear force on L1 at T12/L1 than did the Squat exercise ($p = 0.008$; Table 4.1). Peak compressive force on L1 at T12/L1 did not differ between the Squat and Squat+Vest exercise ($p = 0.089$). The corresponding mean values of peak loading for the Squat+Curl exercise were between those of the Squat and the Squat+Vest exercises. As was noted, the peak forces did not differ between the Squat+Curl and Squat exercises. Additionally, no differences were found between the Squat+Curl and Squat+Vest exercises in peak compressive force on L5 at L5/S1 ($p = 0.077$), in peak compressive force on L1 at T12/L1 ($p = 0.207$), nor in peak anterior shear force on L1 at T12/L1 ($p = 0.054$).

Chapter 5 Discussion

A common and costly public health problem is osteoporotic fracture of the spinal vertebrae, with older women particularly at risk because of the loss of bone that begins during menopause (Old and Calvert, 2004; Riggs et al., 2002). One way to counteract this bone loss is through resistance training exercises, which have been shown to be of benefit to bone mass in pre-, peri-, and postmenopausal women (Bocalini et al., 2010; Martyn-St James and Carroll, 2010). Resistance exercises place mechanical loads on bone that can stimulate bone growth if the load is large enough (Borer, 2005). A challenge in developing effective resistance training programs against vertebral fractures is that, at present, it is largely unknown how much loading different exercises place on the spinal vertebrae. The objective of this study was therefore to determine how different combinations of upper and lower body resistance training exercises affect lumbar loading in middle-aged women. Specifically, it examined how adding different types of upper body resistance to a squat maneuver and how adding a squat to an upper body resistance exercise influenced lumbar loading. The central hypothesis was that adding either static or dynamic upper body resistance to a squat would increase lumbar spine loading above levels observed when the exercises were performed separately. Kinematic and kinetic data were collected for twenty middle-aged women while they performed four sets of exercises:

- A standing bilateral biceps curl with a 2.3 kg dumbbell in each hand (Curl)
- A bodyweight squat (Squat)
- A squat while wearing a 4.5 kg vest (Squat+Vest)
- And, a squat while performing a bilateral biceps curl with the dumbbells (Squat+Curl)

The collected data were run through a biomechanical model of the lumbar spine in order to compare loading between exercises. Peak lumbar loads, as predicted by the model, in both anterior shear and compressive force on L1 at the T12/L1 joint and on L5 at the L5/S1 joint were compared between exercise types. Significant differences in peak loading between the exercises occurred for compressive loads on L5 and for anterior shear loads on L1.

Combining Upper and Lower Body Resistance Exercises

The first specific aim of this study was to compare lumbar loads during upper and lower body resistance exercises when performed simultaneously, as opposed to separately. It was hypothesized that, for 4.5 kg of resistance, combining a biceps curl with a squat would produce larger lumbar loads than either the standing biceps curl or the squat exercise performed by itself. Consistent with this hypothesis, the Squat+Curl exercise produced 606 ±

372 N more peak compressive force on L5 than did the Curl. Additionally, the Squat+Curl produced 302 ± 128 N more peak anterior shear force on L1 at T12/L1 than did the Curl. These observed changes in loading, a 47% increase in peak L5 compressive loading and a 93% increase in peak L1 anterior shear loading when switching from the Curl to Squat+Curl, were both found to be significant in the population tested.

This observed difference in lumbar loading between the Curl and Squat+Curl exercises supports the idea that adding a squat to an upper body resistance exercise produces more loading of the lumbar spine than does isolated upper body resistance. This is likely due to several factors. Lumbar loading during a Squat+Curl exercise arises from the weight of the upper body and dumbbells, the forces used to accelerate both the torso and dumbbells, and the muscle forces used to control the forward inclination of the torso. In contrast, during a standing curl, there is little or no acceleration of the torso and the torso is not forwardly inclined. The forward inclination of the torso during the concurrent squat maneuver and the increased muscle activation, specifically of the back extensors, needed to control this forward inclination are the most likely reasons for the increased forces across the lumbar joints during the Squat+Curl. Past research has shown that spinal loading, in both compression and shear, tend to vary with the magnitude of trunk flexion and corresponding extensor activation (Cappozzo et al., 1985; Russell and Phillips, 1989). Increased core activation could also contribute; studies have shown more activation of the core musculature during multi-joint, free weight exercises than during isolated, single-joint exercises using weight machines (Stone et al., 2002).

In contrast to the effects of adding a squat to a curl, there were no effects of adding a curl to a squat. There were no significant differences in compressive or anterior shear forces at either L1 at the T12/L1 joint or at L5 at the L5/S1 joint between the Squat+Curl exercise and the Squat exercise. The lumbar loading during a squat exercise is thought to depend on the weight of the upper body, the forces used to accelerate the upper body, and the muscle forces used to control the forward inclination of the torso (Cappozzo et al., 1985; Russell and Phillips, 1989). Adding 4.5 kg of upper body resistance to a squat in the form of a biceps curl increased the weight of the upper body by approximately 16% for the average woman in this study and should have added new upper body accelerations during the squat. Therefore, it was hypothesized that the Squat+Curl exercise would produce greater lumbar loads than the Squat. This hypothesis was not supported. The Squat+Curl did produce, on average, 56 ± 205 N more L5/S1 compressive loading and 17 ± 79 N more anterior shear on L1 than the bodyweight squat exercise, which corresponded, on average, to a 3.1% and 2.8% increase in loading, respectively. However, the variability between subjects and the marginal increases in loading resulted in no statistically significant difference between the exercises. Potential reasons for this will be discussed in the next section. Nevertheless, the results do indicate a trend for the Squat+Curl to produce higher lumbar loading than a Squat alone, and more testing should be done with heavier upper body resistance to explore this possibility.

The results of comparing the Squat+Curl to a Curl exercise and to a Squat exercise suggest that adding a squat to an upper body resistance exercise can improve the effectiveness of the upper body resistance in loading the spine. However, adding an upper body resistance exercise, in the form of a biceps curl with 2.3 kg in each hand, to a lower body resistance exercise, in the form of a squat, did not load the spine more than the lower body exercise alone.

Static versus Dynamic Upper Body Resistance

The second specific aim of this study was to compare the effects of dynamic versus static upper body resistance on lumbar spine loading during a concurrent squat maneuver. It was hypothesized that static resistance in the form of a weighted vest would create larger lumbar loading than would squats with no added weight. It was further hypothesized that, for a given amount of upper body resistance, dynamic resistance in the form of a biceps curl would produce greater lumbar loading than static resistance. As predicted, 4.5 kg of static upper body resistance in the form of a weighted vest did produce significantly more lumbar loading than a body weight squat. On average, the vest added approximately 16% more weight to the upper body weight of our participants. The AnyBody model predictions showed a 167 ± 245 N increase in peak compressive force on L5 and a 72 ± 108 N increase in peak anterior shear on L1 at the T12/L1 joint when the 4.5 kg vest was added to the Squat. Thus, the Squat+Vest exercise increased peak compressive force on L5 by 9% and increased peak anterior shear loading on L1 by 12%. As mentioned before, lumbar loading during a squat exercise arises from the weight of the upper body, the forces used to accelerate it, and the muscle forces used to control its forward inclination (Cappozzo et al., 1985; Russell and Phillips, 1989). The weighted vest acted to increase all three of these forces by increasing the effective mass of the upper body, raising its center of mass, and increasing its moment of inertia about the lumbar spine in the sagittal plane. In particular, by increasing both the weight of the upper body and, probably, its lever arm in the “seated” position of the squat, the vest would act to increase the trunk extensor muscle activity needed to hold the upper body in place. However, the 9% and 12% percent increases in peak loading, in compression at L5 and anterior shear at L1, respectively, were slightly less than the 16% of upper body weight that was added when wearing the vest; 16% of added static weight does not lead to 16% increases in loading. This is probably due to small postural adjustments the participants made to protect the low back as the static load is added; these adjustments are the likely reason for the results seen during the dynamic lift, Squat+Curl.

As was already noted, the Squat+Curl exercise did not produce significantly larger peak loads on the lumbar spine than did the Squat exercise. For the compressive force on L5 at L5/S1 and the anterior shear force on L1 at T12/L1, the average peak loading of the dynamic resistance, Squat+Curl, fell between that for the bodyweight squat and the squat with added static resistance, Squat+Vest. However, as was the case between the Squat and Squat+Curl exercises, the observed 111 ± 264 N difference in peak L5 compression and 54 ± 118 N difference in anterior shear on L1 between the Squat+Vest and Squat+Curl exercises were not statistically significant. This contradicts the hypothesis that the dynamic resistance of a bicep curl would produce greater lumbar loading than the static resistance of the weighted vest when added to a squat. The explanation for the unexpected results for the Squat+Curl exercise could lie in the type of dynamic upper body resistance that was used in this study. The peak loading tended to correspond with the peak muscle activity in all of the exercises and corresponded to the deepest point of the squat for most of the participants across almost all trials for the squatting exercises. This is likely due to this “seated” position of the squat having the largest forward inclination of the torso, placing the upper body’s center of mass at the point most anterior to its axis of rotation and maximizing the shear component of the upper body’s weight relative to the spine. As was noted above, adding weight to the shoulders in the form of a vest effectively increased both the weight of the upper body and its lever arm in the “seated” position of the squat, increasing the trunk extensor muscle activity needed to hold the upper body in place. The increased weight of the upper body and increased muscle activity due to the forwardly inclined torso would both act to increase lumbar loading. However, when the weight was added as a dynamic biceps curl, with elbow extension corresponding to the “seated” squat position, it may have led to a more erect posture at the bottom of the squat. Keeping the torso more erect during a Squat+Curl would decrease the lever arm of the upper body’s center of mass, resulting in less core activation being needed to control the forward inclination of the trunk, and would decrease the shear component of the upper body’s weight. Consistent with this, previous studies have found that decreased trunk inclination will lead to decreased compressive and shear forces across the lumbar joints (Cappozzo et al., 1985; Russell and Phillips, 1989). Therefore, changes in trunk inclination could explain why although 16% more weight was added to the upper body during the Squat+Curl relative to the Squat, only roughly 3% increases in loading were observed.

The present results suggest that adding static upper body resistance, in the form of a 4.5 kg weighted vest, to a squat exercise increases the amount of peak compression on L5 at L5/S1 and the peak anterior shear on L1 at T12/L1 during the exercise. The corresponding peak loading during the Squat+Curl exercise appeared to fall between that of the Squat and Squat+Vest but was not statistically different from either. So, along with being a simpler exercise to perform, adding static upper body resistance to a squat may produce greater peak loading of the lumbar spine than adding dynamic upper body resistance for low added weights.

Another observation worth noting is that there was a lot of variability between participants in loading for each exercise and in differences in loading between exercises. The primary factors influencing this variability are likely differences in upper body weight and in the forward inclination of the torso, as previously discussed. Another, secondary influence could have been differences in pelvic tilt. Work done by Delitto and Rose (1992) on EMG recordings during lifting tasks with two different postures has shown that the EMG activity of the erector spinae muscles was greater when subjects maintained an anterior tilt of the pelvis than when they maintained a posterior tilt. It is possible that the present participants performed the exercises with various amounts of pelvic tilt, leading to a high variability in peak loads. Beyond the potential differences in trunk inclination discussed earlier, varying amounts of pelvic tilt, among other subtle differences in lifting technique (e.g. differences in lifting speed), could help to explain why the peak forces in the lumbar spine were not found to be greater with dynamic upper body resistance than with static upper body resistance. Perhaps participants performed the Squat+Curl exercise with less forward inclination and anterior pelvic tilt than they did with the Squat+Vest or Squat exercises. Although we visually monitored the participants as they performed the exercises to try to ensure that proper technique was used, some variation in force patterns was observed. This suggests that technique may have differed subtly in some of the women and may have influenced the observed results. That lifting technique may dictate the amount and type of vertebral loading is yet another important thing for practitioners to keep in mind.

Implications for Osteoporosis Prevention Programs

Repeated mechanical loading of a bone above normal physiological levels will lead to increased bone density in the regions of bone where the stresses are applied, whereas disuse leads to rapid bone resorption (Ozcivici et al., 2010). As discussed in the review of literature, these tissue-level changes can be induced by exercise and are reflected by changes in bone mass (BMC and/or BMD). Furthermore, higher loads placed on the bone should result in greater relative increases in bone mass or better maintenance thereof (Ozcivici et al., 2010). Numerous studies have shown that exercise programs can lead to improvements in or maintenance of bone mass at the hip and/or spine in women (Kemmler et al., 2004; Kemmler et al., 2011; Martyn-St James and Carroll, 2010; Winters-Stone and Snow, 2006). This study aims to build on these previous studies and create a better understanding of the biomechanical loading to the lumbar spine during upper body and lower body resistance training. Potentially, these findings can help practitioners develop exercise programs that target bone at both the hip and the lumbar spine.

The results of this study should suggest to practitioners that lower body squats can be added to upper body resistance exercises in order to increase lumbar loading. It is likely more beneficial to lumbar bone mass, according to these results, to perform a biceps curl combined with a squat exercise, as opposed to performing the curl in isolation, when the added resistance is 4.5 kg. At this low weight, however, there seems to be no added benefit to lumbar bone mass to add a curl to a squat exercise. Additionally, when comparing the effects of adding static upper body resistance versus dynamic upper body resistance to a squat, it was determined that, for 4.5 kg of static resistance, use of a weighted vest should be recommended over a dynamic biceps curl exercise with equivalent weight.

An important issue to address is the idea of whether these exercises, as performed, would actually have any effect on lumbar BMD and whether the differences between the exercises (Curl vs. Squat+Curl; Squat vs. Squat+Curl vs. Squat+Vest) are actually meaningful in terms of their expected effects on bone density. In order to have a fuller understanding of the loads produced in this study, it is possible to compare them to the loads experienced during standing. According to previous research, erect posture produces compressive loads of approximately 500-800 N in the lumbar spine, with the L5 region experiencing loads at the higher end of that range (Kurutz, 2010). Consistent with this, the AnyBody model predicted that peak compressive loads on L5 at L5/S1 while our participants stood still prior to beginning the Squat exercise (i.e. without added weight) ranged from 600-1200 N with the average force being 882 ± 264 N (n=19). Peak anterior shear on L1 at T12/L1 was calculated to be 232 ± 78 N (n=19) during the corresponding period of standing. Using these numbers, it was estimated that the Squat+Vest exercise increases peak L5 compression to 175-275% of the levels experienced while standing and increases peak L1 anterior shear force to 250-350% of that during quiet standing. Although the lumbar loading nearly doubles, at least, during the Squat+Vest compared to when standing, the 4.5 kg resistance used in this protocol may be too light to elicit an osteogenic response in the lumbar spine. In a study by Winters-Stone and Snow (2006), two groups of middle-aged women participated in exercise programs that included resistance training. One group performed lower body exercises with a weighted vest and the other group added dynamic upper body exercises, such as curls and rows, with resistance bands that created a resistance of their 8-12 repetition maximum. Both hip and lumbar bone mass were tested and it was found that the group that did both lower and upper body exercises showed beneficial changes in lumbar bone mass. The group performing only lower body training with vests whose weight was progressively increased to 10-13% of body weight, corresponding to 6-8 kg in the present study, showed no changes in lumbar BMD. These findings support other studies in the literature, in which lower body resistance training, including squat exercises with static weight added to the shoulders, has repeatedly been shown to improve hip but not lumbar bone mass (Martyn-St James and Carroll, 2010). Combining those and the present findings, it appears that compressive and anterior shear loading of the lumbar spine in the seated squat position at 2000 N and 680 N, respectively, are ineffective at influencing lumbar bone mass (Bassey et al., 1998; Winters-Stone and Snow, 2006).

A study that could help determine what loads are needed to have an effect on lumbar bone comes from Morris et al. (2000). Their study associated compressive loads of 2694 ± 609 N, equal to 4.6 times body weight, in combination with shear loads of 606 ± 117 N at L4/L5 with increased bone density of the lumbar spine in female rowers. By comparison, the largest compressive loads in the present study, observed for the Squat+Vest exercise, were only 2002 ± 402 N, or slightly over three times body weight, while the largest shear loads were 682 ± 134 N. The International Osteoporosis Foundation (IOF) recommends exercises at an intensity of 60%-80% of one repetition maximum for bone health, which for women of this study, would be in the 30-40 kg range for a squat exercise (International Osteoporosis Foundation, 2013; Seo et al., 2012). Because 4.5 kg of added static resistance created loads of roughly three times body weight, it is likely that lifting the IOF recommended weight would create loads at or above the 4.6 times body weight level within the lumbar spine. Extrapolation of the present results would suggest that a 23 kg vest would be needed to produce a compressive load of 2694 N at L5 during a Squat+Vest. However, the actual internal loads these larger resistances would produce are not known and have not been experimentally measured in this subject population. The protocol used in this study could be used to estimate these internal loads if the study was repeated with larger loads. However, increasing the amount of strength required to perform the Squat+Curl or Squat+Vest exercise decreases the number of women who can safely perform the exercise, decreasing the effectiveness of the intervention at the population level. Furthermore, it may be the case that the loads found by Morris et al. (2000) may be larger than necessary to elicit an osteogenic response within the lumbar spine. Together, the findings of Winters-Stone and Snow (2006), Morris et al. (2000), and the present study suggest a range of what actual load you may need to add to a squat for a positive bone response. It needs to be more than 4.5 kg but may not need to be as large as 23 kg. It should also be noted that these estimates assume that the spinal loading is acting largely alone in providing the osteogenic stimulus. Additional factors, such as pharmaceutical interventions, could potentially increase the effectiveness of resistance exercises by sensitizing the relevant osteogenic pathways (Jee and Tian, 2005), thereby lowering the amount of load needed to elicit a response.

Although combined upper and lower body resistance exercise has been found to lead to improvements in lumbar bone mass in a middle-aged female population (Winters-Stone and Snow, 2006), the exact mechanism whereby it did so is unknown. The present study is based on the premise, supported by previous findings (Lanyon, 1996), that peak loading is a primary measure of an exercise's level of benefit to lumbar bone mass. However, this may not be the case. Direction of loading may be more important. The spine is strongest in compressive loading because it is subject to compressive forces on a daily basis during walking and standing (Ferguson and Steffen, 2003). Dynamic resistance exercises that introduce bending and twisting of the lumbar spine might be more effective than the Squat+Curl or Squat+Vest exercise in eliciting positive changes in lumbar bone density because atypical loading of the vertebral column improves trabecular integrity in multiple loading directions (Prakash et al., 2007). We chose to study the Squat+Curl because it was one of the exercises that was differentially performed by the groups who did and did not exhibit positive changes in lumbar bone mass in the study of Winters-Stone and Snow (2006). In considering peak loading alone, the present results suggest that the Squat+Curl was not one of the exercises that elicited the positive changes in lumbar bone mass, as the peak lumbar loads did not differ from those for a Squat+Vest, for which no influence on lumbar BMD has been shown (Winters-Stone and Snow, 2006). However, other dynamic upper body resistance exercises, such as front raises, dumbbell shoulder press, bent over rows, and lateral raises, have yet to be tested and, even at the level of resistance presently tested, might produce osteogenic loading of the lumbar spine. Practitioners should not dismiss the idea that dynamic upper body resistance combined with a squat is beneficial to lumbar bone mass. The present results only indicate that biceps curls performed with low levels of resistance (2.3 kg dumbbells) in combination with a squat do not create higher loads on lumbar vertebrae than squatting with body weight.

In conclusion, this study should suggest to practitioners that, for middle-aged women, the use of a 4.5 kg weighted vest should be recommended over a bodyweight squat exercise to increase lumbar loading. Furthermore, it indicates that bicep curls can be combined with a squat in order to create larger lumbar loads than standing curls; but the lumbar loads created by this "squat+curl" exercise are no different than the loads produces when squatting with a vest of equivalent weight. Taken in the context of the past studies that were discussed in this section, it appears that it is not necessary to include biceps curl exercises, performed either alone or in combination with a squat, in a resistance training program that targets bone mass of the lumbar spine. It further appears that 4.5 kg of added static upper body resistance is not enough to elicit positive changes in lumbar bone. It is probable that the actual amount lies somewhere between 4.5 kg and 23 kg, and it may vary for each individual. More research needs to be done to determine how increased resistance, different lifts, alternate lifting techniques, and age affect lumbar loading in order to give practitioners more specific recommendations about lifts to include in an exercise-based osteoporosis prevention program.

Limitations

An accurate biomechanical model must account for both trunk muscle activity and lifting exertion dynamics in order to correctly model the loads acting on the lumbar spine (Granata and Marras, 1995a). The AnyBody Modeling System software used in this study is a quasi-static model that uses an optimization method to determine muscle forces (de Zee et al., 2007). One limitation of using a quasi-static model is that it does not take into account the activation dynamics of the muscles. The estimated muscle force can change from any value to another instantaneously, sometimes creating physiologically unreasonable estimates of the forces acting across a joint. However, the speed at which the tested tasks were performed was arguably slow enough that this limitation most likely had negligible effect on the results. Another limitation of the model used is that it estimated muscle activation by minimizing a mathematical criterion using optimization methods. In this case, the model estimated muscle activity primarily by minimizing the maximum muscle stresses. The human body doesn't necessarily recruit muscles in this way, and therefore, error is introduced into the analysis. In particular, optimization methods tend to underestimate coactivation because it is inefficient (Marras and Sommerich, 1991). As previously mentioned, trunk muscle coactivation plays an important role in determining lumbar loading (Granata and Marras, 1995b). Therefore, the lumbar loading predicted by the AnyBody model in this experiment may be smaller than the actual loading that occured while the women performed the tasks. Ideally, electromyography (EMG) measures would have been included in the study to verify that the model produced reasonable levels of muscle activity. Yet another source of error from the model could have come from the scaling of the generic lumbar spine to the individual. The model was scaled to the dimensions and strength of each individual using an assumed set of scaling functions; however, human anatomy is variable and a scaling function's accuracy changes from individual to individual. The AnyBody model used also does not include all strucures of the spine, which may reduce the accuracy of the predicted loading (Han et al., 2012). Nor does the model take into account variations in intra-abdominal pressure (IAP) between trials or between women. Increases in IAP from not breathing during a squat are thought to decrease lumbar loading significantly (McGill et al., 1990). The model assumes the same behavior in everyone. In that case, differences in actual IAP between women and/or trials would cause increased variability in the error between the predicted and actual loading. Nevertheless, it will be noted that the present model was found to estimate measured intradiscal pressure during a static sagittal lifting task to within 5.3% (de Zee et al., 2007), even without scaling to the individual.

It would also have been ideal to be able to determine the loading on different areas of the vertebral body. Given that the anterior portion of the vertebral body is usually the part that collapses in a fracture (Prakash et al., 2007), it would be beneficial to know if a certain type of upper body loading produces higher anterior compressive forces on the vertebra. This would allow appropriate inclusion or exclusion of the associated exercises for individuals at low and high risk of fracture, respectively. The AnyBody software modeled each vertebra as a single rigid body, so total loading was all that was reported. This is not an important limitation, however, because the total load allows us to identify gross differences in overall osteogenic potential between exercises, which is of clinical significance.

Another potential limitation of this study is that all participants used a 4.5 kg vest or two 2.3 kg dumbbells during the exercises, regardless of their body weight. Often, the loads lifted in resistance training programs are based on a percentage of body weight (Winters-Stone and Snow, 2006). Some of the variation we saw in lifting technique and spinal loading could have been due to the fact that the added resistance in this study was not a fixed percentage of body weight. However, all participants fell into the range of lifting 5.4% to 8.8% of their body weight (mean ± SD: 7.5 ± 1%). Such a small range is functionally unimportant.

Finally, the results of this study are limited to the population and tasks studied: women, aged 35-50, performing squats with added upper body resistance as described in the methods. The population studied may also have been more physically fit than average due to the inclusion criteria for the study. The results cannot necessarily be extended to all combined lower and upper body resistance training exercises, nor can they necessarily be extended to older or sedentary populations. Again, these are not major limitations, as the bicep curl and squat are exercises often included in any resistance training program, and the population of women tested in this study are of the age at which you would want to begin a resistance-training-based program to prevent the bone losses that begin at menopause. If desired, the present procedures could be repeated with different resistance exercises and/or an older subject population.

Chapter 6 Conclusion

Osteoporosis is a major global health concern, and spinal fractures are the most prevelant form of osteoporotic fracture (Burge et al., 2007). Exercise programs have been found to be effective in augmenting and maintaining bone mass at both the hip and spine in premenopausal and postmenopausal women, which may reduce the risk of osteoporotic fracture (Bocalini et al., 2010; Friedlander et al., 1995; McNamara and Gunter, 2012). In premenopausal women, Winters-Stone and Snow (2006) found that an exercise program that included combined upper and lower body resistance training improved bone mineral density (BMD) of both the lumbar spine and hip, whereas lower body exercise without upper body involvement yielded improvements in BMD at the hip but not the spine. This suggested that upper body involvement is needed in a resistance training program in order for the program to have an effect on lumbar spine BMD. However, there was a gap in the research surrounding these programs. That is, specific exercises, such as squats, curls, or a combination of the two exercises, had not previously studied with regards to their potential for osteogenic effects on the lumbar spine.

The objective of this study was to examine how different combinations of upper and lower body resistance training exercises affect lumbar loading in middle-aged women. The central hypothesis was that adding either static or dynamic upper body resistance to a squat would increase lumbar spine loading above levels observed when the exercises were performed separately by the middle-aged female participants. Two specific aims were addressed. The first aim was to compare lumbar loads during upper and lower body resistance exercises when performed simultaneously, as opposed to separately. It was hypothesized that combining a bicep curl with a squat would produce larger lumbar loads than a standing bicep curl or squat exercise performed in isolation. The second aim was to compare the effects of different types of upper body resistance added to a squat on lumbar spine loading in middle-aged women. It was hypothesized that static resistance, in the form of a weighted vest, would create larger lumbar loads than squats with no added weight and that dynamic resistance, in the form of a bicep curl, would produce greater lumbar loading than would an equivalent static resistance.

Kinematic and kinetic data were collected while twenty women, aged 35-50, performed four sets of exercises in a counterbalanced order: a standing bilateral biceps curl with a 2.3 kg dumbbell in each hand, a bodyweight squat, a squat while wearing a 4.5 kg vest, and a squat while performing a bilateral biceps curl with the dumbbells. The collected data were run through a biomechanical model of the lumbar spine (de Zee et al., 2007) to estimate the loading of the lumbar vertebrae during each exercise. Peak model-predicted compressive and anterior shear loads acting on L5 at L5/S1 and on L1 at T12/L1 were compared between exercise types.

Significant differences in peak loading between the exercises occurred for compressive loads at the L5/S1 and T12/L1 joints and for anterior shear loads on L1 at the T12/L1 joint. With regards to the first specific aim, combining the bicep curl with a squat produced larger loads than did the standing bicep curl performed in isolation, as was hypothesized. However, in contrast to our hypothesis, combining the bicep curl with a squat did not produce larger lumbar loads than did the squat exercise performed in isolation. With regards to the second specific aim, adding static resistance, in the form of the weighted vest, created larger loads than did squats with no added weight, as was hypothesized. However, in contrast to our hypothesis, adding dynamic resistance, in the form of the bicep curl, to a squat exercise did not produce greater lumbar loading than did adding the equivalent static resistance in the form of the weighted vest. Peak lumbar loading for the squat with the added dynamic resistance did not differ significantly from that for the squat with added static resistance or for the squat without added resistance.

In practical terms, the results of this study suggest that, in middle-aged women, squatting with a 4.5 kg weighted vest produces larger peak lumbar loads than a bodyweight squat, but squatting while doing biceps curls of equivalent weight instead does not. However, squatting while doing biceps curls does create higher lumbar loads than a standing biceps curl exercise. The recommendation from these findings to practitioners should be that, at 4.5 kg of added resistance, adding a static weighted vest is the best option of the exercises tested in this study to load the lumbar spine. Adding static resistance in the form of a weighted vest results in greater lumbar loading than a bodyweight squat, creates no less loading than a squat with a curl, and is simpler to perform than a squat with a curl. However, the average peak loads produced during this exercise are likely not large enough to elicit positive changes in bone mass at the lumbar spine. Although these findings are only a small step toward creating effective resistance-training-based osteoporosis prevention programs, this study is a good first step in expanding the knowledge regarding which resistance training exercises can help prevent osteoporosis. Future studies can build off of these findings in order to give practitioners more specific recommendations about lifts to include in an exercise-based osteoporosis prevention program.

Future Research

In order to develop a good understanding of how specific resistance training exercises influence lumbar loading and lead to improvements in lumbar bone, more research is needed. First, the effect of increasing the amount of weight lifted on lumbar loading and the changes in loading observed when exercises other than a curl are added to a squat should be studied. From these findings, selected exercises can be tested in older populations of women to find if similar loading changes occur between exercises in peri- and postmenopausal women. Other topics that need to be explored are the effects of different lifting techniques, pelvic tilt, and sex on lumbar loading, as well as the combined effects of resistance training and osteoporosis drug regimens on changes in bone mass.

A longitudinal cohort study would be the next step to determining if the various lifts identified as potentially beneficial to lumbar bone can actually have an effect. Such a study might compare a cohort of perimenopausal women performing combined dynamic resistance exercises against a cohort doing the same types of exercises, but instead working the muscle groups separately. Pre- and post-intervention measures of bone mass, as well as the biomechanical analysis protocol used to determine lumbar loading in this study, would be incorporated into a six- or twelve-month resistance training program in attempt to correlate loading with changes in bone.

Because the manner in which a vertebra is loaded may be more important than the total load applied, knowing the stresses and forces acting on different areas of the lumbar vertebrae during a resistance exercise would be useful. In order to understand the distribution of loading on the vertebral body, a finite element modeling analysis to determine where and how the loads are being applied to the vertebrae could serve as a follow-up analysis. Specifically, this could allow the determination of appropriate exercises, if there are any, to improve bone mass of the anterior portion of the vertebral body, a region prone to wedge-type osteoporotic fracture. Furthermore, this would allow appropriate inclusion or exclusion of the associated exercises for individuals at low and high risk of fracture, respectively.

Finally, the hip is the site of the most costly osteoporotic fractures (Kanis, 2007). A future direction of this research could be to analyze resistance exercises for the loading at the hip. By continuing to study the loading caused at various anatomical locations by different resistance exercises, appropriate exercises to improve bone mass can be incorporated into resistance training programs.

Summary

This study used a detailed musculoskeletal model of the lumbar spine, validated for a number of daily activities, to identify loading differences in resistance training tasks. A combined Squat+Curl was found to produce higher peak compressive loads at L5/S1 and higher anterior shear loads on L1 at T12/L1 than an isolated curl exercise, but no difference was found between the Squat+Curl and an isolated squat exercise. This study also found that the Squat+Vest exercise provided significantly higher peak compressive loads at L5/S1 and higher peak anterior shear loads on the L1 vertebra at T12/L1 than a bodyweight squat. No differences in peak lumbar loading were observed between a Squat+Curl exercise and either a bodyweight squat or a Squat+Vest exercise, suggesting that lumbar loading during a Squat+Curl relative to the other two exercises does not vary in a consistent manner between participants. The main conclusions practitioners can take from this study are: at low levels of resistance, specifically the 4.5 kg used in this study, (1) combining a biceps curl with a squat will produce larger lumbar loads than will a standing biceps curl and (2) the static resistance of a weighted vest increases loading of the lumbar spine when compared to a bodyweight squat, and may even provide higher loads to the lumbar region than adding a dynamic exercise such as biceps curls. However, based on past studies, it is unlikely that the average peak loads experienced by the participants during any of the exercises tested in this study were large enough to elicit positive changes in lumbar bone mass. These results provide foundational information that is important for osteoporosis prevention programs. Until now, practitioners have included or excluded specific resistance exercises in training programs for osteoporosis prevention without data on the internal loads each exercise places on lumbar bone. Continuing this line of study can help create research-based resistance training programs to target site-specific improvements in bone mass. More research needs to be done to determine what exercises should be included in an osteoporosis prevention program.

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Appendices

Appendix A Participant Consent Form

Project Title:	EFFECTS OF UPPER BODY RESISTANCE TRAINING ON LUMBAR LOADING
Principal Investigator:	Michael Pavol
Student Researcher:	Elizabeth Doran
Co-Investigators:	Gabe Haberly
Version Date:	6/08/12

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1. WHAT IS THE PURPOSE OF THIS FORM?

This form contains information you will need to help you decide whether to be in this study or not. Please read the form carefully and ask the study team member(s) questions about anything that is not clear.

2. WHY IS THIS STUDY BEING DONE?

Older women are at risk of suffering fractures of the spinal vertebrae because of the loss of bone that begins during menopause. One way to slow this bone loss is through resistance training (weight lifting) exercises that apply larger-than-normal loads to the bone. The purpose of this study is therefore to determine how certain combinations of upper- and lower-body resistance exercises influence the loading of the vertebrae of the lumbar spine in women. The loading of the hip joint may also be determined. This study is being conducted for a master’s thesis. The results may also be published in scientific journals, presented at scientific meetings, used to seek funding for follow-up studies, and used for educational purposes.

Up to 40 individuals may be invited to take part in this study.

3. WHY AM I BEING INVITED TO TAKE PART IN THIS STUDY?

You are being invited to take part in this study because you are a healthy adult woman, 35-50 years of age; you have regularly participated in moderate-to-high intensity physical activity for the past 4 weeks; you do not have osteoporosis; you do not have a history of severe back injury or recent or chronic back pain; and you do not have a past or present injury or condition that would make participating in this study difficult or painful or that might prevent you from performing the required tasks correctly.

4. WHAT WILL HAPPEN IF I TAKE PART IN THIS RESEARCH STUDY?

If you agree to take part in this research study, you will come to the Biomechanics Laboratory at Oregon State University for testing. The study activities include completing a questionnaire, performing warm-up exercises, preparation for motion capture, performing sets of different resistance training exercises, and having body measurements taken. Details are as follows:

- **Questionnaire:** You will record information about your health history and your recent physical activity on a questionnaire. We may ask you to return for testing on a different day or end your participation in this study as a result of the information you provide.
- **Warm-up Exercises:** You will change into spandex shorts (or other shorts of mid-thigh length or shorter), a tank top or sleeveless shirt, and athletic shoes. We will measure your thigh length. You will then walk for 3 minutes. Next, you will perform one set of 3 or more repetitions of each of 5 different exercises that are the same or similar to those that you will perform during testing: biceps curls with 2 lb. in each hand, biceps curls with 5 lb. in each hand, squats, squats with a weighted vest, and a combined squat and biceps curl exercise with 5 lb. in each hand.

- **Preparation for Motion Capture:** We will tape a set of 27 reflective markers to your skin and clothing. We may also tape your shirt to the back of your neck. Three more markers will be on a thin elastic strap that will be wrapped snugly around your trunk, above the waist. Another 4 markers will be on a headband that you will wear. The motion of these markers will be recorded by our cameras during each data collection trial that follows.

- **Resistance Training Exercises:** You will be filmed one or more times while standing still. You will then perform one set each of the following exercises:

  1. **Biceps Curl:** You will stand with a 5 lb. dumbbell in each hand. You will begin with your upper arms at your sides, your elbows flexed, palms facing your body, and the dumbells at your shoulders. Using just your elbows, you will lower both dumbells together in front of you until your elbows are fully extended and then you will raise both dumbells together back to where they started.

  2. **Squat:** You will stand with your arms folded across your chest and your hands at your shoulders. A chair will be behind you. During the first part of the exercise, you will lower your hips towards the ground by flexing your hips, knees, and ankles, like sitting down onto a chair. Once you have lowered your hips as far as you feel you safely can, without touching the chair, you will stand back up by extending your hips, knees, and ankles.

  3. **Squat with Weighted Vest:** This exercise will be the same as the squat exercise, except that you will be wearing a vest that will weigh about 10 lb. Two more reflective markers will be taped to your trunk after your put on the vest and, before you perfom the first squat with the vest, you will be filmed one or more times while standing still.

  4. **Squat and Biceps Curl:** In this exercise, you will perform the biceps curl exercise and the squat exercise at the same time. The timing of the exercise will be such that the dumbbells and your hips are lowered together and then raised back up together.

  The set you will perform for each exercise will consist of 5 repetitions in a row, with a brief pause between repetitions. Each repetition should be performed so it takes about 1 second for the downward phase and 1 second for the upward phase. During each repetition, we will film your movements and record the forces acting on your feet. For each repetition that you perform incorrectly, or in which a data collection error occurs, you will perform another repetition, up to a maximum of 8 repetitions of each exercise. You will be given at least 2 minutes of rest between sets of exercises.

- **Body Measurements:** We will measure your height, weight, and some other body dimensions, including your foot length, ankle width, knee width, hip width, and arm width at the shoulder. Weight will be measured using a scale. Standing height will be measured using a type of wall-mounted ruler. The other measurements will be made using calipers or a measuring tape.

Study duration: The testing will occur in a single session that will last about 1-1.5 hours.

Video Recordings: Being filmed by the motion capture system is a required part of participating in this study. You will not be identifiable in the recordings, as our cameras will only record the markers that are attached to your body. Nevertheless, you should not enroll in this study if you do not wish to be recorded.

Future contact: We may contact you in the future for another similar study. You may ask us to stop contacting you at any time.

5. WHAT ARE THE RISKS AND POSSIBLE DISCOMFORTS OF THIS STUDY?

Possible discomforts associated with participating in the study include: hand discomfort from holding the dumbbells, fatigue from the exercises, and muscle soreness for a few days after the testing. We will need to touch you to apply and remove the reflective markers. Possible, but unlikely, risks associated with participating in the study include pulling a muscle, suffering a herniated disk in your spine, or injuring your knee. If you lose your balance during a squat, you could experience a fall that results in injury, ranging in possible severity from a bruise to a broken bone. You could also suffer a bruise or broken bone if you drop a dumbbell on your foot.

Several steps have been taken to reduce the risk involved in participating in this study. We have limited the number of exercises and repetitions you will perform and how much weight you will lift. You will undergo a warm-up to prepare your muscles and we will end your participation if you find the exercises too difficult. We will monitor and correct your form during the exercises. A chair will be behind you during the squat exercises, in case you lose your balance. We will let you rest as much as you want. The exercises will be stopped if you say that you are in pain or if we judge that you cannot safely continue. You may also stop the testing at any time for any reason. In particular, **you should immediately stop exercising if you experience any pain.**

6. WHAT HAPPENS IF I AM INJURED?

Oregon State University has no program to pay for research-related injuries. If you think that you have been injured as a result of being in this study, we need you to tell us. You can do this during your testing session or by contacting Michael Pavol afterwards, either at (541) 737-5928 or at mike.pavol@oregonstate.edu. Besides telling us, you should also contact your physician.

7. WHAT ARE THE BENEFITS OF THIS STUDY?

This study is not designed to benefit you directly. However, the knowledge gained may help in developing exercise programs to reduce the risk of vertebral fractures due to osteoporosis.

8. WILL I BE PAID FOR BEING IN THIS STUDY?

You will not be paid for being in this research study. If you complete the testing, you will receive a $5 gift card to Starbucks. If we choose to end your participation or if you choose to withdraw from the study before the testing is complete, you will not receive the gift card.

9. WHO WILL SEE THE INFORMATION I GIVE?

The information you provide during this research study will be kept confidential to the extent permitted by law. Research records will be stored securely and only researchers will have access to the records. Federal regulatory agencies and the Oregon State University Institutional Review Board (a committee that reviews and approves research studies) may inspect and copy records pertaining to this research. Some of these records could contain information that personally identifies you.

If the results of this project are published, your identity will not be made public.

To help ensure confidentiality, we will identify your data only by an assigned subject code, and not by name. In addition, the motion capture system will record only the markers that are attached to you; no identifiable images of you will be recorded or saved. Any documents that include your name will be stored in a filing cabinet in the Biomechanics Laboratory at Oregon State University. This laboratory is kept locked when not occupied by the laboratory staff.

10. WHAT OTHER CHOICES DO I HAVE IF I DO NOT TAKE PART IN THIS STUDY?

Participation in this study is voluntary. If you decide to participate, you are free to withdraw at any time without penalty. You will not be treated differently if you decide to stop taking part in the study. If you choose to withdraw from this project before it ends, the researchers may keep information collected about you and this information may be included in study reports.

Participation terminated by investigator: In some circumstances, your participation in this study may be ended without your consent. This will happen if you cannot meet the criteria for participating in the study. It will also happen if you are unable to perform an exercise correctly during the warm-up or if you find the warm-up exercises to be painful or too difficult.

11. WHO DO I CONTACT IF I HAVE QUESTIONS?

If you have any questions about this research project, please contact: Michael Pavol, at (541) 737-5928 or by email at mike.pavol@oregonstate.edu.

If you have questions about your rights or welfare as a participant, please contact the Oregon State University Institutional Review Board (IRB) Office, at (541) 737-8008 or by email at IRB@oregonstate.edu.

12. WHAT DOES MY SIGNATURE ON THIS CONSENT FORM MEAN?

Your signature indicates that this study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

Do not sign after the expiration date: 06/17/2013

Participant's Name (printed): ____

______________________________	______________________________
(Signature of Participant)	(Date)
______________________________	______________________________
(Signature of Person Obtaining Consent)	(Date)

Appendix B Physical Activity and Health History Questionnaire

Personal Information:

Age: _______

Physical Activity History:

Moderate-to-high intensity physical activity includes such activities as strength training, yoga/Pilates, aerobics, dance, swimming, bicycling, running, etc.

☐ Yes ☐ No Did you participate in 20 minutes or more of moderate-to-high intensity physical activity on at least 2 days per week for each of the past 4 weeks?

Health History:

A *squat exercise* is like sitting down and then standing back up, except without a chair.
A *biceps curl exercise* involves lowering and then lifting a weight by bending just your elbow.
Do you have a past or present injury or condition that would make it difficult or painful for you to perform:

☐ Yes ☐ No A squat exercise while wearing a 10 lb. weight vest
☐ Yes ☐ No A bicep curl exercise with both arms while holding a 5 lb. weight in each hand
☐ Yes ☐ No The same bicep curl exercise while you are also performing a squat exercise

Have you ever had any of the following?

☐ Yes ☐ No Chronic low back pain or a serious back injury
☐ Yes ☐ No Surgery on your back, hip, knee, shoulder, or elbow

Have you had any of the following in the past 6 months?

☐ Yes ☐ No Balance problems or dizziness
☐ Yes ☐ No Back pain (not including mild soreness)
☐ Yes ☐ No Broken bone
☐ Yes ☐ No Head injury, concussion, or loss of consciousness (e.g. fainting)
☐ Yes ☐ No Pregnancy
☐ Yes ☐ No Surgery (not including dental surgery)

Do you currently have any of the following?

☐ Yes ☐ No Osteoporosis or bone disease
☐ Yes ☐ No Neurological problems or conditions (e.g. epilepsy, Multiple Sclerosis, Parkinson’s)
☐ Yes ☐ No A heart or lung problem that limits your ability to exercise
☐ Yes ☐ No Cold, flu, or sinus symptoms

☐ Yes ☐ No Have you taken any of the following types of drugs or medications in the past 24 hours?

Alcohol (2 or more beers, glasses of wine, or “hard” alcoholic drinks)
Sedatives or anxiety/tension relief medication (e.g. Halcion, Xanax, Phenobarbital)
Recreational drugs (e.g. marijuana, cocaine)
Antihistamines (excluding non-drowsy, used as directed)
Anti-inflammatory medication/pain relievers (e.g. aspirin, Ibuprofen)

☐ Yes ☐ No Is there any other information that you feel we should know about your health? If Yes, please explain.