ANALYSIS OF LUMBAR SPINE KINEMATICS DURING TRUNK FLEXION AND EXTENSION MOTIONS

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(ABSTRACT)

The effectiveness of exercise has been increasingly studied as exercise has been popular for the improvement of physical performance and rehabilitation of lumbar spine. A variety of exercises have been used to reduce back pain or spinal degeneration. However, there are no studies to determine effects of exercise on lumbar spine kinematics, including lumbar-pelvic coordination and instantaneous axis of rotation. The current study aimed to examine these lumbar spine kinematical changes due to exercise and therapy. We hypothesized that exercise and therapy will affect the changes of lumbar spine kinematics.

Lumbar-Pelvic motions were recorded from 86 healthy subjects while performing lifting and lowering tasks of 10% and 25% of body weight. The influence of exercise was quantified from coefficients of curve-fitting for pelvic and lumbar angles. There was a significant difference ($p<0.05$) for the range of lumbar motion (distribution, D) between the control group and the cardiovascular exercise group after 12-week program. However, there was no significance for lumbar-pelvic coordination, C.

A second study was performed to investigate the changes of instantaneous axis of rotation (IAR) at which trunk angle reached 25º. Results indicated that a superior-inferior location of IAR was significantly ($p<0.05$) modified by the cardiovascular exercise after 12 weeks, but there was no significant effectiveness of the physical therapy exercise.

Finding of lumbar spine kinematics during lifting and lowering a weight which are the most popular manual handling activities may provide great understanding of the exercise effectiveness. Future studies are recommended to assess whether the changes of lumbar spine kinematics lead to the decrease instances of lumbar spine injuries or low back pain.

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CHAPTER 1 – INTRODUCTION

The lifting of loads is a primary risk factor for occupational low back disorders (Bigos et al., 1986) which is one of the most prevalent health problems in industrial workers (Svensson and Andersson, 1983). Lifting and manual materials handling cause 50 to 75 % of all back injuries (Snook, 1989; Bigos et al., 1986). During lifting, sagittal trunk movements cause pain in over 90 % of low back pain (LBP) patients (Bergquist-Ullman, 1977). Almost 80 percent of Americans experience back pain during their lifetime (Frymoyer and Cats-Baril, 1991), which cause substantial financial costs (Grazier et al., 1984). As a result, low back stabilizing exercises have become a popular topic for the improvement of occupational tasks and for the rehabilitation of back pain.

Exercise has been a key for the treatment of LBP, improvement of physical performance or stability of the lumbar spine. In fact, various exercises have been proposed to prevent and treat LBP because the increased strength of the trunk muscles appears to be essential for lumbar spine stability (Wilson and Maier, 1986; Dreisinger and Nelson, 1996). There are several studies that report the trunk and lumbar spine kinematics, including range of motion (Mayer et al., 2004; Mannion et al., 1999; Ng et al., 2002), curvature of the spine (Mitnitski et al., 1998; Berhonnaud et al., 2005) and lumbar-pelvic coordination (Granata and Sanford, 2000; Nelson et al., 1995). However, we are unaware of studies to quantify the changes of the lumbar spine kinematics due to exercise or therapies over time.

Sagittal trunk motion consists of flexion of the lumbar spine and rotation of the pelvis (Granata and Sanford, 2000). The coordination of pelvic and lumbar spine movement is one possible method to understand the lumbar spine kinematics and LBP (Lariviere et al., 2000; Mitnitski et al., 1998). There is no agreement on whether the lumbar and pelvic components move at the same time (Burgess-Limerick and Abernethy, 1992; Mayer et al., 1984; Potvin et al., 1991) or in a sequence (Davis et al., 1965; Farfan, 1975; Farfan, 1978). Another lumbar spine kinematic parameter is the instantaneous axis of rotation (IAR), which can be defined by a pure rotation axis that represents combination of rotation and translation (Panjabi et al., 2000). It describes the relative motion of an object from one position to another. In fact, the IAR is a kinematic parameter that characterizes the movement of human body segments generally and spinal vertebrae specifically (Zhang et al., 2003). In addition, it can be used as a clinical diagnostic tool which can help assess motion abnormalities caused by pathologies such as spinal instability (Dvorak et al., 1991) or hyper-mobility and joint impairment in general (Water and Panjabi, 1988). Trunk motion due to abnormal rotation is recognized as a risk factor for low back disorders (Zhang et al., 2003). Therefore, different location of the IAR has clinical significance as a diagnostic tool (Yoshiokca et al., 1990).

Exercise may influence the kinematics of lumbar spine in terms of range of motion (ROM), Lumbar-Pelvic (LP) coordination and the instantaneous axis of rotation (IAR). The purpose of this study was to quantify changes in lumbar spine kinematics attributed to exercises, including physical therapy core stabilizing exercise and cardiovascular exercise over time. The influence of exercise was quantified from coefficients of curve-fitting for ROM and LP coordination, and the location of the IAR relative to the sacrum.

HYPOTHESES

1. Spinal kinematics are modified by prophylactic stabilizing exercises

SPECIFIC AIMS

1. Quantify changes in spinal kinematic coordination of lifting before and after a 12 week program of prophylactic physical conditioning

Lumbar-pelvic movement coordination and lumbar spine instantaneous axis of rotation were quantified before, during and after the exercise intervention.

CHAPTER 2 – BACKGROUND

2.1 Lumbar Spine Kinematics

2.1.1 Basic Lumbar Spine and Kinematics

Lumbar Spine

The spine is a mechanical structure and consists of three major regions, including cervical (7 vertebrae), thoracic (12 vertebrae) and lumbar (5 vertebrae) (Figure 2.1). It has three fundamental biomechanical functions: transmitting forces (weights) and bending moments to the pelvis, allowing physical motions and protecting the delicate spinal cord (White and Panjabi, 1990). Each vertebra is stacked on top of the other and between each vertebra is an intervertebral disc, which is viscoelastic and exhibits creep and relaxation behavior (White and Panjabi, 1990). Moreover, the discs help to absorb pressure, distribute stress, and keep the vertebrae from grinding against each other.

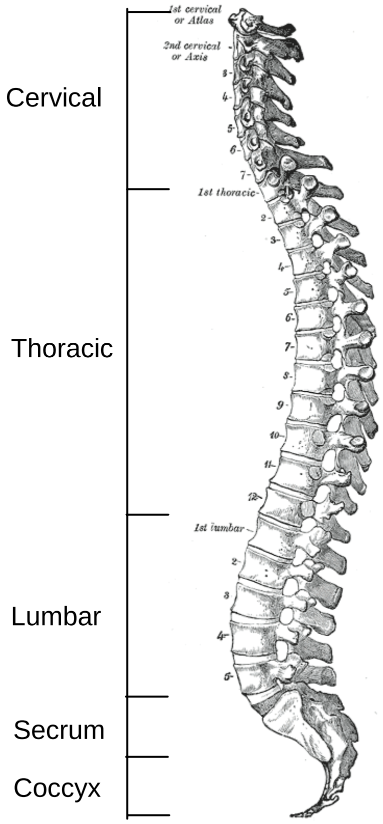

Figure 2.1. Spinal column (image from Gray, 1918, www.bartleby.com/107/)

Ligaments, Tendons

The vertebrae and discs are held together by groups of ligaments (Figure 2.2). Ligaments connect bone to bone and functions allowing adequate physiologic movements, protecting the spinal cord and providing stability to the spine (White and Panjabi, 1990). On the other hand, tendons connect muscle to bone unlike ligaments. Muscles and muscle tendons affect the relative stability of joints. In fact, the tendons and muscles help to stabilize the spine by holding the articulating bone ends together and protect against excessive movement in any direction (Hall, 1999).

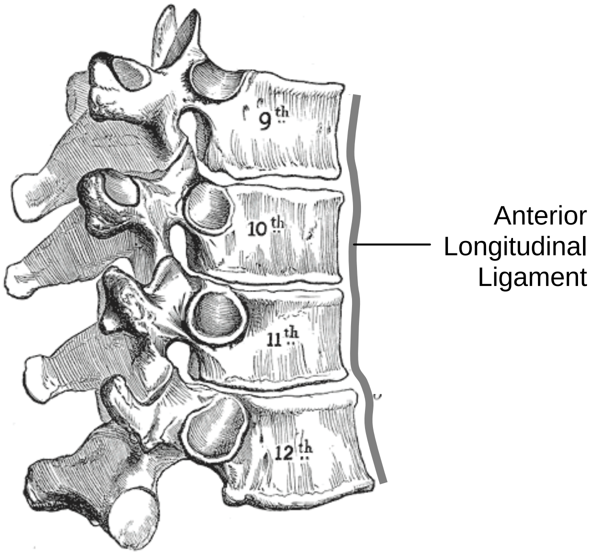

Figure 2.2. Spinal ligaments (image from Gray, 1918, www.bartleby.com/107/)

Spinal Joints

The vertebrae are articulated at the intervertebral discs and at the facet joints (Figure 2.3). The facet joints are links that connect vertebrae together. They are located at the posterior area of the vertebrae body. They are clinically important because facet joints are not only a direct source of pain but also structures for stabilization (Hazlett and Kinnard, 1982). In addition, the facet joints help to make the spine flexible and to carry large compressive loads. These loads change with the body posture.

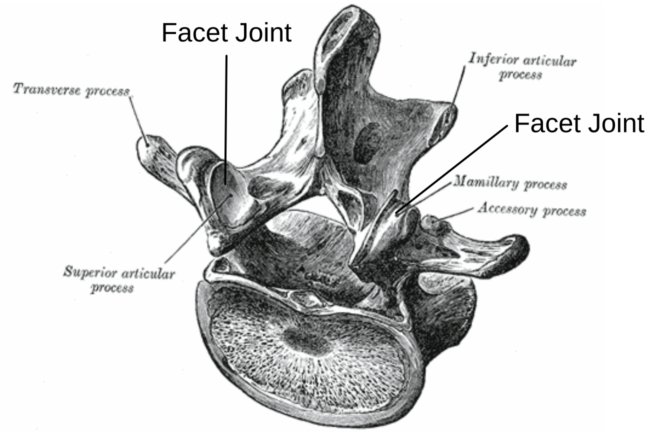

Figure 2.3. Spinal facet joints (image from Gray, 1918, www.bartleby.com/107/)

Nerve Center

The delicate spinal cord is enclosed within the relatively hard spinal canal, made of rigid vertebrae connected end-to-end in space (White and Panjabi, 1990). The bones that create the spinal canal help protect the spinal cord from injury (Figure 2.4). The spinal canal works as follows: it decreases in length when the spine is extended and increased when the spine is flexed. Small nerve roots branch off from the spinal cord through spaces on between each vertebra called neuroforamen and extend out into the entire body. The spinal cord and the nerves are part of the central nervous system that includes the brain. In short, the nerves are the body's neural message system.

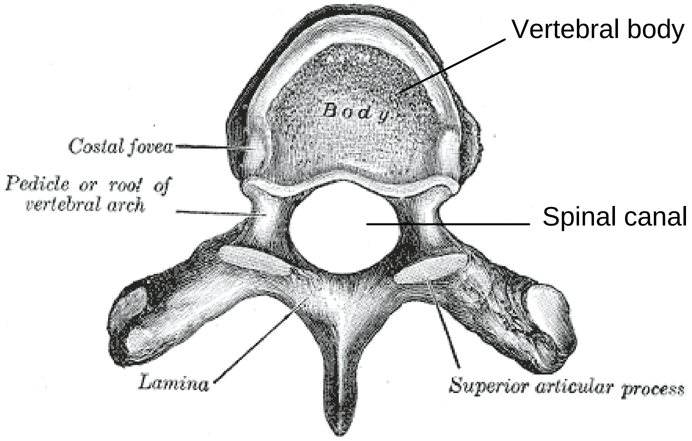

Figure 2.4. Spinal nerve structures (image from Gray, 1918, www.bartleby.com/107/)

Basic Lumbar Spine Kinematics

Kinematics is the study that concerns motion of particles and rigid bodies without consideration of the forces involved (White and Panjabi, 1978). Abnormal kinematics of the human lumbar vertebrae is widely considered to play an important role in LBP (Pope and DeVocht, 1999). Here are some major aspects of the kinematics of the spine. However, two main parameters relative to this study, including range of motion and instantaneous axes of rotation, will be detailed in the next section.

Range of Motion (ROM, lumbar distribution) is an angle through which a joint moves from anatomical position to the extreme limit of segment motion in a particular direction. Examination of the ROM for the lumbar spine is the common physical examination used to assess the low back functions of patients with back pain (Ng, et al., 2002). It is also known as an indication of the two points at the extremes of the physiologic range of translation and rotation of a vertebra for each of the six degrees of freedom.

Instantaneous Axis of Rotation (IAR) is a line in the body which does not move at the instant moment for a composite motion of rotation and translation (Amevo, et al. 1991). This axis is perpendicular to the motion plane. Planar motion is fully defined by the position of the IAR and the magnitude of the rotation about it. Rolander (1966) demonstrated abnormal IARs in the lumbar spine with disc degeneration and presumed instability.

Pattern of Motion (lumbar coordination) is defined by the configuration of a line that the centroid of a body in motion forms as it moves from one point to another. Changes in the normal coupling or the instantaneous axes of rotation are considered as a motion with abnormal patterns (White and Panjabi, 1990).

Coupling is applied to motion in which rotation or translation of a rigid body about one axis is consistently associated with rotation or translation of that same rigid body about another axis. There are certain abnormal patterns of motion described in association with various clinical situations (White and Panjabi, 1990). Abnormal coupling patterns have been described in the lumbar spine as a possible sign of instability (Pearcy and Tibrewal, 1984).

The instantaneous motion of a rigid body in three-dimensional space can be analyzed as a simple screw motion, which is Helical Axis of Motion (HAM) (White and Panjabi, 1990). The HAM is a superposition of rotation and translation about and along the same axis. This axis has the same direction as the resultant of the three rotations given sequentially about the x, y and z axes. The location and orientation of this axis and the designation of the quantities of its rotation and translation constitute a complete, precise, three-dimensional description of the motion for a given moving rigid body in space,.

2.1.2 Range of Motion and Lumbar-Pelvic Movement

Many studies have investigated the range of lumbar motion and lumbar-pelvic (LP) movement or coordination. Basic understanding of these parameters from previous studies may provide the insight of this current study.

Range of Motion

Trunk movements usually consisted of flexion of the lumbar spine and rotation of the pelvis according to David et at (1965). Sequential images of a movement have been used to study the motion of the thoracic and lumbar spine during weight lifting. The range of lumbar movements was of the order of 50 degree, being greater when stooping than when bending the knees. They concluded that when lifting with bent knees the delay in onset of continuous lumbar extension was proportional to the weight of the load.

There have been studied to investigate the effect of gender, age and other factors on ROM. An investigation by Sulliva et al (1994) determined the effect of gender and age on lumbar spine sagittal plane ROM in healthy volunteers. They reported that distinct differences exist between men and women in flexibility and extensibility, whereas little difference exists between genders for lumbar ROM. Lumbar ROM, flexibility and extensibility declined as age increased. Another in vitro study by Yamamoto et al (1989) was done to quantitatively determine three-dimensional movements of the whole spine and lumbosacral joint. The ranges of motion of the lumbar spine are influenced by age and degeneration. Increased stiffness in the degenerated intervertebral discs is the main cause of the reduction in mobility with aging. They concluded that in flexion and extension, more motion took place at lower levels (L4-5, L5-S1) of the vertebral column than at upper levels. A gender effect was also shown in the study of Gatton and Pearcy (1999). They investigated the sequence of intervertebral joint movements and range of motion during three tasks involving lumbar unconstrained flexion. There was a statistical difference in the range of spinal motion between males and females during unloaded flexion, with males having a significantly higher mean range of spinal flexion than females.

Ng et al (2002) examined the relationship between ROM and lumbar lordosis in two groups: back pain patients and matched controls. Results showed that there were no significant differences between the back pain and control groups in flexion, extension, lateral flexion, lumbar ROM and lumbar lordosis. They concluded that when a back pain patient is within pain-free range while measuring, lumbar ROM and lumbar lordosis may not be the parameters that distinguish between back pain patients and subjects without back pain.

Lumbar-pelvic movements

The movement patterns of lumbar spine have been debated. There are two major movements to describe the LP coordination: simultaneously or sequentially. Nelson et al (1995) proposed to examine the dynamic relationship between the lumbar spine and pelvis during trunk motion and to determine the effect of trunk extension or flexion on lumbar-pelvic rhythm. An electromagnetic tracking device was used to monitor simultaneous lumbar and pelvic motion as subjects lifted and lowered a box with knees extended. They concluded that during trunk flexion there was a greater tendency for lumbar and pelvic rotations to occur simultaneously, whereas movement tended to be sequential during extension. Another study was done by Harada et al (2000) to evaluate the differences in motion characteristics of the normal lumbar spine between flexion and extension. Cineradiographic motion analysis was performed in asymptomatic healthy male volunteers for two different lumbar motions. They concluded that the lumbar spine moves sequentially during flexion and extension. In other words, during forward flexion of the lumbar spine, initial motion started from upper segments to the lower segments with phase lags. During trunk extension, initial motion started from the lower segments to the upper segments. More recently, Lee and Wong (2002) examined the contributions of the lumbar spine and hip during flexion and extension. Movements of the lumbar spine and hips were measured in healthy subjects using an electromagnetic tracking device. Movement sensors were attached to the L1 spinous process, the sacrum and the thighs. The ratio of the maximum magnitude of spine movement to that of the hip was determined. They concluded that during forward and backward bending of the trunk, the overall contributions of the lumbar spine and hip were similar, but the spine had a greater contribution to the early stage of the movement.

The following studies investigated the movement patterns only during trunk flexion. The purposes of the studies by Esola et al (1996) and McClure et al (1997) were to establish the amount and pattern of lumbar spine and hip motion during forward bending, and determine differences in motion in subjects with and without a history of low back pain. A three-dimensional optoelectric motion analysis system was used to measure the range and velocity of lumbar spine and hip motion during forward bending. Each subject performed three trials of forward bending that were averaged and used for statistical analysis. There were no group differences for total range of lumbar spine and hip motion or velocity during forward bending. They concluded that the lumbar spine had a greater contribution to early forward bending (like Lee and Wong's results), and the hips had a greater contribution to late forward bending. Results also suggest that although people with a history of low back pain have range of lumbar spine and hip motion during forward bending similar to those of healthy subjects, the pattern of motion is different. However, Gatton and Pearcy (1999) reported that no single variable such as age, height, weight, BMI or sex was found to significantly differentiate subjects' movement sequences. In fact, a variety of movement sequences were observed. Therefore, the results from this study indicate that there is no single movement sequence exhibited by a sample population.

The influence of load and lifting velocity on LP coordination was investigated by Granata and Sanford (2000). By testing healthy subjects, coordinated motions of the pelvis and low-thoracic spine were evaluated using eigenvector analyses and a ratio of lumbar and pelvic angles. Results show that L/P ratio was significantly greater at slow exertions than at fast ones and lumbar spine contributed more to the total trunk motion during 10 kg lifting tasks than 0.1 kg lifts. However, they suggested that unloaded motions may be different from the loaded spinal coordination.

2.1.3 Instantaneous Axis of Rotation

The location of IAR for each vertebra has been studied using cadavers and normal volunteers for the cervical, thoracic and lumbar spines. Cossette at al (1971) suggested that disc degeneration is partly due to torsional strains and that under such loading, the axial rotation of the disc is close to its geometric center. To investigate this, it was decided to determine the IAR of the L3-L4 disc. They found that the IAR of the L3-L4 disc was anterior to the facet joints and in the region of the posterior aspect of the vertebral body. They concluded that movement of the IAR was due to free play in the joint and that the position of the IAR was such as to ensure a safe level of stress to all components of the joint. The same location of IAR was found by Gertzbein et al (1984). They reported that IAR of the L4-5 spinal segment while moving from full extension to full flexion is located in the posterior half of the intervertebral disc. Yoshioka et al (1990) examined the motion characteristic of the normal lumbar spine from L1 to L5. The shift of IAR in the anterior-posterior axis reflected translational movements whereas the ones in the superior-inferior axis reflected rotational movements of the vertebra. They concluded that the L4 vertebra showed a translation-predominant motion characteristic and the L5 vertebra had a rotation-predominant motion characteristic during trunk flexion.

The instantaneous axis of rotation has proven to be a useful parameter of vertebral motion. The abnormal location of IAR has been shown to correlate with spinal pain (Bogduk, et al., 1995). Seligman et al (1984) studied IAR in various stages of degenerative disc disease comparing them with normal spines. They found that the normal IAR fell within the posterior half of the disc space. Also, it was reported that the IAR path-lengths increased significantly in the earliest stages of degenerative disc disease and moderate disc degeneration. Another clinical suggestion was provided by Haher et al (1991). They applied compressive loads to human cadaver spine to test the location of the IAR during flexion and extension, and concluded that understanding the exact location of it after a specific injury would allow the clinician to objectively choose the best surgical approach and the appropriate instrumentation. Furthermore, the effects of load magnitude and movement speed on the IAR were investigated during a lifting task (Zhang, et al., 2003). Results suggested that the IAR locations and vertebral angular displacement were not significantly affected by the speed or load variation.

The preceding is an overview of spinal kinematics and it is possible to describe the normal kinematics of the human spine. The major reason of analyzing spine kinematics is of its own clinical role. Insight into this role could be useful in LBP prevention and rehabilitation. To study this it is necessary to measure the lumbar spine 3-D movements using electromagnetic motion sensor.

2.2 Electromagnetic Motion Tracking Sensor

Electromagnetic real-time motion tracking sensors, Flock of Birds (FOB, Ascension Technology, Burlington, VT, USA) in our study, allow a virtual reality system to monitor the position and orientation of selected body parts of the user using pulsed DC magnetic fields. Electromagnetic sensors are increasingly used as a kinematic measuring tool according to Perie et al.(2002). The advantages of the sensors are that they can record 6-degree-of-freedom (6-DOF) motions. Furthermore, Schuler et al (2005) reported that the system was readily available and was able to record data continuously. The first biomechanical application of electromagnetic motion tracking devices was the kinematic study of the lumbar spine using short-range transmitters by Adams and Dolan (1991).

Motion sensors, also called 6-DOF devices, provide accurate position (x, y and z coordinates) and orientation (yaw, pitch and roll) measurements with respect to a reference point or state. Relative angular motion between two body segments can then be computed from their global orientations. The following three components are generally required: a source that generates a signal, a sensor that receives the signal and a control box that processes the signal and communicates with the computer (figure 2.5). Measurements with the FOB are reliable and it also offers the advantage of collecting anatomically-based, three-dimensional and orientation data during dynamic activities as per the results of Umberger et al (1999). However, the accuracy usually decreases with the distance of the sensor from the source. Static accuracy of position and orientation with standard range transmitters is 1.8 mm and 0.5 º from the manufacturer's technical literature. In addition, Milne et al (1996) concluded that FOB is insensitive to surgical alloys of a shape and volume commonly used in upper-extremity orthopedic implants.

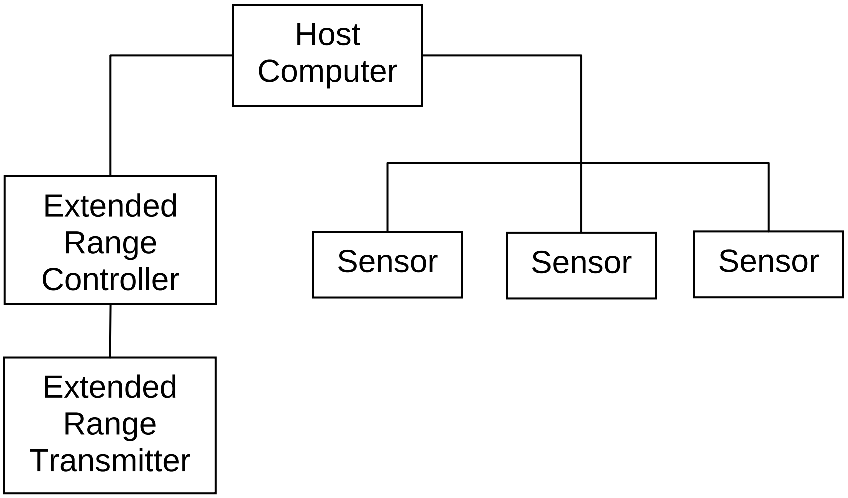

Figure 2.5. Flock of birds block diagram

2.2.1 Motion Tracking Sensor Placement

Spinal motions in this study were recorded from electromagnetic motion sensors secured to the skin surface by double-sided tape over the spinous processes of first sacral (S1) and 10th thoracic (T10) vertebrae. Sensor placement was selected to accurately record lumbar spinal motion. The sacral S1 is the lower boundary of the lumbar spine movements and T10 is 2 vertebrae above the last thoracic vertebra (T12) that is covered by a ribcage. It may be assumed that vertebrae above the thoracic T10 are a rigid body when we consider only lumbar spine movements. Moreover, many studies in the past used these two spinal processes to investigate lumbar spine motion (Marras and Granata, 1997; Granata and Sanford, 2000), so it would be easy to compare with previous results using such marker placements.

2.2.2 Motion Tracking Sensor Processing

Angle data of each electromagnetic sensor was reported as Euler angle rotations, θ_z, θ_y, θ_x about the Z, Y’, and X’’ axes. The Z axis corresponds to positive vertical direction with rotations about this axis, θ_z, representing twisting of the trunk. The Y axis is the vector pointing laterally to the subject’s right side and the Y’ axis is this vector after being rotated θ_z around the Z axis. Rotations about this axis, θ_y, equate to trunk flexion/extension and are the primary concern of this study. The X axis originally points anteriorly out of the trunk and the X’’ axis is the vector after being rotated θ_y around the Y' axis. There were no significant motions about this axis in this study. Because position and rotation data in sagittal plane are dominant movements and other movements are small enough to ignore for the axial rotation during lifting and lowering, data in the sagittal plane only were analyzed in the current study. Figure 2.6 and figure 2.7 show the typical position and angle raw data in sagittal plane during flexion and extension. Motion sensor data recorded in this fashion may subsequently be used to study lumbar spine kinematics.

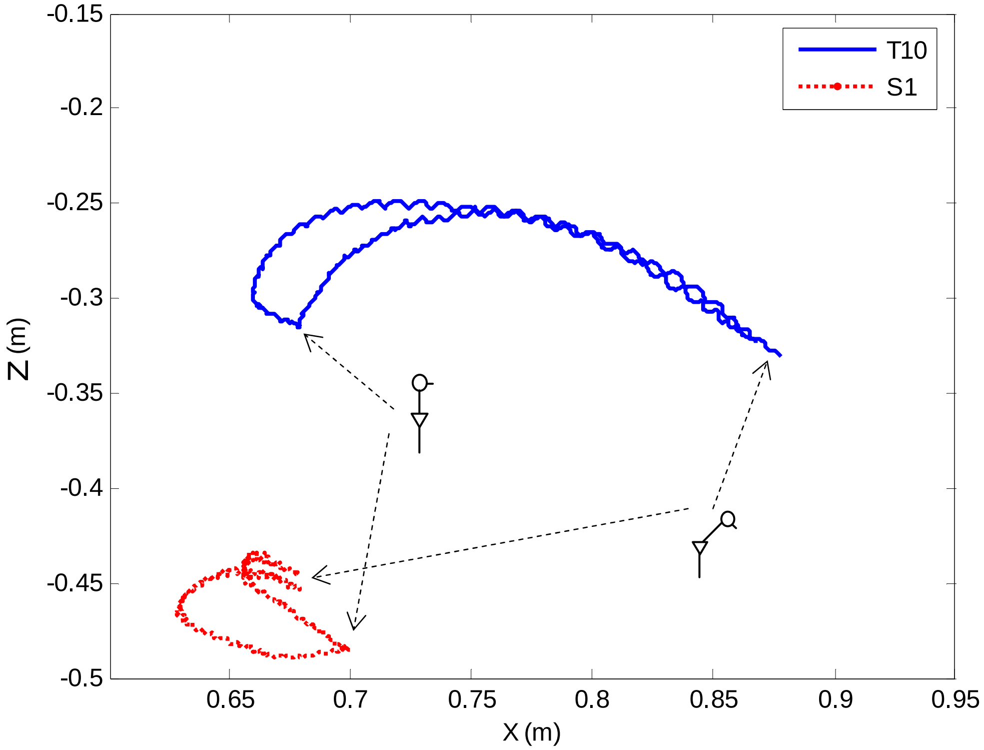

Figure 2.6. Typical raw sagittal position trajectories of motion sensors on the spinous processes of T10 and S1 during extension and flexion

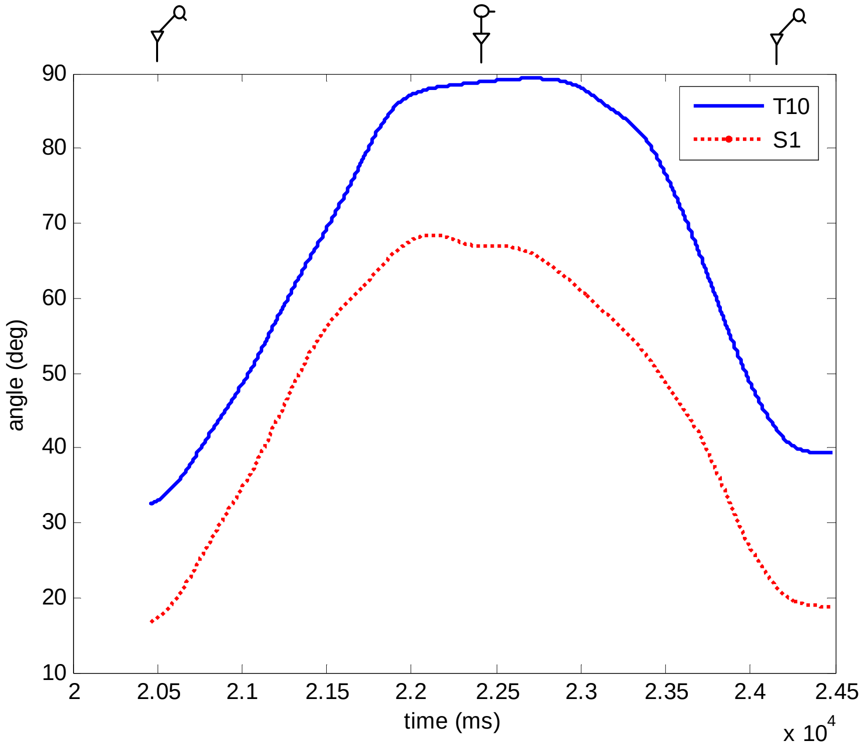

Figure 2.7. Typical raw sagittal angles of motion sensors
on the spinous precesses of T10 and S1 during extension and flexion

2.3 Effects of Physical Therapy and Cardiovascular Exercises

Exercise is a widely prescribed treatment for chronic low back pain, with demonstrated effectiveness for improving function and work. Most studies have observed improvements in global pain ratings after exercise programs and many have observed that exercise can lessen the behavioral, cognitive and disability aspects of back pain syndromes (Rainville, et al., 2004).

Regular exercise by back pain patients may be relatively safe, without adding unreasonable risk for additional injury or pain because exercise does not increase the risk of back pain in the asymptomatic population (Rainville, et al., 2000). Also, a compelling reason to use exercise for the treatment of chronic back pain is that it may reduce back pain intensity (Rainville, et al., 2004). Therefore, Rainville et al (2000) concluded that individuals with low back pain could benefit from the general positive health effects of exercise.

It is, however, recognized that psychosocial, behavioral, cognitive and affective factors play crucial roles in the development of chronic low back pain syndromes and especially back pain-related disability. It supports that exercise may be used as a therapeutic modality to address these issues by understanding how these factors influence back pain (Rainville, et al., 2004).

2.3.1 *Physical Therapy*

Physical therapy exercise for low back pain includes stretching, rehabilitation or functional restoration programs. It mainly focuses on the improvement of trunk muscles. Many studies have been done to test the effectiveness of this exercise in the past.

Physical therapy exercise is beneficial regarding improvements in physical capacity. Kohles et al (1989) described a study to determine if the evolution of the treatment program resulted in increased gains in physical capacity between two groups: a group of chronic low back pain (CLBP) patients undergoing comprehensive functional restoration program in 1983 and a similar group of patients who completed the rehabilitation program in 1987. Patients in each group were assessed on measures of isokinetic trunk strength and spinal range of motion at program admission and discharge. It was concluded that functional restoration continues to be successful with CLBP patients. In Curtis et al's study (1994), the functional performance of lifting capacity differences among four separate CLBP patient groups were examined by using standardized isokinetic and isoinertial lifting performance measurements. 193 consecutive patients were assessed at three separate points in time: at initial evaluation, at admission to the intensive 3-week phase of a functional restoration program and follow up after program discharge. Results clearly demonstrate the effectiveness of a functional restoration program to enhance gains in human performance in CLBP patients with and without prior surgery. More recentrly, Rainville et al (2004) concluded that exercise may be useful for improving back function for patients with low back pain because the most obvious benefit of exercise is its ability to improve or maintain musculoskeletal and cardiovascular function. Stretching exercises can be used to eliminate impaired flexibility and restore normal trunk range of motion. However, they suggested that in order to be successful, stretching must be performed within the patient's physiological end range that does not induce back discomfort. Stretching within the painful range is safe and acceptable to patients when their health-care providers suggest it with confidence.

Physical therapy exercises are used for the reduction of pain. Trunk muscle strength and the effect of trunk muscle exercises on chronic low back pain were investigated in patients with chronic low back pain by Takemasa et al (1995). This study analyzed the differences in trunk muscle strength and effect of trunk muscle exercises between two groups of patients: patients with organic lumbar lesions (experimental group) and without such lesions (control group). The exercises increased trunk muscle strength but did not completely eliminate the low back pain induced by the organic lumbar lesions in the experimental group. Increasing trunk muscle strength was extremely effective in patients of the control group, in which decreased trunk muscle strength was a major factor in chronic low back pain. Mannion et al (1999) examined the relative efficacy of three active therapies for chronic low back pain. Patients with chronic low back pain were randomized to following three treatments: modern active physiotherapy, muscle reconditioning on training devices or low-impact aerobics. Then, they attended therapy treatments twice a week for 3 months. After therapy, significant reductions were observed in pain intensity, frequency and disability in all three groups. Furthermore, Descarreaux et al (2002) compared the effectiveness of 2 home exercise programs in decreasing disability and pain related to sub-acute and chronic nonspecific low back pain. To do so, they compared a specific (individualized) exercise program which targeted increased trunk and hip muscle (experimental group) with a program of commonly prescribed exercises for low back pain (control group). All subjects were evaluated by physical evaluation of lumbar muscle forces, extensibility and range of motion. The results suggest that applying a specific physical evaluation and exercise prescription is an appropriated treatment for people with sub-acute or chronic nonspecific pain.

Physical therapy has positive impacts on the muscle strength. Fritz et al (1998) concluded that the physical therapy treatment for segmental instability often focuses on exercises designed to improve stability of the spine. Several muscle groups have been identified in the literature as potentially playing an important role, including stabilizing the spine. The lumbar erector spinae muscles are the primary source of extension torque for lifting tasks; therefore, strengthening this muscle group has been advocated. Keller et al (2003) compared muscle strength, cross-sectional area and density of the back muscles in two categories of patients with chronic low back pain, including lumbar fusion and cognitive intervention with exercises. The results show that patients with chronic low back pain who followed cognitive intervention with exercise programs showed significant improvement in muscle strength compared with patients who underwent lumbar fusion.

2.3.2 Cardiovascular Exercise

Cardiovascular exercise includes walking, jogging, running and aerobic activities. Many studies have been done to test the efficacy of these exercises regarding pain reduction and physical functions.

Cardiovascular exercises have been prescribed to reduce back pain. Sugano et al (2000) compared the psychological effects of water exercise and land stretching by measuring anxiety in chronic LBP patients. The water exercise program contained not only stretching, but also walking, jogging, muscle strengthening, swimming and relaxation and the land program consisted mainly of stretching. After both exercise programs, the subjective pain scores of the patients showed a significant decrease and both exercise groups had decreased state of anxiety. van der Velde and Mierau (2000) found that a 6-week program of aerobic and flexibility exercises reduced 31 % of back pain in 258 chronic low back pain patients. In addition, cardiorespiratory fitness was not predictive of future industrial back injury, but was related to relief of chronic disabling pain (Suni et al., 1998).

Cardiovascular exercise is used for functional improvement of the spine. The aim of a study by Ganzit et al (1998) was to verify the usefulness of isokintic testing in athletes with chronic low back pain to obtain quantitative information for rehabilitation purposes. One group was treated for 3 months with postural exercises, including running, cycling, triathlon, tennis, soccer, basketball, volleyball, skiing and golf, 2 or 3 times a week. The other group was treated for the same period of time with resistive exercises performed by resorting to specific machines. This study concluded that the two rehabilitation programs had the same positive effect on the course of LBP before and after treatment.

There are other positive effects of cardiovascular exercise. Sculco et al (2001) investigated the effects of short and long-term aerobic exercise, including walking or cycling, on LBP patients. They concluded that low to moderate aerobic exercise appears to improve mood states and work status as well as reducing the need for physical therapy referrals and pain medication prescriptions for LBP patients in the care of a neurosurgeon.

Prophylactic exercise has been recommended for control of occupationally-related risk of LBP in healthy workers (Gundewall, et al., 1993; van Poppel, et al., 1997). Compressive and shear loads during occupational manual material handling tasks have been shown to correlate with risk of low back disorder (LBD) (Kelsey, et al., 1984; Kumar 1998). Although psychosocial variables contribute to LBD risk (Videman and Battie 1999), recent literature suggests the most predictive variables include spinal load. Physical conditioning and therapeutic exercises are designed, in part, to modify control of muscle recruitment (Houglum and Perrin 2005) which is the most important factor influencing spinal load. Therefore, changes in muscle recruitment associated with prophylactic exercise may influence spinal load, further LBP. For instance, Harreby et al (1997) investigated the relation between physical exercise and LBP among asymptomatic subjects. Results showed that physical activity for at least 3 h/week reduces the risk of LBP and prevalence. Also, van Poppel et al (1997) concluded that exercise has some effect in the prevention of back pain in industry.

In summary, exercise can be viewed as safe activities to decrease the risk of back pain or degeneration. In fact, exercise can be perceived for three positive aspects of low back disorder. First, exercise can improve impairments in function, including range of motion, strength and endurance. Second, exercise can reduce back pain intensity. Finally, exercise may be useful for reducing back pain related disability as to lessen fear about back pain.

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CHAPTER 3

CHANGES IN SPINAL KINEMATICS WITH PROPHYLACTIC EXERCISE

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3.1 Introduction

Lumbar spine flexion is formed by coordinated multi-segment motion. During a sagittal lifting task the flexion in the lumbar spine is unevenly distributed from L5-S1 through L1-T12 motion segments (White and Panjabi, 1998). Empirical characterization of this movement distribution by in vivo measurement of individual motion segments is limited when using non-invasive techniques. However, the instantaneous axis of rotation (IAR) is a convenient method to investigate the distribution of intervertebral motion (Nachemson, 1990). The IAR is a virtual rotation axis representing the combination of rotation and translation of the thorax with respect to the pelvis (Panjabi, et al., 2000). For example, if all torso flexion were to occur at the L1-T12 motion segment then the IAR would exist at a location near the L1-T12 intervertebral joint. Conversely, if all torso flexion were to occur at L5-S1 then the IAR would exist near the L5-S1 joint. Because the movement is continuously distributed throughout the lumbar spine the IAR resides somewhere between S1 and T12. Changes in the movement distribution within the lumbar spine must therefore be accompanied by changes in the IAR. Our goal was to test whether the distribution of flexion rotation within the lumbar spine is changed by trunk extension exertion effort and prophylactic exercise. The IAR was used as a measure of this distribution.

Sagittal trunk movements consist of flexibility of the lumbar spine and rotation of the pelvis. The Lumbar-Pelvic (LP) coordination is an important parameter to understand the lumbar spine kinematics and LBP during trunk flexion and extension (Mitnitski, et al., 1998; Lariviere, et al., 2000). For instance, lumbar contribution to LP coordination during trunk movements influences dynamic spinal posture that influences spinal load to the discs and associated risks of low back pain. Also, torso muscle length influences lumbar curvature, lordosis, which is a principle component of LP coordination (Granata and Sanford, 2000). There has been studied to provide that the LP coordination may be an effective tool for distinguishing between LBP and healthy individuals (Esola, et al., 1996; McClure, et al., 1997). Therefore, it is necessary to investigate the changes of LP coordination after exercises.

Stability exercises have been prescribed for the rehabilitation and prophylactic control of low back pain (Rolander, 1966; Nachemson, 1990; Hides, et al., 2001; Rainville, et al., 2004). These exercises are designed, in part, to modify control of spinal kinematics because abnormal spinal motion is recognized as a risk factor for low back disorders (Zhang, et al., 2003; Houglum and Perrin, 2005). Most studies agree that torso range of motion (ROM) improves with therapy (Mannion, et al., 1999; Mayer, et al., 2004) although this conclusion is not unanimous (Ng, et al., 2002). Others have recorded significant effects of treatment regarding the coordination between torso and pelvic flexion (Mayer, et al., 1984; Esola, et al., 1996; McClure, et al., 1997). However, less is known regarding coordinated distribution of movement within the lumbar spine. The IAR has been used to assess motion abnormalities caused by pathologies such as disc degeneration and clinical instability (Dvorak, et al., 1991; Fritz, et al., 1998), hypermobility and joint impairment (Water and Panjabi, 1988; Yoshioka, et al., 1990) by means of between-subject experimental designs. It is unclear whether therapeutic stabilizing exercises modify within-subject distribution of flexion within the lumbar spine.

The specific aim of this study was to quantify changes in the lumbar spine kinematics associated with a 12 week program of core-stability and cardiovascular exercises. Movement patterns were evaluated before and after the exercise intervention by recording kinematics of lifting at two exertion levels. It was hypothesized that a program of cardiovascular and therapeutic exercise would influence lumbar-pelvic movement coordination and the IAR in both heavy exertion and light lifting efforts.

Kinematics of the lumbar spine is controlled primarily by muscle recruitment in concert with resistance from passive spinal tissues. Therefore, one might expect the distribution of multi-segment movement to be influenced by changes in muscle recruitment associated with trunk extension effort. Studies have observed significant changes in lumbar-pelvic coordination with lifting exertion (Mitnitski, et al., 1998; Granata and Sanford, 2000) and lifting phase, i.e. trunk extension phase versus trunk flexion phase (Nelson, et al., 1995). Recent evidence suggests that the distribution of lumbar kinematics may change with trunk extension effort and recruitment patterns (Lee, et al., in press, b). Specifically, the dynamic inertia of the torso appears to change with exertion effort thereby indicating modified IAR. However, this conclusion remains to be confirmed with empirical measurements of movement kinematics.

A secondary specific aim of this study was to quantify changes in lumbar spine kinematics associated with effort. It was hypothesized that weight of a lifted load would modify lumbar kinematics.

3.2 Method

Study Participants

Eighty-six healthy subjects with no self-reported history of low back pain participated. Subjects were delimited to healthy adults in order to establish experimental protocols and to establish a normative database before we begin future studies to investigate patients with low-back pain. Subjects were randomly assigned to 3 groups including: 1) a non-exercise control group (29 subjects), 2) a physical therapy (PT) core-stabilizing exercise group (29 subjects) and 3) a cardiovascular exercise group (28 subjects). There were no statistical differences between subject characteristics of the three groups (Table 3.1). Subjects were excluded if they had any cardiovascular condition or physical limitation that might prohibit participation in a randomized exercise group, were currently engaged in vigorous exercise more than one hour per week for past 6 weeks, or if they were unable to perform the tests or exercises. Participants provided informed consent approved by institutional review board at Virginia Tech prior to experimental assessment.

Table 3.1 Demographic data of three groups.
Values shown are mean (± standard deviation)

	Control	PT Exercise	Cardio Exercise
Gender (M/F)	15 / 14	15 / 14	14 / 14
Height (cm)	172.8 (± 11.4)	173.9 (± 10.0)	172.8 (± 12.5)
Weight (kg)	70.6 (± 15.8)	72.6 (± 14.8)	72.4 (± 15.2)
Age (year)	22.3 (± 3.1)	21.9 (± 2.6)	22.5 (± 2.6)

Exercise Intervention

The stability exercise group performed 8 core stability exercises every day for 12 weeks (Appendix D). Exercises included: cat/camel, bracing, one-legged standing balance, bird-dog, sit-to-stand, heel slide, marching, and hip bridge as described in Houglum & Perrin (Houglum and Perrin, 2005). Each exercise was performed 2 minutes per day for a total of 16 minutes of torso stabilizing exercise every day. Individual training sessions were scheduled for each subject prior to the initial experimental session to instruct them how to perform the exercises. They also received a printed copy of the exercise instructions in a log book wherein subjects recorded their daily exercise activities. According to these logs the average subject compliance for the stability exercise group was 91% based on the number of days exercised versus the prescribed 84 workout days (12 weeks).

Participants in the cardiovascular exercise group exercised by outdoor running, indoor treadmill or elliptical machines. Exercise duration and target heart rate (HR) were prescribed for each week as per the American College of Sports Medicine (ACSM) recommendation (Franklin, et al., 2000). A graded workout protocol based on each subject's max heart rate (HR_{max}=220-age) started with a 25 minutes workout sustaining 65% HR_{max} and increased over the weeks to 30 minutes at 85% (Table 3.2). Every subject was provided with a HR monitor for use during their exercise (A-1 Heart Rate Monitor, Polar, Lake Success, NY). The duration of exercise and average HR during each session were recorded by the subjects in their log book. Average self-reported subject compliance for the cardiovascular exercise group was 97.2% based on the number of days exercised versus the prescribed workout days.

Table 3.2. Target heart rate zone and duration

Week	1	2	3	4	5	6	7	8	9	10	11	12
HR zone	50	50	50-60	50-60	65	65	70	70	75	75	80~85	80~85
Duration	20	20	25-30	25-30	25~30	25~30	25~30	25~30	25~30	25~30	25~30	25~30

HR zone (% of max HR), Duration (min)

The control group was not allowed any vigorous workout including running, weight lifting or strength training for a period of 12 weeks. Recreational or leisure sports were also limited to no more than 1 hour per week for the period of this study.

Protocol

Subjects visited the laboratory on four separate occasions. A baseline biomechanical assessment was performed prior to initiation of the exercise intervention in order to record pelvis and trunk movements during paced lifting exertions. Electromagnetic motion sensors (Ascension

Technology, Burlington, VT, USA) were attached by double sided tape to the skin surface over the spinous processes of first sacral (S1) and 10th thoracic (T10) vertebrae as described in previous studies (Granata and Sanford, 2000). The lifting exertion required subjects to lift a box with 10% and 25% of body mass. The lift origin was a platform 50 cm anterior to the subjects with a surface elevation of 30 cm above the ground. Subjects lifted the box to an upright posture with 90^0 of elbows flexion then returned it to the origin (Figure 3.1). Lifting and lowering tasks were performed with straight legs thereby restricting the motion to the hips and torso. Lifting rate was established by an audible tone from a metronome providing 2 seconds for the lifting movement and 2 seconds for the lowing movement. Subjects were allowed to practice the lifting task until they were comfortable with the motion and timing. Three sets of each lifting and lowering motion were recorded in each load condition during every experimental visit. Similar measurements were recorded after 4, 8 and 12 weeks of exercise.

To test whether there was a change in physical conditioning associated with the exercise interventions the subjects performed a maximum isometric strength test and a cardiovascular assessment test on the first and last experimental visits. During the maximum strength test trunk extension force was measured by asking the subjects to pull against a handle with knees and elbows straight. The handle was connected to the floor by a cable with cable length adjusted such that the handle was at knee elevation during the exertion. Tension in the cable was recorded during two exertions each 5 seconds in duration. Two minutes of rest were provided between exertions. Strength was computed from the mean value of the middle 3 seconds of each trial averaged across the two trials. Cardiovascular assessment was performed by recording the subjects resting HR as well as their HR during treadmill running. The treadmill was started at a speed of 1.6 km/h and at a zero grade incline. At the end of each minute speed was increased by 1.6 km/h or incline was increased by 1%. HR was recorded prior to changing the treadmill speed. When HR exceeded 85% of estimated maximum the test was terminated. Maximum HR was estimated from a rudimentary calculation of $HR_{Max} = 220 - Age$ [years]. VO_2 Max was estimated from the relation between treadmill speed and grade, VO2 = (0.2*Vel) + (0.9*Vel*Grade [%]) + 3.5 (Franklin, et at., 2000). Also, mechanical load was estimated from a nonlinear relation, Energy = 3.5 + 1.6*Vel + 3*Vel*Grade [%], and compared with HR. The slope of this relation at 85% HR was used to test for change in cardiovascular conditioning.

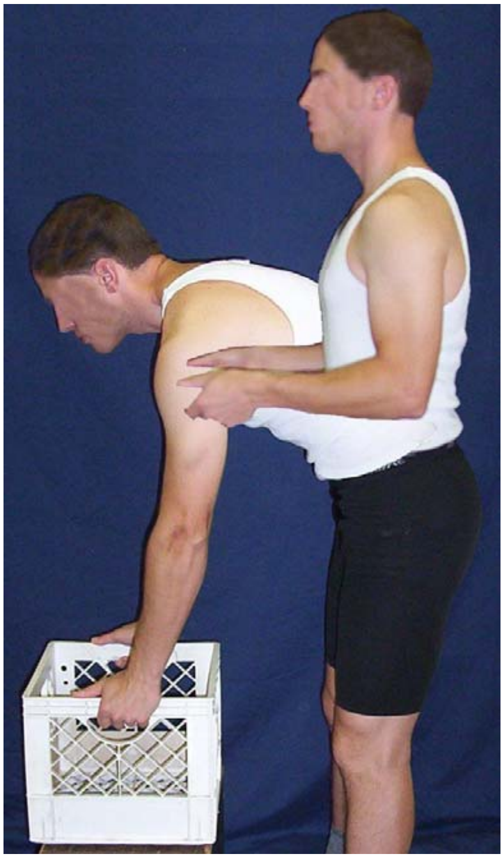


Figure 3.1. Experimental setup. Kinematic and spinal load assessment. Subjects lifted a box containing 10% or 25% body weight from a platform at knee level to an upright posture.

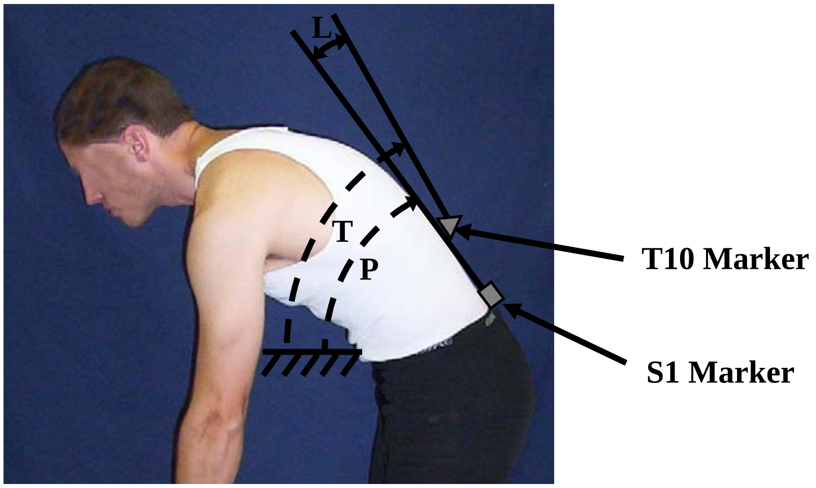


Figure 3.2. Locations of sensors and definitions of raw angles

Analyses

The electromagnetic movement system recorded 3-D angles and 3-D position of each sensor with respect to the transmitter reference. Only sagittal plane data were analyzed in this study of symmetric lifting tasks. Coordinates included displacement in the anterior direction, x-axis, and caudal direction, y-axis, and as well as sagittal plane flexion angle, θ. Lumbar kinematics $[x_L, y_L, \theta_L]^t$ were defined as difference between T10 sensor $[x_T, y_T, \theta_T]^t$ and S1 sensor $[x_S, y_S, \theta_S]^t$ angle (Figure 3.2) and position by means of Euler vector rotation as per the methods of Granata and Sanford (Granata and Sanford, 2000).

$$\begin{bmatrix} x_L \\ y_L \\ \theta_L \end{bmatrix} = \begin{bmatrix} \cos\theta_S & \sin\theta_S & 0 \\ -\sin\theta_S & \cos\theta_S & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_T - x_S \\ y_T - y_S \\ \theta_T - \theta_S \end{bmatrix} \qquad \text{(eqn 1)}$$

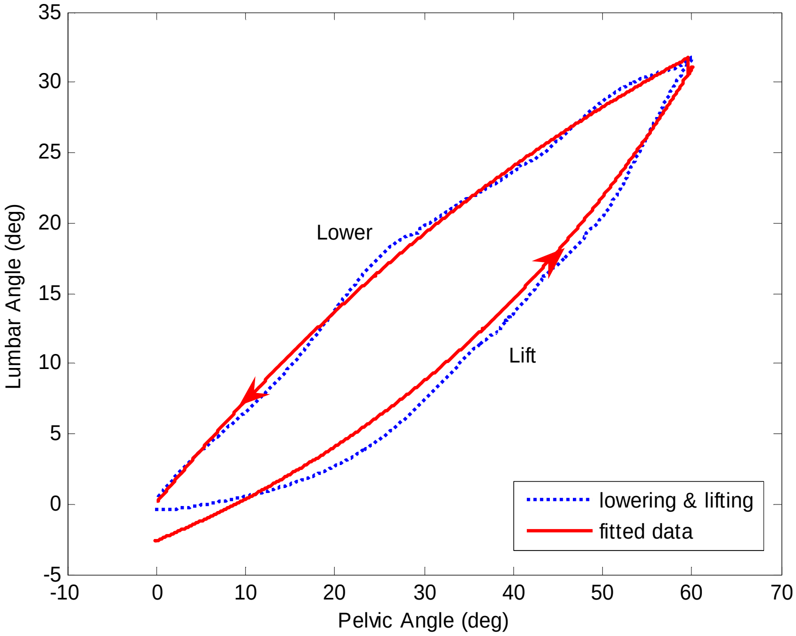


Figure 3.3. Curve-fitting normalized at flexed posture for lifting and lowering (arrow: direction of each task, 0° = horizontal)

To compute the lumbar-pelvic coordination exponential coefficients describing the nonlinear relation between these segments was computed. Lumbar angle θ_L was plotted against the sacral or pelvic flexion angle, θ_S, for each trial (figure 3.3). Mitniski, et al. (1998) concludes that this relationship can be described by an exponential function,

$$\theta_L = \theta_0 + D_L e^{C\theta_s} \qquad \text{(eqn 2)}$$

Where θ_0 is a calibration offset value, i.e. lordosis in an upright posture. Parameter D_L represents the distribution of movement among the lumbar and pelvic segments, i.e. large D_L suggests greater lumbar range-of-motion than pelvic flexion. Parameter C describes the lumbar-pelvic coordination. Large value of coordination C suggests lumbar flexion is initiated after the pelvic movement is nearly completed. Small values of C indicate more simultaneous lumbar and pelvic flexion movements. Parameters were estimated by Levenberg-Marquardt algorithm based upon similar data from previous measurements of trunk kinematics (Granata and Sanford, et al., 2000).

Instantaneous axis of rotation of the lumbar spine was estimated from the measured kinematics $[x_L, y_L, \theta_L]^t$. This IAR represents the anterior and caudal location $[x_{IAR}, y_{IAR}]^t$ of the movement centroid of pure rotation with respect to the sacral movement sensor. Methods for estimating the IAR are described elsewhere. Briefly, a vector normal to the movement trajectory is described by the tangent of θ_L.

$$\frac{x_{IAR}(t) - x_L(t)}{y_{IAR}(t) - y_L(t)} = \tan\theta_L(t) \qquad \text{(eqn 3)}$$

The IAR was determined by comparing the vectors $[x_L, y_L, \theta_L]^t$ recorded t_1 = 30 ms before and another recorded t_2 = 30 ms after the time, t, at which trunk angle reached 25^0 of flexion (Figure 3.4). A trajectory span of 60 ms was selected based on the evidence that the natural frequency of trunk dynamics is approximately 1 Hz (Moorhouse and Granata, 2005). Thus, assuming the IAR does not move notably during this 60 msec time-span of slow trunk motion, then the values $[x_{IAR}(t), y_{IAR}(t)]^t$ are easily determined from the intersection of these vectors

$$\begin{bmatrix} x_{IAR}(t) \\ y_{IAR}(t) \end{bmatrix} = \begin{bmatrix} 1 & -\tan\theta_L(t_1) \\ 1 & -\tan\theta_L(t_2) \end{bmatrix}^{-1} \begin{bmatrix} x_L(t_1) - y_L(t_1) \\ x_L(t_2) - y_L(t_2) \end{bmatrix} \qquad \text{(eqn 4)}$$

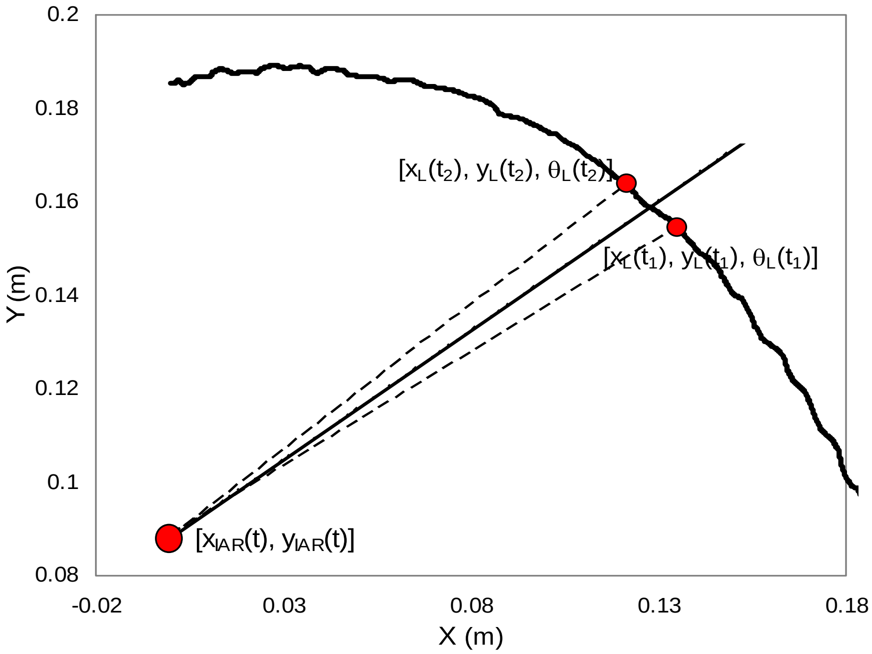


Figure 3.4. Estimation of IAR using the trajectory of lumbar position and angle lumbar $[x_L, y_L, \theta_L]^t$ at 25^0 trunk flexion. Positions and angles are expressed relative to the sacral marker location. Positive X and Y axes are the anterior and superior directions, respectively.

Statistics

Data from weeks 4, 8 and 12 were interpreted as change with respect to the baseline levels. Therefore, prior to statistical analyses the dependent values of x_{IAR} and y_{IAR} were normalized to the mean value of each group recorded during baseline assessments. Group mean baseline values were operationally defined as unity but values for each individual were permitted to vary about that normalized level. Statistical analyses of variance were performed to investigate the principle variables of interest including Group (PT, Control, Cardio), Time (baseline=0, 4, 8, 12 weeks exercise), and Load (10%, 25% body-mass). Additional independent variables of lifting Phase (lifting phase, lowering phase) and Gender (male, female) were included. Dependent variables associated with the lumbar-pelvic kinematics (distribution D_L, temporal coordination C) were evaluated in separate analyses from the IAR data (x_{IAR}, y_{IAR}). Significant main effects from MANOVA were applied in univariate models, ANOVA. Tukey honest-significant difference (HSD) post-hoc analysis was applied to investigate significant effects.

Statistical analysis of the data was performed using commercial statistical software (Statistica, 5.1, Statsoft, Tulsa OK, USA) with a significance level of $p<0.05$.

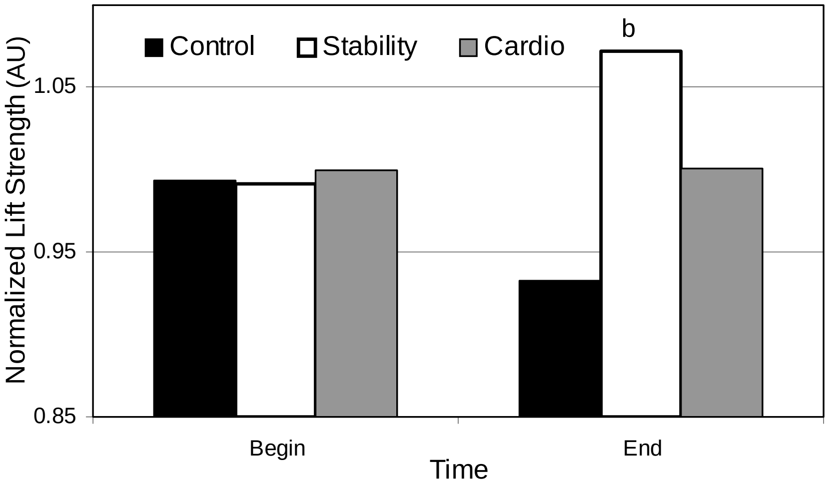
3.3 Results

Physical Conditioning

Maximum lift exertions were recorded to test for changes in the subjects' physical trunk lifting strength. Changes in lift strength within each group failed to achieve statistical significance. However, a significant Group-by-Time interaction (p <0.028) revealed that the stability exercise group demonstrated significantly improvement strength (Figure 3.5) with respect to controls (p=0.004). There were no difference between cardiovascular exercise subjects and either the control or stability exercise group.

Table 3.3. Statistical results (ANOVA) for physical capacity before and after the exercise intervention

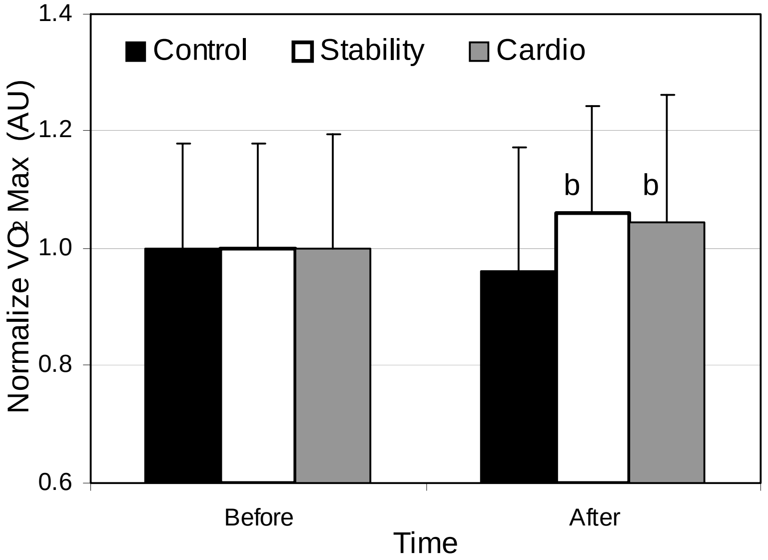
	Lift Strength	VO_2 Max	HR Slope
Group	p =0.651	p =0.101	p =0.568
Time	p =0.749	**p <0.018**	p =0.130
Group x Time	**p <0.028**	**p <0.017**	**p <0.017**



b : significant difference from control group

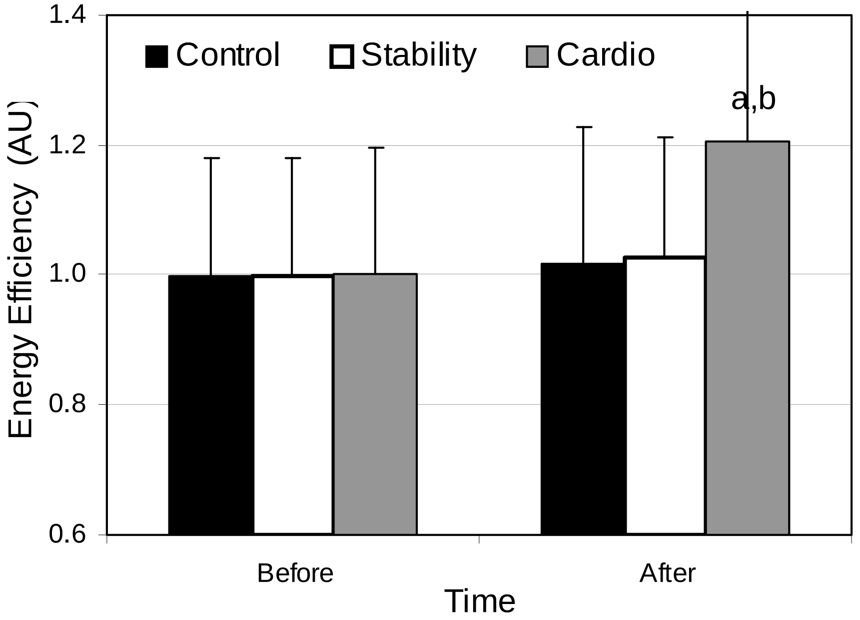
Figure 3.5. Change in lift strength. 49 Subjects in the stability exercise group demonstrated a significant improvement in lift strength relative to control subjects. Values are shown normalized to mean baseline levels

Changes in cardiovascular conditioning were measured from VO_2Max and the HR per unit change in caloric energy with increasing treadmill speed and slope. Change in VO_2Max failed to achieve statistical significance in any of the three groups. However, a Group-by-Time interaction (Figure 3.6) revealed that the changes were sufficient to demonstrate significant improvement in both the stability exercise ($p<0.034$) and cardiovascular exercise ($p<0.024$) groups at the final assessment visit when compared to the control subjects. The energy efficiency was recorded in terms of caloric energy associated with treadmill running per relative to the HR. A Group-by-Time interaction (Figure 3.7) revealed that the cardiovascular exercise group improved significantly ($p<0.003$) between the baseline and final assessment. The cardiovascular group was significantly more efficient after the exercise intervention than the control ($p<0.006$) and stability exercise subjects ($p<0.007$).



b : significant difference from control group

Figure 3.6. VO_2 Max before and after intervention. Exercise groups increased relative to control subjects. Values are shown normalized to mean baseline levels



a : significant within-group difference from baseline

b : significant difference from control group

Figure 3.7. Energy efficiency before and after intervention. Increased within the cardiovascular exercise group. Values are normalized to mean baseline levels

Lumbar – Pelvic Coordination

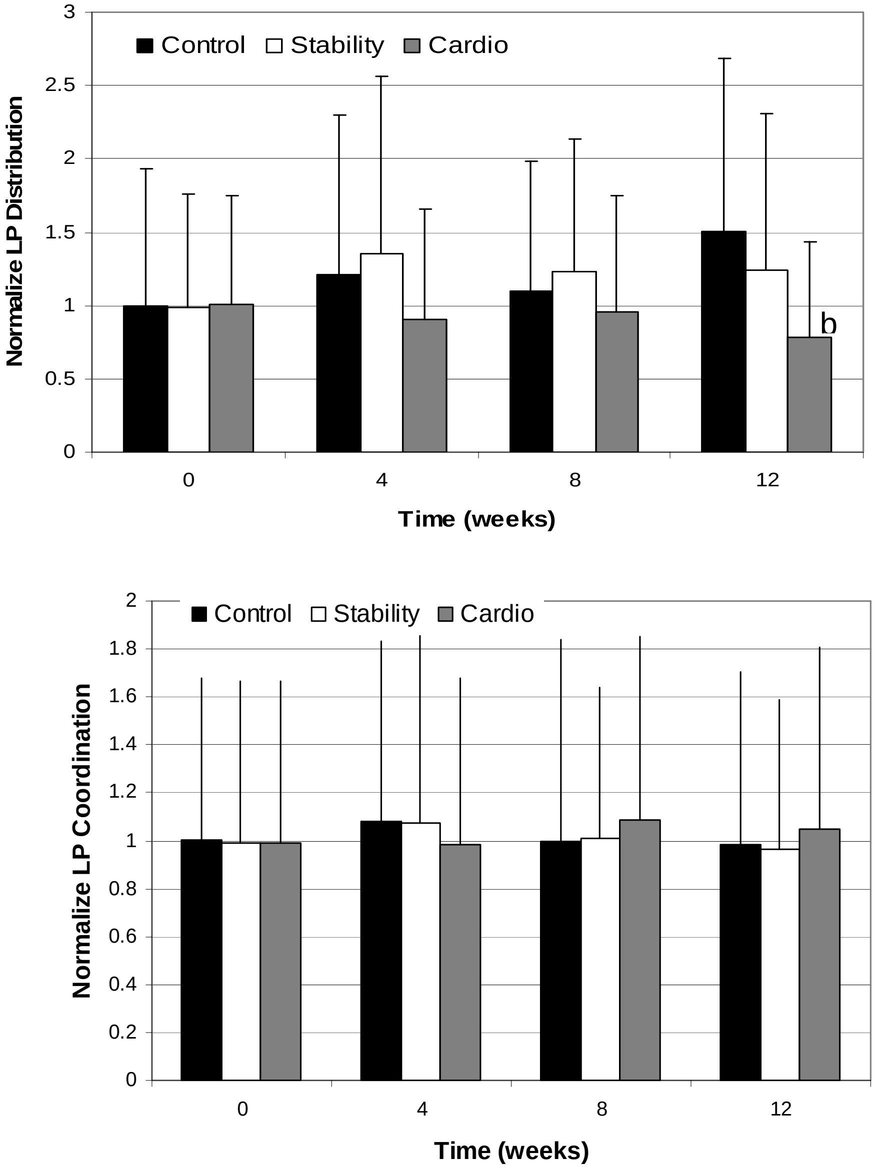
Mean value of the lumbar-pelvic kinematic distribution parameter, D_L, was 50.6 (66.6) degrees while the mean value of the coordination parameter, C, was 0.023 ±0.018 degrees^{-1}. This suggests a nearly even ratio of lumbar and pelvic movement, i.e. one degree change in θ_S was associated with 0.9 degree change in lordosis θ_L on average. Moreover, the coordination, C, represents nearly linear coordination, i.e. simultaneous lumbar and pelvic movements. MANOVA revealed no significant main effects but interactions included effects of Group, Gender, Phase, Load and Time (Table 3.4). Therefore, univariate analyses were performed with all of these independent variables.

Table 3.4. Statistical results of lifting kinematics. D_L represents the relative range of motion in lumbar spine versus the pelvis. C describes relative extent to which the lumbar and pelvic movements are sequential or simultaneous.

	MANOVA	D_L	C
Group	p =0.179	**p <0.036**	p =0.978
Gender	p =0.238	p =0.945	**P <0.010**
Phase	p =0.775	p =0.266	P =0.246
Load	p =0.601	p =0.241	**P <0.038**
Time	p =0.184	p =0.088	P =0.843
Group x Gender	p =0.514	p =0.661	P =0.605
Group x Phase	p =0.680	p =0.333	P =0.471
Group x Load	**p <0.046**	**p <0.015**	P =0.546
Group x Time	p =0.062	**p <0.001**	P =0.901
Gender x Phase	p =0.252	p =0.893	**P <0.028**
Gender x Load	**p <0.001**	**p <0.029**	**P <0.011**
Gender x Time	p =0.122	p =0.109	P =0.608
Phase x Load	**p <0.001**	p =0.062	**P <0.001**
Phase x Time	p =0.770	p =0.078	P =0.406
Load x Time	p =0.255	**p <0.028**	P =0.646

Only significant contributions shown

Univariate analysis (ANOVA) of the kinematic distribution parameter, D_L, demonstrated interactions of Group-by-Time and Group-by-Load (Table 3.4). The lumbar contribution to the total trunk angle was smaller in the cardiovascular exercise group than in control subjects after 12 weeks of exercise. The cardiovascular group also demonstrated smaller lumbar contribution to the total trunk angle, i.e. smaller D, than the stability exercise group, but only when lifting the 25 % BW load. There was a significant difference between the control and cardiovascular exercise groups at 12 week assessments ($p<0.001$), but no significance between the control and stability exercise group. Analyses of the coordination parameter, C, showed no effects associated with time thereby indicating the exercise protocol did not influence lumbar-pelvic coordination. Recall that sequential movement of the pelvis followed by lumbar flexion is represented by larger values of C while simultaneous lumbar and pelvic movement are represented by smaller values of C. Coordination of the male subjects was more simultaneous than in females, but this effect was observed only during when using the heavy load, 25% BW ($p<0.001$). The heavy load was associated with smaller values of C, i.e. simultaneous lumbar and pelvic movement, but this effect was significant only in the lowering phase of the movement.



b : significant difference from control group

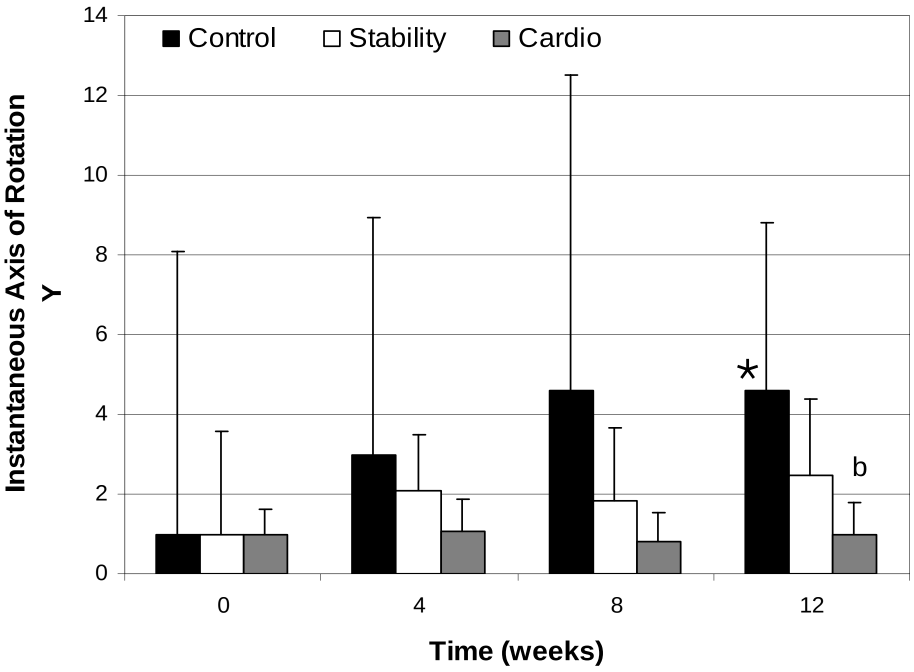
Figure 3.8 Lumbar-pelvic ratio. A) distribution parameter D_L. B) coordination parameter C. No significant effects of exercise training were observed in C. Values are shown normalized to mean baseline levels.

Lumbar Instantaneous Axis of Rotation

Table 3.5. Statistical results of the instantaneous axis of rotation of the lumbar spine. Parameter X_{IAR} and Y_{IAR} represent the anterior-posterior and superior inferior location of the centriod of rotation in the lumbar spine at a trunk angle of 25 degrees flexion.

	MANOVA	X_{IAR}	Y_{IAR}
Group	**p <0.001**	p =0.086	**p <0.001**
Load	**p <0.001**	p =0.179	**P <0.001**
Time	**p <0.001**	p =0.082	**P <0.001**
Group x Load	**p <0.001**	**p <0.001**	**P <0.001**
Group x Time	**p <0.003**	**p <0.029**	**P <0.003**
Load x Time	p =0.378	p =0.911	P =0.177
Group x Load x Time	**p <0.018**	p =0.247	**P <0.002**

Mean value of IAR was 6.4 (7.2) cm above and 2.9 (4.0) cm anterior to the S1 sensor. MANOVA indicated significant main effects for Group, Load and Time (Table 3.5). Although nearly equal numbers of males and females participated in the study gender did not statistically influence the dependent variables (p=0.786). Similarly, movement phase did not significantly affect the dependent variables (p=0.602). Therefore data were pooled across gender and task in univariate analyses. The data were normalized to the mean value of each group recorded during baseline assessments to determine Time-dependent changes. ANOVA was performed to test the effect of exercise Group, Load and Time. A significant Load effect in the MANOVA suggests that the IAR was lower and more posterior when lifting the heavier weigh. However, these trends did not achieve statistical significance in the univariate analyses. Analyses of y_{IAR} revealed a significant main effect for Time that influenced the location of the lumbar IAR. Similar to our hypothesis, the main effect for Load and Group-by-Time interactions succeeded to achieve statistical significance. Although the anterior location of the IAR, x_{IAR}, demonstrated similar trends as y_{IAR} there were no statistically significant effects.



b : significant difference from control group

Figure 3.9. Instantaneous axis of rotation – Group by Time interaction. The control group demonstrated a significant (*) increase in y_{IAR} with time. There was significant difference in IAR between the cardio and control groups at 8 and 12 weeks assessment

Significant 2-way and significant 3-way interaction for the y_{IAR} indicated that the change associated with Time observable in the control group was only significant for the 25% BW condition of lifted Load ($p<0.001$). In the control group the y_{IAR} moved toward a more superior location with significant differences between baseline and week 8 ($p<0.001$) as well as between baseline and week 12 ($p<0.001$). This is attributed to the Hawthorne effect, i.e. change was attributed to increased familiarity with the experimental task. There were no significant Time-dependent changes in y_{IAR} in both stability and cardiovascular exercise groups. Therefore, at the 8 week and 12 week assessment there were significant ($p<0.001$) differences between the control and cardiovascular exercise groups. There were few interesting effects associated with the x_{IAR}. A significant Group-by-Load interaction indicated more anterior IAR in the 25% load condition of the control group but this was not observed in both exercise groups.

3.4 Discussion

Motor coordination between the pelvis and multi-segmental lumbar spine is a necessary condition for the maintenance of acceptable inter-vertebral tissue strain, spinal compression and stability. Marras observed significant kinematic differences between patients with low-back pain and age-matched asymptomatic control subjects (Marras, et al., 2001; Marras, et al., 2004). These differences were attributed to modified recruitment strategies. Whether these muscle strategies were a direct result of the injury, a contribution to the etiology of the injury or a response to avoid kinematically painful postures remains unknown. Nonetheless, it is evident that abnormal kinematics are a marker of musculoskeletal pathology (Marras, et al., 1993; Marras, et al., 1995). Although range-of-motion is a common diagnostic tool, inter-segmental kinematic coordination is also an indicator of low-back pain (Gracovetsky, et al., 1995; Newman, et al., 1996). Abnormal lumbar-pelvic coordination have been observed in individuals with low-back pain (Mayer, et al., 1984; Esola, et al., 1996; McClure, et al., 1997). However, there are few previous studies to investigate whether training can affect within-subject changes in lumbar-pelvic coordination (Mayer, et al., 1984; Li, et al., 1996) and the distribution of movement within the lumbar spine represented by IAR. The current study was motivated by the assumption that quantifiable changes in neuromuscular control and kinematics must be observable in order for an intervention to be successful. Previous evidence suggests that stability training from stability exercises may contribute to small but statistically significant changes in muscle recruitment and torso stability. Therefore, it is necessary to determine whether these motor control changes influence kinematic coordination.

The instantaneous axis of rotation provides insight into the distribution of flexion within the multi-segment lumbar spine. Results show strong evidence that the location of the IAR of the lumbar spine may be influenced by the cardiovascular exercise. However, the effect is indirect, i.e. no change in the exercise group performance unlike a notable Time-dependent changes in the control subjects. The control group unexpectedly demonstrated a significant effect of Time. During the first visit to the laboratory these subjects were instructed as to the nature of the task, but were given no specific instructions regarding lifting technique. Nonetheless, in the novel environment of a research laboratory their lifting performance may have been more carefully controlled than typical. On subsequent visits during weeks 4, 8, and 12 the IAR moved superior, indicating a movement coordination that was associated with progressively greater flexion in L2 through T10 relative to the S1-L3 contribution. Several factors may explain this significant change in the control group. Since their exercise activities were limited we believe these subjects asymptotically approached their normal movement patterns as they became familiar with the experimental task. Note that there was no statistically significant progression in IAR between weeks 8 and 12, indicating a convergence toward steady-state movement coordination. Another possibility is de-conditioning in this group. Exclusion criteria were designed to avoid elite athletes so as to observe improved physical conditioning in the exercise groups. If however the control were mildly active then restrictions regarding physical activity may have resulted in loss of physical conditioning. Regardless of the cause, results highlight the necessity of considering whether specific movement patterns are typical for individuals when examining their performance in an initial diagnostic or research screening.

Unlike the control group, the two exercise groups did not demonstrate a significant change in IAR with Time. There was no statistically significant change associated with the exercise protocols when compared to baseline measurements. Interpretation of the results must therefore be achieved with respect to the control group values. If we can assume that the control group relaxed their movement pattern with repeated laboratory visits, the same was not observed in the exercise groups. As noted above, we believe the results indicate that the subjects may have been self-conscience and /or careful regarding their lifting technique during the baseline assessment. The unique consequence of the exercise protocols was that these subjects appeared to retain this movement pattern. Many issues may have contributed to the sustained kinematic coordination in the exercise groups. One possibility is that the exercises, specifically the therapeutic stabilizing exercises, served as a continuous reminder regarding coordination of lifting movements. Another is the possibility of motor training and modified recruitment dynamics (Thomas, et al., 2003). The stabilizing exercises targeted trunk and hip muscles that contribute to the movement and stability of lumbar-pelvic region. Descarreaux, et al (2004) reported that such exercise seems to have a positive influence on LBP.

It is interesting to note that these group differences in kinematic movements, IAR and lumbar-pelvic distribution, were observed only during the heavy lifting condition. The weight of the lifted load influenced the IAR of the lumbar spine. When lifting a load of 10% body mass, the lumbar flexion appeared to be attributed to greater movement contribution from S1-L3. Increased load tended to shift the kinematic coordination to patterns including greater contribution from L2 through T10. This is reasonable when one considered the muscle activation requirements to achieve biomechanical equilibrium. Models of the lumbar spine indicate greater muscle forces are required at lower lumbar levels than caudal motion segments when generating trunk extension force (Stokes and Gardner-Morse, 1995). Recognizing that the muscle stiffness increases with activation (Lee, et al., in press, a; Moorhouse and Granata, 2005), then the upper lumbar spine may be supported by active tissues with greater compliance than the lower levels. This differentially restricts movement of the lower motion segments compared to the caudal vertebrae with increased trunk extension force. However, only two loads were tested and most existing models fail to allow kinematic freedom of the lumbar vertebrae thereby limiting theoretical proof. Recent measurements of torso dynamics reported greater driving-point mass with increased trunk extension effort (Gardner-Morse and Stokes, 2001; Lee, et al., in press, b). Since change torso mass cannot be explained by exertion effort, the only feasible explanation was a change in the IAR (Lee, et al., in press, b). This was supported by the current results.

Future studies should address limitations in the current protocol. Considering the change in IAR observed in the control subjects a multiple baseline measurements are recommended before the initiating the exercise intervention. Specifically, in future studies the exercise group should be evaluated on multiple occasions to assure steady-state performance before beginning the exercise intervention. One is left to wonder whether the control group would have returned to baseline levels if they were placed on a 12 week stabilizing exercise protocol subsequent to the final measurement recorded in the current study. Although significant changes in the IAR were observed, these measurements were limited to a dynamic trunk posture in a small region about 25 degrees of torso flexion. The movements were also timed to a metronome such that the lifting movement was completed in 2 seconds. The role of exercise interventions in the control of faster movements should be investigated in future studies. Although the data (Figure 3.9) indicate that the week 12 values of IAR were up to 361 % greater than baseline levels, these changes were geometrically small. Mean baseline value of y_{IAR} across all groups was 6.0 ±5.7 cm while mean y_{IAR} was 7.1 ±6.7 cm at week 12. Recall that these values represent the distance superior to the sacral movement sensor. This indicates that IAR at baseline assessment was near the L5-L4 motion segment and moved up to within the L4-L3 motion segment at week 12. Hence the movement of the IAR was anatomically small even for the control group. Finally, subject inclusion criteria were delimited to healthy, asymptomatic adults. Previous studies demonstrated abnormal trunk flexion kinematics in patients with low back pain (Mayer, et al., 1984; Gracovetsky et al., 1995; Newman, et al., 1995; Esola, et al., 1996; McClure, et al., 1997; Marras, et al., 2004). If stability exercises can be designed to improve stabilizing coordination of the torso musculature, then these exercises may simply reinforce existing movement patterns in asymptomatic individuals. Therefore, it is recommended that measurements be repeated in patients with low-back to demonstrate whether therapeutic exercises can successfully modify kinematics of spinal movement.

In summary, the cardiovascular exercise program influenced lumbar-pelvic distribution and lumbar instantaneous axis of rotation. However, the stability exercise program did not dramatically influence them. The lumbar-pelvic distribution trends associated with load, gender and phase in the stability exercise agree with our previously published data (Granata and Stanford, 2000). However, expected changes in kinematics were not observed. Potential limitations include the possibility that 12 weeks of intervention was not sufficient to cause biomechanical change in the stability exercise. Also, one possible reason may be found that the stability exercise is more appropriate for low back patients to rehabilitate unlike healthy individuals in the current study. It is unclear whether changes might be observed if subjects included patients with low-back pain. However, in terms of industrial prophylaxis, the stability exercise interventions did not contribute to biomechanical changes regarding kinematics of lifting, but the cardiovascular exercise did.

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CONCLUSIONS

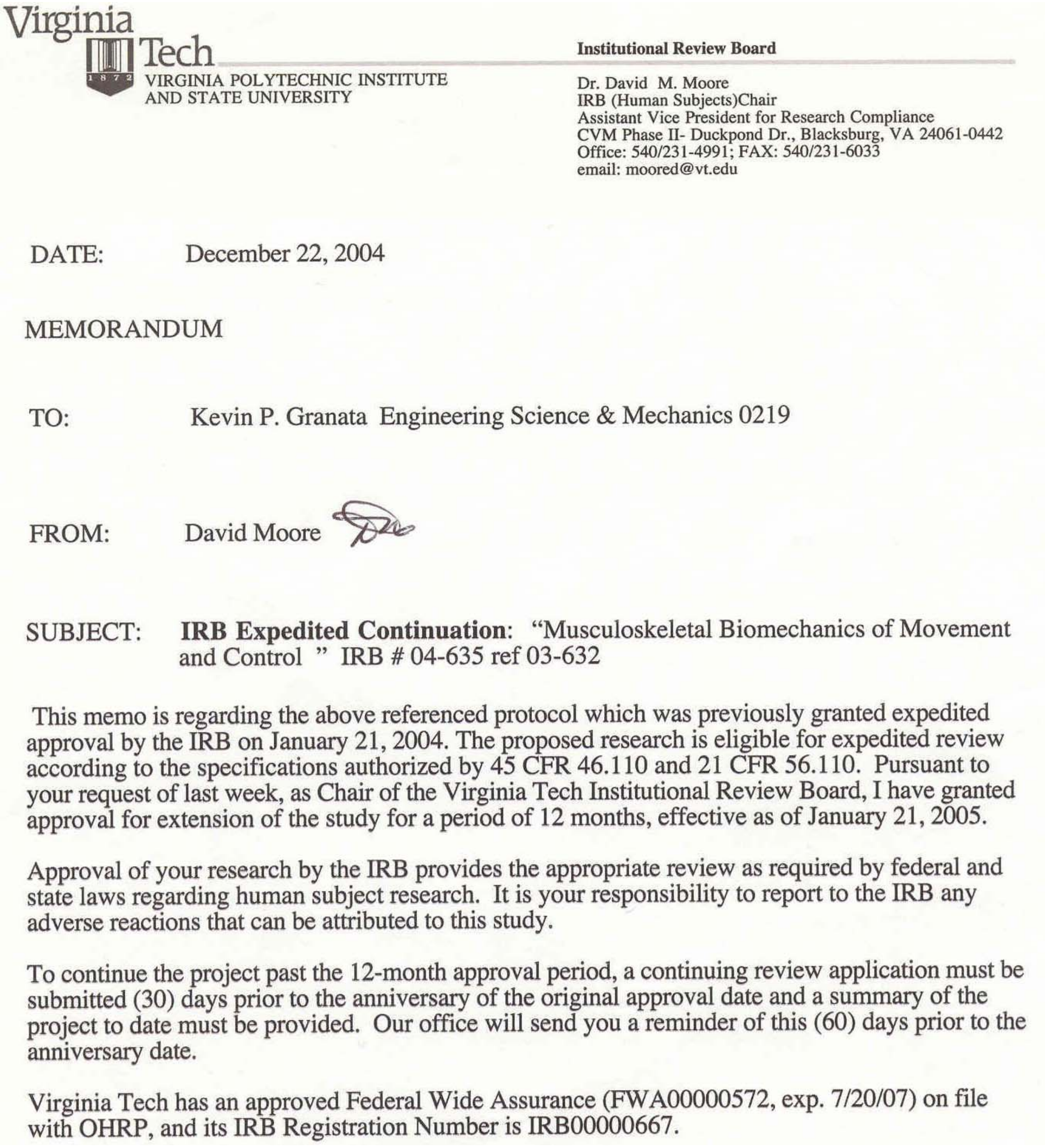
Lumbar spine kinematics during lifting and lowering a weight was examined in this study. Results of this study have demonstrated that cardiovascular exercise significantly affects kinematics of lumbar spine. It was successfully quantified in this study by means of the lumbar-pelvic distribution and coordination which are the coefficients from curve-fitting of pelvic and lumbar angle, and the locations of the IAR at the 25 ° of trunk angle which is relative location from the sacrum during lifting and lowering a weight.

Lumbar-Pelvic (LP) distribution parameter was associated by contribution of lumbar spine. A decreasing trend of LP distribution significantly occurred in the cardiovascular exercise group, but no significance of the physical therapy stability exercise. Therefore, the cardiovascular exercise may contribute to less lumbar movements for the full range of the lift and lower which are the most common tasks in industrial workplaces. However, there was no significant effect on the LP coordination, which shows the type of LP movements.

The instantaneous axis of rotation is a unique characteristic of plane motion. Results of this study demonstrated that the cardiovascular exercise influenced the IAR of lumbar spine. Specifically, the superior-inferior location of the IAR for the cardiovascular exercise group remained at the baseline value, whereas the control group significantly increased for 12 weeks. Further studies should investigate the relationship between the lowered IAR and the instances of lumbar spine injuries or LBP.

Biomechanical understanding of lumbar spine kinematics can be a useful tool for the prevention of low back disorders. It is the hope of the author that the findings of this study contribute to the control of injuries in the future.

Appendix A – IRB approval



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Institutional Review Board

Dr. David M. Moore
IRB (Human Subjects)Chair
Assistant Vice President for Research Compliance
CVM Phase II- Duckpond Dr., Blacksburg, VA 24061-0442
Office: 540/231-4991; FAX: 540/231-6033
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DATE: December 22, 2004

MEMORANDUM

TO: Kevin P. Granata Engineering Science & Mechanics 0219

FROM: David Moore

SUBJECT: **IRB Expedited Continuation**: "Musculoskeletal Biomechanics of Movement and Control " IRB # 04-635 ref 03-632

This memo is regarding the above referenced protocol which was previously granted expedited approval by the IRB on January 21, 2004. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. Pursuant to your request of last week, as Chair of the Virginia Tech Institutional Review Board, I have granted approval for extension of the study for a period of 12 months, effective as of January 21, 2005.

Approval of your research by the IRB provides the appropriate review as required by federal and state laws regarding human subject research. It is your responsibility to report to the IRB any adverse reactions that can be attributed to this study.

To continue the project past the 12-month approval period, a continuing review application must be submitted (30) days prior to the anniversary of the original approval date and a summary of the project to date must be provided. Our office will send you a reminder of this (60) days prior to the anniversary date.

Virginia Tech has an approved Federal Wide Assurance (FWA00000572, exp. 7/20/07) on file with OHRP, and its IRB Registration Number is IRB00000667.

Appendix B – Subject Consent Form

Title of Project: Musculoskeletal Biomechanics of Movement and Control
Investigators: M. Lee, K.P. Granata

Purpose of this Research

To understand musculoskeletal injury and improve clinical diagnoses of injury it is necessary to understand how muscles control force and movement. The purpose of this study is to measure the relation between human movement, force generation and muscle activity. We are also interested in observing how gender, fatigue and physical conditioning influence these parameters. Throughout the course of this project more than 200 subject volunteers will participate including healthy individuals from the age of 18 to 55.

Procedures

We will tape adhesive markers and sensors on your skin around your trunk, legs and arms. These sensors are EMG electrodes that measure the activity of your muscles and position sensors to measure how you move. After some preliminary warm up stretches, we may ask you to push and/or pull as hard as you can against a resistance. We may then ask you to hold or lift a weight or weighted-box and to bend forward and back. We may also ask you to do some fatiguing exertions such as holding or lifting a heavy weight or pushing/pulling against a bar or cable for several minutes. We may also apply a quick but small force to record reflexes. You may be requested to return for repeated testing. Between test sessions you may be asked to participate in specified physical conditioning as per the American College of Sports Medicine recommended guidelines

Risks

The risks of this study are minor. They include a potential skin irritation to the adhesives used in the tape and electrode markers. You may also feel some temporary muscle soreness such as might occur after exercising. Subjects participating in physical conditioning may experience muscle soreness and/or musculoskeletal injury associated with inherent risks of cardiovascular, strength training and therapeutic exercise. To minimize these risks you will be asked to warm-up before the tasks and tell us if you are aware of any history of skin-reaction to tape, history of musculoskeletal injury, cardiovascular limitations.

Benefits

By participating in this study, you will help to increase our understanding musculoskeletal control of movement and musculoskeletal injury mechanisms. We hope to make this research experience interesting and enjoyable for you where you may learn experimental procedures in biomechanical sciences. We do not guarantee or promise that you will receive any of these benefits and no promise of benefits has been made to encourage your participation.

Anonymity and Confidentiality

Experimental data collected from your participation will be coded and matched to this consent form so only members of the research team can determine your identity. Your identity will not be divulged to unauthorized people or agencies. Digital video recorded during the experimental trials will be used to track the movement of the sensors by means of computer analyses and is insufficient video quality to observe individual participant identifying characteristics. Secondary VHS-style video may be recorded to validate the digital motion data. This camera angle is placed to avoid facial or other identifying characteristics. Sometimes it is necessary for an investigator to break confidentiality if a significant health or safety concern is perceived or the participant is believed to be a threat to himself/herself or others.

Compensation

Participants required to return for multiple test sessions or participate in physical conditioning for this protocol will receive payment per the number of test sessions as well as a bonus for full completion of the multi-session research protocol. Subjects participating in experiments as part of course or laboratory procedures will receive appropriate credit for analysis of specified data as described in the course syllabus but not for personal performance during the experimental session. If course credit is involved and the subject chooses not to participate alternative means for earning equivalent credit will be established with the course instructor.

Freedom to Withdraw

You are free to withdraw from a study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of the time of the study (if financial compensation is involved). If you choose to withdraw, you will not be penalized by reduction in points or grade in a course (if course credit is involved). You are free not to answer any questions or respond to experimental situations that they choose without penalty.

There may be circumstances under which the investigator may determine that you should not continue as a subject. You will be compensated for the portion of the project completed.

Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University, by the Department of Engineering science and Mechanics.

21 January 2003	20 January 2004
IRB Approval Date	Approval Expiration Date

Subject's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

- Inform the investigators of all medical conditions that may influence performance or risk
- Comply to the best of my ability with the experimental and safety instructions
- Inform the investigator of any physical and mental discomfort resulting from the experimental protocol

Subject's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

Subject Name (Print):____________________

Subject signature:

Date

____________________ Date____________

Witness (Optional except for certain classes of subjects)

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Investigator(s):	Minhyung Lee	E-mail:	minlee@vt.edu	Phone	231-2022
Faculty Advisor:	K.P. Granata	E-mail:	Granata@vt.edu	Phone	231-7039

____________________ ____________________

Departmental Reviewer/Department Head Telephone/e-mail

David M. Moore
Chair, IRB
Office of Research Compliance
Research & Graduate Studies

Subjects must be given a complete copy (or duplicate original) of the signed Informed Consent

Appendix C – Data Collection Forms

Data Collection Form for Study 1 and 2

EFFECTS OF EXERCISE DURING BOX LIFT

Subject #: 101

Box Lift

10 % BW sym

Trial	Duration	Comments	File names
1	30		s101t1lift1s

25 % BW sym

1	30		s101t1lift2s

Appendix D - Stability Exercise Protocol

All subjects assigned to the stability exercise group performed 8 daily exercises. These included: cat/camel, bracing, standing balance, heel-slide, marching, bird-dog, sit-to-stand and hip bridge. The stability exercise protocol was designed by a licensed physical therapist based on the stability exercises outlined in Houglum [24].

Exercise 1 :

Cat:

- Sag back in pain free range of motion
- Hold head up & look up
- Tighten back muscles for 5-10 seconds
- Return to neutral posture for 1-2 seconds

Camel:

- Arch back in pain free range of motion
- Keep head down
- Tighten abdominal muscles for 5-10 seconds
- Return to neutral posture for 1-2 seconds

Repeat for 2 minutes

Exercise 2 : Bracing

- Feet on floor, knees bent 90°
- Head and shoulders on floor
- Tighten abdominal muscles
- Feel lateral tummy
- Rotate pelvis, press lumbar spine to floor
- Hold for 5-10 seconds
- Relax & Repeat for 2 minutes

- **DONT** hold breath or tighten diaphragm
- **DONT** arch the spine

Exercise 3 : Standing Balance

- Arms on hips
- Stand on one foot 5-10 sec
- Return foot to ground
- Repeat with opposite foot
- Repeat for 2 minutes

- **DONT** shift pelvis laterally

Exercise 4 : Heelslides:

- Repeat #2 while …
- Slide heel to full leg extension
- Return leg to 90^0 knee flexion
- Move slowly and continuously
- Relax leg and abdomen 1-2 sec
- Repeat with opposite leg
- Repeat for 2 minutes
- **DON’T** arch spine (see #2)
- **DON’T** hold your breath

Exercise 5 : Marching

- Repeat #2 while …
- Keep knee flexed 90^0
- Flex thigh until vertical
- Return foot to floor 90^0 knee flex
- Move slowly and continuously
- Relax leg and abdomen 1-2 sec
- Repeat with opposite leg
- Repeat for 2 minutes
- **DON’T** arch spine (see #2)
- **DON’T** hold your breath

Exercise 6 : Bird Dog

- Spine in neutral posture
- Tighten abdominal muscles
- Lift & point arm and opposite leg
- Arm & leg leave ground **simultaneously**
- Move slowly and continuously
- Hold fully extended 1-2 seconds
- Return to 4 point stance
- Relax 1-2 seconds
- Repeat for 2 minutes
- Repeat with opposite arm & leg
- **DONT** arch spine
- **DONT** shift weight or rotate pelvis

Exercise 7 : Sit-to-Stand

- Sit upright on chair
- Right foot 8” ahead of left
- Left hand holds dowel at pelvis
- Left palm facing away from body
- Right hand holds dowel at head
- Right palm facing head
- Tighten abdominal muscles
- Keep spine straight
- Stand slowly & smoothly
- Sit slowly and smoothly
- Repeat 3 times
- Stitch feet and hands
- Repeat sit-to-stand
- Repeat for 2 minutes
- **Keep back straight**

Exercise 8 : Hip Bridge

- Feet on floor, knees bent 90^o
- Head and shoulders on floor
- Tighten abdominal muscles
- Raise hips off floor
- Move slowly and continuously
- Hold for 1-2 seconds
- Return hips to floor
- Relax 1-2 seconds
- Repeat for 2 minutes

Progress in level of difficulty
1.hands on floor near hips, palms down
2.hands on floor near hip, palms up
3.hands crossed over chest

- **DONT** hyperextend spine

- **DONT** arch spine (see #2)

Vita

Minhyung Lee

Minhyung Lee was born in Seoul, South Korea on May 31, 1976 to Sangsub Lee and Dongsun Kim. Minhyung attended HanYang University in Seoul, South Korea for 2 years in Mechanical Engineering, and then transferred to Florida International University in Miami, FL where he graduated with a B.S. degree in Mechanical Engineering in May, 2003. Next he went on to graduate school at Virginia Polytechnic and State University (Virginia Tech), finishing his M.S. in Mechanical Engineering in May, 2006. Working as a graduate research assistant in the Musculoskeletal Biomechanics Laboratory at Virginia Tech, Minhyung's research focused on studying changes in lumbar spinal kinematics due to exercises. During his free time, Minhyung enjoys playing billiard and bowling and watching movies with friends.