Lumbar-pelvic coordination during repetitive lifting of novice and experienced lifters

By

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ABSTRACT

Occurrences of low back disorders are high among individuals working in occupational settings that involve manual material handling tasks, particularly repetitive lifting. This study attempts to better understand the relationship between lumbar-pelvic coordination in repetitive lifting and lower back injury risk by examining differences between inexperienced and experienced lifters. It was hypothesized that experienced lifters would choose a more neutral coordination. Subjects performed repetitive lifting while kinematic and electromyographic (EMG) data was collected. The kinematic data showed that novice subjects approached the limits of their range of motion, during extension while experienced lifters maintained a more neutral lumbar spine during the entire lifting cycle. A second hypothesis was that a more kyphotic lumbar-pelvic coordination pattern preferred by inexperienced lifters would be more energetically efficient due to stretch-shortening dynamics. A computational spine model was also used to determine subjects' erector spinae muscle length during the experiment. EMG data was plotted against muscle length to form average work loops. These work loops were assessed for both the subjects preferred lifting strategy and two strategies trained with biofeedback (kyphotic and neutral). Work loops for the trained neutral lifting strategies encompassed less area, suggesting this style of lifting was more energetically efficient than a more trained kyphotic strategy. Therefore, the second hypothesis was not supported as kyphotic work loops encompassed more area than the other strategies.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Sara Wilson for her guidance throughout my graduate studies. Her support was incredibly appreciated and I am grateful to have worked and learned from her. I would like to thank my fellow graduate students and in particular Tim Craig, for his valuable collaboration and help. I had so many questions throughout this whole process and he always took the time to answer them.

Thank you to the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health (1R03AR061597-01), for supporting this research, and thus allowing me to finish my graduate studies more efficiently.

I would like to thank my husband, Vincent Hall. His constant support and encouragement is what really got me through this, at times, rocky process. And most importantly, thank you to my parents, Cindy Riley and Michael Riley. Their unwavering love provided me with the foundation I needed to accomplish my goals.

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LBD	Lower Back Disorder
ROM	Range of Motion
LA	Lumbar Angle
DOF	Degrees of Freedom
ES	Erector Spinae
EMG	Electromyography

CHAPTER 1 – Introduction

Motivation

In the United States alone, workmen's compensation and medical costs associated with low back pain are estimated to be between $25 and $100 billion [1]. Also in the United States a person has a 50-70% chance of developing chronic low back pain at some point in his or her lifetime [2]. For people under the age of 45, low back pain is one of the most commonly cited causes of physical inactivity [3], with 18% of the overall population of the United States suffering from LBP [4]. Torso flexion and repetitive lifting are known risk factors for low back pain and low back injuries in occupations involving manual materials handling [5-7]. Since torso flexion and repetitive lifting cannot be completely removed from the workplace, it is important to investigate lifting techniques that might reduce injury during repetitive lifting.

Lower Back Disorder (LBD)

A member of the working population in an industrialized country has up to a 70% chance of developing a LBD, including pain in the lumbosacral region and sciatic pain traveling down to the legs, at some point in his or her lifetime [3, 5]. The National Institute for Occupational Safety and Health found there to be strong evidence that LBDs are associated with work-related lifting and forceful movements, as well as other activities such as whole body vibration, bending and twisting, and static work postures [5]. As a result, many studies have been conducted in an attempt to better understand and identify the relationship between these movements and injury [8-11].

Marras et al. [11] conducted a study in which over 400 industrial lifting jobs were analyzed in 48 varied industries. This *in vivo* study looked at how 3-dimensional trunk motion contributed to LBD's in occupational settings involving manual material handling. They were then able to identify which trunk motions contributed most to LBD by analyzing the medical records of industries and categorizing the level of risk of LBD. Maximum sagittal flexion angle during a lift cycle was identified as increasing this risk. When a more upright posture was maintained the possibility of LBD decreased significantly. Other factors that could accurately predict medium and high risk work environments were: load moment, lifting frequency, trunk lateral velocity, and trunk twisting velocity. As such, it is important to further investigate high flexion angle lifting tasks.

During a previous study in our laboratory [9], a subject's lumbar angle range of motion was measured by having subjects move from their most lordotic to most kyphotic lumbar postures (Figure 1.1) while maintaining an upright torso position. This was repeated at several torso flexion angles to obtain a lumbar angle range of motion as a function of torso flexion. The lumbar angle normalized to this range of motion was then assessed in these subjects during repetitive lifting tasks. It was found that subjects often approach the kyphotic limits of their lumbar range of motion during the extension phase of a lifting task. In this paper, it was speculated that such a pattern might elicit a stretch-shortening dynamic in the lumbar musculature that might make it energetically easier than remaining in the center of the range of motion. However, it was also speculated that this pattern could increase injury risk by putting additional strain on the extensor musculature and posterior ligamentous structures of the spine and higher moment loads on the intervertebral disks.

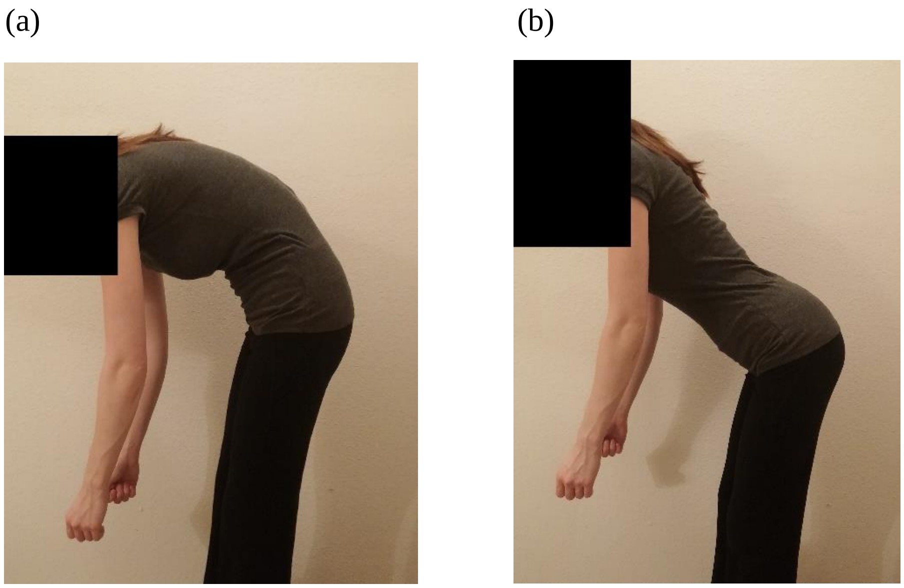

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Figure 1.1 (a) Example of a kyphotic lifting posture. (b)Example of a lordotic lifting posture.

Lumbar Neutral Zone & Elastic Zone:

Panjabi [12] divided spinal motion into two regions: the neutral zone and the elastic zone. The neutral zone is a region near neutral spinal posture where there is little internal resistance to intervertebral movements for a passive spinal column. The elastic zone occurs with greater deformation when there is an increase of internal resistance to further movement. Soft tissue limitations, such as facet joints, ligaments, and the intervertebral disks themselves, begin to restrict further rotation in this zone. Additionally the passive components of the musculature can also act as soft tissue limits. Going to the extremes of lumbar motion, as was observed previously in our lab [9], could potentially move the spine posture from the neutral zone to the elastic zone, engaging and loading these soft tissues.

Solomonow et al. [13] examined one such soft tissue limit, the supraspinal ligament. These authors demonstrated that mechanical deformation of this supraspinal ligament results in a reflexive activation of the nearby paraspinal muscles in an attempt to limit any movement that would bring the vertebrae out of their natural alignment. As such, these tissues also serve an important role in stability and control of spine motion. It was shown that repeated stretching of these ligaments, such as it could occur with repetitive lifting tasks, drastically diminished the stabilizing reflexes, 85% in the first five minutes, potentially reducing their ability to stabilize the spine [14]. Repetitive lifting strategies that repeatedly go towards the elastic zone could, therefore, not only increase loading and strain of the ligaments but also alter the reflexes that provide stability to the lumbar spine, predisposing such a population to injury.

Stretch-Shortening Cycles & Work Loops:

A well-documented phenomenon for cyclic movement is the stretch-shortening cycle of muscles [15-18]. This movement involves the stretching of a muscle before contraction occurs, as opposed to contraction alone (Figure 1.2). It is thought that this stretching allows the muscle and surrounding ligaments and tissue to store elastic energy that can then be released along with the muscle contraction. This is an often observed characteristic in activities such as running and hopping in a variety of animals. However, this activity has also been associated with a risk of injury as eccentric contractions are known to cause muscle damage [15, 19].

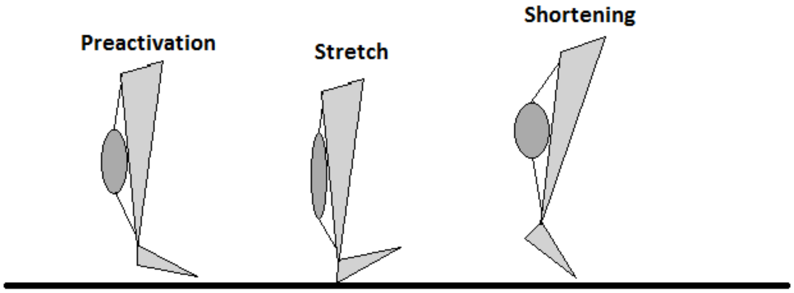

Figure 1.2:Example of the gastrocnemius muscle during a stretch-shortening cycle while running. The leg readies itself for impact during the preactivation phase, then stretches as it makes contact with the ground, before shortening at lift-off.

In order to analyze muscle efficiency during dynamic cyclic movements, researchers often examine work loops. Work loops are plots of the force a muscle exerts relative to its length during a cyclic task. This normally results in a circular plot where the area inside the loop indicates the efficiency of the muscle activity. For a highly efficient activity, this area can become very small. If the work loop develops in the counterclockwise direction as the task is performed this normally indicates that the muscle is generating power and performing work on the environment, such as the loop in Figure 1.3 (a). If the loop is in the clockwise direction (Figure 1.3 (b)), this normally indicated the muscle is absorbing energy as would be done if a person is breaking to slow down their body's inertia. A muscle can also contract very economically if its length does not change drastically while it exerts a force (Figure 1.3 (c)), resulting in a work loop that encompasses very little area [20].

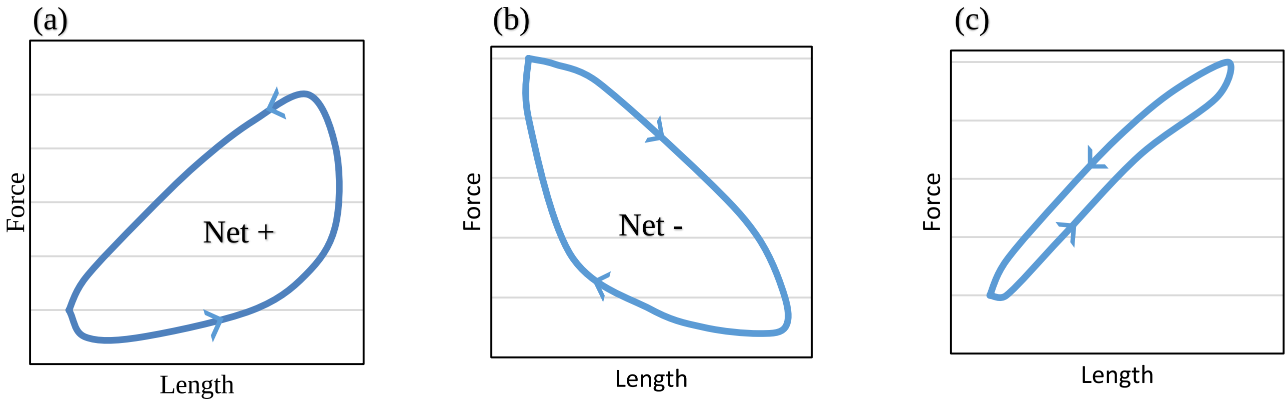

Figure 1.3:Idealized work loops. (a)Work loop is formed in the counterclockwise direction so there is a net positive amount for the area inside the loop. (b) Clockwise work loop so the net work done by the muscle is negative. (c) Efficient work loop, with a net work of almost zero.

Maduri et al. [9] hypothesized that novice lifters' lumbar region was more kyphotic because they were utilizing this stretch-shortening strategy. Essentially stretching the back musculature by rounding the torso forward and then using the extra elastic energy to complete the lift more easily. Ideally, this would result in a work loop similar to the one pictured in Figure 1.3 (c) that encompasses very little area. Therefore, this study aimed to investigate the relationship between the kyphotic lifts and a subject's lumbar range of motion (ROM) to see if they were indeed implementing a more energetically efficient lifting strategy.

Computational Spine Models

Computational models of spine mechanics and kinetics can be used to assess muscle force and motion during lifting tasks. Several computational models of the lumbar spine model the kinematics of the musculature of the lumbar spine to assess the dynamics and mechanics of spine loading and stability [21-24]. Nussbaum and Chaffin [23] developed a deformable and scalable model of the human torso. It consisted of the thoracic and lumbar spine, ribcage, sternum, and sacrum. A set of fifteen anthropometric measures could be inputed to the model to scale it according to individual subjects. Model deformation was inputed from surface markers attached to subjects that measured their movements. Eight muscles were incorporated into this model represented by straight lines. Muscle insertion and termination nodes or locations were included as well as one or more nodes along the muscle length. Muscle lengths were then simply the sum of the distances between these nodes from insertion to termination.

Franklin and Granata [21] developed a model to better study spinal reflexes and reflex delay in relation to spinal stability. The model consisted of five lumbar vertebrae and a thoracic segment, each with three rotational degrees of freedom. Each of these segments was treated like an inverted pendulum with its base on the pelvis. The three-dimensional locations of 90 muscles with insertion and terminating sites were used to provide muscle lengths, velocities, and generalized force vectors for the load conditions subjects underwent for this study. The researchers proceeded to find the delay margin, which is the maximum delay that could be present in a system before that system becomes unstable. This was done by using a method outlined by Chen [25], which analyzes the eigenvalues of the system and determines when they cross the imaginary axis and become unstable.

Cholwicki and McGill [22] developed a spine model using a similar construction to assess the stability of the spine during various dynamic tasks. They found that spinal stability is highest for activities that demand large amounts of muscle activation but that it diminishes for activities that require little muscle activation. Thus spinal stability is not a constant among different dynamic tasks. They theorized this is why it is possible for a person to throw his or her back out when simply picking up a pencil from the floor. A brief loss of stability could result in a quick activation or spasm of the small intrinsic muscle that spans the joint where the instability occurs, possibly overloading the muscle and leading to injury.

For this study we were interested in using a kinematic spinal model to assess the orientation of the lumbar spine and to compute torso muscle lengths based on experimental kinematic data of the pelvis, torso and trunk posture. Such a model can serve as a basis to assess work loop characteristics.

Novice vs. Experienced Lifters

Past studies have examined differences between those with experience in repetitive lifting and novice subjects to better understand strategies that might be useful in avoiding injury [26-29]. It has been thought that these experienced lifters choose better lifting strategies, through experience, to avoid injury. It is also thought that those with poor lifting strategies that might lead to injury would not remain in activities or occupations that required repetitive lifting due to injuries also leading to better lifting strategies in an experienced population. These studies have shown that experienced lifters exhibit different lifting strategies than novice lifters [26-29].

In one experiment [29], spinal compressive loading was assessed for a variety of lifting frequencies and spinal compressive loads were found to decrease when subjects lifted with a more familiar frequency. Novice lifters, when forced to lift at an unfamiliar frequency, showed more simultaneous muscle contractions as opposed to sequential, which has been shown to increase spinal compressive loading [30]. These authors suggested that novice lifters had underdeveloped motor control strategies. Lee and Nussbaum [31] found that experienced workers' movements seemed to place greater emphasis on maintaining total body balance and torso stability. Whereas novice workers seemed willing to sacrifice this stability in order to maintain more constant torso kinematics or kinetics over the range of tasks performed.

Gagnon et al. [27] found experienced lifters exhibited a knee flexion rather than a knee extension during the extension phase of a lifting task. Plamondon et al. [28] found that novice lifters flexed their lumbar spine more than experienced lifters during a task where they transferred boxes from a conveyor to a trolley, although this study was confounded by differences in ages of the two groups. Another study [32] also showed that experienced lifters do flex their lumbar spine less than novice lifters. These latter studies demonstrated that differences in lumbar-pelvic coordination between novice and experienced lifters should be investigated further. However, to the authors' knowledge, lumbar angle as a percent of lumbar ROM had not been previously reported, so it was not known in this previous study how closely the two groups, novice and experienced, approached their ROM limits.

There is a range of lumbar angles a person can assume for every given flexion angle. By rotating the thorax and pelvis, a person's lumbar region can be more rounded and slouched (kyphotic) or more arched and upright (lordotic). Proper control of one's lumbar region at various torso flexion angles can be a challenging task. This is especially true for larger flexion angles which are associated with a more kyphotic spine [33, 34]. Even though some trends do exist, where a person chooses to fall within their lumbar ROM for a given lifting task depends on many factors. One such factor is the experience or familiarity of the subject with the lifting tasks. Therefore, for this study experienced and novice lifters were analyzed separately.

Specific Aims

We know that some lifters approach the limits of their ROM during the extension phase of a lift, however it is unclear if this pattern would be seen among both novice and experienced lifters. We also know that for certain activities, subjects have utilized the stretch-shortening technique to perform more energetically efficiently. However, it is not yet clear if this strategy is being applied during repetitive lifting tasks.

- The first specific aims of this research is to compare the preferred lifting strategies of experienced and novice lifters to see if novice lifters approach the limits of their ROM while experienced lifters avoid these extremes.
- The second specific aim is to examine muscle length and muscle activation to determine if lifters are utilizing a stretch-shortening technique during their preferred or kyphotic lifting strategies. This data will be used to determine which lifting strategies are more energetically efficient than the others.

We hypothesize that during the extension phase of a lifting cycle, novice lifters will have a more kyphotic lumbar region, approaching the limits of their ROM, while experienced lifters will maintain a more neutral or slightly lordotic spinal lumbar region. Additionally, we hypothesize that muscle lengths will be longer for the kyphotic lifts which will be more energetically efficient than the neutral lifts.

The format for this thesis is such that Chapter 2 is presented as a paper that has been submitted for publication. It addresses the first specific aim. The third chapter is also formatted as a paper and addresses the second specific aim.

CHAPTER 2

During repetitive lifting novice lifters exhibit a more kyphotic lifting posture than experienced lifters

Riley, A.E., Craig, T.D., Sharma, N.K., Billinger, S.A., Wilson, S.E.

Submitted for publication

Introduction

In the United States alone, workmen's compensation and medical costs associated with low back pain are estimated to be between $25 and $100 billion [1]. Torso flexion and repetitive lifting are known risk factors for low back pain and low back injuries in occupations involving manual materials handling [5-7]. Punnett et al. [35] examined the trunk postures of automobile assembly workers and found low back disorders to be associated with tasks involving both severe and mild torso flexion. The risk of low back disorders also increased with exposure duration. Since torso flexion and repetitive lifting cannot be completely removed from the workplace, it is important to investigate lifting techniques that might reduce injury during repetitive lifting.

During a previous study in our laboratory [9], a subject's lumbar angle range of motion was measured by having subjects move from their most lordotic to most kyphotic lumbar postures while maintaining an upright torso position. This was repeated at several torso flexion angles to obtain a lumbar angle range of motion as a function of torso flexion. The lumbar angle normalized to this range of motion was then assessed in these subjects during repetitive lifting tasks. It was found that subjects often approach the kyphotic limits of their lumbar range of motion during the extension phase of a lifting task. In this paper, it was speculated that such a pattern might elicit a stretch-shortening dynamic in the lumbar musculature that might make it energetically easier than remaining in the center of the range of motion. However, it was also speculated that this pattern could increase injury risk by putting additional strain on the extensor musculature and posterior ligamentous structures of the spine and higher moment loads on the intervertebral disks.

Past studies have examined differences between those with experience in repetitive lifting and novice subjects to better understand strategies that might be useful in avoiding injury [26-29]. It has been thought that these experienced lifters choose better lifting strategies, through experience, to avoid injury. It is also thought that those with poor lifting strategies that might lead to injury would not remain in activities or occupations that required repetitive lifting due to injuries also leading to better lifting strategies in an experienced population. These studies have shown that experienced lifters exhibit different lifting strategies than novice [26-29]. Gagnon et al. [27] found experienced lifters exhibited a knee flexion rather than a knee extension during the extension phase of a lifting task. Plamondon et al. [28] found that novice lifters flexed their lumbar spine more than experienced lifters during a task where they transferred boxes from a conveyor to a trolley, although this study was confounded by differences in ages of the two groups. This latter study demonstrated differences in lumbar-pelvic coordination between novice and experienced lifters that should be investigated further.

In this study, it was hypothesized that experienced lifters would avoid the extremes of normalized lumbar angles observed previously in novice lifters [9] and that novice lifters would approach the limits of their range of lumbar motion while the experienced lifters would maintain a more neutral spine during lifts.

Methods

Subjects:

Twenty three subjects completed this study (14 men, 9 women, age of 24.7±4 years, height of 1.71±0.10 m, and an average weight of 70.2 ±15.8 kg) with approval from the human subjects committee at the University of Kansas Medical Center and consent of the subjects. Subjects were screened for musculoskeletal disease and a history of low back pain (LBP). On the day of testing they were asked to wear loose fitting clothing, flat soled shoes, and no jewelry. Participants were categorized into two groups, experienced and novice lifters. An experienced lifter was someone who had lifted weights at least three times a week for the last year or more. Ideally, their weight lifting activities included dead lifts, bent-over barbell rows, standing curls, squats, and/or standing military presses, but in general most forms of free weights were considered adequate. The subjects that did not meet these criteria were considered novice lifters. Subjects were excluded from the novice lifters if they had been employed in a position that involved lifting or material handling for greater than three months at four hours per week or more. The experienced lifters group consisted of three women and eight men (average age of 25.2±4, height of 1.74±0.10 m, and weight of 75.7±15.4 kg) and the novice group included six women and six men (average age 24.2±4 years, height of 1.70±0.10 m, and weight of 64.9±14.5 kg).

Test Protocol:

For this study, data from a force plate (Bertech, Columbus, OH) was collected at 100 Hz. Electromagnetic motion sensors (MotionStar, Ascension Technologies, VT) were used to collect position and orientation data from three locations using Motion Monitor software (Innsport, IL).

The motion sensor data was collected at 100 Hz and had a manufacturer reported resolution of 0.08 cm and 0.1° and an RMS accuracy of 0.76 cm and 0.5°. The sensors were placed on the skin at the thoracic level 10 (T10) and the sacral level 1 (S1) spinous process and on the skin at the manubrium with double sided tape. The height of the sensor on the manubrium was used to identify the beginning and end of each lifting cycle and the T10 and S1 markers measured the trunk flexion angle and lumbar angle during the lifting activity. The flexion angle was defined as the angle between the vertical and the line intersecting the position of the T10 and S1 sensors. The lumbar angle was the angle between the T10 and S1 sensors. (Figure 2.1) These definitions were consistent with previous literature descriptions [9, 36].

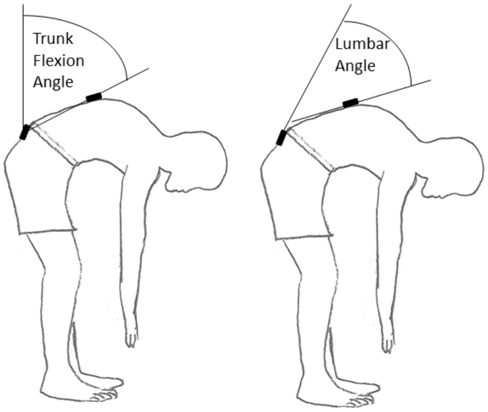

Figure 2.1:Sensors to monitor the flexion and lumbar angles were placed on the T10 and S1 spineous processes.

The range of lumbar curvature for each subject was found using the method described by Maduri et al. [9]. This involved having subjects flex their trunk to reach trunk flexion angles of 0°, 30°, 60°, and 80° as the trunk flexion angles were displayed in real time. The subject would then hold the trunk flexion angle constant while rotating their pelvis and thorax to reach their maximum (kyphotic) and minimum (lordotic) attainable lumbar angles. Once the subject was comfortable with this task, these extremes were measured three times and averaged. These averaged values were defined as the maximum and minimum attainable lumbar angle values for the subject and used to normalize the future lumbar angles as a percentage of the range between the minimum and maximum lumbar angle. For lumbar angles at torso flexion angles between the measured flexion angles of 0°, 30°, 60°, and 80°, the maximum and minimum values were linearly interpolated from their nearest neighbors. Figure 2.2 shows an example of the raw lumbar angles and the same values after normalization.

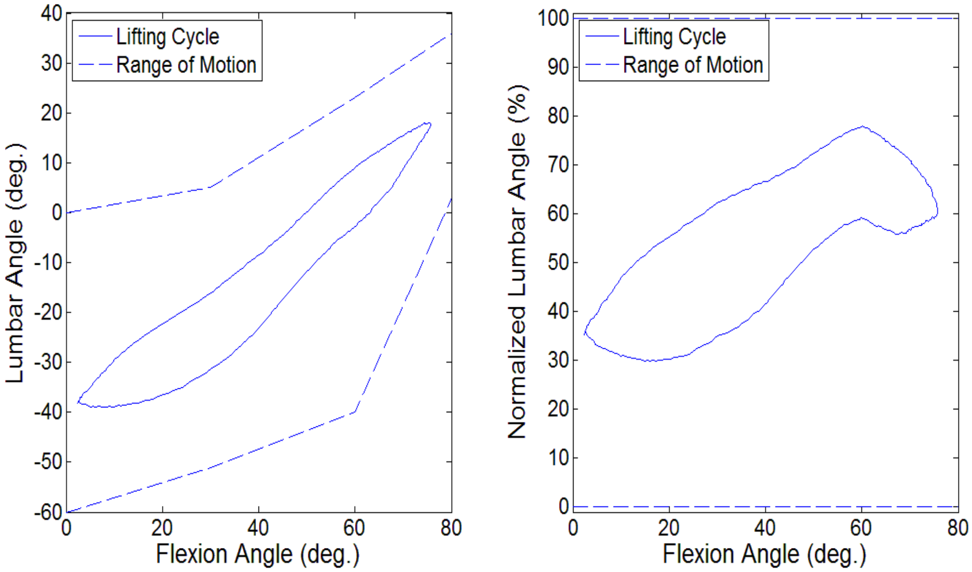

Figure 2.2: Lumbar curvature was measured for each subject. This figure represents a typical lifting cycle (left) that has been normalized using the subject's range of motion on the right.

This experimental protocol included: 1) measurement of maximal lifting force, 2) measurement of spinal range of motion at four trunk flexion angles (0°, 30°, 60°, and 80°), and 3) a lifting task.

To measure maximal lifting force, participants were asked to stand on a force plate and pull up on a rope located just below their knees for five seconds, while avoiding knee flexion.

The mean of the highest 50 data points was defined as the maximum amount of upward force the subjects could exert. Three percent of this maximum force was used as the lifting load throughout the rest of the experiment. Weights approximately equal to 3% of this maximum force were placed in a crate for the lifting task.

Participants then completed straight legged lifts for four minutes, while listening to a metronome to maintain a rate of 15 lifts/minute. They were not given any instructions or visual feedback in order to obtain their preferred lifting strategy. The participants were asked to raise the crate from floor to waist level, pause, and then lower the crate to the floor for a complete lift.

Analysis:

The vertical height of the manubrium sensor was analyzed to pinpoint the time indices for the flexion phase and the extension phase of each lift cycle. Each time the sensor's vertical height reached a minimum represented the time at which the subject reached the bottom of their lift and each maximum of the sensor's vertical height represented the time at which the subject reached the top of a lift. These indices were used to distinguish each lift individually and to single out the extension phase of each lift. Lumbar angles (LA) were normalized using the ROM values (described above) with the following equation:

$$Normalized\ LA = \frac{LA - LA_{min}}{LA_{max} - LA_{min}} * 100.$$

Normalized lumbar angle values during extension and flexion were grouped into four quadrants depending on their corresponding trunk flexion angle: 10-25°, 26-40°, 41-55°, 56-70°. The lumbar angles were averaged together within these groups. A repeated measures ANOVA was performed on the normalized LA averages with two independent variables, group and flexion angle quadrant. A significance level of $p < 0.05$ was considered statistically significant. Post-hoc tests of within-subjects contrasts was performed for statistically significant findings.

Results

Novice lifters exhibited a significantly more kyphotic lifting posture during both the extension and flexion phases of the lift when compared to the experienced group (Table 2.1, Figure 2.3). The novice lifters began the flexion phase of a lift near the middle of their ROM (57%) but quickly climbed to the limits of their range at the end of the flexion phase (86%). During extension, novice lifters spent most of the lift in a kyphotic posture relative to their range (92-95%) before ending the lift only slightly more neutral (70%). Experienced lifters maintained a lordotic posture relative to their range during the flexion phase of a lift, starting low (32%), becoming slightly more neutral (40-41%). For the extension, experienced lifters remained slightly lordotic relative to their range (42-49%) for most of the lift, reaching a neutral posture of 53% in the middle of the lift.

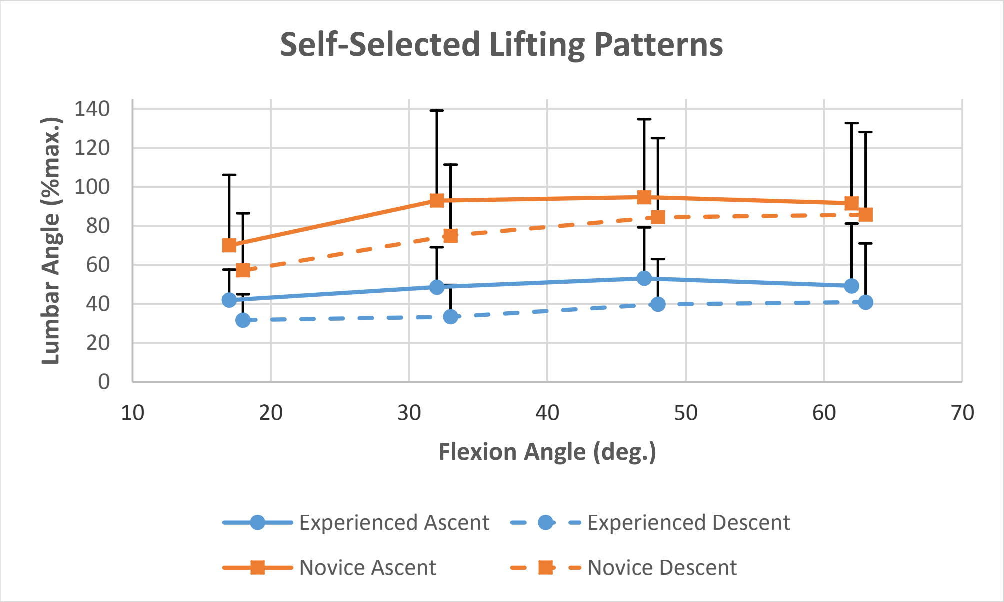

Figure 2.3: Normalized lumbar angle for experienced and novice lifters as a function of torso flexion angle for both the ascent and descent of the lifting cycles.

	Descent Phase				Ascent Phase			
	Quad 1	**Quad 2**	**Quad 3**	**Quad 4**	**Quad 4**	**Quad 3**	**Quad 2**	**Quad 1**
Novice	57.2±29.3	75±36.5	84.4±40.6	85.8±42.4	91.5±41.2	94.7±40	93±46.1	70±36.2
Experienced	31.7±13.2	33.4±16.4	39.8±23.1	40.8±30.1	49.2±32	53.1±26.2	48.5±20.6	41.9±15.6

Table 2.1: Averages and standard deviations of the normalized lumbar angles for four lifting cycles in each of the four truck flexion angle quadrants.

A statistically significant difference ($p<0.05$) was found between the experienced and novice groups for both the extension and flexion portions of the lifting cycles. A repeated measures ANOVA demonstrated that the direction of the lift (extension or flexion) had a significant effect, as did the quadrant and the interaction between direction and quadrant. Quadrant 1 (10°-25°) and quadrant 2 (26°-40°) also had a significant statistical difference. The lifting cycle was not significantly different, as would be expected (Table 2.2).

	p-value
Experience Level	**< 0.05**
Direction	**< 0.05**
Direction*Experience Level	0.852
Quadrant	**< 0.05**
Quad. 1 vs. Quad. 2	**< 0.05**
Quad. 2 vs. Quad. 3	0.182
Quad. 3 vs. Quad. 4	0.567
Quadrant*Experience Level	0.174
Cycle	0.427
Direction*Quadrant	**< 0.05**
Direction*Quad. 1 vs. Quad. 2	**<0.05**
Direction*Quad. 2 vs. Quad. 3	**<0.05**
Direction*Quad. 3 vs. Quad. 4	**<0.05**

Table 2.2: A Huynh-Feldt, repeated measures ANOVA was performed to examine the effects of experience level (novice versus experienced), direction (flexion versus extension), torso flexion angle quadrant (10-25°, 26-40°, 41-55°, and 56-70°), and cycle (repeated lifting cycles) on the normalized lumbar angle. Highlighted p<0.05 values demonstrate that experience, direction and quadrant were significant while cycle was not.

It is possible that the differences observed between the two groups could be due to differences in the ranges of motion of the lumbar angle. To examine this, a secondary ANOVA of the lumbar angle ROM with the independent variables of flexion angle and group was performed and found no statistical difference between the ROM of the two groups (Figure 2.4).

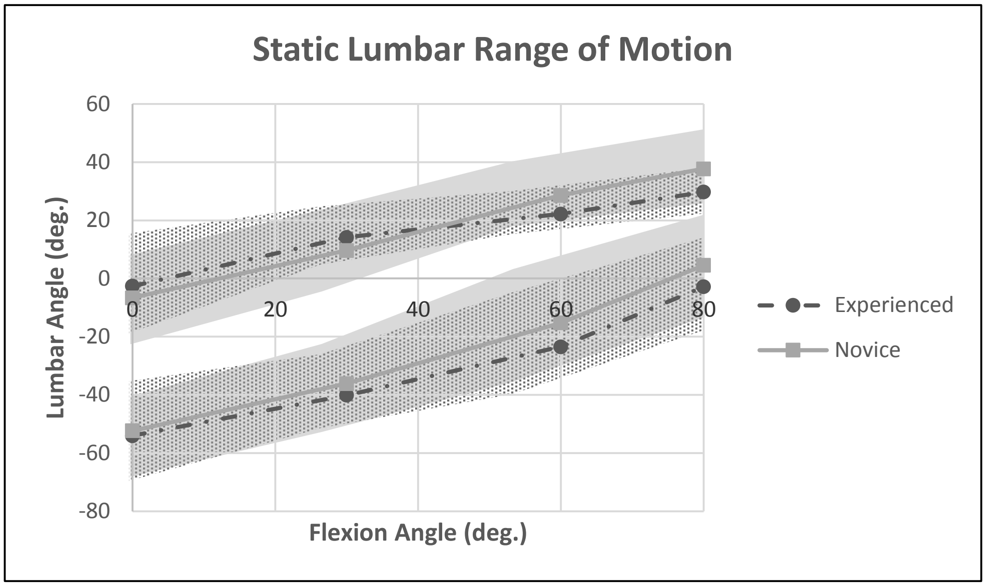

Figure 2.4: The range of motion (ROM) for experienced and novice lifters with the standard deviation shaded in their respective colors. The top two data sets are for the extension of the lifting cycles and the lower two are for the flexion phase. The ROM for experienced lifters was not significantly different from that for novice lifters.

Discussion

For this study, it was hypothesized that experienced lifters would maintain a more neutral lumbar angle relative to their range of motion, while novice lifters would approach the limits of their lumbar ROM during the extension phase of a lift. Our results show a statistically significant difference in lifting patterns for these two groups supporting this hypothesis. The novice group maintained a much more kyphotic posture for both the flexion and extension phases of the lifting cycle, while the experienced group retained a more neutral curvature throughout the entire lifting cycle (Figure 2.3).

There have been many studies aimed at identifying the differences between novice and experienced lifters, with the intention of learning what might be taught to the novice lifters to reduce their risk of injury [29, 31, 37, 38]. In one study [29], spinal compressive loading was assessed for a variety of lifting frequencies and spinal compressive loads were found to decrease when subjects lifted with a more familiar frequency. Novice lifters, when forced to lift at an unfamiliar frequency showed more simultaneous muscle contractions as opposed to sequential, which has been shown to increase spinal compressive loading [30]. These authors suggested that novice lifters had underdeveloped motor control strategies. Lee and Nussbaum [31] found that experienced workers' movements seemed to place greater emphasis on maintaining total body balance and torso stability. Whereas novice workers seemed willing to sacrifice this stability in order to maintain more constant torso kinematics or kinetics over the range of tasks performed. Another study [38] showed that experienced lifters do flex their lumbar spine less than novice lifters. However, to the authors' knowledge, lumbar angle as a percent of lumbar ROM had not been previously reported, so it was not known in this previous study how closely the two groups, novice and experienced, approached their ROM limits.

Panjabi [12] divided spinal motion into two regions: the neutral zone and the elastic zone. The neutral zone is a region near neutral spinal posture where there is little internal resistance to intervertebral movements for a passive spinal column. The elastic zone occurs with greater deformation when there is an increase of internal resistance to further movement. Soft tissue limitations, such as facet joints, ligaments, and the intervertebral disks themselves, begin to restrict further rotation in this zone. Additionally the passive components of the musculature can also act as soft tissue limits. Going to the extremes of lumbar motion, as was observed in the novice subjects of this study, could potentially move the spine posture from the neutral zone to the elastic zone, engaging and loading these soft tissues.

Solomonow et al. [39] examined one such soft tissue limit, the supraspinal ligament. These authors showed that mechanical deformation of this supraspinal ligament results in a reflexive activation of the nearby paraspinal muscles in an attempt to limit any movement that would bring the vertebrae out of their natural alignment. As such, these tissues also serve an important role in stability and control of spine motion. It has been shown that repeated stretching of these ligaments, such as could occur with repetitive lifting tasks, drastically diminished the stabilizing reflexes, 85% in the first five minutes, potentially reducing their ability to stabilize the spine [40]. For the novice lifters in our study, repetitive lifting strategies that repeatedly go towards the elastic zone could, therefore, not only increase loading and strain of the ligaments but also alter the reflexes that provide stability to the lumbar spine, predisposing such a population to injury.

It could be hypothesized that the preference of novice lifters to a more kyphotic posture is due to a greater mechanical efficiency that this movement could provide. Stretch-shortening cycles have been well documented for other activities [41-43] and if subjects are able to initiate a similar cycle during repetitive lifting it could account for the kyphotic posture's common use. Stretch-shortening would result in stretching of the back muscle before contraction. This allows a person to briefly store the elastic energy of the muscles and nearby tendons to be released along with the muscle contraction. However, this activity has also been associated with a risk of injury as eccentric contractions are known to cause muscle damage [15, 19].

One potential limitation of this study was that static lumbar ROM was used to normalize the dynamic lumbar angles recorded during the lifting task. For some subjects, their dynamic ROM appeared to be larger than their static ROM, resulting in normalized lumbar values greater than 100%. Regardless, this study was able to demonstrate that novice and experienced lifters do employ different lumbar-pelvic coordination strategies. Additionally, it was found that the ROM measured for the two groups was not different, confirming that the difference lies in the coordination strategy.

Future work should involve an examination of the energetics of the self-selected lifting strategy to see if novice lifters use this pelvis-first, lumbar-pelvic, coordination strategy to perform the task more metabolically efficiently. Additionally, a biofeedback training method should be developed to teach novice lifters correct lifting techniques and to evaluate how successful such training can be, as well as if such training could be effective in reducing work place related low back injuries. How the lifting patterns of these two groups change over time could also be evaluated, studying the effects of fatigue on lumbar curvature.

In conclusion, this study demonstrated that novice and experienced lifters do maintain different lumbar angles relative to their lumbar ROM during repetitive lifting tasks. Subjects with more lifting experience had a more neutral lumbar spine while novice lifters' lumbar region remained kyphotic for both the flexion and extension phases of a lifting cycle. This resulted in novice lifters approaching the limits of their ROM and potentially increasing their spinal instability and risk of lower back injury.

CHAPTER 3

Energetic efficiency of novice and experienced lifters during preferred and trained repetitive lifting tasks

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Introduction

In manual materials handling occupations, torso flexion and repetitive lifting are recognized risk factors for low back pain and low back injuries [5, 6, 44]. One study of automobile assembly workers [35] found low back disorders were associated with tasks involving both severe and mild torso flexion. Since it is not possible to completely remove repetitive lifting and torso flexion from the workplace, it is important to search for lifting techniques that could potentially reduce this risk of injury.

In a previous study in our laboratory [9], a subject's lumbar angle ROM was measured by having subjects move from their most lordotic to their most kyphotic lumbar postures while maintaining specific torso flexion angles. The lumbar angles were normalized to this ROM and then analyzed while subjects performed repetitive lifting tasks. It was discovered that subjects often approach the kyphotic limits of their lumbar ROM during the extension phase of a lifting cycle. It was then speculated in that paper that this pattern could prompt a stretch-shortening dynamic in the lumbar musculature that might make it energetically easier to perform the lift than remaining in the center of the ROM. However, it was also speculated that this pattern could increase injury risk by putting additional strain on the extensor musculature and posterior ligamentous structures of the spine and higher moment loads on the intervertebral disks.

Past studies have examined differences between those with experience in repetitive lifting and novice subjects to better understand strategies that might be useful in avoiding injury [26-29]. It is believed that experienced lifters choose better lifting strategies to minimize injury. Several studies have shown that experienced lifters exhibit different lifting strategies than novice lifters [26-29]. Plamondon et al. [28] found that novice lifters flexed their lumbar spine more than experienced lifters during a lifting task. Our first study (Chapter 3) demonstrated that experienced lifters maintain a more neutral lumbar spine during the extension phase of a lift whereas novice lifters exhibit a much more kyphotic lifting pattern. In this paper, we examined the role energetics may play in selecting a lifting strategy.

One possible reason novice lifters use a more kyphotic lift is that it utilizes a stretch-shortening technique. This is a well-documented dynamic pattern of muscles-tendon mechanics in many cyclic activities such as running [17, 18, 45]. Stretch-shortening involves storage of energy in the muscle and/or tendon by stretching the muscle prior to contraction. This allows some energy to be stored in the muscle and ligaments as potential energy that is then released, like a spring, when the muscle is contracted. Stretch-shortening can decrease the amount of work a muscle performs during a cyclic activity. Therefore it was hypothesized that novice lifters may utilize this technique by performing kyphotic lifts to reduce muscle fatigue. Experienced lifters, on the other hand, may have learned to avoid this technique because of its potential to cause injury, as it could involve extreme lumbar postures that could put excess loading on ligamentous structures and could involve eccentric contractions, the lengthening of a muscle during a contraction, which has been linked to muscle damage [15].

The goal of the current study was to examine lumbar angle, erector spinae muscle length, and erector spinae EMG during different self-selected and trained lifting strategies and the differences in these data sets for experienced and novice lifters. It was hypothesized that experienced lifters would avoid the extremes of normalized lumbar angles observed previously in novice lifters [9], and in doing so, maintain a more neutral lumbar region with a shorter erector spinae muscle length. It was also hypothesized that a more neutral lifting strategy would be less efficient (as measured by the area within a work loop of muscle force versus length) than a more kyphotic lifting strategy.

Methods

Subjects:

Seventeen subjects completed this study, nine men and eight women, (mean age of 241±4.2 years, weight of 66.4±12.7 kg, and height of 1.70±0.1 meter) with approval from the human subjects committee at the University of Kansas Medical Center. Subjects were screened for musculoskeletal disease and a history of LBP. On the day of testing they were asked to wear loose fitting clothing, flat soled shoes, and no jewelry. Participants were categorized into two groups, experienced and novice lifters. An experienced lifter was someone who had lifted weights at least three times a week for the last year or more. Ideally, their weight lifting activities included dead lifts, bent-over barbell rows, standing curls, squats, and/or standing military presses, but in general most forms of free weights were considered adequate. The subjects that did not meet these criteria were considered novice lifters. Subjects were excluded from the novice lifters if they had been employed in a position that involved lifting or material handling for three months at least an hour a day for four days per week. For this study, the experienced lifters group consisted of three women and five men (24.8±4.1 years of age, weight of 70.9±14.6 kg, and height of 1.71±0.11 m) and the novice group included five women and four men (23.6±4.4 years, weight of 62.3±9.82 kg, and height of 1.70±0.09 m).

Test Protocol:

For this study, a force plate (Bertech, Columbus, OH) was used to collect data at 100 Hz. Electromyography sensor (Delsys, Natick, MA) were placed bilaterally on the erector spinae muscles at the L2/L3 level and muscle activity was collected at 1000 Hz. Electromagnetic motion sensors (MotionStar, Ascension Technologies, VT) were used to collect position and orientation data from three locations using Motion Monitor software (Innsport, IL). The electromyographic data was collected at 100 Hz. These sensors have a reported resolution of 0.08 cm and 0.1° and an RMS accuracy of 0.76 cm and 0.5°. The sensors were placed on the T10 and S1 spinous process and the manubrium with double sided tape. The height of the sensor on the manubrium was used to identify the beginning and end of each lifting cycle and the T10 and sacral markers measured the trunk flexion angle, lumbar angle, and pelvic tilt during the lifting activity. The flexion angle was defined as the angle between the vertical and the line intersecting both sensors. The lumbar angle was the angle between the two sensors. Pelvic tilt was defined as the angle of the sacral marker in the sagittal plane relative to the vertical. (Figure 3.1) These definitions were consistent with previous literature descriptions [36].

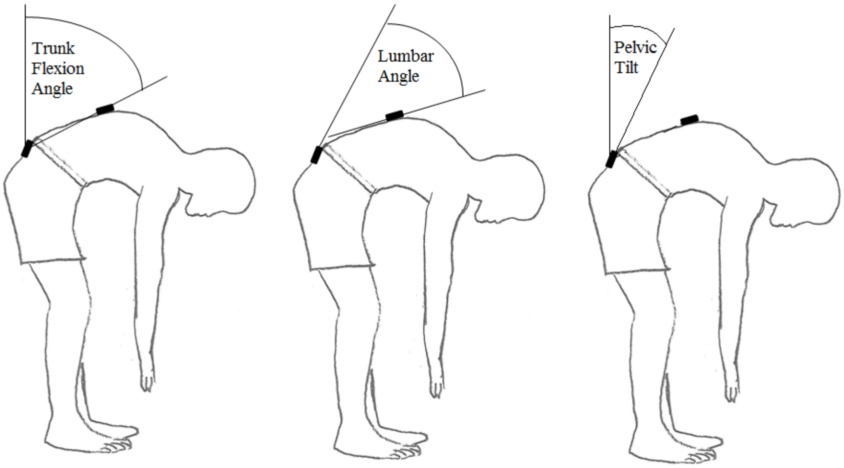

Figure 3.1: Sensors to monitor the flexion and lumbar angles were placed on the T10 and S1 spineous processes.

This experiment included: 1) measurement of maximal lifting force, 2) measurement of spinal range of motion at four trunk flexion angles (0°, 30°, 60°, and 80°), and 3) completion of three different lifting strategies.

Participants were asked to stand on a force plate and pull up on a rope located just below their knees for five seconds, while avoiding knee flexion. The mean of the highest 0.5 seconds of data was defined as the maximum amount of upward force the subjects could exert. 3% of this maximum force was used as the lifting load throughout the rest of the experiment. Weights equal to approximately 3% of this maximum force were placed in a crate for the lifting task.

The range of lumbar curvature for each subject was found using the method described in Maduri et al. [9]. This involved having the subjects flex their torso to reach trunk flexion angles of 0°, 30°, 60°, and 80° as the trunk flexion angles were displayed in real time on a computer screen. The subjects would then hold the trunk flexion angle constant while rotating their pelvis and thorax to reach their maximum (kyphotic) and minimum (lordotic) attainable lumbar angles.

Once the subject was comfortable with this task, these extremes were measured three times and averaged. These averaged values were defined as the maximum attainable lumbar values for the subject and used to normalize the future lumbar angles. All maximum and minimum lumbar angles for trunk flexion angles between the four measured values were linearly interpolated. Figure 3.2 shows an example of the raw lumbar angles and then the same values after normalization.

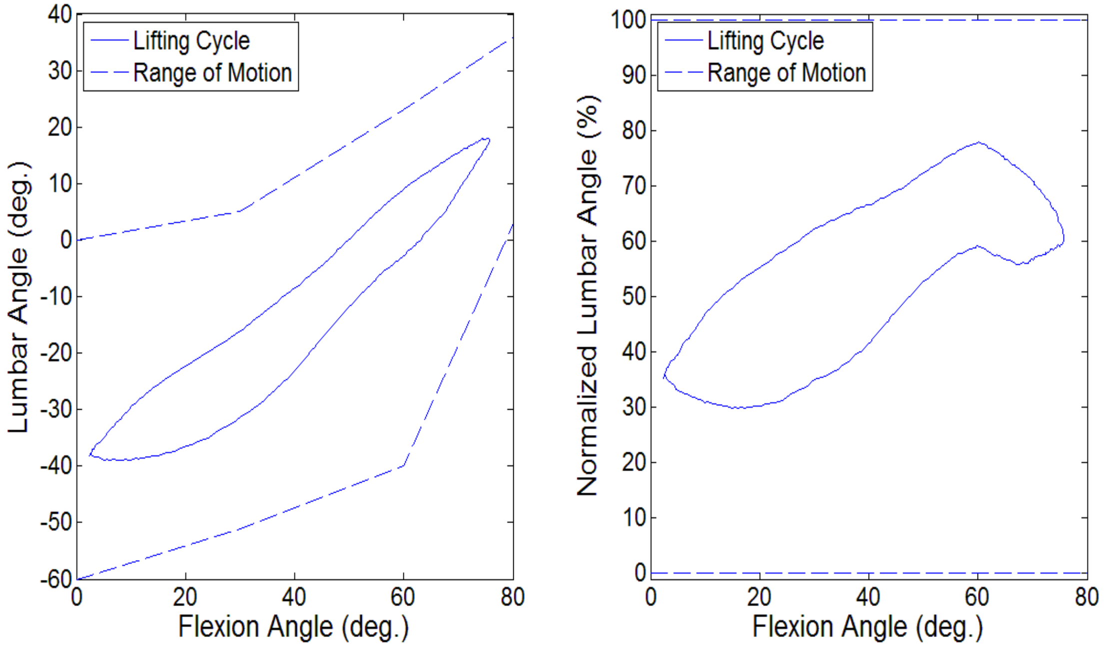

Figure 3.2: Lumbar curvature was measured for each subject. This figure represents a typical lifting cycle (left) that has been normalized using the subject's range of motion on the right.

Participants then completed straight legged lifts for four minutes, while listening to a metronome to maintain a rate of 15 lifts/minute. They were not given any instructions or visual feedback for this task in order to obtain their preferred lifting strategy. After a rest period, subjects were then taught how to use a visual biofeedback display, illustrated in Figure 3.3, to lift with either a kyphotic or neutral lumbar spine. Subject were instructed to ensure the cursor (representing the subjects real time flexion and normalized lumbar angle) entered the target box at some point during the extension phase of each lifting cycle. For the kyphotic strategy, the target box was located at 80-95% of the normalized lumbar angle and for the neutral lifts the target box enclosed 42-58% of the normalized lumbar angle. Subjects were considered trained when they could successfully hit the target box in five consecutive lifts. Each training period was then followed by a four minute lifting period at 15 lifts per minute.

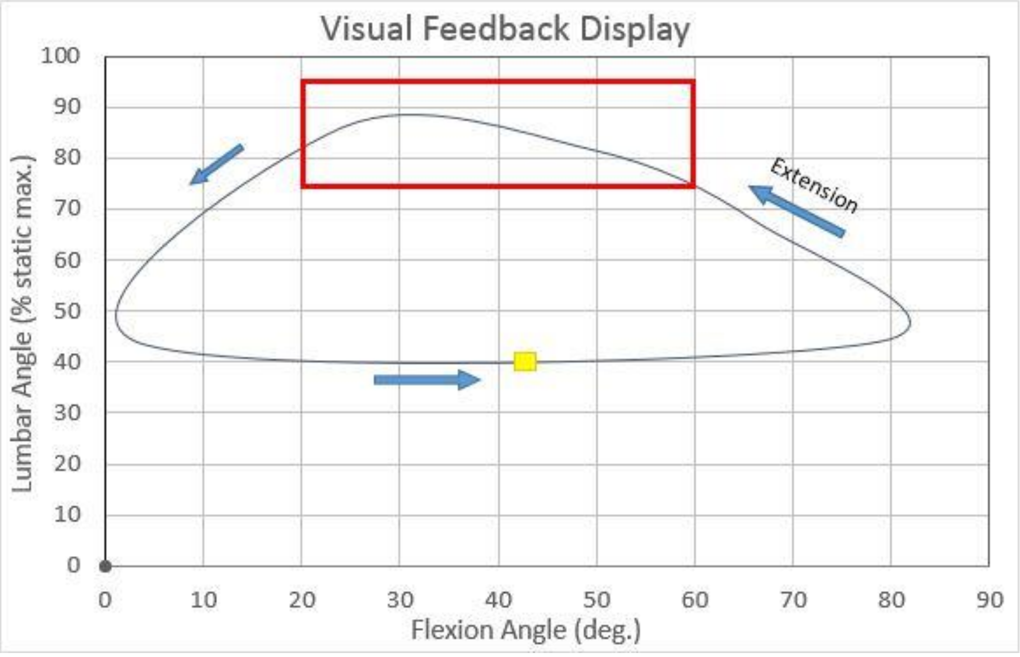

Figure 3.3: Visual feedback display with subject's orientation indicated by the yellow cursor. Participants were instructed to ensure the cursor entered the red target box during the extension phase of the lift. This graph shows an ideal kyphotic lift in blue.

Analysis:

The vertical height of the manubrium sensor was analyzed to pinpoint the time indices for the flexion phase and the extension phase of each lift cycle. Each time the sensor's vertical height reached a minimum represented the time at which the subject reached the bottom of their lift and each maximum of the sensor's vertical height represented the time at which the subject reached the top of a lift. These indices were used to distinguish each lift individually and to single out the extension phase of each lift. Lumbar angles (LA) were normalized using the ROM values (described above) with the following equation:

$$Normalized\ LA = \frac{LA - LA_{min}}{LA_{max} - LA_{min}} * 100.$$

Then, normalized lumbar angle values during extension and flexion were grouped into four quadrants depending on their corresponding trunk flexion angle: 10°-25°, 26°-40°, 41°-55°, 56°-70°. The lumbar angles were averaged together within these groups and their respective experience level, experienced or novice. However, some subjects did not reach the forth flexion angle quadrant (56°-70°) during their lifts so this quadrant was eliminated for the remainder of the analysis.

The EMG data for the right erector spinae was sent through high and low pass filters with cutoff frequencies of 20 and 250 Hz, respectively. Bandstop filters were also applied at: 60, 100 Hz and their multiples.. The data was also demeaned, rectified, and integrated using a moving average with a window size of 100 points. EMG data was normalization based on previously described methods for cyclic activities [46, 47]. They showed that for a cyclic activity involving at least four repetitions, the EMG data could be normalized to the average of the peak values for each cycle. In this paper, the average of the cyclic peaks was taken from each subject's preferred lifting strategy and was used to normalize the EMG data for all lifting strategies. For each lifting strategy, the normalized EMG data for each lift cycle was aligned with the flexion angle and averaged to obtain an average EMG curve for the lifting strategy. The normalized EMG curves during extension and flexion for each lifting strategy were averaged for trunk flexion angle ranges: 10°-25°, 26°-40°, and 41°-55°.

There were two exclusion criteria used to eliminate a subject's EMG data. The first was if the data was not recorded properly and was simply missing for one of the strategies. This occurred when there was a known equipment malfunction or the EMG signal dropped to zero or nearly zero for the majority of the trial (suggesting a loss in electrode contact). The second was if the average of one strategy was at least ten times greater than the average of the other strategies. In these cases it was assumed that the sensor came loose and/or there was excessive noise in the data. Using these two exclusion criteria, nine subjects were removed from this study.

Spine Model:

To assess muscle length, a spine model was created based on the spine model described by Franklin et al. [21]. This model consisted of a pelvis, five lumbar vertebrae, and a thoracic column, Figure 3.4. Each body had three rotational degrees of freedom (DOF), for a total of 21 DOF. The three DOF for each body related to a 1-2-3 rotation sequence, however for this study movements only included rotations in the sagittal plane. The masses and dimensions of the individual rigid bodies were taken from results published by Liu and Laborde [48]. Each lumbar vertebrae was a cylinder with an elliptical cross sectional area that rotated about its center, relative to the vertical.

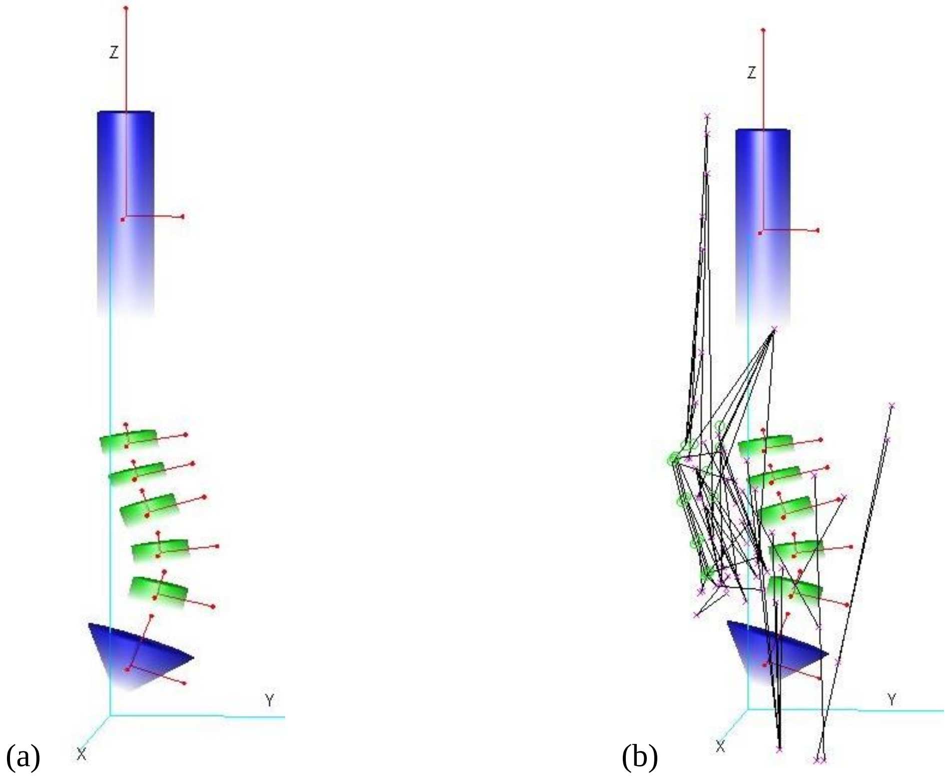

Figure 3.4: (a) Computer model of the spine includes the sacrum, L1-L5, and the thorax. (b) Muscles are represented by straight lines. Only muscles on the right side are pictured for clarity.

The origin and insertion locations of muscles used in this model were taken from work done by Cholewicki and McGill [22] who reported the originating and terminating locations of 90 torso muscles, as well as via points. Via points are used for muscles that must pass over other objects, such as bone or other muscle tissue, to reach their terminating location. They act like eyelets for a shoelace, in that a muscle can pass through them freely if the muscle and eyelet are angled the same direction. However, if they are angled differently, the muscle and eyelet will exert a force on each other, as in Figure 3.5. To use the model, one can input the orientations of the bodies, from which it calculates the new muscle locations and resulting muscle lengths.

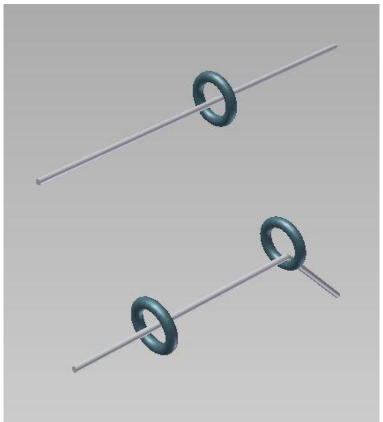

Figure 3.5: Example of via points for model muscles. The top muscle has no force exerted on it by the via point. The lower muscle must move over or around another object so is held in place by the second eyelet.

Inputs for the model included: subject height, flexion angle, pelvic tilt, and lumbar angle. A percentage of subject height was used to find torso height [49], from which the individual spinal segment heights could be estimated [48]. Pelvic tilt was assigned to the pelvic body segment. This simply rotated the pelvis of the model the recorded amount in the sagittal plane. For the lumbar vertebrae, it was assumed that each individual vertebrae consistently makes up a specific percentage of the overall lumbar angle [22, 50]. However, this percentage is different depending on if the lumbar region is kyphotic or lordotic, therefore if the subject's lumbar angle was greater than zero (kyphotic), one set of percentages was used and if it was less than zero (lordotic) another set was applied, all percentages came from work done by Pearcy [51] and are shown in Table 3.1. The flexion angle was assigned to the thoracic column. The model would then calculate new muscle origin and termination locations and from those output the new muscle length. For this study, the longissimus thoracis muscles of the L4 and L5 vertebrae were averaged together for the subject's muscle length. This was then normalized to subject height.

Muscle length was assessed as a function of flexion angle for each subject and averaged together for the flexion angle ranges: 10°-25°, 26°-40°, and 41°-55°.

	Lumbar angle percentage attributed to L1-L5				
	L1	**L2**	**L3**	**L4**	**L5**
Flexion (Kyphotic)	15.3	19.2	23	25	17.3
Extension (Lordotic)	31.2	18.8	6.3	12.5	31.2

Table 3.1: Percentages used to distribute a subject's total lumbar angle among individual lumbar vertebrae depending on if the subject was in extension or flexion.

Statistical Analysis

A mixed measures ANOVA with Huynh Feldt correction was performed, for each of three dependent variables (lumbar angle, ES muscle length and ES normalized EMG), with independent variables: group (experienced or novice), strategy (self-selected, trained neutral, and trained kyphotic), and flexion angle quadrant (10°-25°, 26°-40°, 41°-55°), with group assigned as the between-subjects variable and strategy and quadrant as within-subjects variables. A significance level of $p \geq 0.05$ was considered statistically significant. Post-hoc tests of within – subjects contrasts was performed for statistically significant findings.

Results

For lumbar angles, the self-selected strategies are very similar to those seen in Chapter 2 of this thesis. Here however, we can compare them to the two trained strategies and as can be see in Figure 3.6, the self-selected strategy for the novice lifters is much closer to their kyphotic strategy whereas the self-selected strategy for the experienced group is very similar to their neutral lifting strategy.

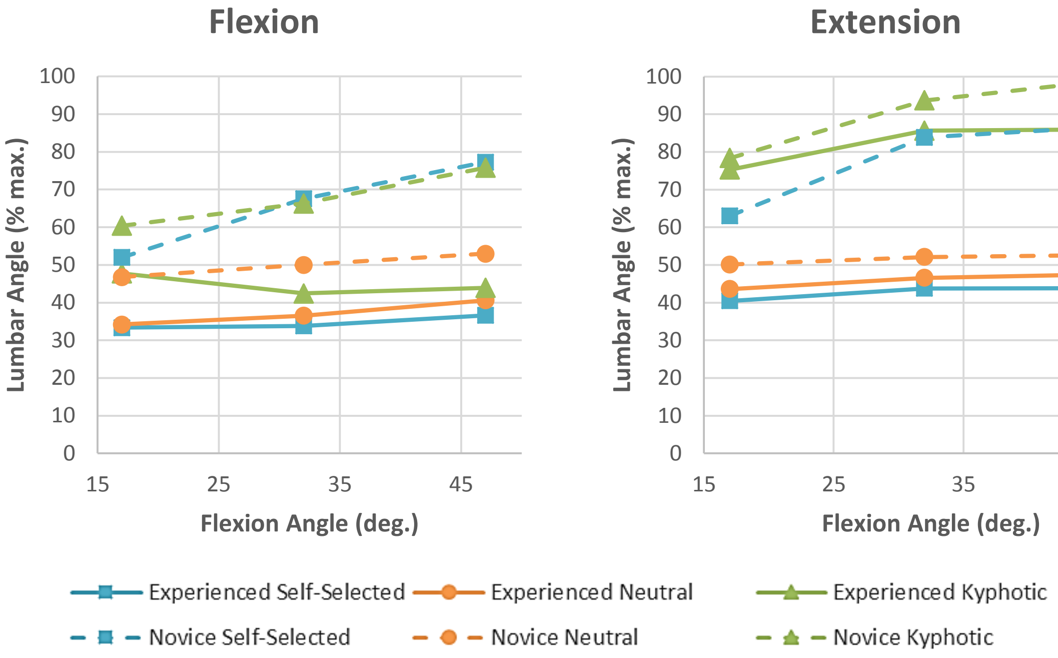

Figure 3.6: Average lumbar angle (normalized to subjects' ROM) for experienced and novice lifters as a function of torso flexion angle for the flexion and extension phases of the lifting cycles.

Statistical significance was found when comparing the lumbar angles of subjects based solely on experience level as well as when comparing the kyphotic strategy with either the self-selected or neutral. There was also a significant difference when experience level was taken into account when comparing self-selected with the kyphotic lifting strategy. However, a significant difference in lumbar angle was not found when comparing neutral lifts to either other strategy, when also considering experience level.

	p-value
Experience Level	< 0.05
Strategy	< 0.05
Self-Selected vs. Neutral	0.175
Self-Selected vs. Kyphotic	< 0.05
Neutral vs. Kyphotic	< 0.05
Quadrant	< 0.05
Quad. 1 vs. Quad. 2	< 0.05
Quad. 2 vs. Quad. 3	0.096
Strategy*Experience Level	0.066
Quadrant*Experience Level	< 0.05
Strategy*Quadrant	< 0.05

Table 3.2: p-values for lumbar angle data from repeated measures ANOVA with experience level as the between subjects factor.

The erector spinae lengths (Figure 3.7), output from the spinal model, give similar patterns to the lumbar angles from Figure 3.6. Again the novice's self-selected lifts are similar to the kyphotic lifts and the experienced lifters' self-selected are very close to their neutral lifting pattern.

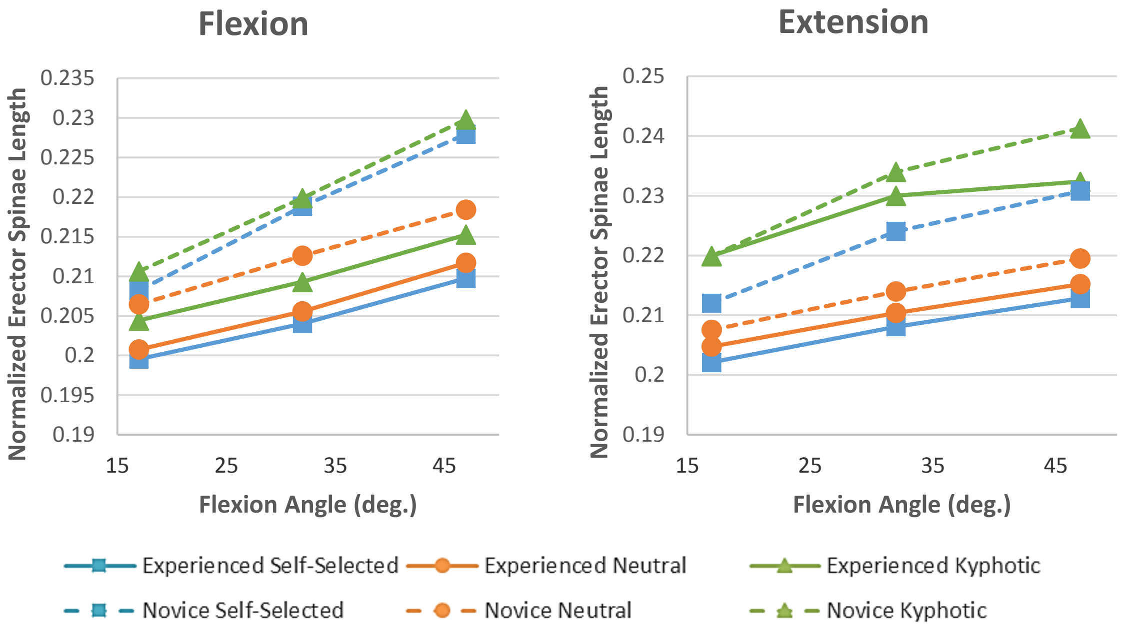

Figure 3.7: Average erector spinae muscle length (normalized to subject height) for experienced and novice lifters as a function of torso flexion angle for the extension phase of the lifting cycles.

As with the lumbar angles, overall the strategies were significantly different, with kyphotic in comparison with the other two strategies still being significant. However, when taking into account experience level, self-selected vs. neutral actually becomes the only strategy comparison to be statistically significant. The quadrant taken with either the experience level or the strategy is also significant.

	p-value
Experience Level	0.204
Strategy	< 0.05
Self-Selected vs. Neutral	0.224
Self-Selected vs. Kyphotic	< 0.05
Neutral vs. Kyphotic	< 0.05
Quadrant	< 0.05
Quad. 1 vs. Quad. 2	< 0.05
Quad. 2 vs. Quad. 3	< 0.05
Strategy*Experience Level	< 0.05
Self-Selected vs. Neutral*Exper. Level	< 0.05
Self-Selected vs. Kyphotic*Exper. Level	0.061
Neutral vs. Kyphotic*Exper. Level	0.831
Quadrant*Experience Level	< 0.05
Strategy*Quadrant	< 0.05

Table 3.3: p-values for erector spinae length from repeated measures ANOVA with experience level as the between subjects factor.

From the EMG readings (Figure 3.8), we could see that experienced lifters' neutral and self-selected lifting patterns followed a similar trajectory. However the neutral strategy was shifted upward so that the entire lifting cycle took place between normalized EMG readings of 0.59 and 0.83 while the self-selected lifting cycle occurred between 0.36 and 0.67. The kyphotic strategy was fairly constant for the decent but varied relativily drastically for the ascent by starting out below the self-selected (0.51) and quickly rising to 0.78 before ending at 0.83.

The self-selected strategy for the novice lifters was similar to that of the experienced group, with only a percent difference of 14% at its highest and 4% at its lowest. The neutral strategy followed a similar path as the experienced but was shifted down with the decent between 0.48 and 0.52. The extension phase of the lift stayed between 0.60 and 0.65 for the three analyzed quadrants. During the kyphotic lifts, the novice lifters' EMG recordings were very similar to the experienced for the first two quadrants during extension (<4%) but reached a 19%

difference by the third quadrant. During flexion, novice subjects' were unique as they started out at 0.46, moving upward to 0.55, before dropping back down to 0.39 in the third quadrant.

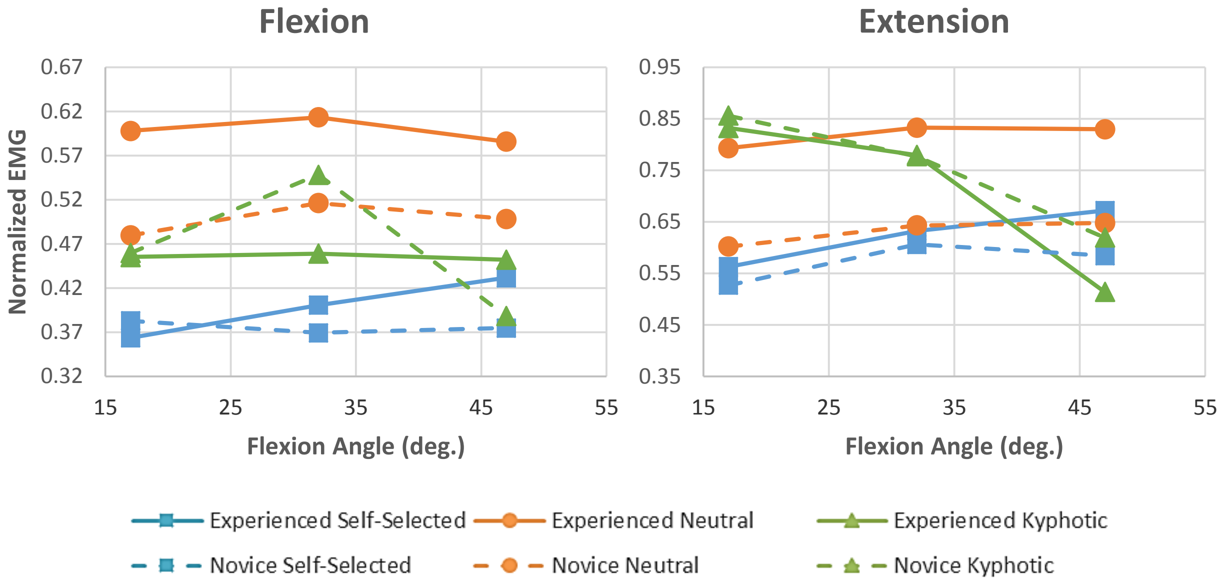

Figure 3.8: Right erector spinae EMG signal for experienced and novice lifters as a function of torso flexion angle for the extension phase of the lifting cycles. All strategies were normalized to their respective average cyclic maximums.

A statistical difference ($p<0.05$) was not found between the novice and experienced lifting groups, nor between the lifting strategies as a whole. There was a statistical significance when the strategy and quadrant were considered together. Cycles were not found to be significant, as would be expected.

	p-value
Experience Level	0.64
Strategy	0.084
Quadrant	0.106
Strategy*Experience Level	0.236
Quadrant*Experience Level	0.831
Strategy*Quadrant	**< 0.05**

Table 3.4: p-values for EMG data from repeated measures ANOVA with experience level as the between subjects factor.

The above EMG and ES length data could then be combined to create averaged work loops for each strategy and experience group. As can be seen in Figure 3.9, the neutral lifting strategies for both groups encompassed much less area than the kyphotic patterns. Also, the preferred lifting strategy for the experienced lifters was similar to the neutral strategy while the novice's preferred appeared to be some combination of the two trained strategies.

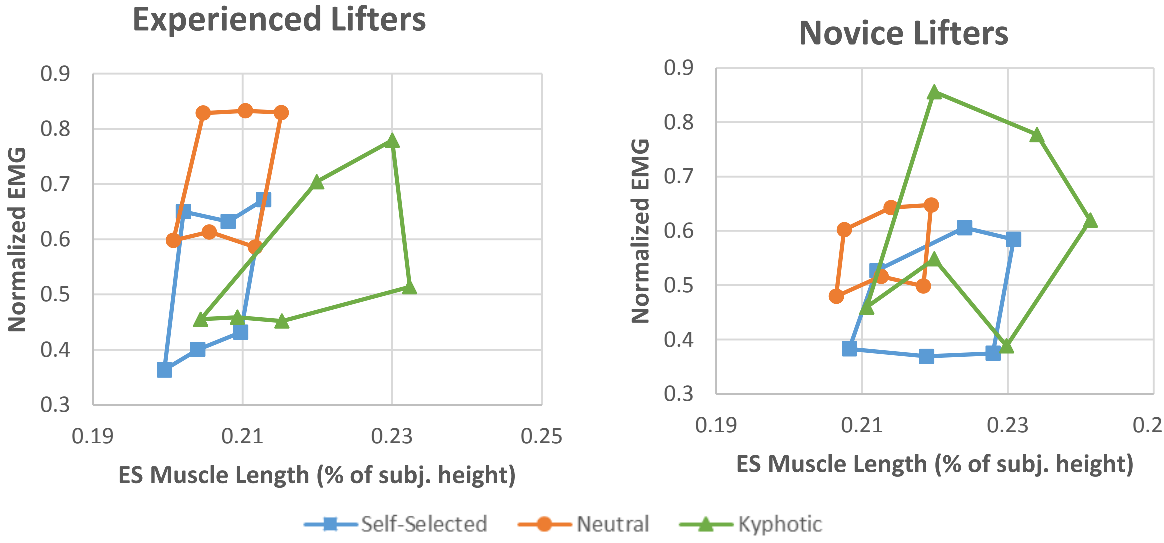

Figure 3.9: Averaged work loops for experienced and novice lifters for all three lifting strategies, for the first three trunk flexion angle quadrants.

Discussion

For this study it was hypothesized that novice lifters would prefer a lifting pattern that would involve them approaching the limits of their lumbar ROM, resulting in a lengthening of the erector spinae muscle, and requiring less muscle activation than the experienced lifters. It was thought that the novice lifting strategy would be more energy efficient as would be shown through its work loop encompassing a smaller area. It was also postulated that this strategy would be similar to the trained, kyphotic strategy. The experienced lifters, on the other hand, would lift with a more neutral spine, it was theorized, resulting in lifts that involved a shorter erector spinae muscle length and greater levels of EMG activation. Also, that these lifts would be less energy efficient as would be evident from a larger work loop area. Additionally, it was believed these lifts would be similar to the trained neutral strategy.

The results of this study show that the initial two hypotheses were correct. Novice lifters did approach the limits of their lumbar ROM, similarly to the kyphotic lifting strategy, whereas experienced lifters naturally lifted much closer to the trained neutral lifting pattern. Also the spine model showed that the erector spinae length was indeed longer for the kyphotic lifts and shorter for the neutral lifting patterns.

However, the results also showed that there was not a significant difference between novice and experienced lifters' muscle activation patterns. As can be seen in Figure 3.8, the two groups of lifters performed fairly similarly for each strategy. For the majority of the lifting cycle, subjects' preferred lifting strategy for both groups resulted in lower EMG readings. The only exception to this was actually the experienced kyphotic lift which was 16 percentage points lower than the self-selected. The kyphotic lifts appear to have required less muscle activation at the beginning of the extension phase but require just as much as neutral towards the top of the lift. This could result from pushing the hips forward earlier, as occurs during a kyphotic lift, and using the hamstring and gluteus muscles more instead of the erector spinae. However, perhaps in order to reach a fully erect position the erector spinae muscles do have to activate to raise the upper torso, seemingly with more force than normal to make up for the extra bending that occurs in the early part of a kyphotic lift. From the averaged work loops, the neutral lifting strategy appears to be more energy efficient than the kyphotic strategy, as it encompasses less area.

As stated in Maduri et al. [9], it was thought that novice subjects' preferred kyphotic lifting strategy would be more energetically efficient and require less muscle activation. In this study novice lifters appeared to approach the limits of their range of motion during extension, potentially increasing their risk of injury, so it was hypothesized there would be an advantage to this type of lift. Comparing the trained lifting strategies, it was expected that, if the kyphotic strategy was more efficient, we would see a smaller work loop area for this trained strategy. It was expected that the neutral strategy would require higher muscle activation and a larger work loop area. This was not observed (and in fact appeared to be more the converse in the novice subjects).

One issue that may have confounded the data is the potential for unfamiliarity of a lifting task altering a subject's performance. For example, in the trained strategies, the training itself might alter the energetics. Coactivation of the subjects' muscles and other energetically expensive changes in muscle coordination would increase the muscle activity and work required. Marras et al. [29] postulated that subjects develop more efficient motor recruitment patterns for lifting frequencies they are more familiar with. When forced to lift at an unfamiliar frequency, potentially similar to the one enforced by this study's metronome, subjects' muscle recruitment strategies became less efficient, with high levels of coactivation and overcompensation, potentially leading to the higher energetics observed in this study. Also, the act of keeping time with a metronome could have initially caused subjects to be more self-aware of their movements, maintain more controlled movements, and thus have a higher level of muscle coactivation. Perhaps once subjects became used to the rate at which they were expected to lift, they could have relaxed and lifted more naturally. Similarly to the imposed frequency, perhaps the training of the subjects itself influenced the muscle activation patterns. A trained lifting strategy is unnatural and could result in higher energetics as well, due to coactivation of muscle groups and poor muscle coordination during the unfamiliar task. While we had hypothesized that the kyphotic lifting strategy would be more energetically efficient than the neutral strategy, this is not what our results showed.

For the analysis of this study, the data was grouped into quadrants and all data points within a quadrant were averaged together. Future studies could look at the muscle length and activity in the quadrants individually. Particularly quadrants two and three, where the most differences between strategies and groups were observed in the averaged data. There was quite a bit of variability in the EMG data specifically within the individual quadrants so there could potentially be a pattern that was lost when the data was averaged together.

In conclusion, this study found that novice subjects naturally lifted similarly to the trained kyphotic strategy, approaching the limits of their ROM. Experienced subjects maintained a much more neutral lumbar region during the entire lifting cycle, very similar to their trained neutral strategy. The computer spine model showed that the erector spinae length was greater for the kyphotic lifts and shorter for the neutral lifts, as would be expected. However, from the averaged work loops, the kyphotic lifts did not appear to be more energetically efficient than the neutral lifting cycle. Therefore, it does not appear, at least from these findings, that novice lifters select a more kyphotic lifting pattern because of its potential to decrease fatigue.

CHAPTER 4 – Conclusion

Conclusions

The objective of this research was to analyze the differences in lumbar angle and muscle activation patterns between novice and experienced lifters during a repetitive lifting task. It was hypothesized that during extension, novice lifters would approach the limits of their lumbar ROM while experienced lifters would avoid these extremes and maintain a more neutral spinal posture. The first study (Chapter 2) confirmed this hypothesis showing that novice lifters' preferred lifting strategy was much more kyphotic for both the extension and flexion phases of a lifting cycle. Experienced lifters, on the other hand, maintained a neutral lumbar region relative to their ROM during the entire lifting cycle.

For Chapter 3, the analysis was taken a step further by comparing the subject's preferred lifting pattern to two trained strategies, neutral and kyphotic. A computer spine model was used to estimate the length of the subject's right erector spinae muscle during the lift which was compared to the muscle's EMG activation levels to create average work loops for the two groups of lifters for each strategy. As would be expected based off the finding from Chapter 2, novice lifter's preferred lifting strategy was very similar to their kyphotic strategy while experienced lifter's preferred lifting strategy very closely mirrored their trained neutral strategy. Likewise, the computational spine model showed that erector spinae lengths were longer for the kyphotic lifts and shorter during the neutral strategy.

It was hypothesized that a possible reason as to why novice lifters approach the limits of their ROM, potentially increasing their risk of injury, was that this type of lift utilized a stretch-shortening technique and was therefore more metabolically efficient. However, the results of the second study (Chapter 3) demonstrated that this does not appear to be the case. From the average work loops, it appeared that the neutral strategy was more energetically efficient than the kyphotic, as its work loop encompassed less area. Also, the work loop for the preferred lifting strategy for experienced lifters encompassed a similar amount of area as did the novice lifters. This gives the impression that the preferred lifting strategy of novice lifters was not chosen for being more energetically efficient.

Future Work

Future research on this topic could involve evaluating the energetic efficiency of the lifting tasks through a different means, such as measuring the amount of CO_2 that a subject expels. This would be a more direct method for gauging the efficiency of each lifting strategy and would not be confounded by the indirect nature of the EMG measurement representing muscle force and the model determination of muscle length.

Additionally, it would be worthwhile to evaluate the subjects' performance over time. For this study, only the initial lifting cycles were assessed and it was speculated that the unfamiliar frequency and patterns subjects were forced to lift at could itself result in less efficient movements. Perhaps as the subjects became more accustomed to the task, they may have lifted more naturally and efficiently. However, the longer a subject lifts the higher the likelihood their muscles will become fatigued leading to less reliable data.

Finally, this research examined experienced lifters versus novice lifters on the thought that experienced lifters would avoid motion patterns that increase the risk of low back injuries.

Future research could strengthen this conclusion by examining whether lifting patterns are predictive of low back injuries over time in the workplace. Additionally, future research could examine whether training low back pain sufferers in more neutral lifting patterns could reduce reinjury rates.

In conclusion, this research found experienced lifters preferred a more neutral lifting strategy relative to novice lifters. While novice lifters prefer a more kyphotic, pelvis-first strategy for the extension phase of lifting. From the averaged muscle force versus length work loops, this difference in lifting preference was not found to be due to any energetic advantage as had been previously hypothesized.

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APPENDIX A – Matlab Code

LiftPosition_001.m: Imports subject data, calculates normalized lumbar angles, and finds quadrant averages.

```
clear;
clc;
close all;
%   Author:         Tim Craig with edit by Alice Riley
%   Date Created:   1/10/2014
%   Revision Date:
%   Revision:
%   Program:        LiftPosition_001.m
%   Purpose:        Examine the repetitive lifting task, specifically
%   looking at the mechanics of the lifting phase. The steps are:
%       1) Load Data & Initialize Variables
%       2) Determine the flexion, lumbar, & normalized lumbar angles
%       4) Plot the data (flexion, normalized lumbar) during the lifting
%       phase. This is the feedback provided during experiment - include
%       target box.

%   Motion Monitor data by columns
%   1       = time step (1000Hz)
%   2-4     = sensor 1 xyz @ T10
%   5-7     = sensor 2 xyz @ sacrum
%   8-10    = sensor 3 xyz @ manubrium
%   11-14   = quaternions sensor 1
%   15-18   = quaternions sensor 2
%   19-22   = rES, lES, rRA, lRA

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Initialize Variables & Read in Stored Data from Excel
subLast = 33;
quad_range = [10 25; 25 40; 40 55; 55 70];

% Range of motion matrix:
% strategy & colstart are used in the loops to select the appropriate
% indexing of the stored values of ROM that was typed into Excel following
% the data collection.
strategy = ['SS1';'NU1';'PF1';'SS2';'NU2';'PF2';'SS3';'NU3';'PF3'];
colstart =  [1 5 9 1 5 9 1 5 9];


% Load the ROM data from the Excel spreadsheet
cd Data
ROMin(3:subLast,:) = xlsread('LiftAnalysisMaxEMG.xls','ROMin',['B3:M' ...
    num2str(subLast)]);
ROMax(3:subLast,:) = xlsread('LiftAnalysisMaxEMG.xls','ROMax',['B3:M' ...
    num2str(subLast)]);
cd ..
```

```
%   Create an output variable to save the results. Initialize all
%   elements to -1000 (out of range of expected).
output              = -1000.*ones(subLast,10,9);
flexion             = -1000.*ones(4000,subLast,9);
lumbar              = -1000.*ones(4000,subLast,9);
lumbarNorm          = -1000.*ones(4000,subLast,9);
pelvic              = -1000.*ones(4000,subLast,9);
cyc_avg_total       = -1000.*ones(subLast,32,9);

%   Index of directional shifts was determined previously using sensor 3z
%   and marking the peaks & valleys.  Verified visually by Alice Riley.
index = zeros(subLast,12,9);
for istrat = 1:9;
    index(3:end,:,istrat) = xlsread('Lifting_Indices2.xls', ...
        strategy(istrat,:), ['B3:M', num2str(subLast)]);
end



for istrat = 1:9;
    for isub = [3 4 6 7 9 10 12:13 15:19 25:33];

        %%   Load the trial data file
        cd Data;        % Change working directory to folder with data
        filename = ['S' num2str(isub) '_LIFT_' strategy(istrat,:) '.exp'];
        data = dlmread(filename,'\t',9,0);      % Remove header from data
        cd ..;          % Return to folder with m files

        % EMG data is removed from the position data & the position data is
        % downsampled to 100Hz from 1000HZ. Convert frame # to time(s).
        dataP = data(1:10:length(data),1:18);
        dataP(:,1)=dataP(:,1)/1000;

        num_cycles = 4;
        %Subject 22 for strategy 9 only has three usable cycles
        if (isub == 22 && istrat == 9)
            num_cycles = 3;
        end

        %% Determine the flexion, lumbar, and pelvis angles
        [flex, lumb, lumbNorm, pelv] = flexLumbar(dataP(:,1:18), ...
            ROMax(isub, colstart(istrat):colstart(istrat)+3), ...
            ROMin(isub, colstart(istrat):colstart(istrat)+3));

        % Making 3D data set (time pt, subject, strategy)
        flexion(1:length(flex),isub,istrat) = flex;
        lumbar(1:length(lumb),isub,istrat) = lumb;
        lumbarNorm(1:length(lumbNorm),isub,istrat) = lumbNorm;
        pelvic(1:length(pelv),isub,istrat) = pelv;

        %% Disect lift cycles into quadrants
        [cycle_avg] = Lift_Average2(flexion(1:length(flex),isub,istrat),...
            lumbarNorm(1:length(lumbNorm),isub,istrat), ...
```

```
            index(isub,:,istrat), quad_range, num_cycles, filename, istrat);

        %Fill the output variable to be saved outside the loop
        cyc_avg_total(isub,:,istrat) = cycle_avg;

    end

%% Save results to Excel
% cd Results;
% %filesave = ['Results ' date];
% filesave = ['FinalResults_Mar-10-2014'];
% page1 = ['avg_quad_sub ' strategy(istrat,:)];
% xlswrite(filesave,cyc_avg_total(25:33,:,1),page1,'B35'); %to save specific
sub data
% %xlswrite(filesave,cyc_avg_total(:,:,istrat),page1,'B11'); %to save all
subject data
% cd ..;

end
```

EXECSIMEdit.m

This is in initiation function for the model. This code loads muscle geometry data and lift posture data from xls files. It calls Statevariables which assigns spine shape. It also calls propmuscEdit (which in turn calls the function analys2.m) to set up the trunk geomtery with muscles. Finally it calls vischeme which creates a schematic of the trunk. At the end of this code, SolverP is called to begin solving the muscle forces.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Edited by: Alice Riley
%Date: 4/14/2014
%Modifications: Program finds new length of the muscle and plots it versus
%the emg of that muscle to find the area in the work loop

close all
clc
clear

global pelvic_tilt
global lumb_angle
global n
global height
global isub
global flex

disp(['Simulation Started:   ' datestr(clock,21)])

subLast = 33; %last subject number
strategy = ['SS1';'NU1';'PF1';'SS2';'NU2';'PF2';'SS3';'NU3';'PF3'];
work_loop_area = zeros(subLast,5,3); %5 work loops, 3 strategies (only used 4
WLs, 5th spot only used if one of the 1st 4 loops is troublesome)
index = Index(subLast);  % Load indices for directional shifts
cycle_avg = zeros(subLast,32,9);
indexNum = [0 0 14 14 0 12 14 0 14 12 0 10 12 8 14 12 11 10 14 0 14 12 14 14
12 12 12 10 12 9 10 8 10;
    0 0 12 12 0 12 12 0 12 12 0 10 12 12 12 10 12 12 10 0 12 12 12 10 10 12
12 8 12 12 8 10 10;
    0 0 14 14 0 14 14 0 14 12 0 12 14 10 12 9 12 10 14 0 14 12 12 12 14 10 10
12 12 9 10 10 10];
quad_range = [10 30; 30 45; 45 60; 60 80];
cycles = 4;

% Inputs from excel files
M=struct;E=struct;
[ROMin, ROMax, EMGMax, height] = ROM(subLast);% Load lumbar ROM, max emg, and
height data
height = height/39.3701; %convert from inches to meters
Mc=muscinput(M,'.\ChMusc\CholeMusc.xls');  %Cholwicki muscle file
%     Mc=muscmat(M);
E=forcinput(E,'LoadLift.xls'); % input external forces (not used for this
thesis)
```

```
Ec=forcmat(E); % applies input forces to a forcing matrix

for istrat = 1:3
    i=1;
    for isub = [3 4 6 7 9 10 12:13 15:19 21:23 24:33]
        Lo_total = zeros(subLast,3000,3);%only first three strategies

        para  %sets up spine mechanics and basic geometry parameters
        %(sub. height is input)
        [lumb_angle, pelvic_tilt, flex, norm_emg] = LoadData(ROMin, ROMax,
...
            EMGMax, isub, istrat);

        for n = 1:length(pelvic_tilt)
            Statevariables;  %input lordosis and pelvic angles

            % muscle default l
            [Lo,CSA]=propmuscEdit(Statevar2,Statevar1,Vars,Mc,Ec); %Lo=new
muscle length
            CSA = 1*CSA;

            Lo_total(isub,n,istrat) = mean(Lo(13:14)); %muscle length during
movement

            %if any(n==index(isub,:,istrat))
            %%% initial build
            flagd=1;
            if(flagd==1)
                vischeme(Statevar2,Statevar1,Mc,Ec,V,zeros(size(Mc,1),1));
                drawnow % flush pending graphics events
                hold off
            end
        end

        %% Disect lift cycles into quadrants
        cycle_avg(isub,:,istrat) =
Length_Average2(flex(1:index(isub,indexNum(istrat,isub),istrat)),...
            Lo_total(isub,1:index(isub,indexNum(istrat,isub),istrat),istrat),
...
            index(isub,1:indexNum(istrat,isub),istrat), quad_range,
cycles,isub);

        %%
        % %         i=i+1;
        % %         Lo_total(isub,536,istrat)
        % %         figure(i)
        %                figure(isub*10+istrat)
        %                 subplot(3,2,1)
        %                 plot(lumb_angle(:))
        %                 ylabel('Lumbar Angle')
        %                 hold on
        %
plot(index(isub,1:2:indexNum(istrat,isub),istrat),lumb_angle(index(isub,1:2:i
ndexNum(istrat,isub),istrat)),'go')
```

```
        %
plot(index(isub,2:2:indexNum(istrat,isub),istrat),lumb_angle(index(isub,2:2:i
ndexNum(istrat,isub),istrat)),'ro')
        %                 tname = ['Subject#' num2str(isub) '  Strategy: '
strategy(istrat,:)];
        %                 title(tname)
        %
        %                 subplot(3,2,2)
        %                 plot(flex(:))
        %                 ylabel('Flexion Angle')
        %                 hold on
        %
plot(index(isub,1:2:indexNum(istrat,isub),istrat),flex(index(isub,1:2:indexNu
m(istrat,isub),istrat)),'go')
        %
plot(index(isub,2:2:indexNum(istrat,isub),istrat),flex(index(isub,2:2:indexNu
m(istrat,isub),istrat)),'ro')
        %
        %                 subplot(3,2,3)
        %                 plot(pelvic_tilt(:))
        %                 ylabel('Pelvic Tilt')
        %                 hold on
        %
plot(index(isub,1:2:indexNum(istrat,isub),istrat),pelvic_tilt(index(isub,1:2:
indexNum(istrat,isub),istrat)),'go')
        %
plot(index(isub,2:2:indexNum(istrat,isub),istrat),pelvic_tilt(index(isub,2:2:
indexNum(istrat,isub),istrat)),'ro')
        %
        %                 subplot(3,2,4)
        %                 plot(Lo_total(isub,:,istrat))
        %                 ylabel('Muscle Length')
        %                 hold on
        %
plot(index(isub,1:2:indexNum(istrat,isub),istrat),Lo_total(isub,index(isub,1:
2:indexNum(istrat,isub),istrat),istrat),'go')
        %
plot(index(isub,2:2:indexNum(istrat,isub),istrat),Lo_total(isub,index(isub,2:
2:indexNum(istrat,isub),istrat),istrat),'ro')
        %                 Lo_total(isub,536,istrat)
        %
        %                 subplot(3,2,5)
        %                 plot(norm_emg(:,1))
        %                 ylabel('Normalized EMG')
        %                 hold on
        %
plot(index(isub,1:2:indexNum(istrat,isub),istrat),norm_emg(index(isub,1:2:ind
exNum(istrat,isub),istrat)),'go')
        %
plot(index(isub,2:2:indexNum(istrat,isub),istrat),norm_emg(index(isub,2:2:ind
exNum(istrat,isub),istrat)),'ro')
        %                         lname = ['Average EMG = ' num2str(avgEMG)];
        %                         legend(lname)
        %
```

```
        %% Save figures
        %         pause(0.00001);
        %         frame_h = get(handle(gcf),'JavaFrame');
        %         set(frame_h,'Maximized',1); %maximize figure
        %         cd Results;
        %         filesave = ['Total_Check' num2str(isub) '.bmp'];
        %         saveas(gcf,filesave)
        %         cd ..;

    end

    %% Save ES length average results to Excel
    % cd Results;
    % %filesave = ['ESResults ' date];
    % filesave = ['FinalResults_Mar-11-2014'];
    % page1 = ['avg_ES_length ' strategy(istrat,:)];
    % %xlswrite(filesave,cyc_avg_total(25:33,:,1),page1,'B35'); %to save
specific sub data
    % xlswrite(filesave,cycle_avg(:,:,istrat),page1,'B11'); %to save all
subject data
    % cd ..;
end
```

anatomvert_test03.m: Function called by EXECSIMEdit.m -> Statevariables (calculates angles of individual lumbar vertebrae based off the overall lumbar angle)

```
function [Lordang]=anatomvert_test03()
% specify relative vertebral positions and offset measure
%in anterior-posterior angles.
%Indices and L numbers are annoyingly off because of the conversion from C++
to Matlab which begins indexing at 1 instead of 0.
%Body 8=Newtonian
%Body 7=Pelvis
%Body 6=L5
%Body 5=L4
%Body 4=L3
%Body 3=L2
%Body 2=L1
%Body 1=Upper Trunk

global lumb_angle
global pelvic_tilt
global flex
global n

Lordang=zeros(7,1);
Lordang(7)=toRadians('degrees',-pelvic_tilt(n));  %Pelvis
lumb = -(lumb_angle(n));

if (lumb_angle(n) < 0)  %lumbar vert. are in extension (lordotic)
    Lordang(6)=toRadians('degrees',lumb*0.312);       %L5
    Lordang(5)=toRadians('degrees',lumb*0.125);       %L4
    Lordang(4)=toRadians('degrees',lumb*0.063);       %L3
    Lordang(3)=toRadians('degrees',lumb*0.188);       %L2
    Lordang(2)=toRadians('degrees',lumb*0.312);       %L1
    Lordang(1)=toRadians('degrees',-flex(n));         %Thorax
else
    %lumbar vert. are in flexion (kyphotic)
    Lordang(6)=toRadians('degrees',lumb*0.173);       %L5
    Lordang(5)=toRadians('degrees',lumb*0.25);        %L4
    Lordang(4)=toRadians('degrees',lumb*0.23);        %L3
    Lordang(3)=toRadians('degrees',lumb*0.192);       %L2
    Lordang(2)=toRadians('degrees',lumb*0.153);       %L1
    Lordang(1)=toRadians('degrees',-flex(n));         %Thorax
end

    Lordang(6)=Lordang(6)+Lordang(7);
    Lordang(5)=Lordang(5)+Lordang(6);
    Lordang(4)=Lordang(4)+Lordang(5);
    Lordang(3)=Lordang(3)+Lordang(4);
    Lordang(2)=Lordang(2)+Lordang(3);
   % Lordang(1)=Lordang(1)+Lordang(2);

%percentages for individual lumbar angles were taken from Pearcey (1985)
%Table 6
end
```

EMGPeakNormalize.m: Program used to analyze the EMG data.

```
%   Author:         Alice Riley
%   Date Created:   7/15/2014
%   Program:        EMGPeakNormalize.m
%   Purpose:        This program imports trial EMG data and averages four
%                   clean peak values together to use as a normalization
%                   constant for the trial as a whole. EMG data is then
%                   averaged within flexion angle quadrants.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear
clc

subLast = 33;
quad_range = [10 25; 25 40; 40 55; 55 70];
fsampling = 1000;  %sampling frequency
colstart =  [1 5 9 1 5 9 1 5 9];
strategy = ['SS1';'NU1';'PF1';'SS2';'NU2';'PF2';'SS3';'NU3';'PF3'];
%Number of indices for each subject and strategy
indexNum = [0 0 14 14 0 12 14 0 14 12 0 10 12 8 14 12 11 10 14 0 14 12 14 14
12 12 12 10 12 9 10 8 10;
    0 0 12 12 0 12 12 0 12 12 0 10 12 12 12 10 12 12 10 0 12 12 12 10 10 12
12 8 12 12 8 10 10;
    0 0 14 14 0 14 14 0 14 12 0 12 14 10 12 9 12 10 14 0 14 12 12 12 14 10 10
12 12 9 10 10 10];

gain = [0 0 0 0;   %gain for each subject, for each muscle
    0 0 0 0;
    10000 10000 10000 1000;
    1000 1000 1000 1000;
    0 0 0 0;
    10000 10000 10000 10000;
    1000 1000 1000 1000;
    0 0 0 0;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 100 1000 1000;   %Left ES gain moved to 100 after max test
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    0 0 0 0;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    0 0 0 0;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
```

```
    1000 1000 1000 1000; %Subj.#27
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    1000 1000 1000 1000;
    ];

index = Index(subLast);  % Load indices for directional shifts
% Load the ROM data from the Excel spreadsheet
cd Data
ROMin(3:subLast,:) = xlsread('LiftAnalysisMaxEMG.xls','ROMin',['B3:M' ...
    num2str(subLast)]);
ROMax(3:subLast,:) = xlsread('LiftAnalysisMaxEMG.xls','ROMax',['B3:M' ...
    num2str(subLast)]);
cd ..

strat = ['SS1';'NU1';'PF1';'SS2';'NU2';'PF2';'SS3';'NU3';'PF3'];
%  1 - Right ES
%  2 - Left ES
%  3 - Right RA
%  4 - Left RA

%%
datapath=('C:\Users\Alice\Documents\MATLAB\LiftingResearch\DataAnalysis\Posit
ion Analysis\Data\');
for istrat = 1
    for isub = [3 4 6 13 15 18 22 23 25:33]
        filename = [datapath 'S' num2str(isub) '_LIFT_' strat(istrat,:)
'.exp'];
        data = dlmread(filename,'\t',9,0);  %load data
        dataEMG = data(:,19);  %keep only the right ES data
        iemg = EMGclean(dataEMG,gain(isub,1)); %filter data (1 for right ES)

        % EMG data is removed from the position data & the position data is
        % downsampled to 100Hz from 1000HZ. Convert frame # to time(s).
        dataP = data(1:10:length(data),1:18);
        dataP(:,1)=dataP(:,1)/1000;

        %% Determine the flexion, lumbar, and pelvis angles
        [flex, lumb, lumbNorm, pelv] = flexLumbar(dataP(:,1:18), ...
            ROMax(isub, colstart(istrat):colstart(istrat)+3), ...
            ROMin(isub, colstart(istrat):colstart(istrat)+3));
        clear lumb lumbNorm pelv

       %Find moving average of data
        window = 100;
        for n = 1:size(iemg)-(window-1)
            set = iemg(n:(n+(window-1)));
            MovAvgEMG(n) = mean(set);
        end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %Data sets that weren't long enough to do 4 complete work loops or had section of bad data.
        if (isub==32 && istrat==1)
            cycles = 3;
            phases = 7;
        elseif (isub==31 && istrat==2)
            cycles = 3;
            phases = 7;
        elseif (isub==28 && istrat==2)
            cycles = 3;
            phases = 7;
        else
            cycles = 4;
            phases = 8;
        end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %% Identify EMG peak maximums
        l = length(iemg);
        avght = mean(iemg);
        ht = avght + (avght/3);
        dist = l/14;    %time for a cycle to occur/2 (if max # of cycles is 7)
        [peak, ipeak] = findpeaks(iemg(10*index(isub,1,istrat):end),'MINPEAKHEIGHT',ht,'MINPEAKDISTANCE',round(dist));

        %Helps to prevent cutoff peak at beginning of data
        if ipeak(1) < 0.01*l/2
            ipeak(1) = [];
            peak(1) = [];
        end

        %Remove errant peaks (found by visual inspection)
        if (isub == 25 && istrat == 1)
            peak(4)=[];
            ipeak(4)=[];
            peak(3)=[];
            ipeak(3)=[];
        elseif (isub == 13 && istrat == 1)
            peak(5) = [];
            ipeak(5) = [];
            peak(1) = [];
            ipeak(1) = [];
        elseif((isub == 18||isub == 30||isub == 32) && istrat == 1)
            peak(3)=[];
            ipeak(3)=[];
        elseif (isub == 3 && istrat == 2)
            peak(4) = [];
            ipeak(4) = [];
            peak(2) = [];
            ipeak(2) = [];
        elseif ((isub == 13||isub == 33) && istrat == 2)
```

```
    peak(4) = [];
    ipeak(4) = [];
elseif (isub == 29 && istrat == 2)
    peak(3) = [];
    ipeak(3) = [];
elseif (isub == 31 && istrat == 2)
    peak(4) = [];
    ipeak(4) = [];
    peak(2) = [];
    ipeak(2) = [];
elseif (isub == 6 && istrat == 3)
    peak(1) = [];
    ipeak(1) = [];
elseif (isub == 23 && istrat == 3)
    peak(2) = [];
    ipeak(2) = [];
elseif (isub == 25 && istrat == 3)
    peak(2) = [];
    ipeak(2) = [];
elseif (isub == 27 && istrat == 3)
    peak(5) = [];
    ipeak(5) = [];
    peak(3) = [];
    ipeak(3) = [];
elseif (isub == 28 && istrat == 3)
    peak(2) = [];
    ipeak(2) = [];
elseif (isub == 30 && istrat == 3)
    peak(1) = [];
    ipeak(1) = [];
elseif ((isub == 31||isub == 32) && istrat == 3)
    peak(6) = [];
    ipeak(6) = [];
    peak(4) = [];
    ipeak(4) = [];
    peak(2) = [];
    ipeak(2) = [];
end

normVal(isub,istrat) = mean(peak(1:4)); %normalization value
normEMG = iemg./normVal(isub,istrat);
emg = normEMG(1:10:end);

%EMG_Quads2 requires a full data set so interpolate all 4 cycles
%before averaging the quadrants
tail = 1;
for iphase = 1:phases
x = flex(index(isub,iphase,istrat):index(isub,iphase+1,istrat));
y = emg(index(isub,iphase,istrat):index(isub,iphase+1,istrat));

xnew = 10:1:70;
ynew = interp1(x,y,xnew);

emgnew(tail:tail+length(ynew)-1) = ynew;
flexnew(tail:tail+length(xnew)-1) = xnew;
```

```
%         figure(isub+iphase)
%         plot(xnew,ynew,'r')
%         hold on
%         plot(x,y)
%         plot(flexnew(tail:tail+length(xnew)-
1),emgnew(tail:tail+length(xnew)-1),'g--')
        tail = tail+length(ynew);
        end

        indexnew = [1 62 123 184 245 306 367 428 488];
      cycle_avg(isub,:,istrat) =
EMG_Quads2(flexnew,emgnew,indexnew,quad_range,cycles,istrat);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    end
    %
    %     cd Results;
    %     filesave = ['AveragePeakNormalization'];
    %     sheet_name = [strat(istrat,:)];
    %     xlswrite(filesave,normVal,sheet_name,'B11');
    %     cd ..;

    %% Save results to Excel
% cd Results;
% %filesave = ['Results ' date];
% page1 = ['EMG_quads ' strategy(istrat,:)];
% xlswrite(filesave,cycle_avg(:,:,istrat),page1,'B11'); %to save specific sub
data
% %xlswrite(filesave,cyc_avg_total(:,:,istrat),page1,'B11'); %to save all
subject data
% cd ..;
end
```

EMG_Quads2.m: Finds the average of each quadrant for four lifting cycles for each subject. (Same method was used for normalized lumbar angle and muscle length data)

```
% Author:           Alice Riley
% Date Created:     1/14/2014
% Program:          EMG_Quads2.m
%This program looks at data from a single subject and a single strategy(1-9).
%It averages the lumbar angles of each cycle(cycle includes downward and
%lifting parts) within four defined quadrants of flexion angle.

%cycle_avgs is a single row with average data ordered as:
%Lifting Phase  ->  1st cycle, 1st quad
%                   2nd cycle, 1st quad
%                   3rd cycle, 1st quad
%                   4th cycle, 1st quad
%                   1st cycle, 2nd quad
%                   2nd cycle, 2nd quad...
%Downward Phase ->  1st cycle, 1st quad
%                   2nd cycle, 1st quad...(Same as lifting phase)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Used for testing
% index = xlsread('Lifting_Indices.xls','PelvisFirst1','B9:J9');
% data = xlsread('S10_LIFT_PF1.xlsx','B1','B2:D2529');
% flexion = data(1:index(end),1);
% lumbar_norm = data(1:index(end),3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [cycle_avgs] =
EMG_Quads2(flexion,emg,index,quad_range,cycles,istrat)
%% Break into Quadrants

% Initialize the output variable size
cycle_avgs = -1000.*ones(1,32);
count = 1;
for iquad = 1:4
    for icycle = 1:4
        if (cycles == 3 && icycle == 4)
            count = count + 1;
            break
        end
        % lumbar values for individual lifting phase
        lift_lumbar = emg(index(2*icycle-1):index(icycle*2));
        lift_flexion = flexion(index(2*icycle-1):index(icycle*2));
        % lumbar values for individual lowering phase
        down_lumbar = emg(index(2*icycle):index(icycle*2+1));
        down_flexion = flexion(index(2*icycle):index(icycle*2+1));

        % finds lift indices of the cycle for the current quad
```

```
        lquad = find(lift_flexion > quad_range(iquad,1) & ...
            lift_flexion <= quad_range(iquad,2));
        % finds downward indices of the cycle for the current quad
        dquad = find(down_flexion > quad_range(iquad,1) & ...
            down_flexion <= quad_range(iquad,2));

        cycle_avgs(count) = nanmean(lift_lumbar(lquad));
        cycle_avgs(count+16) = nanmean(down_lumbar(dquad));

        %%%    Check to see the points that are being averaged
%                figure(10*iquad+icycle)
%                plot(lift_flexion, lift_lumbar)
%                hold on
%                plot(down_flexion, down_lumbar)
%                plot(lift_flexion(lquad),lift_lumbar(lquad),'go')
%                plot(down_flexion(dquad),down_lumbar(dquad),'ro')

        count = count + 1;
    end
end
end
```

APPENDIX B – Subject Data

Normalized Lumbar Angle – Self-Selected lifting strategy

Self-Selected	Extension				Flexion			
	Quad 1	Quad 2	Quad 3	Quad 4	Quad 1	Quad 2	Quad 3	Quad 4
Subject 3	73.4656	90.7408	94.9062	89.075	66.2929	77.106	87.0259	87.63103
Subject 4	47.1092	45.4555	41.3521	31.698	37.9022	35.22	32.1036	24.09999
Subject 6	99.7295	145.007	172.266	176.61	65.42	97.644	146.093	164.6686
Subject 7	83.397	103.462	130.279	159.28	83.4543	104.15	137.648	155.4486
Subject 9	32.7527	51.78	67.3554	67.828	25.7488	39.552	55.8415	66.04729
Subject 12	147.339	179.051	121.423	88.317	108.7	118.03	85.8877	68.26584
Subject 13	112.799	160.47	140.286	113.22	96.4555	144	139.439	107.1365
Subject 14	62.2726	99.8054	111.616	130.58	43.3257	46.61	58.2101	66.6341
Subject 15	67.3209	80.8638	88.9239	NA	51.3531	64.059	87.8523	NA
Subject 16	70.7386	93.5582	109.445	99.602	34.5112	55.119	92.4362	95.67871
Subject 17	65.675	69.59	65.1751	52.879	57.155	57.569	47.0974	34.74908
Subject 18	26.3705	44.2425	49.8264	56.748	20.9791	35.901	47.0878	61.03565
Subject 19	49.0197	58.5961	69.2965	77.58	37.145	49.467	68.5326	84.87032
Subject 21	19.8295	35.8493	51.598	63.86	10.8684	12.479	15.3026	41.83655
Subject 22	79.1957	110.441	112.908	101.9	69.7362	86.643	104.464	105.8998
Subject 23	35.9875	30.7039	14.1322	NA	30.6008	22.049	8.03223	NA
Subject 24	38.2581	27.3897	34.4618	36.746	29.5955	17.984	26.9795	28.26435
Subject 25	30.5568	45.7169	51.1408	48.709	24.1258	27.324	26.2096	26.82493
Subject 26	28.8381	31.7997	34.5098	42.433	23.8746	28.69	34.3573	42.05464
Subject 27	43.5032	57.3962	64.6282	62.329	34.4652	37.606	46.6131	47.5285
Subject 28	59.5098	71.282	73.429	73.772	52.2867	64.919	70.4202	70.53917
Subject 29	49.5437	59.7281	67.5663	71.688	29.2321	34.976	46.9445	60.07887
Subject 30	32.3419	36.2604	44.9691	46.18	28.8805	31.029	36.3876	37.82277
Subject 31	22.2092	13.5507	2.72656	NA	20.5713	12.049	2.1021	NA
Subject 32	38.5404	41.2979	45.5157	46.016	34.7925	39.08	42.755	44.18417
Subject 33	43.904	39.7681	33.5836	25.53	48.015	40.082	30.8251	22.94766

Normalized Lumbar Angle – Neutral lifting strategy

Neutral	Extension				Flexion			
	Quad 1	Quad 2	Quad 3	Quad 4	Quad 1	Quad 2	Quad 3	Quad 4
Subject 3	55.802	59.2214	61.049	61.523	51.627	55.012	58.961	62.33
Subject 4	60.389	58.9699	57.352	55.989	53.836	49.451	47.244	44.896
Subject 6	46.658	50.3856	53.2	50.099	35.616	32.085	33.793	31.827
Subject 7	78.03	96.9389	124.19	183.7	86.118	112.55	141.85	167.59
Subject 9	49.52	49.4709	59.854	66.68	48.036	53.676	65.013	68.764
Subject 12	45.132	57.4108	57.671	55.129	40.989	44.124	44.095	43.78
Subject 13	53.578	45.9329	43.141	40.309	72.922	97.771	117.04	112.44
Subject 14	58.987	63.0968	38.677	11.605	45.442	40.574	23.98	32.221
Subject 15	29.935	21.6725	28.958	78.002	35.668	54.943	76.854	93.652
Subject 16	28.177	41.2329	49.048	48.536	19.027	28.109	49.099	45.003
Subject 17	78.934	88.86	85.524	79.214	50.078	34.542	38.118	55.092
Subject 18	44.766	49.5461	53.647	58.628	41.893	46.254	47.499	53.93
Subject 19	40.031	49.514	54.066	76.121	35.968	49.292	70.85	82.155
Subject 21	1.0723	17.0307	17.688	21.129	NA	NA	6.4656	19.721
Subject 22	70.068	70.0499	59.732	47.697	59.389	54.528	52.211	43.503
Subject 23	33.854	48.0783	50.281	46.3	22.102	19.527	21.767	23.395
Subject 24	52.811	42.5713	47.533	45.883	48.457	40.003	48.026	44.588
Subject 25	39.805	48.0041	46.114	39.309	32.392	30.679	28.372	26.273
Subject 26	38.344	42.2116	43.575	46.61	31.484	30.416	36.801	46.869
Subject 27	58.368	58.6197	55.448	49.816	50.121	54.35	58.249	59.243
Subject 28	40.921	42.7298	49.695	53.918	44.52	54.715	60.124	57.612
Subject 29	55.844	59.1013	57.595	54.402	36.517	37.995	40.549	44.394
Subject 30	56.33	48.6911	48.139	47.045	51.74	42.391	39.629	37.707
Subject 31	35.087	41.048	39.398	22.85	20.694	18.474	13.506	6.4072
Subject 32	38.999	44.1955	50.458	53.345	28.857	29.485	31.521	34.028
Subject 33	41.008	53.3822	56.97	56.687	25.411	34.252	37.733	36.832

Normalized Lumbar Angle – Kyphotic lifting strategy

Kyphotic	Extension				Flexion			
	Quad 1	Quad 2	Quad 3	Quad 4	Quad 1	Quad 2	Quad 3	Quad 4
Subject 3	76.741	105.421	105.494	94.372	58.067	64.435	73.136	75.421
Subject 4	72.692	86.4551	98.5017	95.453	49.043	50.507	56.494	63.273
Subject 6	101.26	131.693	131.169	120.49	58.383	72.849	93.946	105.39
Subject 7	95.296	138.227	172.104	198.34	101.28	140.36	161.41	185.13
Subject 9	91.674	94.5406	104.65	102.9	78.144	86.414	94.219	93.815
Subject 12	87.263	97.4002	96.4306	86.299	63.248	71.556	76.928	78.68
Subject 13	87.561	102.259	117.371	114.43	83.006	99.523	119.66	116.8
Subject 14	77.191	92.817	78.5933	58.762	43.03	37.79	26.346	21.016
Subject 15	65.678	91.3821	91.0289	74.524	NA	29.243	44.46	55.932
Subject 16	72.741	91.7217	93.8058	78.712	38.962	60.379	85.419	75.459
Subject 17	86.772	82.26	58.8868	47.251	47.03	32.042	30.106	35.281
Subject 18	63.023	71.1863	75.7102	84.275	64.125	73.723	80.907	83.404
Subject 19	84.286	89.8992	96.7925	97.143	74.244	80.556	93.11	93.335
Subject 21	51.885	92.6579	90.4288	79.603	31.048	39.866	63.428	65.8
Subject 22	96.728	89.4543	90.3521	88.59	90.894	81.862	83.698	83.578
Subject 23	94.464	89.9051	79.708	79.676	61.988	50.771	43.722	28.926
Subject 24	91.874	83.2257	92.7966	92.527	84.806	71.864	79.717	77.873
Subject 25	54.823	86.3025	92.6563	80.451	33.969	33.209	32.081	33.129
Subject 26	41.213	53.8689	61.1128	68.121	35.846	45.642	53.411	70.308
Subject 27	87.141	96.1166	98.3849	95.457	51.826	48.361	51.887	59.47
Subject 28	72.73	86.2334	91.1645	88.004	52.741	71.097	84.351	86.368
Subject 29	73.847	85.1169	81.6367	69.366	48.296	47.059	45.151	42.973
Subject 30	97.552	85.2207	85.6139	83.016	68.25	54.872	52.792	53.182
Subject 31	50.472	66.3707	80.6604	77.661	29.048	25.407	23.751	23.054
Subject 32	79.522	83.7559	91.3487	96.977	53.536	49.784	57.747	73.016
Subject 33	92.214	116.98	109.439	96.812	38.878	38.34	36.315	38.114

Erector Spinae Muscle Length – Self-Selected lifting strategy (for reduced subject pool)

Self-Selected	**Extension**				**Flexion**			
	Quad 1	**Quad 2**	**Quad 3**	**Quad 4**	**Quad 1**	**Quad 2**	**Quad 3**	**Quad 4**
Subject 3	0.202	0.212	0.219	0.222	0.2022	0.205	0.214	0.222
Subject 4	0.208	0.213	0.216	0.216	0.203	0.207	0.212	0.215
Subject 6	0.236	0.257	0.264	0.265	0.2218	0.243	0.259	0.263
Subject 13	0.220	0.236	0.244	0.247	0.2137	0.232	0.244	0.246
Subject 15	0.201	0.215	0.222	NA	0.1961	0.209	0.223	NA
Subject 18	0.192	0.203	0.214	0.222	0.1911	0.201	0.214	0.224
Subject 22	0.211	0.232	0.241	0.245	0.2089	0.227	0.241	0.247
Subject 23	0.212	0.215	0.218	0.221	0.2106	0.213	0.217	0.221
Subject 25	0.209	0.214	0.219	0.224	0.2084	0.21	0.212	0.218
Subject 26	0.195	0.200	0.208	0.216	0.1925	0.199	0.208	0.215
Subject 27	0.184	0.194	0.200	0.203	0.1816	0.185	0.19	0.198
Subject 28	0.228	0.24	0.244	0.248	0.2254	0.237	0.243	0.246
Subject 29	0.204	0.213	0.223	0.233	0.1953	0.202	0.213	0.23
Subject 30	0.201	0.209	0.214	0.215	0.1994	0.206	0.21	0.213
Subject 31	0.206	0.205	0.205	0.204	0.2055	0.205	0.204	0.204
Subject 32	0.200	0.207	0.211	0.216	0.197	0.204	0.208	0.215
Subject 33	0.214	0.213	0.213	0.213	0.2154	0.214	0.213	0.212

Erector Spinae Muscle Length – Neutral lifting strategy (for reduced subject pool)

Neutral	**Extension**				**Flexion**			
	Quad 1	**Quad 2**	**Quad 3**	**Quad 4**	**Quad 1**	**Quad 2**	**Quad 3**	**Quad 4**
Subject 3	0.197	0.198	0.201	0.209	0.198	0.198	0.201	0.209
Subject 4	0.214	0.220	0.224	0.227	0.211	0.215	0.218	0.225
Subject 6	0.22	0.230	0.238	0.243	0.214	0.22	0.227	0.237
Subject 13	0.203	0.201	0.215	0.233	0.211	0.229	0.243	0.247
Subject 15	0.194	0.198	0.215	NA	0.195	0.207	0.224	NA
Subject 18	0.196	0.202	0.211	0.219	0.196	0.201	0.209	0.218
Subject 22	0.216	0.221	0.222	0.225	0.211	0.216	0.221	0.224
Subject 23	0.218	0.228	0.23	0.229	0.212	0.214	0.217	0.221
Subject 25	0.209	0.215	0.218	0.219	0.208	0.21	0.212	0.217
Subject 26	0.198	0.205	0.211	0.216	0.195	0.199	0.209	0.217
Subject 27	0.187	0.196	0.199	0.201	0.185	0.195	0.202	0.208
Subject 28	0.215	0.225	0.234	0.241	0.219	0.232	0.238	0.241
Subject 29	0.206	0.210	0.215	0.221	0.198	0.201	0.208	0.219
Subject 30	0.209	0.212	0.213	0.214	0.207	0.208	0.209	0.210
Subject 31	0.211	0.215	0.215	0.211	0.206	0.207	0.208	0.209
Subject 32	0.198	0.206	0.212	0.218	0.194	0.198	0.202	0.209
Subject 33	0.216	0.220	0.224	0.225	0.210	0.213	0.217	0.219

Erector Spinae Muscle Length – Kyphotic lifting strategy (for reduced subject pool)

Kyphotic	**Extension**				**Flexion**			
	Quad 1	**Quad 2**	**Quad 3**	**Quad 4**	**Quad 1**	**Quad 2**	**Quad 3**	**Quad 4**
Subject 3	0.203	0.227	0.228	0.224	0.196	0.201	0.209	0.216
Subject 4	0.222	0.238	0.245	0.243	0.209	0.217	0.225	0.235
Subject 6	0.246	0.261	0.266	0.266	0.222	0.234	0.252	0.261
Subject 13	0.219	0.235	0.245	0.249	0.217	0.234	0.246	0.249
Subject 15	0.209	0.223	0.226	0.224	0.192	0.202	0.216	0.222
Subject 18	0.201	0.210	0.221	0.230	0.201	0.211	0.222	0.230
Subject 22	0.218	0.222	0.234	0.241	0.216	0.222	0.233	0.240
Subject 23	0.236	0.247	0.245	0.242	0.220	0.226	0.232	0.238
Subject 25	0.215	0.233	0.240	0.238	0.209	0.211	0.213	0.222
Subject 26	0.200	0.211	0.219	0.231	0.198	0.208	0.219	0.234
Subject 27	0.202	0.219	0.223	0.223	0.185	0.192	0.199	0.211
Subject 28	0.236	0.248	0.254	0.255	0.222	0.239	0.249	0.254
Subject 29	0.215	0.223	0.226	0.227	0.202	0.205	0.209	0.222
Subject 30	0.242	0.245	0.244	0.235	0.216	0.217	0.218	0.222
Subject 31	0.220	0.230	0.232	0.228	0.209	0.210	0.212	0.216
Subject 32	0.220	0.231	0.238	0.243	0.204	0.210	0.219	0.235
Subject 33	0.235	0.243	0.243	0.239	0.214	0.215	0.217	0.222

Erector Spinae Normalized EMG Activity – Self-Selected lifting strategy (for reduced subject pool)

Self-Selected	Extension				Flexion			
	Quad 1	Quad 2	Quad 3	Quad 4	Quad 1	Quad 2	Quad 3	Quad 4
Subject 3	0.498	0.727	0.715	0.634	0.356	0.487	0.548	0.711
Subject 4	0.74	0.738	0.77	0.781	0.45	0.441	0.469	0.567
Subject 6	0.153	0.161	0.116	0.039	0.435	0.163	0.152	0.062
Subject 13	0.19	0.207	0.138	0.045	0.27	0.217	0.201	0.209
Subject 15	0.625	0.582	0.691	NA	0.276	0.278	0.302	NA
Subject 18	0.54	0.74	0.785	0.704	0.397	0.391	0.33	0.25
Subject 22	0.643	0.688	0.593	0.525	0.308	0.331	0.239	0.181
Subject 23	0.655	0.708	0.717	0.75	0.48	0.458	0.426	0.501
Subject 25	0.647	0.735	0.798	0.642	0.391	0.438	0.466	0.459
Subject 26	0.498	0.647	0.824	0.805	0.287	0.318	0.38	0.455
Subject 27	0.81	0.774	0.653	0.594	0.418	0.428	0.492	0.525
Subject 28	0.804	0.803	0.652	0.516	0.488	0.488	0.554	0.622
Subject 29	0.52	0.668	0.689	0.517	0.316	0.407	0.407	0.412
Subject 30	0.372	0.486	0.532	0.691	0.307	0.411	0.432	0.488
Subject 31	0.335	0.406	0.491	0.601	0.398	0.451	0.548	0.669
Subject 32	0.526	0.673	0.729	0.704	0.341	0.366	0.426	0.43
Subject 33	0.689	0.787	0.776	0.749	0.427	0.454	0.466	0.518

Erector Spinae Normalized EMG Activity – Neutral lifting strategy (for reduced subject pool)

Neutral	Extension				Flexion			
	Quad 1	Quad 2	Quad 3	Quad 4	Quad 1	Quad 2	Quad 3	Quad 4
Subject 3	0.339	0.36	0.371	0.35	0.23	0.253	0.324	0.278
Subject 4	1.011	0.927	0.832	0.807	0.615	0.665	0.697	0.755
Subject 6	0.085	0.103	0.102	0.103	0.07	0.077	0.09	0.121
Subject 13	0.419	0.298	0.332	0.324	0.796	0.875	0.46	0.044
Subject 15	0.965	1.143	1.392	1.11	0.618	0.586	0.295	0.135
Subject 18	0.732	0.868	0.91	0.611	0.512	0.505	0.545	0.292
Subject 22	0.851	0.927	0.878	0.893	0.656	0.623	0.676	0.65
Subject 23	1.173	1.019	0.782	0.733	0.931	0.912	0.792	0.756
Subject 25	0.613	0.658	0.589	0.557	0.428	0.509	0.521	0.567
Subject 26	0.642	0.815	0.84	0.769	0.547	0.605	0.711	0.641
Subject 27	0.923	0.787	0.759	0.895	0.703	0.709	0.764	0.722
Subject 28	0.832	0.902	1.048	0.595	0.573	0.559	0.633	0.551
Subject 29	0.212	0.255	0.256	0.227	0.16	0.184	0.207	0.178
Subject 30	0.42	0.492	0.601	0.712	0.379	0.466	0.492	0.581
Subject 31	1.157	1.024	0.904	0.873	0.802	0.884	1.003	1.187
Subject 32	0.615	0.867	0.95	0.875	0.461	0.617	0.6	0.601
Subject 33	0.943	1.173	1.122	0.961	0.695	0.628	0.528	0.513

Erector Spinae Normalized EMG Activity – Kyphotic lifting strategy (for reduced subject pool)

Kyphotic	Extension				Flexion			
	Quad 1	Quad 2	Quad 3	Quad 4	Quad 1	Quad 2	Quad 3	Quad 4
Subject 3	0.339	0.274	0.152	0.121	0.198	0.185	0.23	0.239
Subject 4	0.898	0.791	0.522	0.063	0.47	0.428	0.439	0.443
Subject 6	0.266	0.142	0.125	0.077	0.041	0.333	0.22	0.045
Subject 13	0.575	0.64	0.328	0.04	0.697	0.625	0.461	0.135
Subject 15	1.278	1.159	0.793	1.005	0.905	0.907	0.73	0.405
Subject 18	1.998	1.144	0.842	0.462	0.651	1.192	0.46	0.137
Subject 22	0.71	0.888	0.838	0.685	0.599	0.534	0.408	0.192
Subject 23	1.091	1.105	0.723	0.451	0.591	0.517	0.503	0.611
Subject 25	0.745	0.785	0.733	0.653	0.483	0.505	0.552	0.59
Subject 26	0.775	0.957	0.755	0.66	0.383	0.395	0.378	0.318
Subject 27	0.978	0.813	0.296	0.11	0.634	0.638	0.677	0.582
Subject 28	1.265	1.143	0.804	0.326	0.553	0.49	0.182	0.078
Subject 29	0.021	0.021	0.017	0.016	0.019	0.019	0.022	0.02
Subject 30	0.244	0.235	0.259	0.49	0.138	0.164	0.16	0.187
Subject 31	0.945	0.758	0.504	0.35	0.532	0.571	0.664	0.773
Subject 32	1.083	1.188	1.231	0.917	0.67	0.703	0.608	0.359
Subject 33	1.325	1.188	0.763	0.089	0.44	0.461	0.482	0.405