Biomechanical changes to the trunk and lower extremities due to variations of the forward lunge exercise

by

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ABSTRACT

Introduction: The forward lunge (FL) is a common weight bearing exercise that simultaneously trains the muscles crossing the hip, knee and ankle joint for strength and endurance. It is commonly used for rehabilitation, injury prevention and improving athletic performance. While the FL is an effective functional exercise, it trains movement primarily in the sagittal plane and previous research has shown that the hip extensors have relatively low activation compared to the knee extensors. Previous research has also shown that by altering the lunge and other lower extremity exercises (i.e., squat and deadlift) it is possible to increase the activation of the hip extensors and muscles that are involved in movements that occur in the frontal plane as well (i.e., abduction/adduction). The purpose of this study is to observe the changes in the kinetics and electromyographic (EMG) activity of the trunk and lower extremities due to variations of the forward lunge exercise.

Methods: Eleven recreational athletes were recruited to perform 4 different types of lunges. The 4 lunges completed were the FL, the FL while increasing flexion at the hip causing the trunk to be in a forward position (FLTF), a lunge in which the subject stepped at a 30° angle to widen the step (WSL), and a WSL while increasing flexing at the hip (WSLTF). Each lunge was performed 3 times with two different external loads (13.6 and 27.2 kg) for a total of 24 lunges. EMG electrodes were placed bilaterally on the lower back and abdominal muscles and also on muscles of the hip and thigh of the lead leg during the lunges. A total of thirty three retroreflective markers were placed on the subject and the dumbbells used for the external load. All lunges were done on two portable force platforms while an 8 camera motion capture system recorded the movement. A multivariate ANOVA was used to test for significant differences and interactions between variables.
Results: Peak internal hip adduction moment, peak external knee varus moment and peak external knee valgus moment were significantly greater during the wide step conditions compared to the straight forward step conditions (P < 0.001). Peak internal hip abduction moment was significantly greater in the straight forward lunges than during the wide step lunges (P < 0.001). Peak internal hip extension and L5/S1 extension moments were significantly greater during the lunges with the trunk forward compared to lunges when the trunk was upright (P < 0.001) and also with the high external load compared to the low external load (P < 0.001). There were no significant differences between any independent variables for the EMG data. There were no significant interactions between any of the independent variables.

Discussion: The increased hip adduction moment seen when the width of the step is increased may help to strengthen these muscles and prevent athletic injuries to this muscle group. However, the increased varus and valgus knee moments may make the wide step lunge a poor choice due to increased medial and lateral compression of the knee joint. The increased hip extensor moment seen during the lunges with the trunk in a forward position and higher external loads may help to strengthen these muscles and possibly reduce injury risk to the knee and lower back during athletic movements. However, the increased L5/S1 extensor moment seen with increasing external load and a forward position of the trunk may increase lower back injury risk during lunge exercises.
CHAPTER I

GENERAL INTRODUCTION

INTRODUCTION

The forward lunge (FL) is a common weight bearing exercise that simultaneously trains the muscles crossing the hip, knee and ankle joint for strength and endurance. The FL consists of an individual starting in an upright standing position with feet shoulder width apart. The exercise begins by taking an elongated step straight forward until the foot of the lead leg is flat on the ground. At this point the ankle, knee and hip simultaneously flex until the knee of the trail leg is about 2.54 to 5.08 cm above the ground (descent phase) (Graham, 2007). The step should be long enough that both knees are at approximately 90° to 100° of flexion at the lowest point and the foot of the lead leg remains flat on the floor. If the step is too short and knee flexion goes beyond 100°, then the knee of the lead leg will go beyond the toes which will lead to increased shear forces on the knee (Escamilla et al., 2008a). The individual then pauses momentarily before forcefully pushing back and up against the ground with the foot of the lead leg and begins to extend at the ankle, knee and hip until the lead foot leaves the ground and returns to the starting position (ascent phase). Through the entire duration of the exercise the trunk and neck remain in an upright and neutral position (Graham, 2007). Hip and knee extensors, as well as ankle plantar flexors, contract eccentrically during the descent phase and concentrically during the ascent phase. Both phases of the exercise are performed in a smooth, controlled manner with each lasting about 2 seconds.

The FL can be used in rehabilitation settings as improperly trained hip and knee muscles have been shown to be common in individuals with iliotibial band syndrome (Fredricson et al., 2000), patellofemoral pain syndrome (Natri et al., 1998 and Robinson and Nee, 2007), and lower
back pain (Kankaapaa et al., 1998). Kankaapaa et al. (1998) observed increased fatigability in hip extensors of patients with low back pain. Tyler et al. (2002) also saw a decrease in hip adductor injuries with an increase in hip muscle strength for hockey players.

The FL is also used during training by both competitive and recreational athletes without injuries for improved function of the lower extremities. Proper training of the hip and knee musculature has been shown to increase the performance of batting during baseball (Shaffer et al., 1993) as well as golfing (Tsai et al., 2004).

Another benefit of the FL is that it is a functional exercise that trains many muscle groups simultaneously rather than isolating a single muscle. Previous studies have used electromyography to observe the relative activation of certain lower extremity muscles during the FL. The gluteus maximus, vastus medialis and hamstring muscles were shown to be activated to 36 ± 17%, 76 ± 19% and 11 ± 6% respectively in a study by Ekstrom et al. (2007) with the FL. In addition, Farrokhi et al. (2008) reported 45.6 ± 8.3% activation levels in the vastus lateralis during the FL. These data suggest that many muscle groups are working together to perform the lunge which may lead to better transfer to real world activities (Rutherford, 1988). However, a drawback to the FL for increasing athletic performance is that it trains muscles and movements primarily in the sagittal plane. While this is beneficial to movements such as straight forward walking and running, many movements that are vital to athletic success require movement and change of direction in both the sagittal and frontal plane such as planting and cutting. Many non-contact injuries to the lower extremities also occur in a combination of these planes such as injuries to the ACL.

Another drawback to the FL is that previous research has suggested that in order for a muscle to increase strength an untrained individual must train at 45 to 50% of their maximum
capacity (Sale et al., 1990, Stone and Coulter, 1994). Some have even suggested that activation must be higher in already trained individuals such as athletes (Ekstrom et al., 2007). The EMG values for the hip extensor muscles listed previously do not reach this level and therefore the lunge may not be as effective at increasing strength in these muscles as in the knee extensor muscles. Farrokhi et al. (2008) showed a significant increase in activation of the biceps femoris muscles of the hamstrings and gluteus maximus (6% and 3.8%, respectively) by flexing at the hip and trunk during the descent phase of the FL. However, both of the values still fell below that believed to be necessary to increase strength even in untrained individuals. This research was done with body weight only and did not utilize any external load. Perhaps with the addition of external loads commonly used during strength routines that involve the lunge exercise these values would increase above the previously mentioned threshold.

Others have shown that increasing the width of stance and increasing the external load during other lower extremity exercises such as the squat and deadlift have shown significant increases in peak joint torques and EMG signals of the hip extensors (McCaw and Melrose, 1999, Escamilla et al., 2000 and 2002). McCaw and Melrose (1999) stated that increasing the width of the stance during a squat may put the gluteus maximus at a less than optimal position on the force-length curve causing it to have increased muscle activation to produce hip extension. However, during this study, the increase in external load was equal to 75% of the subjects’ maximum squat. These loads could be harmful for athletes, particularly those who have suffered previous injuries to the lower extremities or the low back. Perhaps increasing the width of the step during the forward lunge could show increased activation of the hip extensors while sparing the joints as the individual would use a lower load. Lower loads are common to the lunge
compared to the squat as the squat uses both legs to accomplish the ascent and descent phase and the lunge primarily uses the lead leg.

Employing a combination of the previously mentioned alterations to the lunge exercise (increasing step width, flexing forward at the hips and adding/increasing external load) may show even greater increases in hip muscle activation than any of the alterations individually. Increasing the width of the step will also make the exercise occur in the frontal plane as well as the sagittal plane and make it relevant to more athletic movements than just those that occur in the sagittal plane. Hip adductors and abductors would be utilized as well as hip and knee extensors.

The purpose of the this study was to observe the changes in peak internal joint moments and EMG values of the hip and knee extensors and peak internal joint moments of the hip adductors and abductors due to altering the FL by increasing the width of the step, adding a forward position of the trunk and increasing external load. To observe if these changes remain safe for athletes in terms of loading the low back and lower extremities, changes in peak internal L5/S1 moments, EMG values of the erector spinae and rectus abdominis muscles, and external knee varus and valgus moments were calculated. Based on the research cited above, it was believed that peak hip extensor moment and EMG values would increase due to step width, trunk position and increasing external load and that peak hip adduction moment would increase with an increase in step width. It was also hypothesized that peak L5/S1 extension moment and EMG values would only increase as a function of increasing external load. However, due to using much lower loads than that of the previous studies looking at squats and deadlifts, these increases would still remain within reasonable limits for athletes who have suffered injuries. Another hypothesis was that the addition of the external load to the lunge exercise would show greater
activation of all lower extremity muscles compared to those cited in the literature when only
to body weight was used. It was predicted that all muscles sampled would be above the 45 to 50% 
activation threshold to increase strength. One concern of increasing the width of the step is that 
the lead leg may be less stable causing increases in knee varus and valgus external moments. 
However it was believed that with the moderate loads being used these values would remain low 

enough to not increase the risk of injury to the knee.

THESIS ORGANIZATION

This thesis is organized into General Introduction, Manuscript and General Conclusions 
chapters. The manuscript is formatted according to the Journal of Orthopaedic and Sports 
Physical Therapy specifications. The primary author for this article is Christopher J. Sorensen, a 
Master’s student of Kinesiology at Iowa State University. Boyi Dai, a Ph.D. student in 
Kinesiology at the University of North Carolina at Chapel Hill contributed to the experimental 
design. Dr. Jason C. Gillette, an Associate Professor of Kinesiology at Iowa State University, 
contributed to experimental design, data analysis and preparation of the manuscript.

REVIEW OF LITERATURE

1. Hip and Knee Strength Deficiency and Injury

Injuries to a joint are often followed by decreased strength and endurance to the muscles 
crossing that joint. This is often seen by testing the strength of injured versus non-injured 
individuals (Kankaapaa et al., 1998, Fredricson et al., 2000, Ireland et al., 2003, Robinson and 
Nee, 2007) and by testing the strength of a limb with an injured joint versus the non-injured joint 
(Natri et al., 1998, Fredricson et al., 2000, Robinson and Nee, 2007). For this reason it is 
common for physical therapists to try and restore normal function to a joint by restoring pre-
injury strength, endurance (Fredricson et al., 2000) as well as balance between the injured and uninjured limbs (Natri et al., 1998, Fredricson et al., 2000).

Many muscles that cause rotation at the hip joint are biarticular muscles that cross both the hip joint and joints of the lumbar spine (i.e., psoas) or the hip joint and the knee joint (i.e., biceps femoris). Due to the link these muscles create between the multiple joints many researchers have studied hip muscle deficiencies following injuries to the low back (Kankanpaa et al., 1998) and knee (Fredricson et al., 2000, Ireland et al., 2003, Robinson and Nee, 2007). Kankanpaa et al. (1998) looked at back and hip extensor fatigability in 20 women with non-specific low back pain and 15 healthy controls. Subjects were seated in a back extension training unit at 30° of forward trunk flexion while having EMG sampled at the L3/L4 and L5/S1 levels of the paraspinal muscles and the gluteus maximus. After performing a maximum isometric voluntary contraction (MVC) in this position, subjects then performed isometric contractions at 50% of their MVC until they could not maintain this level of contraction. Those with chronic back pain had a lower MVC (140.0 ± 25.0 Nm in patients versus 163.9 ± 32.0 Nm in controls), less endurance time (1.7 ± 0.5 minutes versus 2.0 ± 0.5 minutes), and a significant decrease in gluteus maximus median frequency during the trials. However, there was no significant difference in median frequency of the paraspinal muscle groups. This led the authors to state that the gluteus maximus was the limiting factor causing the decreased endurance time in the patients.

Fredricson et al. (2000) tested hip abduction strength in distance runners with and without iliotibial (IT) band syndrome using a Nicholas Manual Muscle Tester. For the runners with IT band syndrome, strength was tested on both the injured and uninjured leg. Males and females with IT band syndrome showed significantly less hip abduction strength in their injured leg.
compared to their uninjured leg and significantly less strength than the healthy controls. After a 6 week hip abduction strengthening routine, females showed an increase in abduction torque of 34.9% in the injured leg and males showed a 51.4% increase. Twenty-two of the 24 injured runners were able to return to running pain free and had no symptoms at a 6 month follow up session. The authors believed that the weak hip abductors caused increased hip adduction angle and hip internal rotation at heel strike which causes increased external knee valgus moments at the knee. This position causes the IT band to be in increased tension at the beginning of the stance phase which can cause increased impingement of the IT band on the lateral epicondyle.

Ireland et al. (2003) tested abduction and external rotation strength using handheld dynamometry in women with patellofemoral pain syndrome and age matched controls. The women with pain demonstrated 26% less hip abduction strength and 36% less hip external rotation strength. These authors suggested that these strength deficits caused the women to have excessive femur adduction and internal rotation during running. This would cause increased patellar contact pressure due to increased patellar tracking. Robinson and Nee (2007) also tested hip strength (hip extension, abduction and external rotation) in patients with unilateral patellofemoral pain syndrome and healthy controls using hand held dynamometry. These variables were tested on both legs of the patients and controls to test for both strength deficits and asymmetry. Results showed that the patients had significantly less symmetry between their two legs and the symptomatic legs had 52%, 27% and 30% less strength in hip extension, abduction and external rotation, respectively, than the weaker legs of the controls.

Natri et al. (1998) placed 49 patients of patellofemoral pain syndrome on a 6 week treatment regimen that included restoring quadriceps muscle strength in the symptomatic limb back to that of the asymptomatic limb. Forty-five of the patients returned for a 7 year follow up
with three-fourths of them having recovered. The best predicted variable of this recovery was the amount of strength difference between the quadriceps of the two limbs, with the lower the difference, the better the chance the patient had recovered.

Following injuries to the knee such as iliotibial band syndrome and patellofemoral pain syndrome, strength deficits in muscles crossing the hip and knee of the affected limb are often observed. Some studies have shown that strengthening these joints can restore normal function (Natri et al., 1998, Fredricson et al., 2000). Hip extensor endurance has also been observed to be lower in individuals with low back pain by Kankaapaa et al. (1998). However there was no follow up to this study to see if increasing endurance to these muscles reduced back pain.

2. Hip and Thigh Musculature during the Lunge Exercise

The FL is commonly used in rehabilitation and training settings as a means of improving strength and endurance to the muscles crossing the hip and knee. Therefore, many researchers have used EMG to look at activation levels of these muscles during the lunge. Ekstrom et al. (2007) sampled EMG activity of the gluteus maximus, gluteus medius, vastus medialis and hamstring muscles of during a variety of trunk and lower extremity rehabilitation exercises. The only instruction reported by these authors was that the lunge was performed in a controlled manner through a full range of motion with a 5 second pause at the point of maximal knee flexion. The maximum 1 second EMG value during the pause was normalized to a maximum voluntary contraction (MVC). They reported average values of 36 ± 17% for gluteus maximus, 29 ± 12% for gluteus medius, 76 ± 19% for vastus medialis and 11 ± 6% for hamstrings. A limitation of this study was the subject population had an age range of 19 to 58 years, which may have had large variations in their level of fitness and muscular training. Farrokhi et al. (2008) had subjects perform a lunge with the instructions to maintain an upright trunk and lower until
the knee of their lead leg was 2 to 3 cm off the ground during the descent phase. The step taken was equal to the distance from their greater trochanter to the floor found while standing although they did not complete a 5 second pause at the end of the descent phase. This group also recorded the highest 1 second normalized EMG signal during the exercise. The average values were 45.6%, 18.5% and 11.6% of MVC for the vastus lateralis, gluteus maximus and biceps femoris, respectively. They also calculated joint impulses of 1.7, 2.5 and 3.9 Nm/kg for the ankle knee and hip joints, respectively.

Boudreau et al. (2009) looked at EMG activity of the rectus femoris, adductor longus, gluteus maximus, and gluteus medius of the lead leg and gluteus medius of the trail leg during the lunge, single leg squat and step up and over exercises. The step was normalized to measured length from the subject’s anterior superior iliac spine (ASIS) to the medial malleolus. Beginning in an upright standing posture with feet at shoulder width, subjects were instructed to step to the measured distance, lower a comfortable distance, and return to the starting position by extending the lead leg. They reported values of 19.1 ± 11.6% for the rectus femoris, 23.6 ± 36.1% for adductor longus, 21.7 ± 14.7% for gluteus maximus, 17.7 ± 8.8% for the gluteus medius of the lead leg, and 19.0 ± 11.7% for the gluteus medius of the trail leg. These authors reported normalizing the mean amplitude during the exercise, but did not specify if this was a 1 second window or overall average.

The three previous studies mentioned did not use any external load when performing the FL. Ebben et al. (2009) used a load equal to the 6 repetition maximum of the subject while sampling EMG of the rectus femoris, vastus lateralis and biceps femoris. However, this study only reported of normalized root mean square EMG value of 94.3% for the vastus lateralis.
Looking at figures from the article, the normalized peak EMG values for the rectus femoris was just over 80%, the vastus lateralis was close to 90% and biceps femoris was close to 70%.

The forward lunge has been shown to activate many muscles of the thigh and pelvis segments. Activation of knee extensors has been observed to be high enough to achieve both strength and endurance with both body weight only and the use of external load. However, hip extensors may only be able to achieve muscular endurance without the use of external load. Therefore, the addition of external load may be crucial to increase the strength of hip extensors in order to rehabilitate injuries, reduce injury risk and improve athletic performance.

3. Alterations to Lower Extremity Exercises

It is common in both training and rehabilitation settings to slightly alter the technique of exercises in order to increase intensity, change the muscle groups being worked or to train movements in additional planes of motion. Many investigators have looked at biomechanical changes to the lower extremities due to altering the lunge, squat and deadlift exercises. Farrokhi et al. (2008) looked at altering the trunk position during the descent phase of the lunge. Their subjects performed normal lunges as described above, lunges with the trunk in a forward position by flexing at the hips and trunk during the descent phase, and lunges with the trunk in an extended position by extending at the hip and trunk during the descent phase. Significant increases were seen in hip extensor joint impulse and highest 1 second average normalized EMG signals during the lunge with the trunk in a forward position.

Escamilla et al. (2008a, 2008b) used EMG assisted models to compare knee joint stress during a normal lunge with a shorter and longer step (Escamilla et al., 2008a), a forward lunge and a side lunge (step directly to the side in the frontal plane), and lunges with and without a step (Escamilla et al., 2008b). These investigators found lower forces in the long step compared to
the short step, the forward lunge compared to the side lunge, and the lunge without a step compared to with a step. EMG values and internal moments were not reported by these authors.

Other lower extremity exercises that have been studied are the squat and deadlift exercise. A common alteration of these exercises is varying the width of the stance as many lay texts suggest that there is increased use of the knee and hip extensors when using wider stances during these two exercises. McCaw and Melrose (1999) sampled lower extremity muscle activity during the squat at stances of shoulder width, narrow (75% of shoulder width), and wide (140% of shoulder width). Subjects in this study also performed the squat at loads of 60% and 75% of their one repetition maximum. Their main findings were a significant increase in the area under the EMG linear envelope for the adductor longus during the ascent phase of the wide squat and a significant increase for the gluteus maximus during both phases of the wide squat with 75% of maximum load. They stated that the increase in adductor activity was due to increased hip adduction range of motion during the ascent because of a large abduction angle created during the descent phase. The explanation given for the increased gluteus maximus activation was that the hip was abducted and externally rotated during the wide stance which put the gluteus maximus at a less optimal position on the length-tension curve. This resulted in additional motor unit recruitment to accomplish the hip extension needed to perform the exercise. The authors suggested that future research was needed for this explanation considering there was only a change at the 75% of maximum and not 60%.

Another study analyzed powerlifters during competition using either a narrow, medium or wide stance squat (Escamilla et al., 2001). They classified these stances by normalizing them to the digitized distance between the lifters’ shoulder joint centers. They observed 6-11° increase in hip flexion for the lifters using a wider stance which could help explain the increase
in hip extensor muscle activity. However, the subjects in this study were performing a 1 repetition maximum rather than working at a percentage of maximum and muscle activity was not sampled making it difficult to compare with the previous study (Escamilla et al., 2001). In addition the large loads used by the powerlifters in this study may not be comparable to recreational athletes training for performance enhancement or injury prevention.

Escamilla et al. (2002) observed higher vastus medialis and vastus lateralis activity during a sumo style deadlift exercise (wide stance) as opposed to a conventional style dead lift (shoulder width stance) when lifting weights equal to a 12 repetition maximum. They stated that this increase was due to the increase in knee extension moments using this style which was found by an earlier study comparing 2D and 3D kinematic and kinetic analyses of these two styles of deadlift (Escamilla et al., 2000). The latter authors attributed the increase in internal knee extension moments during the sumo style lift to overcoming an increase in external knee flexion moment due to lifter-barbell system center of mass being posterior to the knee axis. Neither of these two studies found a significant increase in hip extensor activity in the wider stances (Escamilla et al., 2000, 2002). This is in agreement with previous research (Cholewicki et al., 1991) that found no difference in hip extension moment when using powerlifters. However, these authors noted that the lifters were able to keep their trunk more upright during the wider stance as opposed to a narrow stance which would lead to no increase in the moment or muscle activity at the hip. The basic technique of any deadlift includes a large hip flexion angle so it is not surprising that there is no difference in hip extensor muscles by altering the stance.

Based on this past research it is reasonable to believe that further alterations to the lunge exercise may show more changes to trunk and lower extremity biomechanics. These changes may lead to increased intensity and make movement of the exercise closer to movements
performed during athletic events. If an athlete is able to increase intensity by altering the technique rather than just increasing the external load this may lead a lower chance of causing damage to tissues during the exercise.

Deficiencies of the muscles crossing the hip and knee joint have been shown to develop after injuries to both the knee and lower back. It has also been shown that restoring these deficiencies can lead to normal function of the joint. The FL is an effective exercise for training these muscles in order to accomplish this. Athletes that were training at high intensities before injury may have to increase the training capacity of the FL by adding external load. However, the addition of too much external load could exacerbate the injury rather than increasing strength. Many researchers have shown that altering technique to lower extremity exercises can increase the intensity to certain muscle groups with increasing the external load. Altering technique of exercises such as the FL may also make the movements more like those performed during athletic events. Therefore, it is important to observe the changes in trunk and lower extremity biomechanics due to altering the technique in order to better understand the potential benefits and risks associated with these alterations.
REFERENCES


CHAPTER II

BIOMECHANICAL CHANGES TO THE TRUNK AND LOWER EXTREMITIES DUE TO VARIATIONS OF THE FORWARD LUNGE EXERCISE

ABSTRACT

STUDY DESIGN: Controlled laboratory biomechanics design using a repeated measures, randomized design.

OBJECTIVES: To observe the kinetic and electromyographic (EMG) changes during four variations of the forward lunge (FL) exercise.

BACKGROUND: The forward lunge (FL) is a common weight bearing exercise that simultaneously trains the muscles crossing the hip, knee and ankle joint for strength and endurance. It is commonly used for rehabilitation, injury prevention and improving athletic performance. While the FL is an effective functional exercise, it trains movement primarily in the sagittal plane and previous research has shown that the hip extensors have relatively low activation compared to the knee extensors. Previous research has also shown that by altering the lunge and other lower extremity exercises (i.e., squat and deadlift) it is possible to increase the activation of the hip extensors and hip abductors/adductors.

METHODS: Eleven recreational athletes were recruited to perform 4 different types of lunges. The 4 lunges completed were the FL, the FL while increasing flexion at the hip causing the trunk to be in a forward position (FLTF), a lunge in which the subject stepped at a 30° angle to widen the step (WSL), and a WSL while increasing flexing at the hip (WSLTF). Each lunge was performed 3 times with two different external loads (13.6 and 27.2 kg) for a total of 24 lunges. EMG electrodes were placed bilaterally on the lower back and abdominal muscles and also on muscles of the hip and thigh of the lead leg during the lunges. All lunges were do\'ne on two
portable force platforms while an 8 camera motion capture system recorded the movement. A multivariate ANOVA was used to test for significant differences and interactions between variables.

**RESULTS:** Peak internal hip adduction moment, peak external knee varus moment and peak external knee valgus moment were significantly greater during the wide step conditions compared to the straight forward step conditions (P < 0.001). Peak internal hip abduction moment was significantly greater in the straight forward lunges than during the wide step lunges (P < 0.001). Peak hip extension moment and L5/S1 extension moment were significantly greater during the lunges with the trunk forward compared to lunges when the trunk was upright (P < 0.001) and also with the high external load compared to the low external load (P < 0.001). There were no significant interactions between any of the independent variables.

**CONCLUSIONS:** Widening the step of the lunge can be useful to increase strength and endurance and potentially reduce the risk of injuries to the hip adductor muscles during athletic movements. However, the increased varus and valgus knee moments may make this variation of the FL harmful to individuals during training, particularly those already suffering from knee injuries. Increasing the forward position of the trunk and increasing the external load during the lunge may be useful to increase the strength of the hip extensor muscles. However, the increased L5/S1 extension moment seen with increasing external load and a forward position of the trunk may be harmful to individuals during training and to those already suffering from low back injuries.
INTRODUCTION

The forward lunge (FL) is a commonly used exercise to train muscles crossing the knee and hip joints. It consists of an individual starting in an upright position with feet shoulder width apart and holding dumbbells at the sides. The exercise begins with the individual taking an elongated step forward and lowering by simultaneously flexing and the knee, hip and ankle joint until the knee of the back leg is 2.54 cm to 5.08 cm off the ground (descent phase). After a momentary pause at this position, the individual then presses up and back on the floor with the foot of the lead leg until returning to the starting position. The FL is commonly used in rehabilitation settings as hip and knee strength deficiencies have both been seen in patients with patellofemoral pain syndrome (PTFS) (Natri et al., 1998, Ireland et al., 2003, Robinson and Nee, 2007), iliotibial (IT) band syndrome (Fredricson et al., 2000), low back pain (Kankaapaa et al., 1998). It can also be used for healthy individuals to both prevent injuries and improve function of the hip and knee joint. Decreased strength and endurance of hip extensors (Kankaapaa et al., 1998) as well as imbalance of hip extensors has been shown to be a risk factor for low back injuries (Nadler et al., 2000). Properly trained hip and thigh muscles have been shown to improve the function of batting in baseball (Shaffer et al., 1993) and golfing (Tsai et al., 2004).

Another benefit of the FL is that it is a functional exercise that trains many muscle groups simultaneously rather than isolating a single muscle. Previous studies have used electromyography to observe the relative activation of lower extremity muscles during the FL. The gluteus maximus, vastus medialis and hamstring muscles had peak normalized electromyographic (EMG) activity of 36 ± 17%, 76 ± 19% and 11 ± 6%, respectively in a study by Ekstrom et al. (2007). In addition, Farrokhi et al. (2008) reported 45.6 ± 8.3% activation levels in the vastus lateralis during the forward lunge with body weight alone. These data
suggest that many muscle groups are working together to perform the FL which may lead to better transfer to world activities (Rutherford, 1988). Farrokhi et al. (2008) also reported joint impulse data for the ankle knee and hip to be 1.7, 2.5 and 3.9 Nms/kg, respectively. However, few other studies have reported kinetic data during the exercise.

The activation levels reported above for the gluteus maximus, hamstrings and possibly vastus lateralis may be too low to increase the muscular strength of even untrained individuals (Sale et al., 1990, Stone and Coulter, 1994). Ebben et al. (2009) had subjects perform the FL with an external load equivalent to that of their 6 repetition maximum while measuring EMG of the vastus lateralis, rectus femoris and biceps femoris. These investigators reported normalized peak EMG values for the rectus femoris just over 80%, the vastus lateralis close to 90% and the biceps femoris close to 70%. While these values should be more than sufficient to increase the strength of these muscles, using an external load equal to one’s 6 repetition max may cause too much stress for an athlete trying to rehabilitate and return from an injury to the knee or back. Other researchers have seen increases in both electrical activity and moments by altering the technique of lower extremity exercises. Increases in EMG activity of the vastus lateralis and gluteus maximus (6% and 3.8%, respectively) were seen during the forward lunge by having the subjects flex forward from the hips and trunk during the descent phase of the exercise. This forward position of the trunk caused the moment arm between the hip joint center and the upper body center of mass to increase, thus increasing the moment.

McCaw and Melrose (1999) observed a significant weight by stance increase in the gluteus maximus with a wider stance and as the external load was increased from 60% to 75% of the subject’s maximum. The authors suggested the increase in gluteus maximus activation was caused by the hip being abducted and externally rotated during the wide stance which put the
gluteus maximus at a less optimal position on the length-tension curve. This resulted in additional motor unit recruitment to accomplish the hip extension needed to perform the exercise. They also stated that future research was needed for this explanation considering there was only a change at the 75% of maximum and not 60%. Escamilla et al. (2002) observed higher vastus medialis and vastus lateralis activity during a sumo style deadlift exercise (wide stance) as opposed to a conventional style dead lift (shoulder width stance) when lifting weights equal to the 12 repetition maximum. The authors attributed the increase in knee extension moments during the sumo style lift to a need to overcome an increase in knee flexion moment due to lifter-barbell system center of mass being posterior to the knee axis.

While the FL does activate multiple muscles simultaneously, a drawback for increasing athletic performance is that it trains muscles and movements primarily in the sagittal plane and may create very small moments in the frontal plane such as hip adduction and abduction. While this is beneficial to movements such as straight forward walking and running, many movements that are vital to athletic success require movement and change of direction in both the sagittal and frontal planes such as planting and cutting. Escamilla et al. (2008) used an EMG assisted model to compare patellofemoral force and stress on the knee between a forward and a lateral lunge (stepping straight laterally as opposed to straight forward). They saw in increase in knee joint stress with the lateral lunge, however, they did not report EMG values or internal moments. When studying the squat exercise, McCaw and Melrose (1999) saw an increase in hip adductor EMG activity during the ascent phase when increasing the width of the stance. This was due to an increase in the adduction range of motion caused by an increase in abduction angle with the wider stance.
Combining the previously mentioned alterations to the lunge and other lower extremity exercises (flexing forward at the hips, adding/increasing external load), may show even greater increases in EMG activity or moments of the lower extremities than any of them individually. Increasing the width of the step will also make the exercise occur in the frontal plane as well as the sagittal plane. This alteration will make the FL relevant to more athletic movements than just those that occur in the sagittal plane by involving the hip adductors and abductors along with the hip and knee extensors.

The purpose of the this study was to observe the changes in peak moments and EMG values of the hip and knee musculature due to altering the FL by increasing the width of the step, adding a forward position of the trunk and increasing external load. To observe if these changes in the FL remain safe to the low back and lower extremities, changes in peak internal L5/S1 extension moments, EMG values of the erector spinae and rectus abdominis muscles, and external knee varus and valgus moments were calculated. Based on the research cited above, it was believed that peak internal hip extensor moment and EMG activity would increase due to step width, trunk position and increasing external load. It was also hypothesized that peak knee extension moment and EMG activity and peak hip adduction moment would increase with an increase in step width. It was also hypothesized that peak L5/S1 extension moment, trunk EMG values, external knee varus and knee valgus moments would increase as a function of increasing external load. It was expected that the addition of the external load to the lunge exercise would show greater activation of all lower extremity muscles compared to those cited in the literature when only body weight was used. It was also expected that all muscles sampled would be above the 45 to 50% activation threshold to increase strength.
METHODS

Subjects

Eleven healthy male subjects that did not have chronic or current low back or lower extremity injuries were recruited for this study, with average ± standard deviation age, height and mass being 24.9 ± 2.6 years, 179.8 ± 4.8 cm and 83.9 ± 14.0 kg. All subjects were currently active in recreational athletics and had experience performing the lunge exercise as part of a regular strength routine. Before participating in this study all subjects read and signed an informed consent form that was approved by the Iowa State University Institutional Review Board.

Equipment

Three-dimensional (3D) kinematic data were recorded at 160 Hz using an 8 camera motion capture system (Vicon MX40, Oxford Metrics Ltd, Oxford, UK). Ground reaction force data were collected at 1600 Hz using two portable force platforms (AMTI OR6 Series, AMTI, MA, USA). The position of the portable force platforms was determined by placing reflective markers on the corners of the force platforms. Electromyographic muscle activity was collected at 1600 Hz using a surface EMG system (Myomonitor, Delsys Inc., MA, USA). Data from these three systems were time synchronized using Vicon Nexus videographic and analog data acquisition system (Oxford Metrics Ltd, Oxford, UK).

Protocol

After signing the informed consent document, subject age and anthropometric data were recorded. Anthropometric data included height, weight, foot length, and ASIS to medial malleolus length. ASIS to medial malleolus length was used to determine the length of the step for all lunge conditions. All other anthropometrics were used to calculate segment masses, center of masses and moments of inertia. The subject was then asked which foot they would use
to kick a ball as this would be the lead leg during the lunges. Once this information had been gathered, the sites where the surface electrodes were to be placed were prepared by shaving with a disposable razor and cleaning with rubbing alcohol. Electrodes were then attached to the right and left erector spinae and right and left rectus abdominis muscles and were secured with pre-wrap and athletic tape. A ground electrode was also placed on the right anterior superior iliac spine.

Once these electrodes were secured, a warm up was performed to prepare the trunk and lower extremity muscles. The warm up consisted of light neuromuscular, strength and flexibility exercises. Subjects then performed two 3 second maximum voluntary isometric contractions (MVIC) of these muscle groups. For the erector spinae, the subject was secured in chair with a pad across his scapula and was instructed to maximally extend his back into the pad. The subject was then secured in the chair with the pad across his chest and instructed to maximally flex the trunk for the rectus abdominis MVIC. After these were complete, electrodes were placed on the gluteus maximus, vastus medialis, vastus lateralis, semitendinosus and biceps femoris muscles of the lead leg. MVICs for the biceps femoris and semitendinosus were performed with the subject seated with his knee flexed just beyond 90 degrees and his heel on a steel bar and foot on the floor. The subject was instructed to maximally flex his knee by pushing his heel into the bar. The MVICs for the vastus medialis and vastus lateralis were performed with the subject seated with his knee flexed just beyond 90 degrees and a strap placed just above his ankle. The subject was instructed to maximally extend his knee while pushing his leg into the strap. The MVICs for the gluteus maximus were performed with the subject standing upright with his hands on a platform and leg strapped to a bar with the strap placed just above his ankle. The subject’s hip
was in a slightly extended position and he was instructed to maximally extend his hip while pressing his leg into the strap.

After all MVICs had been collected, the subject then had retroreflective markers placed bilaterally on the dorsal foot, lateral foot, heels, medial and lateral malleoli, medial and lateral knee joint lines, anterior thighs, greater trochanters, ASIS, posterior superior iliac spines (PSIS) and acromioclavicular joints. Markers were also placed on the sacrum, substernale, suprasternale as well as the anterior and posterior surfaces of the dumbbells. A static capture was taken of the subject in the anatomical position with the full marker set. The medial malleoli, medial knee joint lines, and ASIS markers were removed during the dynamic trials. The removed markers were recreated during the dynamic trials using transforms derived from the static trial. The subject was then given instructions on how to perform the four different types of lunges. For the FL, the subject was told to begin in an upright position with his feet approximately shoulder width and the dumbbells at his sides. He was then instructed to step forward to the mark on the front force platform with his chest upright. Once the foot of the lead leg was on the force plate, the subject was to lower by simultaneously flexing at the hip and knee until the back knee was approximately 2.5 to 5.1 cm above the force plates. The subject then paused momentarily at the bottom position and began the ascent phase by pressing up and back with lead leg until he returned to the starting position (Figure 1).

Instructions for the FL trunk forward (FLTF) were the same as for the FL except subjects were to flex forward from the hips as they lowered while maintaining the trunk in a neutral position. For the forward trunk position, the subject was instructed that the trunk should be at an angle so that the trunk was in a position approximately halfway between an upright position and the position of his thigh at the bottom of the lunge. The wide step lunge (WSL) was the same as
for the FL except the subjects were to take a wide step to the mark on the front force plate that was at a $30^\circ$ angle from the starting position of the lead foot. Subjects were instructed to accomplish this by the use of hip abduction and not to rotate the pelvis or trunk about the vertical axis while keeping their pelvis parallel to the medial lateral axis. If they rotated they would diminish the effect of changing the length of the gluteus maximus. The WSL trunk forward (WSLTTF) was the same as the WSL except the subjects flexed the hip forward during the descent phase while maintaining the trunk in a neutral position. All variations of the lunge were completed with both a low (13.6 kg) and high (27.2 kg) external load for a total of eight different lunge conditions.

All lunges were to take a total of four seconds (2 seconds descent, 2 seconds ascent) to control for velocity of the movement. A metronome was set to 1 beat per second to help the subject with timing. Once instruction had been given and the metronome was set, the subject was allowed to practice all of the lunges for as long as necessary to feel comfortable with each variation.

The lunges were monitored by the principal investigator for technique and movement speed. If the knees of the lead leg went beyond the toes at any point, if the lead foot did not stay flat on the front force plate at any time other than heel strike or push off, if the subject appeared off balance at any point or if the lunge was performed too fast or too slow, then the trial was recollected. The four lunges were performed with two external loads for a total of 8 conditions. Each condition was completed 3 times for a total of 24 trials. The ordering of the conditions was balanced across subjects.

**Data Reduction**
Data were analyzed from the point when the lead leg landed on the front force plate to the moment when it left the front force plate. The threshold of foot landing and leaving was set at 50 N. A fourth order, symmetric Butterworth filter with a cutoff frequency of 6 Hz for video data and 20 Hz for force platform data was used to reduce noise. Raw EMG data for both the MVICs and dynamic trials were bandpass filtered between 20 and 450 Hz and rectified. The EMG linear envelope was then determined by low-pass filtering the data at 10 Hz. The maximum 1 second average was obtained for both the MVICs and the dynamic trials. The EMG data from the dynamic trials were divided by the MVICs to normalize the data. Joint angles were calculated using a flexion-extension, abduction-adduction, internal-external order of rotations. Segment masses, centers of mass, and moments of inertia were calculated based on de Leva (1996). The ankle joint midpoint was defined as the midpoint of the medial and later malleoli and the knee joint center was defined as the midpoint of the medial and lateral knee joint line markers. The hip joint centers were located using the methods of Bell et al. (1990) and the L5/S1 joint center was adapted from de Looze et al. (1992). An inverse dynamics approach was used to calculate 3-D joint moments. All moments were normalized to body mass.

**Statistical analysis**

The kinetic dependent variables of the study were peak internal moment for knee extension, knee flexion, hip extension, hip flexion, hip abduction, hip adduction of the lead leg. Peak external knee valgus and varus moments of the lead leg and peak internal L5/S1 moments were also calculated. The muscle activation dependent variables were peak normalized EMG for the gluteus maximus, vastus medialis, vastus lateralis, biceps femoris, and semitendinosus of the lead leg; and the average of the right and left erector spinae and rectus abdominis muscles. Independent variables were the step direction (forward and wide), trunk position (upright and
forward) and external load (low, 13.6 kg, and high, 27.2 kg). The external loads were chosen by asking participants of pilot testing about the loads they used on a regular basis during training. Pilot subjects reported that the low load was low intensity, and therefore could be thought of as representing muscular endurance training. The high load was moderate to high intensity and therefore could be thought of as representing muscular strength training. A 3x2 multivariate ANOVA was used to test for significant main effects and interactions between independent variables. When significant main effects and/or interactions were found planned comparisons were used tested with a Bonferroni adjusted significance level of 0.05/10 = 0.005 for kinetic variables and 0.05/7 = 0.007 for EMG variables. All data were analyzed in SPSS 16 (SPSS, Chicago, IL, USA).
Figure 1. (a) The subject at the lowest point of the descent phase for the straight forward lunge, (b) straight forward lunge trunk forward, (c) wide step lunge and, (d) wide step lunge trunk forward.
RESULTS

For the kinetic variables, significant main effects were found for step direction ($p < 0.001$), trunk position ($p < 0.001$), and external load ($p < 0.001$). There were no significant interactions between any of the kinetic variables ($p = 0.095$ and higher). For EMG variables, there were no significant main effects for step direction ($p = 0.242$), trunk position ($p = 0.471$), or external load ($p = 0.432$), or any interactions ($p = 0.847$ and higher).

EMG Data

There were no significant main effects for any of the independent variables and there were no significant interactions between variables for the peak normalized EMG data. The averages standard deviations can be seen for each level of the three independent variables in Table 1 for all muscles sampled.
Table 1. Averages (standard deviation) of peak normalized EMG values for each independent variable and for all muscles sampled.

<table>
<thead>
<tr>
<th>Step Width</th>
<th>Trunk Position</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forward</td>
<td>Wide</td>
</tr>
<tr>
<td>Gluteus Maximus</td>
<td>0.679 (0.192)</td>
<td>0.697 (0.253)</td>
</tr>
<tr>
<td>Vastus Medialis</td>
<td>0.969 (0.423)</td>
<td>1.050 (0.417)</td>
</tr>
<tr>
<td>Vastus Lateralis</td>
<td>1.056 (0.386)</td>
<td>1.147 (0.466)</td>
</tr>
<tr>
<td>Biceps Femoris</td>
<td>0.387 (0.169)</td>
<td>0.433 (0.189)</td>
</tr>
<tr>
<td>Semidtendinosus</td>
<td>0.291 (0.194)</td>
<td>0.358 (0.240)</td>
</tr>
<tr>
<td>Erector Spinae</td>
<td>0.678 (0.252)</td>
<td>0.683 (0.264)</td>
</tr>
<tr>
<td>Rectus Abdominis</td>
<td>0.405 (0.215)</td>
<td>0.442 (0.206)</td>
</tr>
</tbody>
</table>

**Kinetic Data**

Peak internal hip adduction moments were significantly greater during the wide step condition compared to the straight forward step condition (p < 0.001) while peak internal hip abduction moment was significantly greater during the straight forward step condition compared to the wide step condition (p < 0.001). Group ensemble curves for hip adduction/abduction can be seen in Figure 2 for both step conditions. Peak internal knee flexion moments were significantly greater during the wide step compared to straight forward step (p = 0.002), while peak internal hip flexion moments were significantly greater during the straight forward condition compared to the wide step (p = 0.002). Peak external knee varus and valgus moments were both significantly
higher during the wide step condition compared to the straight forward step condition (p < 0.001 for both).

Average (standard deviation) peak moments for each independent variable can be seen in Table 2. Peak internal hip extension moments were significantly greater during the trunk forward conditions compared to the trunk upright conditions (p < 0.001) and during the high external load condition compared to the low external load condition (p < 0.001). Group ensemble curves for internal hip extension moments during the trunk forward and upright conditions can be seen in Figure 3. Peak internal L5/S1 extension moments were significantly greater during the trunk forward condition compared to the trunk upright conditions (p < 0.001) and during the high external load compared to low external load condition (p < 0.001). There were no significant interactions between any of the independent variables; however, step direction by trunk position approached significance (p = 0.095).
Table 2. Average (standard deviation) Peak Moments for each independent variable in Nm/kg. (*) indicates a significant increase as a function of step width, trunk position or external load.

<table>
<thead>
<tr>
<th></th>
<th>Step Width</th>
<th>Trunk Position</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forward</td>
<td>Wide</td>
<td>Upright</td>
</tr>
<tr>
<td>Knee Extension</td>
<td>1.426</td>
<td>1.36</td>
<td>1.429</td>
</tr>
<tr>
<td></td>
<td>(0.292)</td>
<td>(0.333)</td>
<td>(0.275)</td>
</tr>
<tr>
<td>Knee Flexion</td>
<td>0.316</td>
<td>0.384*</td>
<td>0.339</td>
</tr>
<tr>
<td></td>
<td>(0.092)</td>
<td>(0.101)</td>
<td>(0.098)</td>
</tr>
<tr>
<td>Knee Varus</td>
<td>0.289</td>
<td>0.508*</td>
<td>0.362</td>
</tr>
<tr>
<td></td>
<td>(0.131)</td>
<td>(0.214)</td>
<td>(0.160)</td>
</tr>
<tr>
<td>Knee Valgus</td>
<td>0.282</td>
<td>0.487*</td>
<td>0.397</td>
</tr>
<tr>
<td></td>
<td>(0.182)</td>
<td>(0.092)</td>
<td>(0.181)</td>
</tr>
<tr>
<td>Hip Extension</td>
<td>2.624</td>
<td>2.632</td>
<td>2.403</td>
</tr>
<tr>
<td></td>
<td>(0.453)</td>
<td>(0.437)</td>
<td>(0.327)</td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>0.229*</td>
<td>0.177</td>
<td>0.201</td>
</tr>
<tr>
<td></td>
<td>(0.078)</td>
<td>(0.072)</td>
<td>(0.077)</td>
</tr>
<tr>
<td>Hip Abduction</td>
<td>0.558*</td>
<td>0.087</td>
<td>0.310</td>
</tr>
<tr>
<td></td>
<td>(0.322)</td>
<td>(0.070)</td>
<td>(0.343)</td>
</tr>
<tr>
<td>Hip Adduction</td>
<td>0.321</td>
<td>0.887*</td>
<td>0.600</td>
</tr>
<tr>
<td></td>
<td>(0.230)</td>
<td>(0.258)</td>
<td>(0.387)</td>
</tr>
<tr>
<td>L5/S1 Extension</td>
<td>1.633</td>
<td>1.708</td>
<td>1.379</td>
</tr>
<tr>
<td></td>
<td>(0.503)</td>
<td>(0.485)</td>
<td>(0.375)</td>
</tr>
<tr>
<td>L5/S1 Flexion</td>
<td>0.279</td>
<td>0.355</td>
<td>0.327</td>
</tr>
<tr>
<td></td>
<td>(0.121)</td>
<td>(0.164)</td>
<td>(0.137)</td>
</tr>
</tbody>
</table>
Figure 2. Group ensemble curves for hip peak hip internal add/abduction moments during the forward and wide step conditions. Positive values represent abduction moments and negative values represent adduction moments.

Figure 3. Group ensemble curves for peak internal hip extension moments during the trunk upright and trunk forward conditions. Positive values represent hip extension moments.
DISCUSSION

The purpose of this study was to observe changes in the kinetics and myoelectric activity of the trunk and lower extremities due to changing the width of the step, position of the trunk and increasing external load during the FL. The first hypothesis was that the peak hip internal extensor moment and gluteus maximus EMG activity would increase due to increasing step width, a forward position of the trunk position and increasing external load. This hypothesis was only partially supported as the data showed a significant increase in peak internal hip extension moment during the trunk forward condition compared to the trunk upright condition and with increased external load, but not during the wide step lunge. The increase in hip extension moment was likely due to an increase in the moment arm between the hip joint center and the upper body center of mass. This would create a greater external hip flexion moment and would cause the hip extensors to generate a greater internal moment to balance the trunk during descent and to return the trunk to an upright position. This agrees with Farrokhi et al. (2008) who found an increase in the hip joint impulse by assuming a forward position in the trunk during the descent phase of the forward lunge. The increase in peak internal hip extension moment due to the forward position of the trunk was nearly identical to the increase due to increasing the external load (Table 2).

The results did not show significant increases in peak EMG of the gluteus maximus during any of the variations of the FL, which did not support the hypothesis and does not agree with the previous research (McCaw and Melrose, 1999, Farrokhi et al., 2008). This could be due to the fact the subjects in this study were asked to step at a 30° angle from the anterior axis of their front foot, which may not have created a wide enough step to change the length of the gluteus maximus. McCaw and Melrose (1999) observed significant increase in gluteus maximus
activity during the squat by increasing the width of the stance to 140% of shoulder width and increasing the external load from 60% to 75% of the subjects’ 1 rep maximum. These authors stated that this increase in gluteus maximus activity may have been due to the gluteus maximus being placed in a less than optimal position on the force-length curve causing it to have to recruit more motor units in order to achieve the necessary hip extension to complete the exercise. Stepping at a 30° angle may not have increased the medio-lateral distance between the subject’s feet enough to see this effect.

Perhaps the higher load was not a high enough percentage of the subject’s maximum capacity to cause a stance by load interaction like that seen by McCaw and Melrose (1999). Subjects were instructed to not rotate their pelvis about the vertical axis during the wide step condition. However, without having practiced this movement before the testing session this could have been difficult for some of the subjects. If the subject did rotate the pelvis about the vertical axis it would diminish the effect of changing the length of the gluteus maximus by reducing the abduction angle created by the wide step. The increase in external load did cause a significant increase in peak hip extensor moment, but did not show a significant change in gluteus maximus EMG. This could be due to the fact that many of the subjects were currently participating in a regular strength training program for the lower extremities that involved using higher external loads for the lunge. Even though the external load caused a greater internal moment, this moment may not have required a greater activation of the gluteus maximus. Perhaps if the load was increased based on the subject’s maximum capacity, an increase in gluteus maximus activity would have been seen due to external load.

There was also no increase in gluteus maximus EMG activity due to the forward position of the trunk despite an increase in peak internal hip extension moment. This could have been
because some of the subjects could not accomplish the forward position of the trunk with hip flexion alone. Many used a combination of hip flexion and trunk flexion. Therefore, increased recruitment of the gluteus maximus may not have been necessary to return the upright position.

It was also hypothesized that peak internal knee extension moment, EMG activity of the vastus lateralis and vastus medialis, and peak hip adduction moment would increase with an increase in step width. Again this hypothesis was only partially supported as a significant increase in hip adduction moment was seen with an increase in step width. This agrees with the findings of McCaw and Melrose (1999) who saw an increase in adductor longus EMG activity during the ascent phase of a squat with a wider stance. It is believed that the increase in hip adduction moment was due to the knee joint moving more laterally relative to the thigh and upper body center of mass creating a larger moment arm in the frontal plane. Peak knee extension moment and EMG of the vastus medialis and vastus lateralis did not increase with an increase in step width, which does not support the hypothesis. This does not agree with Escamilla et al. (2000) who saw an increase in knee extension moment in a sumo style deadlift (wide stance) compared to the conventional style deadlift (narrow stance). The authors stated that the sumo style deadlift moved the barbell posterior to the knee joint causing an increased internal knee extension moment to complete the exercise. The data of the current study may not have shown a similar movement of the external load to the posterior of the knee joint during the wide stance and therefore no increase in internal extension moment was observed. This could also be caused by the fact that the subjects in the Escamilla et al. (2000) study were completing a maximum exertion of the exercise during a competition while the subjects in the current study where performing submaximal loads. Escamilla et al. (2002) observed an increase in EMG activity of the vastus medialis and vastus lateralis during the sumo compared to the conventional...
style deadlift. Subjects in this study used a load equal to that of their 12 repetition maximum which may have caused a greater change in activation when moving from a narrow to a wide stance.

Another hypothesis was that peak L5/S1 internal extension moment and trunk muscle peak EMG values would only increase as a function of increasing external load and not with forward position of the trunk. It was believed that increasing the forward position of the trunk while keeping the back in a neutral position would not cause a significant increase in the moment and therefore would also not cause an increase in electrical activity of the trunk muscles. Again, the hypothesis was partially supported in that the EMG activity of the trunk did not significantly increase due to the forward position of the trunk or the increase in external load. However, the peak internal L5/S1 extension moment did show a significant increase for both variables.

Athletes who have suffered injuries to the low back should be cautious of performing the lunge with a forward position of the trunk or with too high of an external load as this may exacerbate the injury. Peak external knee varus and valgus moments were only expected to increase as a function of increasing external load. This was not supported as neither increased with external load but both increased as step width increased. The increase in varus moment was likely due to the knee joint moving laterally from the thigh and upper body center of mass which caused an increased moment arm in the frontal plane. While the mechanism behind the increase in knee valgus moment is not as clear it could be due to instability of the subjects during the stance phase of the wide step lunge as many of them had never performed this exercise. The increased knee varus and valgus moments could increase medial and lateral compression of the knee joint, respectively. Individuals rehabilitating from knee injuries may want to avoid performing a lunge with a wide step.
The final hypothesis was that the addition of the external load to the lunge exercise would show greater activation of all lower extremity muscles compared to those cited in the literature when only body weight was used. It was believed that all muscles sampled will be above the 45 to 50% activation threshold to increase strength. As seen in Table 1, this hypothesis was supported in that all the lower extremity muscles sampled showed higher peak EMG values than those cited in the literature. Ekstrom et al. (2007) reported peak EMG values of 36 ± 17%, 76 ± 19% and 11 ± 6% for the gluteus, vastus medialis and hamstring muscles, respectively. Farrokhi et al. (2008) reported an activation level of 45.6 ± 8.3% for the vastus lateralis and 11.9 ± 6.4% for the biceps femoris. The current study showed values higher than these for all muscles even during lower load condition for each lunge variation.

Another interesting finding was that internal knee flexion significantly increased with an increase in step width while internal hip flexion moment decreased with an increase in step width. This could represent a relative increase in the knee joint maintaining stability with a wider step as opposed to the hip joint.

While all the subjects in the current study had performed the FL as part of a regular exercise program at some point, not all subjects reported currently using the lunge as part of their training. Also, while all the subjects were recreational athletes, they did not all participate in the same activities. These two facts could have caused variations in the performance of the lunge technique between subjects. None of the subjects had ever performed the FLTF, WSL or WSLTF as part of a regular strength training routine and many reported that they felt unstable during these variations. Some of the subjects had reduced range of motion in the hip joint and had difficulty increasing the forward position of the trunk through hip flexion during the FLTF and WSLTF conditions. Future studies looking at varying the FL lunge technique should recruit
subjects that are currently using the lunge as part of a regular strength routine and also provide a practice session to improve the technique of the lunge variations. Subjects should be observed during the practice session to ensure that they are able to accomplish the forward trunk position through hip flexion rather than flexion of the spine. EMG data of the adductor/abductor muscle groups should also be sampled to observe their activity during the variations.

The current study used the same external loads for all subjects based on subjective data from pilot subjects. Having subjects perform a repetition maximum and then using a load equal to that maximum or a percentage of maximum may provide better insight into the effects of increasing the intensity of the exercise on increasing the EMG activity of the muscles. Future studies should also focus on how the FL, variations of the FL and other functional exercises translate to athletic performance and activities of daily living compared to exercises that isolate muscle groups.

**Conclusion**

Varying the technique of the FL does cause changes to trunk and lower extremity biomechanics. Increasing the forward trunk position causes an increase in the peak internal hip and L5/S1 extension moments while the external knee varus and valgus moments did not change. While this may help strengthen the hip extensors while sparing the knees, individuals who have suffered back injuries may be advised to avoid performing lunges with the trunk in a more forward position. The increase in peak internal hip extension moment was nearly identical for the forward position of the trunk and the increased external load. This may have implications for rehabilitation purposes. This finding may also be beneficial for individuals that train at home and have limited equipment. Individuals who have reached training plateaus and want to change their lower body training routine may find employing this technique useful. Increasing the width
of the step alters moments of the frontal plane such as the internal hip adduction moments as well as the external knee varus and valgus moments. This increase in internal hip adduction moment may help train the muscles that perform this movement and could lead to reduced injuries of these muscles. However, individuals who have suffered knee injuries may be advised to avoid lunges with a wider step.
REFERENCES


CHAPTER III

GENERAL CONCLUSIONS

In both training and rehabilitation, altering the technique of exercises is common in order to target different muscle groups and to train different movements. Varying the technique of the FL does cause changes to trunk and lower extremity biomechanics. Increasing the anterior position of the center mass of the upper body causes an increase in the peak internal hip and L5/S1 extension moments. This can be helpful for healthy individuals, free from back pain, who want to target their hip extensor muscles. This is a way in which individuals that train at home and may not own barbells or enough weight to do squats and deadlifts can increase the intensity of these muscles. It can also be useful for people who already perform squats and deadlifts regularly and want to change their routine either because they have reached a plateau with these exercises or want to add more of a balance aspect to their lower body training. However, this alteration does pose an increased risk for injury due to the increase in L5/S1 extension moment compared to the lunge in the upright position.

Hip adductors can be targeted by increasing the width of the step of the lunge which can be useful to people who are involved in athletics in which cutting movements are common or if they have strained muscles in this area in the past. Another benefit to using this type of lunge as opposed to a hip adduction weight machine is that this is a functional movement that is similar to activities of daily living and athletic movement. Doing lunges in multiple planes may better transfer to movements such as planting and cutting. These types of lunges may help supplement agility training like plyometrics and could possibly help reduce the risk of injury while performing athletic movements that occur in multiple planes. However, there may be an
increased risk for knee injuries by employing the wider step due to increased external varus and valgus moments at the knee.

Future research on variations of the FL should continue to look EMG activity. While there were increasing trends with increasing intensity in some of the independent variables, a low sample size and large variability between subjects also

Functional training is important for both healthy individuals wanting to improve performance and injured individuals who want to return to certain activities. It is important to continue to research these types of exercises in order to better understand the possible benefits and risks as well as their proper technique and progression.
ACKNOWLEDGEMENTS

Thank you to my parents, Curtis and Kathy who have always given me unconditional love and support. They instilled discipline in me to get me to this point in my life and believed in me even when I did not. Thank you to my oldest sister, Jackie, who taught me the importance of responsibility by making sure my siblings and I were up for school every day. Thank you to my brother Matt who taught me that life is meant to be enjoyed and not taken too seriously. Thank you to all my friends who loved me through all of my ups and downs. Thanks to all the wonderful teachers I had at Davis County Community Schools, Simpson College and Iowa State University who helped me to love to learn and experience new things.

A special thank you to Dr. Jason Gillette, Dr. Gary Mirka, and Boyi Dai. Dr. Mirka for helping me complete my first research project. Boyi Dai for helping me immensely with this project and showing me that the world truly is a small place and that there are amazing people everywhere. Dr. Jason Gillette who I returned to school to work with. He always created a great environment to learn and grow while keeping me focused on what is truly important with this line of work: improving the lives of others.

I would like to acknowledge my late sister Lisa Leann Sorensen who to this day was the most caring, compassionate person I have ever known. It is my goal in life to work every day to make this world a better place just as she would have if she was still here. I would never be the person I am today without having known her for 12 years.
APPENDIX A:

INFORMED CONSENT DOCUMENT

Title of Study: Effects of trunk position and step width on biomechanical stresses on the low back and EMG activity of the trunk and lower extremities during the lunge exercise.

Investigators: Christopher J. Sorensen, Jason C. Gillette, Timothy R. Derrick, Gary A. Mirka, Boyi Dai, Michelle Hall, Catherine Stevermer, Lindsey Berhens, Elizabeth Stafford, Dane Danforth, Nicole Nelson

This is a research study. Please take your time deciding if you would like to participate. Please feel free to ask questions at any time.

INTRODUCTION

The purpose of this study is to evaluate the stresses placed on the lower back during different variations of the lunge exercise and compare the differences in muscle activation of the lower body and trunk muscles during these variations. It is believed that the information gained from this study will benefit society by providing insight into optimizing lower body strength training techniques while minimizing the stress placed on the lower back. You are invited to participate in this study because you are a healthy active individual that is familiar with the lunge exercise, between the ages of 18 and 34 years old and have no history of chronic or current lower back, hip, or knee injuries. Chronic injuries to lower back, hip, or knee are described as any injury that has required surgery or required you to limit/alter your activities of daily living for more than 3 consecutive days on more than one occasion. Current injuries are described as any lower back, hip, or knee injury that is currently causing you to limit/alter your activities of daily living.

DESCRIPTION OF PROCEDURES

If you agree to participate in this study you will be asked to complete a session in the biomechanics lab that will last around 2 hours. During this session you will complete a series of strength testing and lunging exercises. Upon arrival you will be asked the following questions regarding inclusion/exclusion criteria: Are you between the ages of 18 and 34? Have you ever suffered a lower back, hip, or knee injury that has caused you to change activities of your daily routine for more than 3 consecutive days? If so, has this injury occurred on more than one occasion? Are you currently suffering from low back, hip, or knee pain that has caused you to alter your daily routine? If you meet the criteria for this study, investigators will then verbally describe the experiment and allow you ample time to ask any questions about the study. Your age will be asked and then your height and weight will be measured. Anthropometric measures including trunk circumference, thigh circumference, thigh length, calf circumference, calf length, foot length, and foot breadth will be recorded. EMG electrodes will be placed on your lower back, abdominal, gluteus maximus, hamstring and quadriceps muscles. You will then complete a brief warmup and stretching period. Three maximal voluntary contractions of the muscles with EMG will then be performed. For the trunk muscles, you will be seated in a device in which your hips will be secured to the seat and a pad will go across your shoulder blades as you sits in
an upright position. You will then maximally extend your trunk into the pad and hold this for three seconds. Next, you will turn and face the other direction so the pad will go across your chest and your hips will once again be secured to a seat. You will then maximally flex your trunk into the pad for 3 seconds. You will then return to the biomechanics lab. You will perform a maximal voluntary contraction of the vastus lateralis and vastus medialis as you sit upright on a table with your legs hanging at a 90 degree angle. An investigator will then hold your right lower leg just above your ankle and you will extend your leg with maximal effort for 3 seconds. For the strength testing of the semitendinosus and biceps femoris you will lay face down on a padded table and flex your right leg to 90 degrees so your lower leg is perpendicular to the table. An investigator will then hold your lower leg at the achilles tendon and you will flex your knee with maximal effort for 3 seconds. For the gluteus maximus test you will be positioned on the table on your hands and knees. An investigator will hold the back of your leg just above the knee. You will then maximally extend at the hip for 3 seconds. There will be 3 repetitions of each strength test and a 1 minute rest period will be given between each trial. These maximum EMG data will be used to normalize the EMG data from the lunging trials. You will then have spherical reflective markers placed on your feet, lower legs, thighs, hips, low back, sternum, and shoulders. These markers will be tracked by an 8 camera motion capture system. You will then receive instructions on how to complete the four variations of the lunge exercise. The four lunges are as follows: 1) a standard straight forward lunge in which you begin with your feet together and you will step forward with your right leg lowering until your left knee is just above the ground and then return to an upright position, 2) a straight forward lunge with trunk flexion in which you do the same as the standard lunge but lean forward with your trunk as you lower to the ground, 3) a 45 degree lunge in which you start with your feet together and step forward with your right foot at a 45 degree angle and once again lower until your left knee is just above the ground and then returns to standing, and 4) a 45 degree lunge with trunk flexion in which you will do the same as the 45 degree lunge but will lean forward with your trunk as you lower. You will perform each lunge 3 times while holding 15 pound dumbbells, 3 times while holding 30 pound dumbbells for a total of 24 trials. During all lunges you will start from one force platform and step to another with your right foot. The distance between the platforms will be adjusted to ensure both of your feet are in the middle of the platform at all phases to reduce the risk of falling. Your lunge form will be monitored at all times to make sure that the knee of your right leg does not extend beyond the toes of your right foot, the left knee is at 90 degrees at the lowest point and that proper speed in used (1-2 seconds for lowering phase, 1-2 seconds for rising phase). This will reduce the risk of injury during the trials.

Risks:

While participating in this study you may be exposed to certain risks of injury. There is a risk for lower back injuries as well as some muscle or joint discomfort while performing maximal voluntary contractions and the lunge exercises. Therefore, you will be required to complete a warmup before these tasks and will be given ample rest time between conditions. Also, investigators will teach you the proper technique for each lunge and allow you enough time to practice so that you are comfortable with all conditions.

Benefits:
If you decide to participate in this study there may be no direct benefit to you. It is hoped that the information gained in this study will benefit society by providing information on optimizing lower body strength training techniques while minimizing the biomechanical stress placed on the lower back.

ALTERNATIVES TO PARTICIPATION

The only alternative is to not participate in this study.

COSTS AND COMPENSATION

You will not have any costs and will not be compensated for participating in this study.

PARTICIPANT RIGHTS

Your participation in this study is completely voluntary and you may refuse to participate or leave the study at any time. If you decide to not participate in the study or leave the study early, it will not result in any penalty or loss of benefits to which you are otherwise entitled.

CONFIDENTIALITY

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy your records for quality assurance and data analysis. These records may contain private information. To ensure confidentiality to the extent permitted by law, the following measures will be taken. The motion analysis is numerical and does not contain video that could identify the participant. Your data will be kept confidential by using alphanumeric identifiers that are unrelated to your name. Your name and information/data will be kept in separate locations. Your informed consent document will be kept in a locked file cabinet in Christopher Sorensen’s office in Forker Building. The research team will keep private all research records that identify you to the extent allowed by law. When the results of the study are reported, the combined information that has been gathered will be presented. If the results are published, your identity will remain confidential.
QUESTIONS OR PROBLEMS

You are encouraged to ask questions at any time during this study.

- For further information about the study contact Christopher Sorensen at 515-450-6097 or Jason Gillette at 515-294-8310.
- If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, 515-294-4566, IRB@iastate.edu, or Director, 515-294-3115, Office of Research Assurances, Iowa State University, Ames, Iowa 50011.

************************************************************************

PARTICIPANT SIGNATURE

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant’s Name (Printed) ________________________________________________

_____________________________________  ________________________

(Participant’s Signature)      (Date)

INVESTIGATOR SIGNATURE

I certify that the participant has been given adequate time to read and learn about the study and all of their questions have been answered. It is my opinion that the participant understands the purpose, risks, benefits and the procedures that will be followed in this study and has voluntarily agreed to participate.

_____________________________________  (Date)

(Signature of Person Obtaining Informed Consent)  (Date)
APPENDIX B:

EXTENDED EMG RESULTS

The following tables show the peak normalized EMG values during both the descent and ascent phase for each of the independent variables. It also shows both left and right erector spinae and left and right rectus abdominis rather than the average of the left and right. The low number of subjects to start (n = 11) and the loss of 3 subjects due to outliers lowered the number of dependent variables used in the statistical model. Many of the muscles sampled show increasing trends during the variations to the exercise. There were also increasing trends during the ascent phase compared to the descent phase. Future studies should recruit more subjects to see if these variables reach statistically significant differences and also to investigate differences between the two phases of the forward lunge.
Table 3. Averages (standard deviation) of peak normalized EMG values for each independent variable during the descent phase for all muscles sampled.

<table>
<thead>
<tr>
<th></th>
<th>Step Width</th>
<th>Trunk Position</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forward</td>
<td>Wide</td>
<td>Upright</td>
</tr>
<tr>
<td>Gluteus Maximus</td>
<td>0.416</td>
<td>0.424</td>
<td>0.420</td>
</tr>
<tr>
<td></td>
<td>(0.248)</td>
<td>(0.243)</td>
<td>(0.236)</td>
</tr>
<tr>
<td>Vastus Medialis</td>
<td>0.870</td>
<td>0.982</td>
<td>0.913</td>
</tr>
<tr>
<td></td>
<td>(0.411)</td>
<td>(0.418)</td>
<td>(0.411)</td>
</tr>
<tr>
<td>Vastus Lateralis</td>
<td>0.845</td>
<td>0.967</td>
<td>0.902</td>
</tr>
<tr>
<td></td>
<td>(0.389)</td>
<td>(0.470)</td>
<td>(0.446)</td>
</tr>
<tr>
<td>Biceps Femoris</td>
<td>0.320</td>
<td>0.322</td>
<td>0.318</td>
</tr>
<tr>
<td></td>
<td>(0.152)</td>
<td>(0.169)</td>
<td>(0.161)</td>
</tr>
<tr>
<td>Semidtendinosus</td>
<td>0.313</td>
<td>0.373</td>
<td>0.352</td>
</tr>
<tr>
<td></td>
<td>(0.199)</td>
<td>(0.234)</td>
<td>(0.225)</td>
</tr>
<tr>
<td>Right Erector Spinae</td>
<td>0.565</td>
<td>0.596</td>
<td>0.559</td>
</tr>
<tr>
<td></td>
<td>(0.297)</td>
<td>(0.388)</td>
<td>(0.353)</td>
</tr>
<tr>
<td>Left Erector Spinae</td>
<td>0.750</td>
<td>0.732</td>
<td>0.718</td>
</tr>
<tr>
<td></td>
<td>(0.320)</td>
<td>(0.328)</td>
<td>(0.314)</td>
</tr>
<tr>
<td>Right Rectus Abdominis</td>
<td>0.443</td>
<td>0.456</td>
<td>0.433</td>
</tr>
<tr>
<td></td>
<td>(0.219)</td>
<td>(0.210)</td>
<td>(0.205)</td>
</tr>
<tr>
<td>Left Rectus Abdominis</td>
<td>0.406</td>
<td>0.411</td>
<td>0.406</td>
</tr>
<tr>
<td></td>
<td>(0.240)</td>
<td>(0.245)</td>
<td>(0.245)</td>
</tr>
</tbody>
</table>
Table 4. Averages (standard deviation) of peak normalized EMG values for each independent variable during the ascent phase for all muscles sampled.

<table>
<thead>
<tr>
<th></th>
<th>Step Width</th>
<th>Trunk Position</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Forward</td>
<td>Wide</td>
</tr>
<tr>
<td>Gluteus Maximus</td>
<td>0.698</td>
<td>0.703</td>
<td>0.715</td>
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<tr>
<td></td>
<td>(0.339)</td>
<td>(0.347)</td>
<td>(0.347)</td>
</tr>
<tr>
<td>Vastus Medialis</td>
<td>1.015</td>
<td>1.007</td>
<td>1.046</td>
</tr>
<tr>
<td></td>
<td>(0.441)</td>
<td>(0.425)</td>
<td>(0.436)</td>
</tr>
<tr>
<td>Vastus Lateralis</td>
<td>1.054</td>
<td>1.067</td>
<td>1.095</td>
</tr>
<tr>
<td></td>
<td>(0.400)</td>
<td>(0.406)</td>
<td>(0.425)</td>
</tr>
<tr>
<td>Biceps Femoris</td>
<td>0.358</td>
<td>0.349</td>
<td>0.413</td>
</tr>
<tr>
<td></td>
<td>(0.152)</td>
<td>(0.149)</td>
<td>(0.179)</td>
</tr>
<tr>
<td>Semidtendinosus</td>
<td>0.307</td>
<td>0.328</td>
<td>0.343</td>
</tr>
<tr>
<td></td>
<td>(0.180)</td>
<td>(0.196)</td>
<td>(0.196)</td>
</tr>
<tr>
<td>Right Erector</td>
<td>0.547</td>
<td>0.503</td>
<td>0.652</td>
</tr>
<tr>
<td>Spinae</td>
<td>(0.311)</td>
<td>(0.287)</td>
<td>(0.358)</td>
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<tr>
<td>Left Erector</td>
<td>0.702</td>
<td>0.684</td>
<td>0.745</td>
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<tr>
<td>Spinae</td>
<td>(0.290)</td>
<td>(0.296)</td>
<td>(0.276)</td>
</tr>
<tr>
<td>Right Rectus</td>
<td>0.452</td>
<td>0.458</td>
<td>0.475</td>
</tr>
<tr>
<td>Abdominis</td>
<td>(0.232)</td>
<td>(0.212)</td>
<td>(0.228)</td>
</tr>
<tr>
<td>Left Rectus</td>
<td>0.405</td>
<td>0.419</td>
<td>0.409</td>
</tr>
<tr>
<td>Abdominis</td>
<td>(0.228)</td>
<td>(0.245)</td>
<td>(0.224)</td>
</tr>
</tbody>
</table>