ANTERIOR CRUCIATE LIGAMENT NEUROMUSCULAR TRAINING PROTOCOL OF THE CORE AND HIP MUSCULTURE: EFFECTS ON FEMALE ATHLETES' LANDING MECHANICS

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Anterior Cruciate Ligament Neuromuscular Training Protocol of the Core and Hip Musculature: Effects On Female Athletes' Landing Mechanics

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Landing is a dynamic activity and considered one of the leading causes of noncontact ACL injuries. Poor biomechanics during dynamic activity resulting from neuromuscular imbalances may contribute to an ACL injury. The purpose of this study was to determine if a trunk and hip neuromuscular training program for female high school athletes facilitates neuromuscular changes during landing mechanics. Participants were assessed using the Landing Error Scoring System (LESS) after a drop box jump, pre-test, mid-test, and post-test. A high LESS score indicates poor landing mechanics. Additionally, participants filled out a survey regarding their perceptions of neuromuscular changes and their landing mechanics. LESS scores decreased significantly between pre to post testing. Participants believed their landing mechanics improved, they became stronger, and they become more aware of their body. Results showed that an eight week hip and trunk neuromuscular program improved landing mechanics and may help decrease noncontact ACL injuries in this population.

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Thank you to my advisor Dr. Pamela Hansen for everything she has done for me. Thank you for always challenging me in a variety of ways and for all the time you have spent with me making me a better researcher, athletic trainer, and student.

Thank you to my graduate committee, Drs. Terbizan, Christensen, and Blodgett Salafia. You all have been a major component in this process and have helped me achieve one of the biggest accomplishments in my life.

DEDICATION

I dedicate this Thesis to my family and friends. This would have not been possible without your constant encouragement and support.

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INTRODUCTION

An anterior cruciate ligament (ACL) injury is a devastating injury for anyone who is physically active. Eighty percent of ACL injuries are from a noncontact mechanism, with landing from a jump being the leading cause.[8] In the high school setting, females have an incidence rate of suffering a noncontact ACL three to eight times higher than their male counterparts.[6] This may be due to females and males demonstrating differences in neuromuscular strength at different times of their lifespan. Specifically, males typically demonstrate an increase growth of neuromuscular control during puberty where females, on average, have little changes throughout puberty.[15]

Growth spurts can cause rapid growth of the femur and tibia in length which causes the body's center of mass to become higher. This change in the body's center of mass, along with no increase in strength and reduced recruitment of surrounding musculature can make the trunk difficult to control in dynamic activity. This decrease in trunk neuromuscular control leads to trunk dominance, along with other neuromuscular imbalances that females exhibit such as ligament dominance, quadriceps dominance, leg dominance, could be the underlying reason of the poor biomechanics that females show during deceleration activities.[9,13] Also, decreased control of the trunk may lead to reduced preactivation of the trunk and hip stabilizers, which may increase lateral trunk positions that can lead to valgus knee loads.[19] Preactivation of the trunk and hip stabilizers may help to counterbalance too much trunk motion.[13] Poor landing techniques can force the knee into a combination of directions. These directions include an anterior, internal/external rotation, medial, or hyperextension direction that are possible mechanism of ACL injuries.[1,2,20] Poor neuromuscular control combined with an erect landing posture, which females commonly display, exacerbates these poor landing mechanics.[4,18] For example, when landing from a jump with a knee flexion of 5˚ to 20˚ combined with a valgus motion and rotation of the knee, the chances of an ACL injury are increased.[18]

The purpose of this study was to determine if a trunk and hip neuromuscular training program facilitated neuromuscular changes during landing mechanics. To address the purpose of the study three questions were examined. First, did the trunk and hip neuromuscular training change landing mechanics in these participants. Second, did the most significant neuromuscular changes occur at four weeks or eight weeks, and lastly, did the participants perceive their landing mechanics improved after completion of the program. This study will help support previous research and the importance of using a trunk and hip neuromuscular strength program to improve landing mechanics and decrease the chances of sustaining a noncontact ACL injury in females.

METHODS

Experimental Approach to the Problem

This study was a repeated measures design. The independent variable was the neuromuscular training protocol and the dependent variable was the participants LESS score. The researchers controlled for age and sex of the participants by only allowing high school (Grades 9^{th}-12^{th}) females to participate in the study.

Subjects

Approval was granted by the North Dakota State University Institutional Review Board. Thirty healthy female high school volleyball, hockey, basketball, softball, track and field, and soccer (15.13±0.99 yrs; 60.76±6.16 kg; 169.91±7.1 cm) volunteered for this study. An informed consent form was signed by the participant and parent. Demographic information was also collected. Exclusion criteria included participants who suffered an ACL repair or any knee surgery in the past year.

Procedures

Testing

The participants performed the drop box jump prior to starting the neuromuscular training program (pre-test) in order to establish a baseline. Participants were reassessed using the drop box jump at mid-test (four weeks) and at the end of the post-test (eight weeks).

To objectively assess jump-landing biomechanics, Padua[17] developed the Landing Error Scoring System (LESS). The LESS has shown to be a reliable and valid assessment to evaluate jump-landing biomechanics that can easily be used by coaches, personal trainers, or athletic trainers.[17]

Prior to the start of the drop box jump, participants had anatomical markers placed on their lateral malleolus, greater trochanter, lateral femoral condyle, midfoot, and sternum to ensure consistency in evaluation of the LESS. After the placement of the anatomical markers, the drop box jump was explained. Participants were instructed to jump forward off a 30 cm box at a distance of 50% of their height, which was marked on the floor for them. After jumping to the marked spot, participants were instructed to jump vertically as high as high as possible.[17] Participants received no feedback or coaching on their technique. The landing mechanics from the drop box jump was scored according to the LESS protocol.

Participants were allowed two familiarization drop box jumps to help become acquainted with the task. After completing the first two jumps, three drop box jumps were videotaped. Camcorders were placed in a sagittal view and a coronal view.

Neuromuscular Training Protocol

Participants were asked to attend at least three training session per week for eight weeks. Prior to each training session participants went through a warm-up. The warm-up consisted of light running, stretching, and dynamic exercises.

The trunk and hip neuromuscular training protocol consisted of 13 exercises, with each exercise having five phases. The protocol includes core stability, plyometrics, balancing, and strengthening exercises that were developed by Myer and his colleagues.[13] The exercises were lateral jumping, single-leg forward hops, prone trunk stability, kneeling trunk stability, single-leg lateral hops, tuck jump, forward lunge, lunge jump, hamstring-specific exercise, single-leg rotatory hop, lateral trunk crunch, trunk flexion, and trunk. Each subject performed the exercise in the current phase with perfect technique before moving to the next phase of the exercise. The co-investigator evaluated each participant while preforming the exercise to determine if the correct technique was demonstrated. The trunk and hip neuromuscular training protocol can be found at Myer et al[13]. This specific trunk and hip neuromuscular training program utilized various exercise equipment in order to make the phases of each exercise more challenging. A BOSU® Sport Balance Trainer (55 cm) (Ashland, Ohio), Swiss Balls (55 cm) (Knoxville, TN), Airex® pads (20” x 16.4” x 2 ½”) (Knoxville, TN), plyometric boxes (30 cm in height), medicine balls, and dumbbell weights were used in increase the difficulty of the various exercises.

Instrumentation

The Landing Error Scoring System (LESS) by Padua[17] was used to score the landing mechanics of the participants. The LESS scored various aspects of how the participant landed. Points are given for poor mechanics. For example, one point is given if the participant lands with an erect posture, knee valgus, asymmetrical foot landing, a stiff landing, and so on. A low score indicates good landing technique and a high score indicates poor landing technique. The LESS score was determined by watching the participant’s video in slow motion while using the Dartfish software program. The program was also used to help measure angles of various joints. All scoring was done by the co- investigator. The LESS scoring criteria can be found in Table 1.

Statistical Analyses

The lowest LESS score of the three drop-box jumps was used for statistical analyses. Data was analyzed by a repeated measures analysis of variance to determine if the trunk and hip neuromuscular strength program decreased LESS scores. Additionally, a T-Test was used to determine significance between pre-test to mid-test, mid-test to post-test, and pre-test to post-test. A Chi-Square test for Goodness of Fit was used for the descriptive data form the survey. All statistical tests used a level of significance of $\alpha < 0.05$. The SPSS version 20 was used for all analysis (Chicago, IL, USA).

RESULTS

Data from 11 (14.91±1.04 yrs; 64.24±5.40 kg; 170.87±6.82 cm) of the 30 participants were used for analyses (Table 2). Only 11participants attended all testing sessions. Table 3 and 4, respectively, indicate the participants academic year and sport. Many of the participants did not make all of the 23 exercise sessions due to prior engagements. Therefore, the number of exercise sessions attended varied (pre-test to mid-test 8.45±1.83, mid-test to post-test 9.73±2.77, and overall sessions attended 18.18±3.79).

Results from the repeated measures ANOVA indicated that the eight week trunk and hip neuromuscular program had a significant effect on the LESS scores, $F(2,20) = 9.36$, $p<0.05$ (Figure 1). Additionally, Significant gains in neuromuscular strength occurred from the pre-test (6.73±1.74) to post-test (4.73±1.49) $t(20) = 3.44$, $p<0.05$. No significance was noted between pre-test and mid-test and mid-test and post-test. A Chi-Square test for Goodness of Fit was used to assess the third research question. The results indicated that the participants significantly felt that the trunk and hip neuromuscular program has improved their landing technique, $\chi^2(1, n= 11) = 4.46$, $p<0.05$, made them stronger, $\chi^2 (2, n = 11) = 11.64$, $p<0.05$, and they became more aware of their body, $\chi^2(1, n = 11) = 4.46$, $p<0.05$. All other survey questions had more positive responses than negative responses, except for the fifth question, but were not significant. Data is represented in Figure 2.

DISCUSSION

Results from this study note that an eight week trunk and hip neuromuscular strength training program can improve landing mechanics of high school females. Injury prevention programs can decrease poor biomechanics of landing technique.[3,5,10,16] DiStefano et al[5] used 27 youth male and female soccer teams that ranged in the age of 10 to 17 through an ACL injury prevention program found similar results. The program was 10 to 15 minutes and was performed three to five times a week for the duration of their season. DiStefano et al[5] also reported that the participants with the highest LESS scores received the most benefit from the injury prevention program. Chappell and Limpisvasti[3] also showed similar results. In their study, 30 female Division I participants went through a six week neuromuscular strength program that focused on core strengthening, dynamic joint stability, balance training, jump training, and plyometric exercises for six days a week with each session lasting about 15 minutes. These results[3,5] showed similar results to our study that an ACL neuromuscular injury prevention training improved the landing mechanics of the participants during a jump landing task.

In another related study, a meta-analyses (with a level of 1 evidence and a grade B recommendation, which indicates the use of sound studies) further supports the use of neuromuscular training programs for the prevention of noncontact ACL injuries.[7] This meta-analysis consisted of five studies that implemented a neuromuscular training program for a female sport team over one competitive season. Three of the sport teams were high school aged females and the two other studies used elite athletes. Four out of the five of the neuromuscular training programs lasted for 10-20 minutes and consisted of plyometrics, strengthening exercises, balancing training, and flexibility training.[7]

The trunk and hip neuromuscular strength training program used in this study developed by Myer et al[l3] utilizes core and hip strengthening through core stability, plyometrics, balancing, and strengthening exercises. Research has shown that females have poorer neuromuscular control of the hamstrings and weaker gluteus medius strength when compared to males, which is an important indicator of poor landing mechanics.[2,4] A study conducted by Leetun et al[12] that examined the differences in hip and core stability between males and females as well as which participants in their study became injured during their sport supports strengthening the hip and core musculature. In Leetun et al[12] study the results showed that females demonstrated significantly reduced side bridge endurance along with hip abduction and external rotation strength. Leetun et al[12] suggested that the weakness of the trunk and hip reduces their ability to stabilize this area leading to excessive motion in the hip or trunk. The excessive motion could potentially lead to the lower extremity moving into positions associated with a noncontact ACL injury. Jacobs et al[11] also supports that weaker hip musculature can lead to potential noncontact ACL mechanisms. Jacobs et al[11] showed that females who had weaker hip abductors also displayed knee valgus when landing from a jump. The results of these studies[11,12] support our study by showing that females have weaker core and hip musculature and that strengthening the core and hip musculature helps to reduce potential noncontact ACL movements. Strengthening the core and hip musculature is important in order to control the body's center of gravity. Weak abdominal muscles may not stabilize the spine when trying to control external forces that may instead cause the spine to extend, laterally flex, or even rotate.[12] Not controlling the body's center of gravity makes it difficult to control the trunk and in turn leads to poor biomechanics during landing or cutting maneuvers.[13]

We also evaluated if participants perceived that their landing technique improved after completing the eight week trunk and hip neuromuscular strength training program. Participants felt that their landing mechanics improved, felt stronger, and were more aware of their bodies after completing the trunk and hip neuromuscular strength program. Clearly, our results show that the participants believed that they benefited from the trunk and hip neuromuscular program while their landing mechanics improved. To our knowledge a survey like this has never been done before, which makes it difficult to connect the results of this study's survey to other studies. While there was a significant decrease in the LESS scores from pre-test to post-test, it should be noted that the pre-test to the mid-test was approaching significance. The investigators of this study believe this is due to the learning effect of proper landing mechanics complied with the muscles quick adaptations commonly seen when stressed. This is strengthened by the results from the mid-test to the post-test that were not approaching significance.

This study used an eight week trunk and hip neuromuscular strength program that improved landing mechanics. A similar study done by Myer et al[14] took participants through a neuromuscular strength program that was seven weeks long and required them to be there three times a week. The study determined that after a seven week program, the high school athletes at high-risk decreased their knee abduction significantly.[14] With the results of the current study indicating significance after eight weeks, along with the results of Myer et al[14] study it may be generalized that a four week neuromuscular program may not be enough to improve landing mechanics, but a minimum of a six week program may alter the landing mechanics of the participants.

In conclusion, this trunk and hip neuromuscular strength program improved the landing mechanics of female high school athletes. This is similar to other studies[3,5,10,16] showing improvement in landing mechanics through a neuromuscular program. The trunk and hip neuromuscular strength program used is based off of Myer et al[13] theory of controlling the body's center of gravity by controlling the trunk's movement. The results found from this study help strengthen this theory.

PRACTICAL IMPLICATIONS

With the compelling evidence that neuromuscular training programs reduce knee injuries such as a noncontact ACL, it is important for athletes to incorporate an injury prevention program into their regime. Many neuromuscular programs consist of exercises that can easily be incorporated into a warm up. Besides adding neuromuscular exercises into an athlete's warm up, it would be more beneficial to add a 20 minute neuromuscular strength program into their weight lifting program. The neuromuscular strength program in this study took participants approximately 20 minutes to complete and could be easily incorporated into a high school athlete's off season weight lifting regime, three times a week without the risk of overtraining. During the competitive season, specific exercises can be implemented into their warm up before practices or games so the athletes do not regress in their neuromuscular gains. This study used a neuromuscular strength program developed by Myer et al[13] to reduce the poor landing mechanics associated with noncontact ACL injuries. It would be beneficial for any high school athlete to take part in a neuromuscular strength program.

LIMITATIONS

The authors are aware there are limitations to the current study. Participants' not attending an average of three times a week was a limitation. Only the participants that attended all the testing sessions and attended a majority of the training sessions were used for data analysis. Additionally, with the lack of a control group it is difficult to determine if the LESS scores decreased only because of the participation in the trunk and hip neuromuscular training program, or if the decrease occurred because of other activities. Other limitations included results of this study can only be applied to the specific trunk and hip neuromuscular strength program used for high school female's landing mechanics. Also, the results of this study that were approaching significance may have been significant with the use of a larger sample size. The authors also cannot determine which phase of each exercise caused the landing mechanics of the participants to improve.

Table 1. LESS Scoring Criteria

LESS Item	Operational Definition	Camera View	LESS Score
1 Knee flexion angle At initial contact	At the time point of initial contact, if the knee of the test leg is flexed more than 30 degrees, score YES. If the knee is not flexed more than 30 degrees, score NO.	Side	Y=0 N=1
2 Hip flexion angle at initial contact	At the time point of initial contact, if the thigh of the test leg is in line with the trunk then the hips are not flexed and score NO. If the thigh of the test leg is flexed on the trunk, score YES.	Side	Y=0 N=1
3 Trunk flexion angle at initial contact	At the time point of initial contact, if the trunk is vertical or extended on the hips, score NO. If the trunk is flexed on the hips, score YES.	Side	Y=0 N=1
4 Ankle plantar-flexion angle at initial contact	If the foot of the test leg lands toe to heel, score YES. If the foot of the test leg lands heel to toe or with a flat foot, score NO.	Side	Y=0 N=1
5 Knee valgus angle at initial contact	At the time point of initial contact, draw a line straight down from the center of the patella. If the line goes through the midfoot, score NO. If the line is medial to the midfoot, score YES.	Front	Y=1 N=0
6 Lateral trunk flexion at angle at initial contact	At the time point of initial contact, if the midline of the trunk is flexed to the left or right side of the body, score YES. If the trunk is not flexed to the left or right side of the body, score NO.	Front	Y=1 N=0
7 Stance width - Wide	Once the entire foot is in contact with the ground, draw a line down from the tip of the shoulders. If the line on the side of the test leg is inside the foot of the test leg then greater than shoulder width (wide), score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Y=1 N=0
8 Stance width – Narrow	Once the entire foot is in contact with the ground, draw, a line down from the tip of the shoulders. If the line on the side of the test leg is outside of the foot of the test leg than shoulder width (narrow), score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Y=1 N=0

(continued)

Table 1. LESS Scoring Criteria (continued)

LESS Item	**Operational Definition**	**Camera View**	**LESS Score**
9 Foot position – Toe In	If the foot of the test leg is internally rotated more than 30 degrees between the time period of initial contact and max knee flexion, then score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Y=1 N=0
10 Foot position – Toe Out	If the foot of the test leg is externally rotated more than 30 degrees between the time period of initial contact and max knee flexion, then score YES. If the foot is not externally rotated more than 30 degrees between the time period of initial contact to max knee flexion, score NO.	Front	Y=1 N=0
11 Symmetric initial foot contact	If one foot lands before the other or if one foot lands heel to toe and the other lands toe to heel, score NO. If the feet land symmetrically, score YES.	Front	Y=0 N=1
12 Knee flexion displacement	If the knee of the test leg flexes more than 45 degrees from initial contact to max knee flexion, score YES. If the knee of the test leg does not flex more than 45 degrees, score NO.	Side	Y=0 N=1
13 Hip flexion at max knee flexion	If the thigh of the test leg flexes more on the trunk from initial contact to max knee flexion angle, score YES.	Side	Y=0 N=1
14 Trunk flexion at max knee flexion	If the trunk flexes more from the point of initial contact to max knee flexion, score YES. If the trunk does not flex more, score NO.	Side	Y=0 N=1
15 Knee valgus displacement	At the point of max knee valgus on the test leg, draw a line straight down from the center of the patella. If the line runs through the great toe or is medial to the great toe, score YES. If the line is lateral to the great toe, score NO.	Front	Y=1 N=0

(continued)

Table 1. LESS Scoring Criteria (continued)

LESS Item	Operational Definition	Camera View	LESS Score
16 Joint displacement	Watch the sagittal plane motion at the hips and knees from initial contact to max knee flexion angle. If the subject goes through large displacement of the trunk, hips, and knees then score SOFT. If the subject goes through some trunk, hip, and knee displacement but not a large amount, then score AVERAGE. If the subject goes through very little, if any trunk, hip, and knee displacement, then score STIFF.	Side	Soft=0 Av.=1 Stiff=2
17 Overall impression	Score EXCELLENT if the subject displays a soft landing and no frontal plane motion at the knee. Score POOR if the subject displays a stiff landing and large frontal plane motion at the knee. All other landings, score AVERAGE.	Side, Front	Ex.=0 Av.=1 Poor=2

Adopted from Padua et al.[17] The landing error scoring system LESS is a valid and reliable clinical assessment tool of jump-landing biomechanics: the jump-ACL study. *Am J Sports Med.* 2009; 37: 1996-2002.

Table 2. Height, Weight, and Age of Participants

	Mean	**SD**
Height (cm)	170.87	±6.82
Weight (kg)	64.24	±5.40
Age	14.91	±1.04

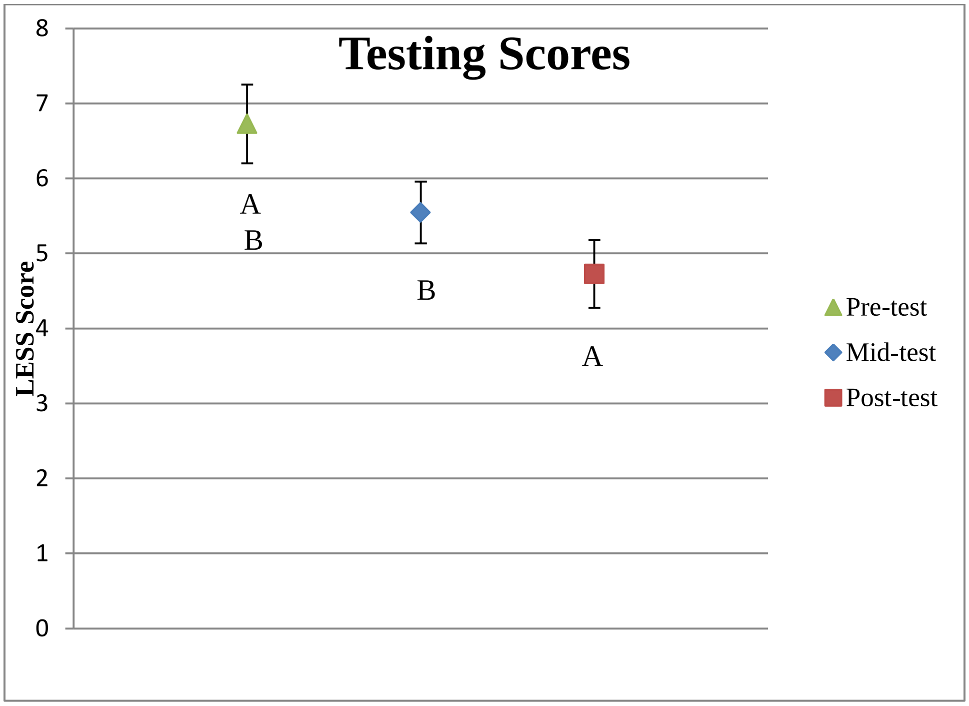
Table 3. Participant's Grade

Grade	**Participants**
9th	5
10th	3
11th	2
12th	1

Table 4. Participant's Sport

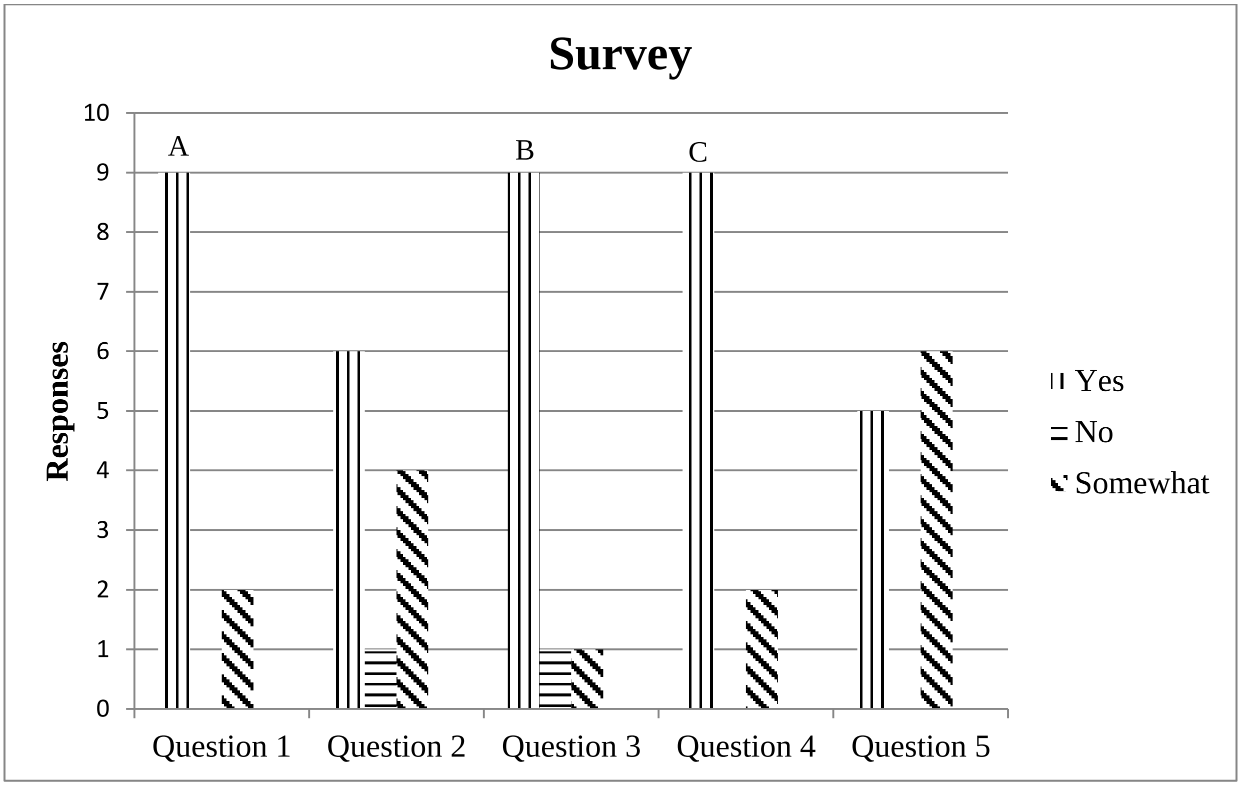
Sport	**Participants**
Volleyball	7
Soccer	3
Hockey	1

Figure 1. LESS Testing Scores



LESS scores at pre, mid, and post-test (means±SD).
A. Significance between pre-test and post-test $t(20) = 3.44$, $p<0.05$.
B. Approaching significance between pre-test to mid-test $t(20) = 2.58$.

Figure 2. Perception Survey



A. Significance, $\chi^2(1, n= 11) = 4.46, p<0.05$.
B. Significance, $\chi^2 (2, n = 11) = 11.64, p<0.05$.
C. Significance $\chi^2(1, n = 11) = 4.46, p<0.05$.
Not at all was an option on the survey, but no participants choose that option.

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APPENDIX A. PROSPECTUS

Introduction

An anterior cruciate ligament (ACL) injury can be devastating and expensive. In the general population, it is estimated that ACL ruptures have an incidence of 1 in 3,000 people per year. Eighty percent of ACL injuries are from a noncontact mechanism, with landing from a jump being the leading cause.[17] The cost of surgical repair is estimated to be about $17,000 per case, making this injury not only devastating but expensive.[16] Noncontact ACL injuries in female high school athletes have an incidence rate of three to eight times higher compared to their male counter partners.[14] There are some factors that contribute to the increased risk of ACL injury to female athletes. These include anatomical, biomechanical, and hormonal factors.

The female athlete's ACL is anatomically different than males. It is smaller in length, cross-sectional area, and in volume.[36] Other anatomical differences include a higher femoral notch along with a smaller femoral notch angle. The female's ACL is less stiff and also fails at a lower load level, even when adjusting for age, body size, and ACL size.[36] Hormonally, the ACL is known to have receptors for estrogen, testosterone, and relaxin. The chance of suffering an ACL during the menstrual cycle is greater during the preovulatory phase compared to the postovulatory phase.[36] The ACL is also placed at risk at any monument where there is an anterior directed force placed on the tibia. Other risk factors include biomechanical factors such as internal or external rotation, knee valgus, hyperextension of the knee, and landing in an erect posture.[7,9,43] These biomechanical factors can be seen during landing, cutting maneuvers, or deceleration techniques.[7]

In a noncontact ACL injury, the knee is stressed in multiple planes that result in the ACL being stressed in more than just one plane of the body.[35,36] This can be seen in a landing technique, in which females display a more erect posture during landing and deceleration activities.[35] Landing technique is one of the primary mechanisms for a noncontact ACL injury.[12] One reason why females exhibit an erect posture during landing is because of poor neuromuscular control, especially poor activation of the hamstrings.[12]

Not only do females show a more erect posture during landing, they also have an increase in knee valgus motion.[35] Knee valgus is more evident in younger athletes who are undergoing a growth spurt, or have just undergone one. The reason for this is because the tibia and femur grow at rapid rates; along with the athlete increasing in body size, this leads to the body's center of mass becoming higher, making it more difficult to control the trunk. This decrease in trunk neuromuscular control can lead to decreased core stability during dynamic activities, which may be the underlying effect of the poor biomechanics of deceleration activities for the female athlete.[28]

With further evaluation of the poor biomechanics of females during dynamic activity that is a result of neuromuscular imbalances. Investigators have shown that females exhibit four types of dominance known as ligament dominance, quadriceps dominance, leg dominance, and trunk dominance.[18,29] These neuromuscular imbalances exhibited during dynamic activity are contributors to noncontact ACL injuries. Correcting these neuromuscular imbalances could possibly be best done by neuromuscular training.[29]

Purpose Statement

The purpose of this study was to determine if a trunk and hip neuromuscular training program for female high school athletes facilitated neuromuscular changes during landing mechanics. The Landing Error Scoring System (LESS) was used to assess neuromuscular adaptations before, middle, and after the neuromuscular training protocol.

Research Questions

1) Did a hip and trunk neuromuscular training protocol change landing mechanics in high school female athletes?
2) Did the participants perceive their landing mechanics have improved after completing the hip and trunk neuromuscular training protocol?
3) When did the most significant neuromuscular changes occur during the program, at four weeks or at eight weeks?

Limitations

1) Results can only be applied to female high school athletes.
2) Results can only be applied to the specific hip and trunk neuromuscular training protocol used.
3) Cannot determine what specific exercises or phase were most beneficial.
4) Results are limited to landing mechanics.

Definition of Terms

Hyperextension: Posterior bowing of the knee.[38]

Neuromuscular training: Training that incorporates a combination of plyometric, strength training, agility, flexibility, postural adaptation, and balance.[43]

Valgus Force: A lateral force applied toward the body's midline.[38]

Varus Force: A medial force applied from the body's midline.[38]

Genu Recurvatum: Hyperextension of the knee.[38]

Literature Review

This literature review discusses the anatomy of the knee and the risk factors for female anterior cruciate ligament (ACL) noncontact injuries including anatomical, hormonal, and biomechanical. Lastly, highlighting neuromuscular training programs was discussed as a possible prevention to noncontact ACL injuries.

Anatomy

The knee is considered a hinge joint. Its primary motions are flexion and extension rotation.[34] The bone structures of the knee consist of the femur, tibia, fibula, and the patella. The stability of this joint is dependent on the ligaments, surrounding musculature, and the joint capsule. The musculature that allows the knee to perform flexion is the biceps femoris, semitendinosus, semimembranosus, gracilis, sartorius, gastrocnemius, popliteus, and the plantaris muscles. For the knee to perform extension, contraction of the quadriceps muscle must occur. The quadriceps group consists of the vastus medialis, vastus lateralis, vastus intermedius, and the rectus femoris. External rotation of tibia is performed by the biceps femoris as the knee joint moves into flexion. Internal rotation of the knee joint is executed by the popliteal, semitendinosus, semimembranosus, sartorius, and gracilis muscles.[34] The other muscle located on the lateral side of knee is the iliotibial band. This muscle acts as a lateral stabilizer instead of taking part in the dynamic movements of the knee.[34]

To stabilize the knee there are four major ligaments that resist unwanted movements. The first major knee stabilizer is the ACL, which is comprised of an anteromedial, intermediate, and posterolateral band twisted together. The purpose of the ACL is to prevent posterior movement of the femur on the tibia. It also stabilizes the tibia against excessive internal rotation, valgus and varus motion. The other major cruciate ligament is the posterior cruciate ligament (PCL), which primarily resists hyperextension of the knee and internal rotation of the tibia. The other stabilizing ligaments are the collateral ligaments. The medial collateral ligament (MCL) is located on the medial side of the knee resists the motions of knee valgus and external rotation.

The lateral collateral ligament (LCL) is located on the lateral aspect of the knee. The LCL resists knee varus and internal rotation of the tibia.[34] These stabilizing ligaments work in conjunction with the afore-mentioned musculature to help stabilize the knee joint.[34] The medial and lateral meniscus contributes to stabilization of the knee also. These structures are located on the tibial plateau and mostly help cushion any compressive forces, maintain spacing, and deepen the articulating joint.[34]

Male and Female Anatomical Differences

When dealing with the ACL and the boney structures of the knee, there are some differences in males and females, especially as they mature during puberty. The female's ACL is smaller in length, cross-sectional area, and volume even after adjusting for body anthropometry.[36] There are also anatomical differences with the femoral notch between males and females. The femoral notch is higher in height along with a larger notch angle when compared to the male's femoral notch.[36] Besides the differences in the size of the ACL and the femoral notch, the female's ACL is also less stiff, and will fail at lower load levels.[36] One factor that may lead to the lower load level of the female's ACL could be due to the lower percentage of collagen fibers in the ACL when adjusting for age and body anthropometrics.[36]

Besides these anatomical ACL differences, there are also knee laxity differences between genders. Females have been observed in displaying greater genu recurvatum, anterior knee laxity, and general joint laxity.[36] Thus, females have 25% to 30% greater frontal-plane and transverse-plane laxity with less torsional stiffness.[36] Additionally, females have also been known to have a greater anterior pelvic tilt, hip anteversion, tibiofemoral angle, and quadriceps angle when compared to males.[36] These differences in individual's lower extremity alignments are different throughout maturation, and also develop at different rates between males and females, potentially putting females at a higher risk of noncontact ACL injury. One of last important differences between genders is that females have been observed with altered knee-joint neuromechanics during weight bearing, which increases their risk of ACL injury.[36]

Risk Factors of Noncontact ACL Injuries

Anatomical factors previously mentioned may contribute to the noncontact ACL injury in young female athletes. Other risk factors such as biomechanical, hormonal, and fatigue components may also play a role.

<u>Prevalence</u>

In the general population it is estimated that ACL ruptures have an incidence of 1 in 3,000 people per year.[17] Of these ACL ruptures, 80% of them have a noncontact mechanism, with the majority of them occurring during the landing phase.[17] This statistic alone is alarming to anyone who is in the healthcare profession, because it is estimated that the price of surgery along with rehabilitation can cost the patient around $17,000.[16] It is important to understand that female athletes are four to six times more likely to sustain a sports-related noncontact ACL injury when compared to males.[36] Furthermore, it has also been reported that 38,000 females experience an ACL tear each year.[43]

There are different rates of injury in the collegiate setting compared to the high school level. At the college level, it is estimated that 1 in 20 female athletes will sustain an ACL injury, whereas at the high school level, about 1 in 50 to 100 female athletes will sustain an ACL injury.[18] To put these numbers in perspective, the National Collegiate Athletic Association (NCAA) reported that more than 150,000 females were participating in varsity sports. The National Federation of State High School Associations (NFSHSA) reported more than 3.2 million females were participating in high school sports. Based on these numbers, more than

50,000 ACL injuries are likely to occur for the female athlete in the collegiate and high school setting.[18] A major reason why females or some athletes in general, are more predisposed to ACL injury is due to their biomechanics.

Biomechanical Factors

It is well know that biomechanical factors play an important role in causing noncontact ACL injuries. A majority of these biomechanical factors focus on landing technique, stopping quickly, a cutting maneuver, or any sharp deceleration task.[7] These mechanisms of injury are termed a noncontact mechanism, with landing from a jump being the most common biomechanical factor.[9] Beutler et al[9] showed that female landing techniques are different when compared to male techniques. The researchers observed that females landed with significantly less hip and knee flexion, increased knee valgus, a wider stance, and less flexion displacement over the landing phase.[9] When landing in an erect posture with less knee, hip, and trunk flexion, the landing forces on the knee are increased up to 10 times the body weight.[10,20] Along with landing on an extended knee the quadriceps has an increase in electromyographic (EMG) activity due to the increased ground reaction forces and quadriceps recruitment.[10] The stresses of landing with an erect posture place the ACL at an increased risk of injury, making this an important concept in injury prevention. In order to decrease the ground reaction forces placed on the knee during an erect landing, the athlete can actively flex her trunk. Actively flexing the trunk can help in increasing knee and hip flexion.[10] Landing in a flexed position will result in reducing the chances of ACL injury by reducing the load placed on the ACL, reducing the ground reaction forces, and reducing the quadriceps force recruitment.[10] Blackburn and Padua[10] showed that landing in a flexed position helped to decrease ground reaction and quadriceps forces. Subjects were instructed to land in a preferred position, then once again in a more flexed position. The researchers recorded the EMG of the quadriceps, angles of the lower extremity, and ground reaction forces during the landings. When the subjects were instructed to land in a position of more flexion the trunk, hip, and knee increased in flexion by 42˚, 31˚, and 22˚ respectively. With the increase in flexion, quadriceps activity and ground reaction forces also decreased.[10]

Results from an observational study agreed with the notion that landing in a flexed position is safer than landing in an erect position. When someone lands from a jump, the quadriceps must lengthen while contracting in order to resist excessive knee flexion.[42] If the knee is flexed to less than 60˚ there is an increase in quadriceps force that results in a strain being placed on the ACL. With this increase in force, (4 kN), anterior tibial translation of 20 mm or greater can occur, which is enough to cause an ACL rupture.[42] The landing force created by the quadriceps can also be increased by late hamstring activation.[42] When landing with a knee flexion angle of 5˚ to 20˚ combined with a valgus motion and rotation of the knee, the chances of an ACL injury are increased.[35]

To further understand the importance of knee flexion angles when dealing with ACL strain, cadaver studies can offer some insight.[13,35,42] It was observed that when the knee was flexed less than 30˚ ACL tensile forces where similar to the anterior shear forces applied when using a robotic arm equipped with a 6-degrees-of-freedom force transducer.[35] When the knee was flexed to more than 60˚ the ACL tensile force was smaller compared to when the knee was only flexed to 30˚.[35] To further understand the importance of knee flexion angles, when applying 110N of anterior force to the ACL at different knee flexion angles, similar observation were reported. When the knee was flexed to 30˚ there was about 90 N of tensile force applied to the ACL compared to only 70 N at 60˚ and 59 N at 90˚ of knee flexion.[35]

Another study looked at 11 cadaveric knees for the change in length of the ACL by releasing a 150 N weight onto an impact rod striking the femur was evaluated.[42] The knee was placed at 25˚ of flexion, simulating the forces that can be placed on the ACL when landing one-legged. The forces being placed on the knee were equal to approximately twice the body weight of an average American, similar to the two to four times the body weight usually seen when landing.[42] The results of this study revealed that the relative strain placed on the ACL was significantly correlated with the change in quadriceps force and the change in knee flexion induced by the impact force. However, there was not a significant correlation to the impact force itself and the strain placed on the ACL.[42] The limitation of comparing a cadaver knee to a live individual's knee is important, but these results show that body position is important when trying to decrease stresses placed on the knee.

Along with body positioning during landing, cutting, or any deceleration activity, muscle contraction is also an important influence on ACL injury. Quadriceps muscle contraction is known to be a component in placing anterior force on the tibia.[35] Previous studies have reported that the angle between the infrapatellar tendon and the longitudinal axis of the tibia is the largest when the knee is near full extension.[21,35] This means that the quadriceps contraction force with the knee at near full extension can increase the tensile forces placed on the ACL, increasing the risk of injury.[35] Along with quadriceps contraction there can be anterior translation, internal rotation, and valgus motion to the tibia.[13]

Another important group of muscles that can play a significant role in ACL stresses is the hamstrings. The major role of the hamstrings is thought to be that they produce posterior shear forces. With contraction of the quadriceps, the hamstrings can also produce compressive forces at the knee joint resulting in increased stability.[4,37] Hamstring contraction will result in decreased tensile forces placed on the ACL created by the force of the quadriceps contraction; these forces have also been observed to decrease as knee flexion increased.[35] It has been hypothesized that the gastrocnemius muscle can produce enough force to cause strain on the anterior cruciate ligament. There is not enough research, and too much contradiction, on this topic to adequately determine what role the gastrocnemius has on ACL injury.[35] Most of the contradiction in this literature comes from the different methods used in the studies. Methods ranging from using computer models to cadavers and generating force by the scientist themselves leads to too many limitations in these few studies[35] in order to determine the rule of the gastrocnemius in ACL injury.

The quadriceps and hamstrings have mostly been related to anterior and posterior translation of the tibia. While noncontact ACL injuries can happen in one plane, the chances are increased when forces from multiplanes are placed on the knee. The ACL is loaded in a variety of ways through sagittal and nonsagittal mechanisms during sporting events due to the different postures of the athlete.[36] Through the sagittal plane, hyperextension is an obvious mechanism for a noncontact ACL injury due to the load being placed on the ligament.[35] When this mechanism is combined with either internal or external rotation, the ACL tensile forces are doubled when the knee is flexed to 20° or more.[25,26] Other motions that place tensile forces on the ACL are frontal-plane and transverse-plane motions. Valgus and varus positioning of the knee combined with internal or external rotation have been commonly observed during ACL injuries.[35] It has been reported that internal rotation doubles the ACL load more than external rotation when combined with an anterior shear force.[8,24,26] This implies that when the knee is in internal rotation, combined with excessive quadriceps force, there are substantial tensile forces placed on the ACL increasing the risk of injury.[35] Valgus and varus movements combined with an anterior shear force have been reported to also increase the strain placed on the ACL.[35]

When a frontal-plane force is placed on the knee combined with an anterior shear force, the ACL tension is greater than just placing an anterior shear force alone.[8,24] It is unlikely that a valgus force and an anterior shear force will occur alone during a noncontact ACL injury; it is more likely that an internal rotation will accompany these motions.[35] Kanamori et al[22] examined the differences between an internal and external load combined with a valgus load. The researchers observed that an internal and valgus load led to twice as much tensile force placed on the ACL compared to an external and valgus load.[22]

Hormonal Effects

Understanding the biomechanical and musculature factors is important; however, hormones may also play a role. During the female's menstrual cycle estrogen (especially estradiol), progesterone, relaxin, and testerone fluctuate.[45] Some researchers believe that during the menstrual cycle females are more likely to tear their ACL due to increased knee laxity, but there is a lot of contradicting research on this subject.[2] Adachi et al[2] had 18 subjects who had sustained an ACL injury complete a questionnaire that showed a significant association between the phases of the menstrual cycle and the time of ACL injuries.[2] The phases of the menstrual cycle were split up into the follicular phase (the first day through the ninth day), the ovulatory phase (day 10-14), and the luteal phase (day 15 though the end of the cycle).[2] The subjects reported a significant reduction in their activity level during the first phase of their menstrual cycle, and there were no differences between the last two phases.[2] Even though the subjects had a reduction in activity level during their first phase, most (13 of 18) of the ACL injuries occurred during the second phase followed by three injuries in the third phase and one injury in the first phase.[2] This study concluded that being in a particular phase of the menstrual cycle can be a risk factor for females sustaining an ACL injury, but a study done by Abt et al[1] disagrees.

In Abt et al's[1] study, 10 subjects were recruited to attend six neuromuscular training sessions over two months. Blood samples were taken at the onset of menses, post-ovulatory, and during the mid-luteal phase which was determined by urine samples.[1] The participant's postural stability, fine motor control, isokinetic testing of the quadriceps and hamstrings, and a functional assessment of a single-leg stop jump were tested. It was observed that the levels of estradiol were significantly higher during the post-ovulatory and mid-luteal phase when compared to the menses phase.[1] Progesterone was significantly lower during the post-ovulatory phase and menses compared to the mid-luteal phase.[1] Even though there were differences in hormones during various phases of the menstrual cycle, there were no significant differences in postural stability, fine motor coordination, isokinetic strength of the quadriceps and hamstrings.[1] There were also no significant differences in the single-leg stop jump between any of the phases of the menstrual cycle.[1] The study by Abt et al[1] showed, in contradiction to the study by Acdia et al[2] that the changing levels of estradiol and progesterone do not appear to increase the risk of females sustaining an ACL injury.

Clearly, there are contradicting results on whether the menstrual cycle plays a role in a female's chances of sustaining an ACL injury. The contradictions in the literature may be due to many factors such as individual variation in hormonal status, individual response to hormones that make some females demonstrate more knee laxity while others demonstrate little, when the individual enters the different phases of the menstrual cycle, and when scientists test hormone levels during each phase.[45]

While hormones of the female athlete may or may not play a role in noncontact ACL injuries, all athletes become more susceptible for injury as fatigue occurs. Fatigue is an extrinsic factor that affects the musculoskeletal and neurological system that can increase the risk of lower extremity injuries by changing lower extremity landing mechanics.[7] It has been reported that athletic injuries occur in the later stages of activities and competitions, indicating that exercise and fatigue may influence dynamic knee stability.[7] Fatigue can decrease motor control performance, increase knee joint laxity, decrease balance skills, and also decrease proprioception.[7] These are the reasons why many believe that resistance to fatigue can be a modifiable risk factor that could improve lower extremity alignment throughout dynamic movement. Benjaminse et al[7] evaluated kinematic characteristics of the hip and knee joints during a single-leg stop-jump task before and after exercise. Their results indicated fatigue is an important factor when dealing with injuries. The subjects in the study decreased their overall jump height from 17.71 ± 4.53 pre-fatigue to 16.70 ± 4.01 percent in relation to their body height post-fatigue.[7] The participants also showed significantly less maximal knee valgus angles and knee flexion angles at initial contact for post-fatigue landings.[7] While the subjects landed with less maximal knee valgus, they did land with less knee flexion post-fatigue (12.3˚ ± 6.6˚ for females and 10.6˚ ± 4.9˚ for males).[7] This suggests that when the participants became fatigued they tended to land in a more erect posture. The author believed that this happened because landing with less knee flexion requires less eccentric muscular strength.[7] While the subjects showed less degrees of knee valgus in this study, landing in an erect posture can lead to anterior tibial translation leading to ACL injury.[7]

Prevention with Neuromuscular Programs

Neuromuscular training is one way to prevent noncontact ACL injuries. In order to prevent noncontact ACL injuries in females, it is important to first know the differences in neuromuscular control between males and females, and how neuromuscular strength changes as female athletes mature.

Females and males demonstrate differences in neuromuscular strength at different times of their lifespan. Men typically demonstrate a quick growth of neuromuscular control during puberty where women, on average, have little changes throughout puberty.[29] To put this into perspective, vertical jump height increases steadily in boys during puberty but not in girls.[29] Before the age of 14, there are no differences in peak leg power between the two genders. After the age of 14 males have significantly greater power, and females usually experience a plateau of power around the age of 16.[27] While there are gender differences in ACL injury risk during adolescents, there is no evidence of gender difference in ACL injury risk in prepubescent athletes.[28] Following their growth spurt female athletes have higher rates of sprains when compared to male athletes, and this continues into maturity.[40] This is due to that fact that during peak height velocity the pubertal athlete’s tibia and femur grow at rapid rates.[39] The rapid growth of the tibia and femur causes an increase in the height of the body’s center of mass, which results in muscular control of the trunk being more difficult.[28] The absence of strength and the recruitment of the musculature at the hip and trunk can lead to decreased control of the trunks musculature during dynamic movements.[15] Because of the decreased trunk control, the trunk and hip stabilizers may preactivate to counterbalance the motion, which may regulate lower extremity posture.[28] Reducing preactivation of the trunk and hip stabilizers may increase lateral trunk positions, which can lead to valgus knee loads.[41] This could be one underlying factor why female athletes show lower extremity valgus loads during dynamic activities.[28] With the decrease in core stability and muscular synergism of the trunk and hip can result in controlling the body's center of gravity becoming more difficult, leading to an increase in ACL injury.[41,44]

In a study[5] that looked into the differences of neuromuscular control in prepubescent athletes, children (27 females and 25 males) between the ages of 9 to 10 were measured on muscular strength, lower limb symmetry in a single-legged hop test, and lower limb control and position during a drop-jump screening test. The researcher determined from the drop-jump test that there were no differences between males and females in mean hip separation for pre-landing, landing, and takeoff.[5] There were also no differences found between males and females for isokinetic testing, asymmetrical lower limb symmetry, mean limb symmetry for the timed side-hop test, and the cross-over hop test for distance.[5] The males did show greater separation between their ankles compared to females in all phases (pre-landing 35 ± 5 cm and 28 ± 5 cm, landing 32 ± 6 cm and 24 ± 6 cm, and takeoff 32 ± 6 cm and 24 ± 5 cm respectively).[5] The males also showed greater separation between their knees during pre-landing and landing when compared to the females (pre-landing 22 ± 4 cm and 17 ± 4 cm, landing 18 ± 7 cm and 14 ± 5 cm respectively).[5] While the males showed a larger landing base, 76% of them still exhibited knee valgus alignment compared to 93% of the girls during the drop-jump test. The author concluded that even young athletes should be exposed to neuromuscular training.[5]

A study by Barber-Westin[6] that evaluated the effects of chronological age and gender in isokinetic lower extremity strength, lower limb alignment during a drop-jump test, and lower limb symmetry during a single-legged hop test was evaluated. The study consisted of 916 females and 224 males aged from 9 to 17. The study concluded that there was no significant difference between genders until the age of 14 when comparing mean knee extension and flexion peak data.[6] After the age of 14, the male athletes showed significantly greater mean extension and flexion peak torques than the females, but there were no significant differences between the genders for hamstring-quadriceps ratio at any age.[6] Males also showed greater mean limb symmetry at the age of 15 compared to the females in the crossover hop test for distance. When comparing lower limb alignment for the females at the different age groups, the researchers found a distinct valgus alignment in 78% of the female athletes aged 9 to 12 years, 81% of athletes aged 13 years, 83% of athletes aged 14 years, 71% of athletes aged 15 years, and 74% of athletes aged 16 to 17 years.[6] For the males there was a distinct valgus alignment measured in 79% of male athletes aged from 9 to 12 years, 70% of athletes aged 13 years, 62% of athletes aged 14 years, 67% aged 15 years, and 80% of athletes aged 16 to 17 years.[6] There were also significant differences during the pre-landing phase on the drop-jump test between the genders when evaluating ankle separation distance.[6] Male athletes had greater mean ankle separation distances in the 9 to 12 year old group, but females had greater mean ankle separation in the 13 to 15 and the 16 to 17 age groups.[6] These studies done by Barber-Westin et al[5,6] showed differences between the genders for landing mechanics, but showed no significant differences in terms of knee valgus between the genders at any age. Even though these particular studies results differ from other studies about gender and knee valgus differences, the results still concluded that females have different landing mechanics that can predispose them to ACL injury.

A study done by Hewett et al[19] showed contradictory results to these previous studies. Hewett et al[19] took 81 males and 100 females that were preadolescent and adolescent athletes and classified them into prepubertal, early pubertal, and late or postpubertal groups. The authors specifically looked at how growth and development decreases neuromuscular control of the knee, and what methods are the best ways to identify female athletes with decreased dynamic control of the knee.[19] This study showed that the tibial and thigh lengths for the females and males in the early pubertal and late pubertal stages were increased relative to those of their prepubertal counterparts.[19] Also, the tibial and thigh lengths of the females and males were increased relative to those of the females and males in the early pubertal stage.[19] It was also revealed that there were no differences in medial knee motion between males and females prior to maturation.[19] This differed in the later stages, when females in the late pubertal stage showed significantly greater medial knee motion than the males did at the same stage.[19] The medial motion of the knee was correlated to the tibial length in the female athletes, but not in the male athletes.[19] Females in the late pubertal stage displayed a greater lower extremity valgus angle compared to the males in the same stage at initial contact (5˚ ± 1˚ compared to 1˚ ± 1˚).[19] These differences grew during landing (30˚ ± 3˚ compared to 19˚ ± 3˚).[19] There were similar results for the females in the prepubertal group (2˚ ± 2˚) and early puberty (1˚ ± 1˚) for lower extremity valgus angle at initial contact.[19] The same group also showed a greater maximum valgus angle than the prepubertal females (14˚ ± 4˚), and the females in early pubertal stage (20˚ ± 3˚).[19]

For hamstring peak torques, males showed a significant increase with maturity with the highest value in the postpubertal stage, as for females hamstring peak torque stayed the same as maturation increased.[19] When comparing hamstring peak torque ratios, females displayed significantly lower values for all the stages. Quadriceps peak torques followed a similar path; the males showed significantly greater values as they went through maturation with their highest being in the postpubertal stage, whereas females did not show any significant changes throughout maturation. When comparing quadriceps peak torque between genders and throughout the stages, the authors noted that there was a 12% deficit in the prepubertal stage, 11% deficit in the early pubertal stage, and an 18% deficit in the postpubertal stage for females.[19]

The results of this study showed that there was a substantial increase in neuromuscular strength and coordination following the growth spurt of males in adolescents, and females did not show similar increases.[19] Females in this study demonstrated decreases in neuromuscular control of the knee during early puberty which lasted into late puberty, while males showed better neuromuscular control during late puberty than what they showed during early puberty.[19] Males regain their neuromuscular control following their neuromuscular spurt, where females do not show similar neuromuscular adaptions. This can lead to decreased dynamic stability in the female athlete. This study determined that musculoskeletal changes that occur with maturation are related to poor neuromuscular control of the knee in female athletes.[19] This poor neuromuscular control of the knee during dynamic activity that females show can put them at an increased risk of sustaining a noncontact ACL injury.

Specific Female Neuromuscular Differences

Other neuromuscular imbalances that females can exhibit include ligament dominance, quadriceps dominance, and leg dominance.[29] Ligament dominance is when the ligaments of the knee absorb a significant portion of the ground reaction forces, rather than the lower extremities musculature. This type of dominance can result in high valgus knee motions which can lead to higher ground reaction forces.[29] This is commonly seen in single-leg landing, pivoting, or deceleration where the female athlete allows the ground reaction forces to control the direction of her lower extremity.[29] Quadriceps dominance is defined as an imbalance between the quadriceps and the hamstring recruitment patterns.[29] The overreliance of the quadriceps muscles can lead to imbalances in strength and coordination between the quadriceps and hamstrings. Quadriceps dominance can also be related to landing in an erect posture by an early activation of the quadriceps, or a delayed activation of the hamstrings.[29] Leg dominance is defined as the imbalance between the muscular strength and joint kinematics in contralateral lower extremity measure.[29] Female athletes have been previously reported to have lower hamstring torques in the non-dominant limb compared to the dominant limb.[29] These side-to-side imbalances in muscular strength and coordination can increase the chances of sustaining an ACL injury.

In order to treat the three previously listed areas of dominance that females can show, it is imperative to identify them first. Identification of ligament dominance can be done by a box-drop test followed by a maximal-effort leap.[29] The ligament-dominant athlete may display more valgus motion at that knee compared contralaterally. To correct for ligament dominance, an athlete should first be taught to use the knee as a single-plane hinge joint, and try to control unwanted valgus and varus movements. It is also imperative to make the athlete aware of the issue and then teach the proper technique.[29] To identify quadriceps dominance, it is easiest to evaluate the subject on an isokinetic dynamometer or a leg-curl and leg-extension machines. If a hamstring-to-quadriceps ratio is less than 55%, quadriceps dominance may be present.[29] If objective measures are not available, an athlete can be tested on their ability to hop and hold a single-leg stance in deep knee flexion. The ability to hold this position of deep knee flexion, knee angle greater than 90˚, requires more recruitment of the hamstrings than quadriceps.[29] The inability to hold this position may indicate quadriceps dominance. In order to treat quadriceps dominance the clinician should emphasize cocontraction of the hamstrings and quadriceps.[29] It is of equal importance to use deep flexion angles of the knee in order for the quadriceps to decrease anterior tibial translation, and to put the hamstrings into an ACL protective position.[29]

To identify leg dominance, a dynamometer or leg-curl and leg-extension machine can be used. A difference of 20% in strength or power between the limbs indicates a neuromuscular imbalance.[23] To treat this imbalance between limbs it is best to emphasize double-leg movements, progressing into single-leg movements.[29] Another imbalance that females have been reported to show is trunk dominance, which is characterized by an increase in motion of the body's center of mass use to decreased neuromuscular control of the body's mass during single-leg landing, pivoting, or deceleration.[18] When correcting these differences, or training an athlete in a neuromuscular prevention program, strength training alone is not enough.

Strength Training

A study conducted by Herman et al[17] evaluated the differences of landing mechanics during a stop-jump task between subjects in a strength training group and a control group. The strength program consisted of three sessions per week for nine weeks with each session being separated by at least one day. The subjects preformed three sets of 8 to 12 repetitions with the initial level of resistance being 60% of their average maximum voluntary isometric contraction (MVIC). When the subject completed the target set and repetitions, the resistance was increased by 10%. The muscles targeted in this particular strength program were the quadriceps, hamstrings, gluteus medius, and the gluteus maximus. The results revealed that there were significant differences between the groups and time for strength values of all four muscles targeted.[17] For each of the muscles, the MVIC strength of the intervention group at the time of the follow up data collection was greater than what it was at baseline collection, and the average increases were between 35% and 48%.[17] When assessing the subjects during the stop-jump task, there were no significant interactions between the interaction and control groups. This means that the intervention group did not change their lower extremity motion patterns during landing. It was concluded that strength training alone is not sufficient in altering lower extremity biomechanics, but is a necessary tool to be included when using other methods such as plyometrics, balance and agility training when trying to alter lower extremity biomechanics.[17]

Neuromuscular Programs

Shultz et al[36] described a recent ACL retreat in 2010 where researchers came together and evaluated what they knew, did not know, and important areas that needed to be better understood on the topics of neuromuscular and biomechanical factors affecting ACL injuries. From this information, we know that the ACL is loaded in a variety of sagittal and nonsagittal mechanisms, that ACL strain is related to the maximal load and timing of ground reaction forces, that females typically show more of an erect posture during landing, and that maturation influences biomechanical and neuromuscular factors.[36] We also know that the trunk, core, and upper body influence the lower extremity biomechanical and neuromuscular factors. Fatigue is also suggested to increase ACL injury along with hip position and stiffness.[36] With the knowledge we have today, clinicians should try to incorporate this into their ACL prevention programs.

Anterior cruciate ligament neuromuscular training programs have strong evidence behind them suggesting that they can decrease the chances of an ACL injury by altering biomechanical risk factors.[30] These programs work by mostly correcting knee valgus movements and at the same time improving performance capabilities of female athletes.[30] In order to have an effective neuromuscular training program, the clinician needs to utilize plyometrics, biomechanical technique, strength training, balance training, and core stability.[18,30] These factors should be used together, because using one by itself may not be as effective as a combination of all of them. These programs can be used during pre-season and in-season training programs.[18] The pre-season training programs should occur three times a week lasting six to eight weeks in duration, where in-season is used as a maintenance program lasting only 15 minutes three times a week.[18] Neuromuscular control being used as an intervention or prevention of ACL injury is likely to have the greatest impact because this is where adaptation readily occurs in athletes, however it must be guided by a trained health care professional.[18]

Neuromuscular training has been reported to have an efficacy rate of 50% in decreasing ACL injury risk for female athletes in landing and cutting sports.[18] Since females demonstrate knee valgus along with other noncontact ACL risk during pivoting or landing, they are more likely to respond to neuromuscular training.[28] Neuromuscular training should be incorporated at or near the onset of puberty in order to improve lower extremity strength and power, reduce dangerous biomechanics related to ACL injury risk, and to improve single-leg balance.[28]

In a meta-analysis conducted by Grindstaff et al[16] that evaluated intervention programs conducted by other scientists, the researchers determined how many athletes would need to go through their neuromuscular training program in order to prevent one ACL injury. The authors also calculated the percentage of risk that is reduced for the individuals who participated in the neuromuscular intervention program.[16] The first study consisted of the authors examining their training protocol on female and male high school basketball and soccer players over one season. The program was 60 to 90 minutes in length that concentrated on flexibility, plyometrics, and weight training that was performed three times a week for six weeks. Over the course of the season there were no noncontact ACL injuries for the intervention group. There were three noncontact ACL injuries during soccer and three more occurred during basketball for the control group. This led to a prevention of one noncontact ACL over one season of these sports, in that 97 soccer players and 63 basketball players would need to participate in the intervention program.[16] The percentage of risk reduced for this study was 100% due to that fact that there were no noncontact ACL injuries in the intervention program.[16]

The second study analyzed by Grindstaff et al[16] evaluated Norwegian female handball athletes in which the first year acted as the control and the next two years acted as the intervention. The players participated in a program that consisted of running, jumping, agility, and balance exercises where proper technique was instructed. The program lasted for five to seven weeks three times a week for 15 minutes during the pre-season, during season the subjects performed the program once a week. During the control year, there were 18 noncontact ACL injuries compared to only 10 and 7 during the intervention years. This led to 109 athletes would need to participate in this particular program in order to prevent one noncontact ACL injury, and 48% of the subjects in the intervention years decreased their risk of sustaining a noncontact ACL.[16]

The third study that was analyzed evaluated female soccer players from the age of 14 to 18 years over two seasons. The prevention program consisted of a 20 minute warm-up performed three times a week which consisted of stretching, strengthening, plyometrics, and some sport specific agility drills. During the two seasons six noncontact ACL injuries occurred in the intervention group and 67 occurred in the control group. In order to prevent one noncontact ACL over one season, 70 athletes would need to participate in the program, and for the ones who did participate in the program it led to an 82% decrease risk of sustaining a noncontact ACL.[16]

The fourth study that the authors analyzed evaluated German female handball players over one season. The intervention program consisted of a six-phase balance and jump training program being performed three times a week for 10 minutes before practice. There were no noncontact ACL injuries in their intervention group compared to five in the control group over one season. This led to 28 athletes would need to participate in their program to prevent one noncontact ACL. Since there was no noncontact ACL injuries in the intervention group, there was a 100% decreased risk for these athletes.[16]

In their fifth study they analyzed, the authors examined female and male handball players aged from 15 to 17 years. They were randomly placed into a control or intervention group that consisted of a warm-up, balance training, and plyometric training. The intervention was performed 15 to 20 minutes before 15 practices, and then once per week for the remainder of the eight month season. During the season there was one noncontact ACL compared to five in the control group. This led to 193 athletes would need to participate in this program to prevent one ACL injury, but for the intervention group the chances of sustaining a noncontact ACL decreased 81%.[16] When the authors pooled all the results together from the studies they analyzed, they found that in order to prevent one noncontact ACL injury, 89 athletes would need to participate in a neuromuscular ACL prevention program.[16] For the subjects that participated in the program, they had a 70% decreased rate of sustaining a noncontact ACL injury.[16]

In a different meta-analysis, Yoo et al[43] evaluated seven studies that investigated neuromuscular training on the prevention of ACL injuries in female athletes and found them to be effective. The neuromuscular programs consisted of plyometric, strengthening, and balancing exercise with subjects under the age of 18 and above. The meta-analysis revealed that plyometrics and strengthening components of the neuromuscular programs were more essential to the program than balancing. With seven neuromuscular programs being successful in reducing the chances of sustaining a noncontact ACL injury, the results showed to be more effective in the population under the age of 18 compared to the older population.[43]

Chappell and Limpisvasti[11] also evaluated a neuromuscular training program that included 10 exercises consisting of core strengthening, plyometric training, and jumping exercises. The study used a drop jump task and a stop jump task for their measurements. The study added further evidence that even a short six week neuromuscular training program for 10 to 15 minutes before practice can help reduce potential noncontact mechanisms. Knee flexion angles at foot strike decreased for both the drop jump and stop jump task, but the stop jump task did not reach statistical significance.[11] For knee valgus angles there were no differences after the neuromuscular training, but there was a decrease in for the dynamic knee valgus moment for both jumping task. This shows that the knee valgus occurred in the second half of the landing phase, instead of the first half where investigators believe an ACL injury is more likely to occur.[11]

These studies[11,16,43] suggest that neuromuscular training in preventing noncontact ACL injuries can be beneficial for the athletes who perform them. They are more beneficial in the female population, especially for the younger female athlete, even if the program consists of a limited amount of time before practice.

Summary

In summary, there are many factors that can result in a noncontact ACL injury. Females commonly exhibit biomechanical and neuromuscular risks, which typically start with puberty and last throughout their lives. While males can still sustain a noncontact ACL injury, females are at the highest risk of such an injury. In order to decrease the risk of this injury, it seems like neuromuscular and biomechanical changes are the best modifiable way. Using neuromuscular training to prevent ACL injuries the clinician should know how to properly perform each exercise and know what is utilized in a successful program. It is important to incorporate proper landing techniques, strength, flexibility, core stability, and balance in every neuromuscular program. If these areas are used in a neuromuscular program, it has been shown to substantially decrease the risk of ACL injury in athletes. Every sports team should incorporate some sort of neuromuscular ACL prevention program in order to protect their athletes from a season ending injury.

Methods

The purpose of this study was to determine if a trunk and hip neuromuscular training program facilitated neuromuscular changes during landing mechanics. To address the purpose of the study three questions were examined. First, did the hip and trunk neuromuscular training change landing mechanics in these participants. Second, did the most significant neuromuscular changes occur at four weeks or eight weeks, and lastly, did the participants perceive their landing mechanics improved after completion of the program.

Subjects

All procedures were approved by the North Dakota State University's Institutional Review Board (Appendix B.).Thirty healthy female athletes (15.13±0.99 yrs; 60.76±6.16 kg; 169.91±7.1 cm) from Moorhead High School in Moorhead, MN volunteered for this study. They were participants in the sports of volleyball, hockey, basketball, softball, track and field, and soccer. Athletes that have had a pervious ACL surgery were excluded. All subjects, along with a parent or guardian, signed a written consent form.

Procedures

Interested participants along with their parents first reported to a meeting at Moorhead High School where they were informed on the purpose of the study and filled out an informed consent form. Other interested participants that could not make the initial meeting came to the first testing day where they filled out the informed consent form with their parents. On the first day of the study, the participants reported to Moorhead High School's gymnasium where they completed a demographic form. The demographic form consisted of their age, height, sport(s), academic year in school, and any previous knee injuries (Appendix C.).

The drop box jump was first explained to the participants. However, the scoring procedure was not shared in order to decrease any coaching effect. Participants were instructed to jump forward, not vertically, off a 30 cm box. The distance that they needed to jump forward off of the box was 50% of their height, which was marked on the floor for them. After jumping to the marked spot, participants jumped as high as possible vertically. Appendix D. displays the drop box jump. The landing mechanics from the drop box jump was scored according to the LESS protocol. During the jump, participants received no feedback or coaching on their technique, but were encouraged to jump as high as possible for the vertical jump. A successful jump was defined as jumping off of both feet from the box, jumping forward but not vertically off of the box, and completing the task with no hesitation or pauses.[33] Participants first had two familiarization trials followed by three successful trials that were videotaped. Two camcorders were placed in a sagittal view and a coronal view of the participants. The LESS score was determined by watching the video in slow motion while also using the Dartfish computer program in order to properly score the participants landing mechanics. Participants also had anatomical markers placed on their lateral malleolus, greater trochanter, lateral femoral condyle, midfoot, and sternum to ensure consistency in evaluation of the LESS. The LESS scoring criteria can be found in Table A1. The participants performed the box jump prior to starting the hip and trunk neuromuscular training program in order to establish a baseline. Participants were reassessed with the box jump at four weeks and at eight weeks for a mid-test and post-test.

The neuromuscular training protocol consists of 13 exercises with each exercise having five individual phases. Training sessions were offered four times a week for eight weeks. In order to complete the neuromuscular training protocol, each participant will need to complete three training sessions per week. Participants will not be allowed to participate in more than three sessions a week. The exercises consist of core stability, plyometrics, balancing, and strengthening exercises that were developed by Myer et al.[28] The hip and trunk neuromuscular protocol can be found in Table A2. In order to move on to the next phase of the exercise, the athlete must perform the exercise in the current phase with perfect technique. The correct technique needed in order to advance to the next phase was determined by the co-investigator. At the end of the eight weeks the participants ending phase of each exercise was documented. Participants also filled out a questionnaire on their perception of the neuromuscular training protocol (Appendix E.).

Instrumentation

The hip and trunk neuromuscular program consists of the following exercises: lateral jumping, single-leg forward hops, prone trunk stability, kneeling trunk stability, single-leg lateral hops, tuck jump, forward lunge, lunge jump, hamstring-specific exercise, single-leg rotatory hop, lateral trunk crunch, trunk flexion, and trunk extension . A BOSU® Sport Balance Trainer (55 cm), Swiss Balls (55 cm), and Airex® pads (20” x 16.4” x 2 ½”), plyometric boxes (30 cm in height), medicine balls, and dumbbell weights were used for the varying exercises.[28] The LESS scoring system objectifies poor landing biomechanics that can potentially lead to noncontact ACL injury. The scoring system has a interrater reliability $ICC_{2,k} = 0.84$ and SEM = 0.71 and an intrarater reliability of $ICC_{2,1} = 0.91$ and SEM 0.42, showing the effectiveness of the Landing Error Scoring System.[33] Video analysis was done by using the computer program Dartfish to help measure angles of various joints and body positioning.

Statistical Analysis

The lowest LESS score out of the three drop-box jumps were used for statistical analyses. Data was analyzed by a repeated measures analysis of variance to determine if the neuromuscular strength program decreased LESS scores. Additionally, a t-test was used to determine significance between pre-test to mid-test, mid-test to post-test, and pre-test to post-test. For descriptive data, a Chi Square Goodness of Fit test was used. All statistical test used a level of significance of $\alpha < 0.05$. The SPSS version 20 was used for all analysis (Chicago, IL, USA).

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Table A1. LESS Scoring Criteria

LESS Item	Operational Definition	Camera View	LESS Score
1 Knee flexion angle At initial contact	At the time point of initial contact, if the knee of the test leg is flexed more than 30 degrees, score YES. If the knee is not flexed more than 30 degrees, score NO.	Side	Y=0 N=1
2 Hip flexion angle at initial contact	At the time point of initial contact, if the thigh of the test leg is in line with the trunk then the hips are not flexed and score NO. If the thigh of the test leg is flexed on the trunk, score YES.	Side	Y=0 N=1
3 Trunk flexion angle at initial contact	At the time point of initial contact, if the trunk is vertical or extended on the hips, score NO. If the trunk is flexed on the hips, score YES.	Side	Y=0 N=1
4 Ankle plantar-flexion angle at initial contact	If the foot of the test leg lands toe to heel, score YES. If the foot of the test leg lands heel to toe or with a flat foot, score NO.	Side	Y=0 N=1
5 Knee valgus angle at initial contact	At the time point of initial contact, draw a line straight down from the center of the patella. If the line goes through the midfoot, score NO. If the line is medial to the midfoot, score YES.	Front	Y=1 N=0
6 Lateral trunk flexion at angle at initial contact	At the time point of initial contact, if the midline of the trunk is flexed to the left or right side of the body, score YES. If the trunk is not flexed to the left or right side of the body, score NO.	Front	Y=1 N=0
7 Stance width - Wide	Once the entire foot is in contact with the ground, draw a line down from the tip of the shoulders. If the line on the side of the test leg is inside the foot of the test leg then greater than shoulder width (wide), score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Y=1 N=0
8 Stance width – Narrow	Once the entire foot is in contact with the ground, draw, a line down from the tip of the shoulders. If the line on the side of the test leg is outside of the foot of the test leg than shoulder width (narrow), score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Y=1 N=0

(continued)

Table A1. LESS Scoring Criteria (continued)

LESS Item	Operational Definition	Camera View	LESS Score
9 Foot position – Toe In	If the foot of the test leg is internally rotated more than 30 degrees between the time period of initial contact and max knee flexion, then score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Y=1 N=0
10 Foot position – Toe Out	If the foot of the test leg is externally rotated more than 30 degrees between the time period of initial contact and max knee flexion, then score YES. If the foot is not externally rotated more than 30 degrees between the time period of initial contact to max knee flexion, score NO.	Front	Y=1 N=0
11 Symmetric initial foot contact	If one foot lands before the other or if one foot lands heel to toe and the other lands toe to heel, score NO. If the feet land symmetrically, score YES.	Front	Y=0 N=1
12 Knee flexion displacement	If the knee of the test leg flexes more than 45 degrees from initial contact to max knee flexion, score YES. If the knee of the test leg does not flex more than 45 degrees, score NO.	Side	Y=0 N=1
13 Hip flexion at max knee flexion	If the thigh of the test leg flexes more on the trunk from initial contact to max knee flexion angle, score YES.	Side	Y=0 N=1
14 Trunk flexion at max knee flexion	If the trunk flexes more from the point of initial contact to max knee flexion, score YES. If the trunk does not flex more, score NO.	Side	Y=0 N=1
15 Knee valgus displacement	At the point of max knee valgus on the test leg, draw a line straight down from the center of the patella. If the line runs through the great toe or is medial to the great toe, score YES. If the line is lateral to the great toe, score NO.	Front	Y=1 N=0

(continued)

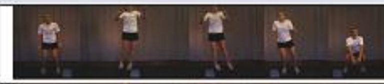
Table A1. LESS Scoring Criteria (continued)

LESS Item	Operational Definition	Camera View	LESS Score
16 Joint displacement	Watch the sagittal plane motion at the hips and knees from initial contact to max knee flexion angle. If the subject goes through large displacement of the trunk, hips, and knees then score SOFT. If the subject goes through some trunk, hip, and knee displacement but not a large amount, then score AVERAGE. If the subject goes through very little, if any trunk, hip, and knee displacement, then score STIFF.	Side	Soft=0 Av.=1 Stiff=2
17 Overall impression	Score EXCELLENT if the subject displays a soft landing and no frontal plane motion at the knee. Score POOR if the subject displays a stiff landing and large frontal plane motion at the knee. All other landings, score AVERAGE.	Side, Front	Ex.=0 Av.=1 Poor=2

Adopted from Padua et al. The landing error scoring system LESS is a valid and reliable clinical assessment tool of jump-landing biomechanics: the jump-ACL study. *Am J Sports Med.* 2009; 37: 1996-2002.

Table A2. Neuromuscular Exercises and Phases

Lateral jumping progression

Phase 1—Lateral jump and hold The athlete prepares for this exercise by standing with her feet close together and her knees slightly bent. The athlete should jump laterally over a line, keeping her knees bent and staying close to the line. When she lands on the opposite side, she should descend into a deep hold immediately.	
Phase 2—Lateral jumps The athlete prepares for this exercise by standing with her feet close together and knees slightly bent on one side of the line. The athlete should jump sideways over the line, keeping her knees bent and staying close to the line. When the athlete lands on the opposite side, she should redirect back to the initial position immediately. The athlete should repeat this sequence as quickly as she can while maintaining proper form. When teaching this exercise, encourage the athlete to achieve as many repetitions as possible in the allotted time by jumping close to the lines, shortening the ground contact time, and not using excessive height on the jumps. Do not allow the athlete to perform a double hop on the side of the line. Early in the training, the athlete may focus on the line; as her technique improves, encourage her to shift her visual focus away from the line to outside cues.	
Phase 3—Lateral hop and hold The athlete prepares for this exercise by standing on one foot with her knee slightly bent. The athlete should jump sideways over a line, keeping her knee bent and staying close to the line. When she lands on the opposite side, she should descend into a single-leg deep hold immediately.	
Phase 4—Lateral hops The athlete prepares for this exercise by standing on one leg with her knee slightly bent on one side of the line. The athlete should jump sideways over the line, keeping her knee bent and staying close to the line. When the athlete lands on the opposite side, she should redirect back to the initial position immediately. When teaching this exercise, encourage the athlete to achieve as many repetitions as possible in the allotted time by jumping close to the lines, shortening the ground contact time, and not using excessive height on the jumps. Do not allow the athlete to perform a double hop on the side of the line. Early in the training the athlete may focus on the line; as her technique improves encourage her to shift her visual focus away from the line to outside cues.	
Phases 5–10—Hops The athlete begins facing a quadrant pattern standing on a single limb with her support knee slightly bent. She will hop diagonally, landing in the opposite quadrant, maintaining forward stance, and holding the deep knee flexion landing for 3 seconds. The athlete then hops laterally into the side quadrant, again holding the landing. Next, the athlete will hop diagonally backward holding the landing. Finally, she hops laterally into the initial quadrant holding the landing. The athlete should repeat this figure 8 pattern for the required number of sets. Encourage the athlete to maintain balance during each landing, keeping her eyes up and her focus away from her feet.	

Single-leg anterior progression

Phase 1—Step-hold The athlete starts by taking a quick step forward and continues by balancing in a deep hold position on the leg onto which she stepped.	
Phase 2—Jump–single-leg hold The athlete will begin this exercise in the athletic position. The athlete proceeds to jump forward, landing and balancing on one leg in a deep hold position.	
Phase 3—Hop hold Starting in a balanced position on one foot, the athlete hops forward, landing and balancing on one leg in a deep hold position.	
Phase 4—Hop-hop-hold The athlete hops forward twice quickly, landing and balancing on one leg in a deep hold position.	
Phase V—Crossover hop-hop-hold The athlete hops forward while alternating legs three times quickly, landing and balancing on one leg in a deep hold position.	

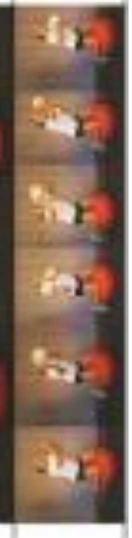
(continued)

Table A2. Neuromuscular Exercises and Phases (continued)

Prone trunk stability progression	
Phase 1—BOSU (round) toe touch swimmers The athlete begins in a prone position with her abdomen centered on the round side of the BOSU and her arms overhead and legs extended. The athlete reaches back with one arm to touch opposite foot and returns to the outstretched superman position.	
Phase 2—BOSU (round) swimmers with partner perturbations The athlete begins in prone position with abdomen centered on the round side of the BOSU and with her arms overhead and legs extended. The movement is initiated by elevating the opposite arm and leg, and held for 3 seconds. A partner will offer random perturbations by stepping on different sides of the BOSU during the exercise.	
Phase 3—Prone bridge (elbows and knees) hip extension opposed shoulder flexion The athlete begins in prone position with her elbows flexed and balanced on an Airex pad and knees on the ground. The movement is initiated by elevating the opposite arm and leg, and held for a single count and finished by returning to the original position.	
Phase 4—Prone bridge (elbows and toes) hip extension The athlete begins in prone position with elbows flexed and balanced on an Airex pad and toes on the ground. The movement is initiated by elevating the each leg individually, held for a single count, and finished by returning to the original position.	
Phase 5—Prone bridge (elbows and toes) hip extension opposite shoulder flexion The athlete begins in prone position with elbows flexed and balanced on an Airex pad and toes on the ground. The movement is initiated by elevating the opposite arm and leg, held for a single count, and finished by returning to the original position.	

(continued)

Table A2. Neuromuscular Exercises and Phases (continued)

Kneeling trunk stability progression	
Phase 1—BOSU (round) double-knee hold The athlete begins this exercise by balancing in a kneeling position with her knees on each side of the round side of the BOSU. The athlete will maintain this balanced position with the hips slightly flexed for the duration of the exercise.	
Phase 2—BOSU (round) single-knee hold The athlete begins this exercise by balancing in a kneeling position with one knee directly in the middle of the round side of the BOSU and the other knee extended out to the side. The athlete will maintain this balanced position with the hip slightly flexed for the duration of the exercise.	
Phase 3—Swiss ball bilateral kneel The athlete kneels and balances on Swiss ball with feet off the ground. A spotter should be available at all times in front of the athlete.	
Phase 4—Swiss ball bilateral kneel with partner perturbations The athlete kneels and balances on Swiss ball with her feet off of the ground. Once the athlete is stabilized, a partner can perturb the ball by kicking in unanticipated directions. A spotter should be available at all times in front of the athlete.	
Phase 5—Swiss ball bilateral kneel with lateral ball catch The athlete kneels and balances on Swiss ball with feet off the ground. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	

(continued)

Table A2. Neuromuscular Exercises and Phases (continued)

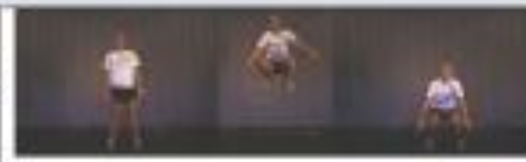
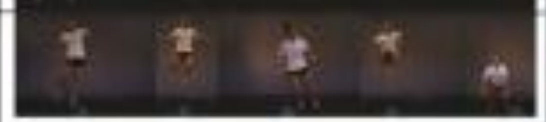
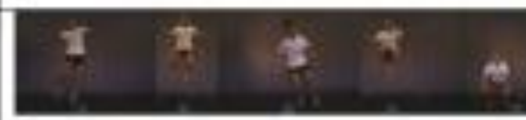
Single-leg lateral progression	
Phase 1—Single-leg lateral Airex hop hold Athlete starts on one side of the Airex pad and hops laterally onto the Airex. The athlete should maintain balance and hold the knee in a flexed position. The athlete then hops off the other side of the Airex onto the ground, maintains balance, and then repeats the exercise in the other direction.	
Phase 2—Single-leg lateral BOSU (round) hop hold Athlete starts on one side of the BOSU and hops laterally onto the BOSU. The athlete should maintain balance and hold the knee in a flexed position. The athlete then hops off the other side of the BOSU onto the ground, maintains balance, and then repeats the exercise in the other direction.	
Phase 3—Single-leg lateral BOSU (Round) hop hold with ball catch The athlete starts on one side of the BOSU and hops laterally onto the BOSU. The athlete should maintain balance and hold the knee in a flexed position. The athlete then hops off the other side of the BOSU onto the ground, maintains balance, and then repeats the exercise in the other direction. The athlete is challenged further by having to catch and return a ball upon each landing.	
Phase 4—Single-leg four-way BOSU (round) hop hold The athlete starts in a single-leg athletic position immediately behind the BOSU. The athlete hops forward onto the round side of the BOSU and lands in a balanced position. After achieving a balanced single leg stance on the BOSU, the athlete proceeds to hop off the BOSU laterally and assumes this same stance on the floor immediately next to the BOSU. The athlete then will continue to hop on and off the BOSU, achieving a balanced athletic position, in each of the four directions: forward, backward, lateral, and medial.	
Phase 5—Single-leg four-way BOSU (round) hop hold with ball catch The athlete starts in a single-leg athletic position immediately behind the BOSU. The athlete hops forward onto the round side of the BOSU and lands in a balanced position. After achieving a balanced single-leg stance on the BOSU, the athlete proceeds to hop off the BOSU laterally and assumes this same stance on the floor immediately next to the BOSU. The athlete then will continue to hop on and off the BOSU, achieving a balanced athletic position, in each of the four directions: forward, backward, lateral, and medial. A ball should be tossed back and forth with a partner upon landing to increase the difficulty of this exercise.	

Hamstring-specific progression	
Phase 1—BOSU (flat) pelvic bridge The athlete lays supine with her hip and knees flexed and her feet planted on the flat side of the BOSU. The athlete then extends her hips and elevates her trunk off the ground to execute a pelvic bridge. This position should be held for 3 seconds before repeating the next repetition.	
Phase 2—BOSU (flat) single-leg pelvic bridge The athlete lays supine with her hip and knees flexed and a single foot planted on the flat side of the BOSU and the contralateral leg fully extended. The athlete then extends her hips and elevates her trunk off the ground to execute a pelvic bridge. This position should be held for 3 seconds before repeating the next repetition.	
Phase 3—BOSU (flat) single leg pelvic bridge The athlete lays supine with her hip and knees flexed and a single foot planted on the flat side of the BOSU and the contralateral leg fully extended holding a ball directly above her in her hands. The athlete then extends her hips and elevates her trunk off the ground to execute a pelvic bridge. This position should be held for 3 seconds before repeating the next repetition. A weight plate is positioned on the hips to add resistance.	
Phase 4—Supine Swiss ball hamstring curl The athlete lays supine with her hip and knees flexed with both heels planted on top of a Swiss ball. The athlete then extends her hips and elevates her trunk off the ground while pulling her heels in to her buttocks.	
Phase 5—Russian hamstring curl with lateral touch The athlete begins in a kneeling position with a partner providing foot support and torso support (with band assistance). The athlete extends at the knee to lower her torso toward the ground. Once touching the BOSU with her chest, the athlete swivels her trunk and returns to the original position. The coach should provide enough assistance so that the exercise can be performed without flexing at the hip.	

(continued)

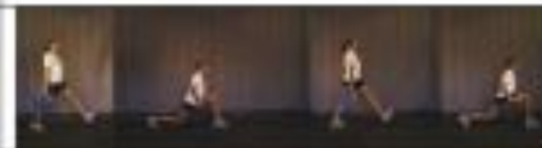
Table A2. Neuromuscular Exercises and Phases (continued)

Tuck jump progression

Phase 1—Single tuck jump soft landing The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump the athlete should be positioned in the air with her thighs parallel to the ground. On landing, the athlete should land softly, using a toe to midfoot rocker landing. The athlete should not continue this jump if she cannot control the high landing force or keep her knees aligned during landing. If the athlete is unable to raise the knees to the proper height, it may be valuable to instruct her to grasp the knees and then bring the thighs to horizontal.	
Phase 2—Double tuck jump Similar to the single tuck jump but with an additional jump performed immediately after the first jump. The athlete should focus on maintaining good form and minimizing time on the ground between jumps.	
Phase 3—Repeated tuck jump The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump, the athlete should be positioned in the air with her thighs parallel to the ground. When landing, the athlete immediately should begin the next tuck jump.	
Phase 4—Side-to-side tuck jumps The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump over a barrier with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump, the athlete should be positioned in the air with her thighs parallel to the ground. When landing, the athlete immediately should begin the next tuck jump back to the other side of the barrier.	
Phase 5—Side-to-side reaction barrier tuck jumps The athlete starts in the athletic position with her feet shoulder width apart. The athlete initiates a vertical jump over a barrier with a slight crouch downward while she extends her arms behind her. The athlete then swings her arms forward as she simultaneously jumps straight up and pulls her knees up as high as possible. At the highest point of the jump, the athlete should be positioned in the air with her thighs parallel to the ground. When landing the athlete immediately should begin the next tuck jump. When prompted, the athlete should jump to the other side of the barrier without breaking rhythm.	

(continued)

Table A2. Neuromuscular Exercises and Phases (continued)

Lunge progression	
Phase 1—Front lunges The athlete begins by stepping forward from a standing position. The step should be exaggerated in length to the point that her front leg is positioned with the knee flexed to 90° and the lower leg completely vertical. The back leg should be as straight as possible and the torso upright. Emphasis should be placed on getting the hips as low as possible while maintaining the previously described body position. Driving off the front leg and returning to the original position complete the exercise.	
Phase 2—Walking lunges The athlete performs a lunge and instead of returning to the start position she steps through with the back limb and proceeds forward with a lunge on the opposite limb. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise. An alternative coaching method is to instruct the athlete to attempt to maintain a constant low center of gravity and roll through the lunges. This increases the intensity of the exercise and attempts to mimic motions frequently occurring in sports.	
Phase 3—Walking lunges unilaterally weighted The athlete performs a lunge, and instead of returning to the start position, she steps through with the back limb and proceeds forward with a lunge on the opposite limb while holding a dumbbell in one hand. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise. This exercise is repeated with the dumbbell in the opposite hand.	
Phase 4—Walking lunges with plate crossover The athlete performs a lunge, and instead of returning to the start position, she steps through with the back limb and proceeds forward with a lunge on the opposite limb while reaching with a weight plate to the open side of the body. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise.	
Phase 5—Walking lunges with unilateral shoulder press The athlete performs a lunge, and instead of returning to the start position, she steps through with the back limb and proceeds forward with a lunge on the opposite limb while pressing a dumbbell above her head. The weight should move up and down with the same tempo and direction as the lunge. Encourage the athlete to lunge her front limb far enough out so that her knee does not advance beyond her ankle during the exercise.	

(continued)

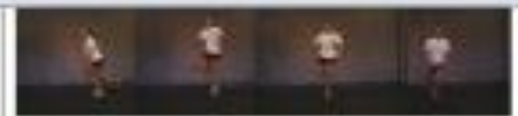
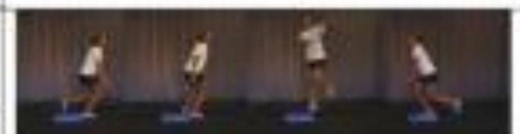
Table A2. Neuromuscular Exercises and Phases (continued)

lunge jump progression

Phase 1—Lunge jumps The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is fully extended at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg, maintaining the starting position during flight and landing. The jump is repeated as quickly as possible while still achieving maximum vertical height. To coach this jump, encourage the athlete to keep the back leg straight and use it only for balance support. The front leg obtains vertical power. Stance support percentages are approximately 80% for the front leg and 20% for the back.	
Phase 2—Scissor jumps The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is fully extended at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg and switch the position of the legs while in flight. The jump is repeated as quickly as possible while still achieving maximum vertical height. The athlete will be jumping off alternate legs on each jump during this exercise.	
Phase 3—Lunge jumps unilaterally weighted The athlete starts in an extended stride position with her hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is extended fully at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg, maintaining the starting position during flight and landing. The jump is repeated as quickly as possible while still achieving maximum vertical height. To unilaterally weight this exercise, a dumbbell should be held in one hand. This exercise then is repeated with the dumbbell in the opposite hand.	
Phase 4—Scissor jumps unilaterally weighted The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is extended fully at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg and switch the position of the legs while in flight. The jump is repeated as quickly as possible, while still achieving maximum vertical height. To unilaterally weight this exercise, a dumbbell should be held in one hand. The athlete will be jumping off alternate legs on each jump during this exercise. This exercise is repeated with the dumbbell in the opposite hand.	
Phase 5—Scissor jumps with ball swivel The athlete starts in an extended stride position with the hips pushed forward, and the front knee positioned directly above the ankle and flexed to 90°. The back leg is extended fully at the hip and knee providing minimal support for the stance. The athlete should jump vertically off of the front support leg and switch the position of the legs while in flight. The jump is repeated as quickly as possible while still achieving maximum vertical height. To unilaterally weight this exercise, a medicine ball should be swiveled to the open side of the body during each jump. The athlete will be jumping off alternate legs.	

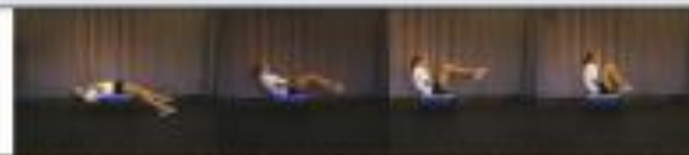
(continued)

Table A2. Neuromuscular Exercises and Phases (continued)

Single-leg rotatory progression	
Phase 1—Single-leg 90° hop hold The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 90°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds to be counted as a successful landing. Coach this jump with care to protect the athlete from injury. Start the athlete with a submaximal effort so she can experience the difficulty of the jump. Continue to increase the intensity of the jump as the athlete improves her ability to stick and hold the final landing. Have the athlete keep her focus away from her feet, to help prevent too much forward lean.	
Phase 2—Single-leg 90° Airex hop hold The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 90°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing. Coach this jump with care to protect the athlete from injury.	
Phase 3—Single-leg 90° hop-hold reaction ball catch The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 90°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing. Upon landing a ball will be passed back and forth with the athlete to increase the difficulty of a successful landing.	
Phase 4—Single-leg 180° Airex hop hold The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 180°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing.	
Phase 5—Single-leg 180° Airex hop-hold reaction ball catch The starting position for this jump is with the athlete in a semicrouched position on the single limb being trained. The jump should focus on attaining maximum height while maintaining good form upon landing. During the flight phase, the athlete should rotate 180°. The landing occurs on the same leg and should be performed with deep knee flexion (to 90°). The landing should be held for a minimum of 3 seconds on an Airex pad to be counted as a successful landing. Upon landing, a ball will be passed back and forth with the athlete to increase the difficulty of a successful landing.	

(continued)

Table A2. Neuromuscular Exercises and Phases (continued)

Trunk flexion progression	
Phase 1—Box double crunch The athlete starts out supine on a plyometric box or similar object and flexes her trunk simultaneous with hip flexion.	
Phase 2—Box swivel double crunch Athlete starts in a supine position on a plyo box with arms placed across chest. The athlete flexes her trunk simultaneous with hip flexion. As the trunk and hip are maximally flexed, the athlete rotates at the trunk, touching each elbow to the opposite knee.	
Phase 3—BOSU (round) swivel ball touches (feet up) Athlete starts sitting on the round side of a BOSU holding a medicine ball. The athlete will proceed to swivel at the trunk to touch the medicine ball to the floor for each repetition.	
Phase 4—BOSU (round) double crunch Athlete starts sitting on the round side of a BOSU. The athlete flexes her trunk simultaneous with hip flexion.	
Phase 5—BOSU (round) swivel double crunch Athlete starts sitting on the round side of a BOSU. The athlete flexes her trunk simultaneous with hip flexion. As the trunk and hip are maximally flexed, the athlete rotates at the trunk touching each elbow to the opposite knee.	

(continued)

Table A2. Neuromuscular Exercises and Phases (continued)

Lateral trunk progression

Phase 1—BOSU (round) lateral crunch The athlete starts lying on her side with her hip located in the center of the round side of the BOSU. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions.	
Phase 2—Box lateral crunch Athlete starts in a supine position on a plyo box with arms placed on the back of the head. The athlete flexes her trunk simultaneously with hip flexion. As the trunk and hip are maximally flexed, the athlete rotates at the trunk touching each elbow to the opposite knee.	
Phase 3—BOSU (round) lateral crunch with ball catch Athlete starts lying on side with hip located top of the round side of a BOSU. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	
Phase 4—Swiss ball lateral crunch Athlete starts lying on side with hip located top of a Swiss ball. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions.	
Phase 5—Swiss ball lateral crunch with ball catch Athlete starts lying on side with hip located top of a Swiss ball. The athlete's feet and legs must be anchored during this exercise by the trainer or a stationary object. The athlete will proceed to bend laterally at the waist back and forth for the prescribed repetitions. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	

Trunk extension progression

Phase 1—Swiss ball back hyperextensions The athlete begins in a prone position on the Swiss ball, with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending her hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained for a short pause and then returned to the flexed position.	
Phase 2—Swiss ball back hyperextensions with ball reach The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. While performing this motion the athlete will also extend and return a medicine ball from the chest to full shoulder and elbow extension and back to the chest.	
Phase 3—Swiss ball hyperextensions with back fly The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained while the athlete brings dumbbells out to the side similar to a back fly exercise.	
Phase 4—Swiss ball hyperextensions with ball reach lateral The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained while the athlete brings a medicine ball above her head and slightly to the side.	
Phase 5—Swiss ball hyperextensions with lateral ball catch The athlete begins in a prone position on the Swiss ball with her hips centered on top of the Swiss ball and a partner anchoring her feet to the floor. The movement is initiated by extending hips and lower back to bring the athlete into a position of slight hyperextension. The position should be maintained while the athlete brings a medicine ball above her head and slightly to the side. A ball should be tossed back and forth with a partner to increase the difficulty of this exercise.	

Adopted from Myer, GD, Chu, DA, Brent, JL, Hewett, TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med.* 2008; 27: 425-448.

APPENDIX B. INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

NDSU NORTH DAKOTA STATE UNIVERSITY

Institutional Review Board

Office of the Vice President for Research, Creative Activities and Technology Transfer
NDSU Dept. 4000
1735 NDSU Research Park Drive
Research 1, P.O. Box 6050
Fargo, ND 58108-6050

701.231.8995
Fax 701.231.8098

Federalwide Assurance #FWA00002439

May 21, 2012

Pamela Hansen
Department of Health, Nutrition & Exercise Sciences
BBFH

IRB Approval of Protocol #**HE12200**, "**Trunk and Hip Neuromuscular Training Protocol Effects on the Female Athletes**"
Co-investigator(s) and research team: **Charley Young, Hilaree Leif**

Approval period: May 21, 2012 to May 20, 2013 **Continuing Review Report Due: April 1, 2013**

Research site(s): **Moorhead High School** Funding agency: **n/a**
Review Type: Full Board, meeting date – May 11, 2012
Risk Level: No more than minimal risk
IRB approval is based on original submission, with revised: permission, assent, and consent forms (received May 21, 2012).

Additional approval is required:

- prior to implementation of any proposed changes to the protocol (*Protocol Amendment Request Form*).
- for continuation of the project beyond the approval period (*Continuing Review/Completion Report Form).* A reminder is typically sent two months prior to the expiration date; timely submission of the report is your responsibility. To avoid a lapse in approval, suspension of recruitment, and/or data collection, a report must be received, and the protocol reviewed and approved prior to the expiration date.

A report is required for:

- any research-related injuries, adverse events, or other unanticipated problems involving risks to participants or others within 72 hours of known occurrence (*Report of Unanticipated Problem or Serious Adverse Event Form*).
- any significant new findings that may affect risks to participants.
- closure of the project (*Continuing Review/Completion Report Form*).

Research records are subject to random or directed audits at any time to verify compliance with IRB regulations and NDSU policies.

Thank you for cooperating with NDSU IRB procedures, and best wishes for a successful study.

Sincerely,
Kristy Shirley
Kristy Shirley, CIP
Research Compliance Administrator

Last printed 5/21/2012 12:27:00 PM

NDSU is an EO/AA university.

APPENDIX C. DEMOGRAPHIC FORM

Neuromuscular Trunk and Hip Strength Training Program to Reduce Risk of ACL and Other Knee Injuries Demographic Form

---

ID Number ________________

Gender: ____ Male ____ Female

Height: ____Feet ____ Inches

Weight: ______lbs.

Grade you will be entering in fall: ____9 ____10 ____11 ____12

Age: ____13 ____14 ____15 ____16 ____17 ____18 ____Other

Dominate Leg: ____Right ____Left

(Dominate Leg is determined by which leg you prefer to kick a ball)

Sport(s): ____

Have you had ACL injury or surgery? ___Yes ____No

Have you had any other knee surgery? ___Yes ____No

Have you started menstrating (getting your periods)? ___Yes ____No

When was your last menstural cycle? ______________ (Month/Day/Year)

Previous Knee Injuries:

Type of Injury __________________________ ____Right ____Left

Surgery Required ___Yes ____No Date of Surgery ___/___/20___

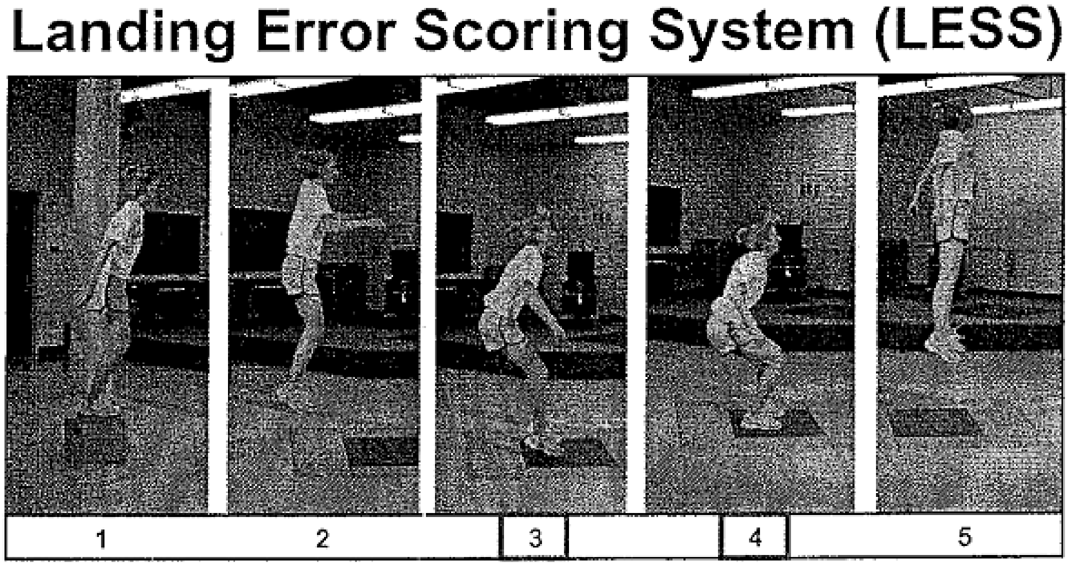
Type of Surgery ____

Type of Injury __________________________ ____Right ____Left

Surgery Required ___Yes ____No Date of Surgery ___/___/20___

Type of Surgery ____

APPENDIX D. DROP BOX JUMP



Adopted from Padua D (2011). *Identifying Modifiable Risk Factors for ACL Injury and Re-Injury.*

APPENDIX E. PERCEPTION SURVEY

Please Circle One Answer

1.) Do you feel that your landing technique has become better?
   a. Yes   b. No   c. Somewhat   d. Not at all
2.) Do you feel more confident with your landing form?
   a. Yes   b. No   c. Somewhat   d. Not at all
3.) Do you feel that this hip and trunk neuromuscular training program has made you stronger?
   a. Yes   b. No   c. Somewhat   d. Not at all
4.) Has the hip and trunk neuromuscular training program helped you to become more aware of your body?
   a. Yes.   b. No   c. Somewhat   d. Not at all
5.) Has the hip and trunk neuromuscular training program helped you to be more in control of your body?
   a. Yes   b. No   c. Somewhat   d. Not at all