The Association Between Measures of Core Stability and Biomechanics of the Trunk and Knee During a Single Leg Squat

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ABSTRACT

ANDREA S. JARVIS: The Association Between Measures of Core Stability and Biomechanics of the Trunk and Knee During a Single Leg Squat
(Under the Direction of Dr. Darin A. Padua)

Objective: To determine the relationship between clinical measures of core stability and trunk and knee kinematics and kinetics. **Design:** Results of the four core stability tests compared to data obtained performing a single leg squat. **Subjects:** 31 recreationally active individuals (9 males and 22 females, age = 22.1±2.9 years, height = 169.7±9.1 cm, weight = 68.4±10.5 kg). **Statistical Analysis:** Pearson r and Spearman's rho correlational analyses; independent samples t-tests. **Main Outcome Measure(s):** Knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, trunk flexion displacement, peak trunk flexion angle, peak normalized knee valgus angle. **Results:** A significant positive relationship between core stability and trunk flexion displacement was observed. **Significance:** Additional research needs to be done in order to propose a direct relationship between core stability and non-contact knee injury prevention. **Key Words:** Core stability, knee valgus, trunk flexion, single leg squat.

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CHAPTER 1

INTRODUCTION

It has been estimated that there are over 100,000 anterior cruciate ligament (ACL) injuries in the United States annually [1, 2]. Treatment usually necessitates surgical intervention, painful rehabilitation, and considerable time lost from sports. The cost of treating these injuries adds up to almost one billion dollars per year [3]. Of all ACL injuries, 70% occur in non-contact situation [3]. There is immense interest in discovering ways to reduce the number of non-contact ACL tears since many of the risk factors associated with this injury are believed to be modifiable.

Several risk factors for non-contact ACL injuries have been identified and divided into 4 categories: environmental, hormonal, anatomical, and biomechanical [3, 4]. Environmental factors include any equipment, such as knee braces, as well as the type of shoes worn by the athlete. Hormonal factors refer to the theorized changes that take place in the mechanical properties of ligaments based on the levels of estrogen and progesterone present throughout the different phases of the female menstrual cycle [5]. Anatomical factors include an increased Q angle, the size and shape of the femoral notch, excessive tibial rotation, and excessive pronation [4]. Biomechanical factors include muscle activation patterns and alterations in joint angles. The biomechanical risk factors are commonly focused on in research because they are the most easily modifiable.

Certain kinematic patterns have been proposed to predispose athletes to ACL injury. Ireland et al described a "position of no return" in regards to understanding the biomechanics behind the mechanism for non-contact ACL injury [6]. This position consists of trunk forward flexion and rotation to the opposite side, hip adduction and internal rotation, decreased knee flexion, knee valgus, external tibial rotation, and foot pronation. She suggested that neuromuscular training of muscles proximal to the knee may prevent athletes from adopting this dangerous posture during athletic activity.

Trunk positioning has been shown to have an influence on lower extremity kinematics which may play a role in ACL injury risk [7]. Blackburn and Padua found that increased trunk flexion, as compared to a more erect posture, produced an increase in knee flexion during a drop landing task. These results suggest that trunk motions do affect knee kinematics and can, therefore, potentially affect the risk for ACL injury.

The trunk is a very large body of mass that has to be controlled and manipulated during athletic activity. Any lack of control may increase the moment requirements and kinematic demands of the lower extremity musculature; these changes may insult the system, thereby causing injury. Core stability is, therefore, believed to be an important aspect to athletic performance and injury risk.

Research has identified the ability to control trunk motion following perturbation and trunk proprioception as factors that may predispose individuals to non-contact ACL injury [8, 9]. Zazulak et al demonstrated that athletes who sustained a knee ligament injury had greater trunk displacement following an unexpected perturbation compared to those who did not experience an injury [8]. Trunk displacement was assessed using a customized perturbation device that measured trunk displacement after the release of a sustained force. Subjects were then tracked for injuries over a 3 year period. Of the 277 subjects initially tested, 25 sustained knee injuries. They were able to determine that trunk displacement was greater in ACL injured athletes compared to uninjured athletes, and that lateral displacement was the strongest predictor of knee ligament injury. Based on these results, they concluded that core stability was an important factor related to the risk of knee injuries. Unfortunately the method of assessing core stability in this study is not applicable in the clinical setting. Thus, it is not known if clinical measures of core stability may provide insight into risk of injury.

A significant amount of research has been devoted to identifying factors that predispose individuals to non-contact knee injuries. However, little research has focused on how core stability may be related to the risk of injury. It is possible that decreased core stability may allow for excessive and uncontrolled trunk motions, which may in turn impact knee position and loading. Specifically, the inability to control lateral trunk flexion and rotation may facilitate increased knee valgus alignment and loading and poor sagittal plane trunk control can influence knee flexion angle and moments. It seems reasonable that core stability may influence the risk of injury due to core stability's influence on knee joint position and loading; however, research has not investigated the relationship between core stability and knee joint position and loading. Therefore, the purpose of this study is to determine the relationship between clinical measures of core stability and kinematics of the trunk and knee during a single leg squat.

Predictor Variables

Four independent variables will be evaluated during this study:

1. The number of errors committed during an abdominal hollowing maneuver
2. Time to failure during performance of prone plank to fatigue test

3. Time to failure during performance of lateral musculature endurance test

4. Pass or failure of the quadruped arm leg raise

Criterion Variables

Seven dependent variables will be evaluated during this study:

1. Knee valgus range of displacement (degrees) during the descent phase of the single leg squat

2. Peak knee valgus angle (degrees) during the descent phase of the single leg squat

3. Lateral trunk flexion displacement (degrees) during the descent phase of the single leg squat

4. Peak lateral trunk flexion angle (degrees) during the descent phase of the single leg squat

5. Trunk flexion displacement (degrees) throughout the descent phase of the single leg squat

6. Peak trunk flexion angle (degrees) during the descent phase of the single leg squat task

7. Peak normalized knee valgus moment during the descent phase of the single leg squat

Research Questions

Research Question 1. What is the relationship between performance of the abdominal hollowing maneuver and biomechanics of the trunk and knee during a single leg squat?

RQ1a: What is the association between number of errors committed during an abdominal hollowing maneuver and knee valgus displacement during the descent phase of the single leg squat?

RQ1b: What is the association between number of errors committed during an abdominal hollowing maneuver and peak knee valgus angle during the descent phase of the single leg squat?

RQ1c: What is the association between number of errors committed during an abdominal hollowing maneuver and lateral trunk flexion displacement during the descent phase of the single leg squat?

RQ1d: What is the association between number of errors committed during an abdominal hollowing maneuver and peak lateral trunk flexion angle during the descent phase of the single leg squat?

RQ1e: What is the association between number of errors committed during an abdominal hollowing maneuver and trunk flexion displacement during the descent phase of the single leg squat?

RQ1f: What is the association between number of errors committed during an abdominal hollowing maneuver and peak trunk flexion angle during the descent phase of the single leg squat?

RQ1g: What is the association between number of errors committed during an abdominal hollowing maneuver and peak normalized knee valgus moment during the descent phase of the single leg squat?

Research Question 2. What is the relationship between performance of the prone plank to fatigue test and biomechanics of the trunk and knee during a single leg squat?

RQ2a: What is the association between time to failure during the prone plank to fatigue test and knee valgus displacement during the descent phase of the single leg squat?

RQ2b: What is the association between time to failure during the prone plank to fatigue test and peak knee valgus angle during the descent phase of the single leg squat?

RQ2c: What is the association between time to failure during the prone plank to fatigue test and lateral trunk flexion displacement during the descent phase of the single leg squat?

RQ2d: What is the association between time to failure during the prone plank to fatigue test and peak lateral trunk flexion angle during the descent phase of the single leg squat?

RQ2e: What is the association between time to failure during the prone plank to fatigue test and trunk flexion displacement during the descent phase of the single leg squat?

RQ2f: What is the association between time to failure during the prone plank to fatigue test and peak trunk flexion angle during the descent phase of the single leg squat?

RQ2g: What is the association between time to failure during the prone plank to fatigue test and peak normalized knee valgus moment during the descent phase of the single leg squat?

Research Question 3. What is the relationship between performance of the lateral musculature endurance test and biomechanics of the trunk and knee during a single leg squat?

RQ3a: What is the association between time to failure during the lateral musculature endurance test and knee valgus displacement during the descent phase of the single leg squat?

RQ3b: What is the association between time to failure during the lateral musculature endurance test and peak knee valgus angle during the descent phase of the single leg squat?

RQ3c: What is the association between time to failure during the lateral musculature endurance test and lateral trunk flexion displacement during the descent phase of the single leg squat?

RQ3d: What is the association between time to failure during the lateral musculature endurance test and peak lateral trunk flexion angle during the descent phase of the single leg squat?

RQ3e: What is the association between time to failure during the lateral musculature endurance test and trunk flexion displacement during the descent phase of the single leg squat?

RQ3f: What is the association between time to failure during the lateral musculature endurance test and peak trunk flexion angle during the descent phase of the single leg squat?

RQ3g: What is the association between time to failure during the lateral musculature endurance test and peak normalized knee valgus moment during the descent phase of the single leg squat?

Research Question 4. What is the relationship between performance of the quadruped arm leg raise and biomechanics of the trunk and knee during a single leg squat?

RQ4a: What is the association between pass or failure of the quadruped arm leg raise and knee valgus displacement during the descent phase of the single leg squat?

RQ4b: What is the association between pass or failure of the quadruped arm leg raise and peak knee valgus angle during the descent phase of the single leg squat?

RQ4c: What is the association between pass or failure of the quadruped arm leg raise and lateral trunk flexion displacement during the descent phase of the single leg squat?

RQ4d: What is the association between pass or failure of the quadruped arm leg raise and peak lateral trunk flexion angle during the descent phase of the single leg squat?

RQ4e: What is the association between pass or failure of the quadruped arm leg raise and trunk flexion displacement during the descent phase of the single leg squat?

RQ4f: What is the association between pass or failure of the quadruped arm leg raise and peak trunk flexion angle during the descent phase of the single leg squat?

RQ4g: What is the association between pass or failure of the quadruped arm leg raise and peak normalized knee valgus moment during the descent phase of the single leg squat?

Null Hypotheses

1. H_0 = There is no relationship between the performance of the abdominal hollowing maneuver and trunk and knee biomechanics.

1a: H_0 = There is no association between the number of errors committed during the abdominal hollowing maneuver and knee valgus displacement.

1b: H_0 = There is no association between the number of errors committed during the abdominal hollowing maneuver and peak knee valgus angle.

1c: H_0 = There is no association between the number of errors committed during the abdominal hollowing maneuver and lateral trunk flexion displacement.

1d: H_0 = There is no association between the number of errors committed during the abdominal hollowing maneuver and peak lateral trunk flexion angle.

1e: H_0 = There is no association between the number of errors committed during the abdominal hollowing maneuver and trunk flexion displacement.

1f: H_0 = There is no association between the number of errors committed during the abdominal hollowing maneuver and peak trunk flexion angle.

1g: H_0 = There is no association between the number of errors committed during the abdominal hollowing maneuver and peak normalized knee valgus moment.

2. H_0 = There is no relationship between the performance of the prone plank to fatigue test and trunk and knee biomechanics.

2a: H_0 = There is no association between time to failure during the prone plank to fatigue test and knee valgus displacement.

2b: H_0 = There is no association between time to failure during the prone plank to fatigue test and peak knee valgus angle.

2c: H_0 = There is no association between time to failure during the prone plank to fatigue test and lateral trunk flexion displacement.

2d: H_0 = There is no association between time to failure during the prone plank to fatigue test and peak lateral trunk flexion angle.

2e: H_0 = There is no association between time to failure during the prone plank to fatigue test and trunk flexion displacement.

2f: H_0 = There is no association between time to failure during the prone plank to fatigue test and peak trunk flexion angle.

2g: H_0 = There is no association between time to failure during the prone plank to fatigue test and peak normalized knee valgus moment.

3. H_0 = There is no relationship between the performance of the lateral musculature endurance test and trunk and knee biomechanics.

3a: H_0 = There is no association between time to failure during the lateral musculature endurance test and knee valgus displacement.

3b: H_0 = There is no association between time to failure during the lateral musculature endurance test and peak knee valgus angle.

3c: H_0 = There is no association between time to failure during the lateral musculature endurance test and lateral trunk flexion displacement.

3d: H_0 = There is no association between time to failure during the lateral musculature endurance test and peak lateral trunk flexion angle.

3e: H_0 = There is no association between time to failure during the lateral musculature endurance test and trunk flexion displacement.

3f: H_0 = There is no association between time to failure during the lateral musculature endurance test and peak trunk flexion angle.

3g: H_0 = There is no association between time to failure during the lateral musculature endurance test and peak normalized knee valgus moment.

4. H_0 = There is no relationship between the performance of the quadruped arm leg raise and trunk and knee biomechanics.

4a: H_0 = There is no association between pass or failure of the quadruped arm leg raise and knee valgus displacement.

4b: H_0 = There is no association between pass or failure of the quadruped arm leg raise and peak knee valgus angle.

4c: H_0 = There is no association between pass or failure of the quadruped arm leg raise and lateral trunk flexion displacement.

4d: H_0 = There is no association between pass or failure of the quadruped arm leg raise and peak lateral trunk flexion angle.

4e: H_0 = There is no association between pass or failure of the quadruped arm leg raise and trunk flexion displacement.

4f: H_0 = There is no association between pass or failure of the quadruped arm leg raise and peak trunk flexion angle.

4g: H_0 = There is no association between pass or failure of the quadruped arm leg raise and peak normalized knee valgus moment.

Research Hypotheses

1. There is a relationship between performance of the abdominal hollowing maneuver and trunk and knee biomechanics.

1a: There is a direct relationship between performance of the abdominal hollowing maneuver and knee valgus displacement; as the number of errors increases, knee valgus displacement will increase.

1b: There is a direct relationship between performance of the abdominal hollowing maneuver and peak knee valgus angle; as the number of errors increases, peak knee valgus angle will increase.

1c: There is a direct relationship between performance of the abdominal hollowing maneuver and lateral trunk flexion displacement; as the number of errors increases, lateral trunk flexion displacement will increase.

1d: There is a direct relationship between performance of the abdominal hollowing maneuver and peak lateral trunk flexion angle; as the number of errors increases, peak lateral trunk flexion angle will increase.

1e: There is a direct relationship between performance of the abdominal hollowing maneuver and trunk flexion displacement; as the number of errors increases, trunk flexion displacement will increase.

1f: There is a direct relationship between performance of the abdominal hollowing maneuver and peak trunk flexion angle; as the number of errors increases, peak trunk flexion angle will increase.

1g: There is a direct relationship between performance of the abdominal hollowing maneuver and peak normalized knee valgus moment; as the number of errors increases, peak normalized knee valgus moment will increase.

2. There is a relationship between performance of the prone plank to fatigue test and trunk and knee biomechanics.

2a: There is an inverse relationship between performance of the prone plank to fatigue test and knee valgus displacement; as time to failure increases, knee valgus displacement will decrease.

2b: There is an inverse relationship between performance of the prone plank to fatigue test and peak knee valgus angle; as time to failure increases, peak knee valgus angle will decrease.

2c: There is an inverse relationship between performance of the prone plank to fatigue test and lateral trunk flexion displacement; as time to failure increases, lateral trunk flexion displacement will decrease.

2d: There is an inverse relationship between performance of the prone plank to fatigue test and peak lateral trunk flexion angle; as time to failure increases, peak lateral trunk flexion angle will decrease.

2e: There is an inverse relationship between performance of the prone plank to fatigue test and trunk flexion displacement; as time to failure increases, trunk flexion displacement will decrease.

2f: There is an inverse relationship between performance of the prone plank to fatigue test and peak trunk flexion angle; as time to failure increases, peak trunk flexion angle will decrease.

2g: There is an inverse relationship between performance of the prone plank to fatigue test and peak normalized knee valgus moment; as time to failure increases, peak normalized knee valgus moment will decrease.

3. There is a relationship between performance of the lateral musculature endurance test and trunk and knee biomechanics.

3a: There is an inverse relationship between performance of the lateral musculature endurance test and knee valgus displacement; as time to failure increases, knee valgus displacement will decrease.

3b: There is an inverse relationship between performance of the lateral musculature endurance test and peak knee valgus angle; as time to failure increases, peak knee valgus angle will decrease.

3c: There is an inverse relationship between performance of the lateral musculature endurance test and lateral trunk flexion displacement; as time to failure increases, lateral trunk flexion displacement will decrease.

3d: There is an inverse relationship between performance of the lateral musculature endurance test and peak lateral trunk flexion angle; as time to failure increases, peak lateral trunk flexion angle will decrease.

3e: There is an inverse relationship between performance of the lateral musculature endurance test and trunk flexion displacement; as time to failure increases, trunk flexion displacement will decrease.

3f: There is an inverse relationship between performance of the lateral musculature endurance test and peak trunk flexion angle; as time to failure increases, peak trunk flexion angle will decrease.

3g: There is an inverse relationship between performance of the lateral musculature endurance test and peak normalized knee valgus moment; as time to failure increases, peak normalized knee valgus moment will decrease.

4. There is a relationship between performance of the quadruped arm leg raise and trunk and knee biomechanics.

4a: There is a direct relationship between performance of the quadruped arm leg raise and knee valgus displacement; if no rotation occurs, knee valgus displacement will decrease.

4b: There is a direct relationship between performance of the quadruped arm leg raise and peak knee valgus angle; if no rotation occurs, peak knee valgus angle will decrease.

4c: There is a direct relationship between performance of the quadruped arm leg raise and lateral trunk flexion displacement; if no rotation occurs, lateral trunk flexion displacement will decrease.

4d: There is a direct relationship between performance of the quadruped arm leg raise and peak lateral trunk flexion angle; if no rotation occurs, peak lateral trunk flexion angle will decrease.

4e: There is a direct relationship between performance of the quadruped arm leg raise and trunk flexion displacement; if no rotation occurs, trunk flexion displacement will decrease.

4f: There is a direct relationship between performance of the quadruped arm leg raise and peak trunk flexion angle; if no rotation occurs, peak trunk flexion angle will decrease.

4g: There is a direct relationship between performance of the quadruped arm leg raise and peak normalized knee valgus moment; if no rotation occurs, peak normalized knee valgus moment will decrease.

Operational Definitions

Core Stability: The body's capacity to maintain a relative position of the trunk and pelvis for a prolonged period of time, as it pertains to a specific stability test.

Abdominal Hollowing Maneuver: A voluntary contraction of the transverse abdominis where the isolation of that muscle occurs without any motion in the rest of the body. The test begins with the subject in the crook-lying position: supine with both knees flexed to 90 degrees. The subject will be instructed to draw their belly button in and up towards their spine [10]. Failure will be measured in the number of errors committed regarding the subject's ability to maintain a neutral spine, a motionless pelvis, rib cage, and shoulders, the ability to breathe normally during the contraction, and the ability to hold the contraction for at least 10 seconds.

Prone Plank: Testing begins with the subject lying prone with arms bent and positioned so that elbows are directly below shoulders and upper arms are perpendicular to the floor. The feet are together. Time starts when the subject then lifts their hips off the floor so that body weight is entirely supported by forearms and toes. The goal is to maintain a straight line from the shoulders to the ankles with the line running through the hips [11, 12]. Time to failure will be measured in seconds and will be defined as the point when the subject loses the straight-back posture and hips return to the ground.

Lateral Musculature Endurance Test: The test begins with the subject lying in full side-bridge position on their dominant side. Legs are extended, and the top foot is placed in front of the lower foot for support. Subjects support themselves on one elbow and on their feet while lifting their hips off the floor. The uninvolved arm is positioned with the hand on the hip. Time to failure will be measured in seconds and will be defined as the point when the subject loses the straight-back posture and the hip returns to the ground [13-16].

Quadruped Arm Leg Raise: also referred to as the "bird dog, " this test begins with the subject on hands and knees, with hands positioned directly below shoulders, knees directly below hips, and back straight. The subject will then lift one arm and the opposite leg and raise them until they are parallel to the ground. The position will be held for ten seconds. This will then be repeated with the other arm and leg. Failure occurs if instability is observed and is defined as shoulder or hip rotation upon the removal of the sturdy base of support.

Single Leg Squat: Subjects will begin standing on their dominant leg, defined as the leg used to kick a ball for distance, with the toes pointing straight ahead and hands on hips. Subjects will be instructed to squat as if they were sitting in a chair, will squat to approximately 60 degrees of knee flexion, and then return to the start position.

Descent Phase: the phase of the single leg squat task during which knee flexion is occurring from 0-60 degrees.

Assumptions

The following limitations and assumptions applied to this study:

1. The sample used was indicative of the general population.

2. Subjects were truthful about their physical activity level and lack of previous lower extremity injury.

3. Trunk and knee biomechanics during a single leg squat represent those during more dynamic tasks.

4. The four clinical core strength tests were valid measures of core stability.

5. All instruments used are valid and reliable.

Delimitations

The following delimitations applied to this study:

1. All subjects were healthy and free of lower extremity injury and back pain for at least 3 months prior to data collection.

Limitations

The following limitations will apply to this study:

1. Factors other than core stability may influence lower extremity positioning.

2. May not be able to generalize the results of this study to other populations

3. The single leg squat is less physically demanding and may not accurately represent the motions created during more dynamic activities.

CHAPTER 2

LITERATURE REVIEW

Introduction

Anterior cruciate ligament injuries are common in athletics. While some ACL injuries are a result of contact, a majority of them occur in non-contact situations [3]. Treatment usually necessitates surgical intervention, painful rehabilitation, and considerable time lost from sports. For these reasons, there is considerable interest in determining ways to prevent ACL injuries from occurring. Current literature is focused on examining possible predisposing factors to ACL injury. The purpose of this review is to identify and evaluate other studies that have examined potential risk-factors for knee injury in order to establish the basis for a connection between core stability and non-contact ACL injury.

Anatomy of the Knee

The knee is one of the most complex joints in the body. The knee joint is formed by the femur, tibia, and patella. The rounded femoral condyles roll across the superior surface of the tibia during flexion and extension, so points of contact are constantly changing. The knee is, therefore, much less stable than other hinge joints, and it relies on muscular and ligamentous structures for support.

The main muscles that move the knee are the quadriceps and hamstring muscles. The 4 quadriceps are the main knee extensors. They insert on the superior pole of the patella and via the patellar tendon to the tibial tuberosity. The 3 hamstrings are the main knee flexors. They insert on the head of the fibula, and the medial and lateral condyles of the tibia.

Seven major ligaments are responsible for stabilization of the knee. These include the patellar ligament, tibial collateral ligament, fibular collateral ligament, two superficial popliteal ligaments, the posterior cruciate ligament, and the anterior cruciate ligament (ACL).

The ACL consists of two fiber bundles, each named for their insertion points on the tibia. The larger anteromedial bundle inserts anteromedially on the tibial side and originates more proximally on the femoral side than the posterolateral bundle. Studies indicate that the anteromedial bundle is tight during knee flexion, while the posterolateral bundle is tight during knee extension. The ACL is responsible for preventing anterior tibial translation as well as rotary instability [17].

Epidemiology

The incidence of non-contact anterior cruciate ligament (ACL) injuries in young to middle-aged athletes is high. It has been estimated that there are over 100,000 ACL injuries in the United States annually [1, 2], with an estimated cost of almost a billion dollars per year. Seventy percent of these ACL injuries occur in non-contact situations [3], with females sustaining non-contact ACL injuries at a rate of 2-8 times greater than males for similar sports [18]. The consequences of ACL injury may include time lost from work, school, or sports, as well as long-term consequences such as the development of degenerative joint disease [19]. As such, there is a great interest in identifying those at risk for non-contact ACL tears since many of the risk factors associated with this injury are believed to be modifiable.

Risk Factors

Biomechanical Factors Associated with ACL Injury

Biomechanical risk factors include neuromuscular control and proprioceptive deficits. The position of knee valgus is one of the most researched contributors to the mechanism of ACL injury [3, 18, 20-24].

Hewett et al [23] attempted to predict ACL injury risk by identifying female athletes that displayed decreased neuromuscular control and increased valgus joint loading during prescreening evaluations. The 205 subjects were asked to perform 3 successful drop vertical jump trials and knee flexion and abduction angles were captured with retro-reflective markers and a camera-based motion analysis system. The subjects were followed for a period of 13 months during which time 9 athletes sustained non-contact ACL injuries. The results show that the injured athletes displayed 8 degrees greater knee abduction angles and 2.5 times greater knee abduction moments compared to the non-injured athletes. The authors concluded that females who displayed increased knee valgus angle and increased external knee valgus moments during a jump-landing task were at an increased risk of sustaining a non-contact ACL injury [4].

Knee valgus can also be affected by muscular forces acting on the knee [3, 24]. Dynamic stability can be defined as the ability of a joint to maintain its position after perturbation. Dynamic stability of the knee depends on accurate sensory input and appropriate motor responses to meet the demands of rapid changes created during cutting, stopping, landing, and other athletic movements [9]. Dynamic stability is contingent on neuromuscular control of the displacement of all contributing body segments during movement. Inadequate neuromuscular control of body segments proximal to the knee joint may compromise dynamic stability of the lower extremity and result in increased torque, which may increase strain on the knee ligaments and lead to injury.

Zazulak et al demonstrated that athletes who sustained a knee ligament injury also had greater trunk displacement [8, 9]. In one study, trunk control was assessed through the use of a customized perturbation device that measured trunk displacement after the release of a sustained force. Their subjects were followed over a 3 year period, and knee injuries were recorded. Of the 277 subjects, 25 sustained knee injuries. They were able to determine that trunk displacement was greater in ACL injured athletes than uninjured athletes, and that lateral displacement was the strongest predictor of knee ligament injury [8]. Based on these results, the authors concluded that there are factors related to core stability that may predict risk for knee injuries.

Factors Influencing ACL Loading

Anterior Shear Force

Knee flexion angle greatly influences ACL loading as quadriceps contractions at low knee flexion angles (0-30°) can generate significant anterior tibial shear forces that facilitate high levels of ACL loading [25-28].

Draganich et al attempted to determine if the hamstrings coactivate with the quadriceps. 6 male subjects participated in the study. Two postitions were tested, seated and prone, and the subjects were instructed to move their legs through a range of motion from 90 degrees to 0 degrees of knee flexion with varying amounts of weight attached to the ankle. Data were collected on the vastus medialis, rectus femoris, vastus lateralis, long head of the biceps femoris, semitendinosus, and semimembranosus using surface EMG. The results do indicate that the hamstrings coactivate with the quadriceps. The authors conclude that the coactivation of the hamstrings works to prevent anterior tibial displacement caused by contraction of the quadriceps in less than 90 degrees of knee flexion [28].

DeMorat et al studied the effects of aggressive quadriceps loading on knee kinematics, knee structures, and anterior laxity of the knee. 4500 N of quadriceps loading force was applied to 13 cadaveric knees held at 20 degrees of knee flexion. This resulted in 2 specimiens with tibial plateau fractures, 6 with ACL injuries at the femoral insertion of the ligament, and 5 with no significant change in the ACL. The authors conclude that aggressive quadriceps loading with the knee near full extension produces enough anterior tibial translation to significantly injure the ACL [27]. They further suggest that the quadriceps can be considered among the intrinsic risk factors for non-contact ACL injury.

Knee Valgus and Tibial Internal Rotation

Isolated knee valgus and tibial internal rotation also causes ACL loading, but the magnitude of ACL loading is smaller in comparison to isolated anterior tibial shear force [29]. However, when knee valgus and tibial internal rotation are applied in combination with each other or with anterior tibial shear force the amount of ACL load is greatly magnified [29-32].

Tibial External Rotation

While tibial internal rotation creates greater tensile load on the ACL [29], external rotation of the tibial has been shown in MRI based modeling studies to cause the ACL to impinge upon the lateral wall of the femoral intercondylar notch [33, 34].

Specific movement patterns commonly occurring during ACL and lower extremity injury include decreased sagittal plane joint flexion of the knee and hip in combination with increased knee valgus and leg rotation [6, 20, 22, 35]. For example, Ireland described a "position of no return" which is considered to create high risk for non-contact ACL injury. The position involves trunk forward flexion and rotation to the opposite side, hip adduction and internal rotation, knee valgus and limited flexion, and tibial external rotation [6]. Boden et al examined the mechanisms of ACL injury through surveys and videotape of the injuries. These revealed that most injury was through non-contact mechanisms during a sharp deceleration with a change in direction where the knee was close to full extension. Additionally, those injuries cause by contact were most often injured as a result of valgus stress on the knee [20]. Similarly, Olsen et al identified the most common injury mechanism for ACLs to be a plant-and-cut motion where there was forceful valgus movement, external or internal rotation, and the knee was close to full extension [22].

If trunk motion is shown to influence the movement and loading patterns associated with ACL injury than this may explain the findings of Zazulak who found trunk motion following perturbation and trunk proprioception were associated with ACL injury rates [8, 9].

Influence of Trunk Motion on Knee Biomechanics

It is not entirely clear how trunk stability and proprioception may directly impact ACL injury risk as demonstrated by Zazulak [8, 9]. However, it is possible that uncontrolled and excessive trunk motion during functional tasks can influence knee joint motion and loading patterns, as the trunk represents a large mass that must remain over the foot during functional tasks.

Sagittal Plane Trunk Motion

Devita and Skelly attempted to identify and compare ground reaction forces, joint positions and joint moments during soft and stiff landings. 8 female athletes participated in the study and were asked to perform 2 types of vertical drop tasks, one with a relatively large amount of knee flexion and one with a relatively small amount of knee flexion upon landing. The stiff landing condition resulted in a more erect body posture with less trunk, hip and knee flexion and larger ground reaction forces as compared to the soft landing condition.

The authors concluded that trunk and hip flexion are important sagittal plane movement patterns as even small amounts of trunk and hip flexion are associated with increased vertical ground reaction force [36].

Though the previous study only looked at females, other studies have repeatedly shown that females demonstrate less knee, hip, and trunk flexion in comparison to their male counterparts [37-39]. Chappell et al attempted to identify gender differences in movement patterns during a vertical stop-jump task. 17 male and 19 female recreational athletes each performed 3 successful trials of the task. EMG data was collected for the vastus lateralis, rectus femoris, vastus medialis oblique, biceps femoris, semimembranosis, and semitendinosis muscles. 3-dimensional videographic data was collected for knee flexion, varus and valgus angle, internal and external rotation, and hip flexion, internal and external rotation, abduction, and adduction. They found that there were gender differences in muscle activation and knee and hip motion. The results showed that female subjects generally displayed decrease knee flexion, hip flexion, hip abduction, and hip external rotation as compared to male subjects. Also, female subjects showed increased knee internal rotation and quadriceps activation compared to male subjects [37]. Both Malinzak et al and McLean et al found similar results using more dynamic tasks such as running, side-cutting, and cross-cutting and side-stepping, side-jumping, and shuttle-running, respectively.

Blackburn and Padua investigated trunk positioning and its influence on lower extremity kinematics [7]. 20 male and 20 female subjects were asked to perform 2 types of drop-landing tasks, the first with their natural or preferred landing and the second with instructions to flex the trunk. Trunk, knee and hip kinematic data were collected using an electromagnetic sensor system. The authors found that increased trunk flexion, as compared to a more erect posture, produced an increase in knee flexion during a drop landing task. These results suggest that trunk motions do affect knee kinematics and can, therefore, potentially affect the risk for ACL injury. Though the authors only looked at forward flexion and its effect on knee flexion angle, the relationship they found suggests that there may also be a link between lateral trunk flexion and knee valgus angle, though further research is needed in order to assert that.

Frontal Plane Trunk Motion

Lateral trunk flexion has been shown to influence knee valgus loading during functional tasks. Dempsey et al attempted to identify the effect of various sidestep cutting techniques on knee loads. 15 male subjects performed sidestep maneuvers in their normal position and 9 imposed postures: trunk rotating in the opposite direction, torso leaning in the same direction, torso leaning in the opposite direction, knee in extension, knee in flexion, foot placed close to the body, foot placed away from the body, foot turned in, and foot turned out. The results showed that the imposed postures of torso leaning in the opposite direction and foot placed away from the body caused increased knee valgus moments. The authors conclude that these postures may place individuals at higher risk of ACL injury due to the increased knee loads and subsequent strain on the ACL [40].

Similarly, Chaudhari et al investigated that influence of variations in arm position on the valgus loading of the knee. 11 subjects performed a side-step cut with their arms in 4 different positions: no upper body constraints, holding a football in the arm on the same side as the stance foot, holding a football in the arm on the opposite side from the stance foot, and holding a lacrosse stick vertically in front of the body. The results showed that knee valgus moment was significantly affected by the arm position with the lacrosse stick and the football in the arm on the same side causing the most change compared to baseline. The authors conclude that constraining the arm on the same side as the stance foot can contribute to a greater risk for non-contact ACL injury. They also hypothesize that constraining the arm may prevent it from stabilizing the torso in the frontal plane [41].

Lateral trunk flexion places the body's center of mass more lateral relative to the knee joint, hence facilitating greater external knee valgus moments. As a result, the amount of ACL loading may be greater as external knee valgus moments are increased with the knee positioned between 0-45° of flexion [42].

While lateral trunk flexion and sagittal plane trunk flexion have been shown to influence knee biomechanics it is not known if core stability influences either trunk kinematics or knee biomechanics. If core stability influences these variables than assessment of core stability during large scale clinical screenings may be important to identify individuals who are prone to display high risk lower extremity biomechanics that may increase their risk for future injury.

It is reasonable to conclude that core stability directly influences trunk motion during functional tasks since it is the core musculature that is responsible for producing as well as preventing movement of the torso. Since trunk positioning has been shown to affect knee motion, it follows logically that core stability is also, though perhaps indirectly, related to knee motion.

The Core

Akuthota et al describe the core as a "muscular box" with the abdominals, paraspinals, gluteals, the diaphragm, the pelvic floor and hip girdle musculature making up its sides [43] and working together to provide spinal stability. The core is comprised of both active and passive components; the active components of the core include the muscles and intraabdominal pressure, whereas the passive components include bone and ligaments. The core musculature can be further separated into local and global systems [44]. The local system is comprised of all the muscles that have their origin or insertion on the vertebrae with the exception of the psoas. The primary function of the local system is to control the curvature of the lumbar spine and give sagittal and lateral stiffness to maintain mechanical stability [10, 44]. Essentially, the local muscles are responsible for segmental stability. The global system is comprised of the muscles that have their origins on the pelvis and insertions on the thoracic cage, and includes the erector spinae, internal obliques, external obliques, rectus abdominis, and quadratus lumborum muscles [10, 44]. The global muscles are large torque producing muscles and their function is to provide general trunk stabilization.

In 2004, Akuthota et al reviewed the available literature on core strengthening. Though the transverse abdominis and multifidus are often singled out, all core muscles are required for optimal stabilization. These include the erector spinae, quadratus lumborum, internal oblique, external oblique, rectus abdominis, gluteus maximus, gluteus medius, psoas, diaphragm and pelvic floor muscles. In order to best strengthen these muscles, a program should combine motor control and stabilization and should move through a functional progression from activities such as sitting, standing, and walking through more athletic activities [45]. Traditional core strengthening exercises such as roman chairs, back extensor machines, and sit ups have been shown to be unsafe in that they increase the load in the spine. Exercises performed with a neutral spine have been suggested as safer but are less related to functional activities. Because athletic activity includes movement in the sagittal, frontal, and transverse planes, the core should be evaluated and trained in these planes as well. Core evaluation methods have generally not been well validated but the multidirectional reach test, star excursion balance test, and single leg squat test are among those that have been [45].

Much of the research involving core strength and stability is in relation to back pain. In 2005, Barr et al attempted to identify the key concepts behind lumbar stabilization and treatment of low back pain. The authors determined that spine stability consists of 3 components: bone and ligamentous structures, muscular strength and endurance, and neural control. These components are interdependent and instability could result from a deficiency in any one of them [46].

In 2007, Barr et al described how structural changes, muscular deficiencies, and poor or ineffective neural control can all contribute to core instability. Literature regarding low back pain has demonstrated that subjects with LBP tend to have a delayed contraction of the transverse abdominis as well as deficits in proprioception, balance, and the ability to react to unexpected perturbations as compared to subjects without LBP [47].

Core stability is necessary in order to resist perturbations as well as to provide a stable base of movement of the extremities [16]. Preparatory muscle contractions have been observed in the transverse abdominis. The transverse abdominis has been shown to be the first muscle activated in conjunction with lower extremity movement [16, 43, 46], though the amount of time significantly decreased in subjects with low back injury,

Assessment of Core Stability

Despite a lack of research investigating its effects, core stability is commonly connected with enhancing athletic performance [43, 48]. One of the primary issues with core stability is the lack of consensus on how best to evaluate it.

Tse et al attempted to develop and validate an intervention program designed to improve selected core endurance parameters [15]. The authors used 4 tests that had been previously identified by McGill as valid and reliable for showing torso muscular endurance [13]. The tests are referred to as the back extensor endurance, the flexor or abdominal endurance test, and the side bridge or lateral musculature endurance tests. The tests were shown to have reliability coefficients between 0.97 and 0.99.

Lanning et al attempted to measure trunk endurance and hip strength using different clinical methods of evaluation [49]. The purpose was to develop baseline measures for each test. The authors focused on 5 tests: the back-extensor endurance test, the 60-second tall kneeling test, the hip external rotation strength test, the double-leg lowering test, and the Star Excursion Balance Test. They found the average scores to be 53 ± 13 repetitions, 30 ± 8 repetitions, 7 ± 4 kg, 50 degrees ±10 degrees, and 94 ±9 cm, respectively.

Leetun et al did a prospective study comparing core stability measures between male and female and injured and uninjured athletes. Four tests were performed to evaluate the strength of the anterior, posterior, and lateral muscles that contribute to core stability and included the hip abduction isometric strength test, the hip external rotation isometric strength test, a modified Beiring-Sorenson back extensor test, and a side bridge test. The results showed that males produced greater hip abduction, hip external rotation, and lateral muscular measures. The results also showed that uninjured athletes had greater hip abduction and hip external rotation measures [14]. The authors conclude that core stability does play some role in injury prevention.

Liemohn et al attempted to develop a reliability measurement for 4 core stabilization tests including a kneeling arm raise, a quadruped arm raise performed parallel to the tilt axis of the stability platform, a quadruped arm raise performed perpendicular to the tilt axis of the stability platform and a bridging task. 16 subjects performed multiple trials over multiple days. The results show that performing 5 trials on each of 3 days is sufficient to achieve good reliability [50].

McGill et al attempted to establish isometric endurance holding times to use in clinical assessments of core strength. 75 subjects, both male and female, were asked to perform 4 muscular endurance tests including a modified Biering-Sorenson back extensor test, a flexor endurance test, and a side bridge test on both their right and left sides. The results showed that while females had greater back extension scores with an average of189 seconds, males had greater right and left side bridge scores with averages of 94 and 97 seconds respectively, and there was no difference in flexor endurance scores with an average of 147 seconds. The tests were performed multiple times and had a reliability of greater than 0.97 [13].

Chanthapetch et al evaluated the effectiveness abdominal muscles contractions during the abdominal hollowing maneuver in 4 different positions including crook lying, prone lying, four-point kneeling, and wall support standing. They found that all four positions produced effective transverse abdominis contractions with minimal activity from the rectus abdominis and external obliques [51].

Richardson et al discuss the also abdominal hollowing maneuver, though as a rehabilitation technique to relieve back pain. The authors focus on a co-contraction of the transverse abdominis and the multifidus in 3 different positions including four point kneeling, prone, and upright. The authors describe some different techniques in teaching the maneuver such as visualization of the muscle contraction and verbal instructions such as "draw your abdomen up and in" and "pull your navel up towards your spine" [10].

Cowley et al attempted to test the reliability of the plank to fatigue test, also referred to as the prone plank. The authors describe prone plank as an isometric exercise often used in core stability training programs which tests the ability to maintain a neutral spine. 8 subjects participated in testing over 3 days. The reliability testing resulted in an intraclass correlation coefficient of 0.85 [12].

Though the quadruped arm raise has been discussed in the literature [50], there is not much information available on the quadruped arm and leg raise. Barr et al briefly describe the maneuver in reference to a core strengthening program. The authors consider the quadruped arm and leg raise to be an intermediate exercise and it consists of moving the arm and leg simultaneously through a large range of motion [47].

For the purposes of this study, the abdominal hollowing maneuver, prone plank to fatigue test, lateral musculature endurance test, and quadruped arm leg raise were selected as assessment measures for core stability. These 4 tests were chosen for several reasons. First, the tests are easily performed in a clinical environment as they require no outside materials. They are commonly used in core strengthening programs and, therefore, may be familiar to the subject being asked to perform them, which may produce a more accurate result. Also, since no one core muscle is responsible for producing core stability, the tests attempt to evaluate different muscles in order to achieve a more complete evaluation of the core.

Summary

ACL injuries are devastating to the athletes that suffer them. In attempts to minimize the risk of such injuries, certain factors have been identified in the literature as being indicative of future ACL injury. Of these, the biomechanical factors are most easily modifiable. Core stability has not been named as a primary factor, but has been mentioned in the literature as related to this issue. More research needs to be done in order to determine the relationship between core stability and non-contact ACL injury.

CHAPTER 3

METHODOLGY

Subjects

Thirty five recreationally active males and females between the ages of 18-30 years were recruited from the general population of The University of North Carolina at Chapel Hill. Recreationally active was defined as physical activity 3 times per week for at least 30 minutes. In order to participate in this study, subjects had no history of knee surgery, were free from lower extremity injury for the past 3 months, and had no episodes of back pain for at least 3 months prior to testing. Prior to data collection, subjects read and signed an informed consent form approved by the university's institutional review board.

Instrumentation

An electromagnetic motion tracking system (Ascension Technologies, Inc., Burlington, VT) was used to measure knee kinematics at a sampling rate of 100 Hz. A non-conductive forceplate (Bertec Corp., Columbus, OH) was used to collect kinetic data at a sampling rate of 1000 Hz. The Motion Monitor software system (Innovative Sports Training, Inc., Chicago, IL) was used to record the measurements. A standard digital stop watch was used to measure time (seconds) during 3 of the 4 core stabilization tests.

Procedures

All testing was conducted in the Sports Medicine Research Laboratory at the University of North Carolina at Chapel Hill. All testing for each subject was performed during a single session lasting approximately 1 hour. Subjects were dressed in a t-shirt and shorts with their own athletic shoe. Subjects filled out a general health questionnaire. Subjects then completed a self-paced five minute warm up on a stationary bike.

Four electromagnetic tracking sensors, placed on the spinous process of C7, sacrum, lateral thigh, and shank, defined the trunk, pelvis and dominant leg. The dominant leg was defined as the leg used to kick a ball for maximal distance. Sensors were secured with double-sided tape, pre-wrap, and athletic tape in order to minimize movement during the trials. Additional landmarks were then digitized and included the spinous process of T12, medial femoral condyle, lateral femoral condyle, medial malleolus, lateral malleolus, left anterior superior iliac spine, and right anterior superior iliac spine.

Single Leg Squat Task

Subjects were given a standard set of instructions on how to perform the single leg squat. Subjects began standing on their dominant leg with the toes pointing straight ahead and hands on the hips. Subjects were instructed to squat as if they were sitting in a chair without allowing the knee to go over the toes, the heel to come off the ground, and the non-dominant leg to touch the dominant leg during the task. Subjects squatted to approximately 60 degrees of knee flexion and then returned to the start position. Subjects were allowed practice until they indicated that they were comfortable with the task and then testing began. Each subject performed 5 successful and consecutive single leg squat trials. A successful trial was defined as the subject maintaining balance and squatting at least 60 degrees of knee flexion while also keeping the heel on the ground, the hands on the hips, and not allowing the knee to go past the toes.

Core Stability Testing

Core stability was assessed via a battery of 4 clinical tests: the abdominal hollowing maneuver, the prone plank to fatigue test, the lateral musculature endurance test, and the quadruped arm leg raise. In attempts to control for an effect of fatigue, the order of the tests was randomized, determined by the subject drawing slips of paper. Subjects were given time to familiarize themselves with each test prior to data collection. Each test was performed once and subjects were allowed 2 minutes of rest in between each test.

Abdominal Hollowing Maneuver

The abdominal hollowing maneuver began with the subject in the crook-lying position; the subject lay supine with both knees flexed to 90 degrees (Figure 1). The subject was instructed to draw their belly button in and up towards their spine [10]. The maneuver was evaluated by counting the number of errors committed during the contraction. The tester palpated one side of the abdomen just medial to the anterior superior iliac spine to ensure transverse abdominis contraction. Possible errors included: 1.) the inability to maintain a neutral spine 2.) movement of the pelvis 3.) movement of the rib cage 4.) movement of the shoulders 5.) the inability to breathe normally during the contraction and 6.) the inability to hold the contraction for at least 10 seconds.

Seven subjects participated in a small reliability study that was conducted over 2 days in order to assess intratester reliability for the 4 core stability measures. The abdominal hollowing maneuver had a reliability of 0.875, describing the percent agreement from day 1 to day 2.

Prone Plank to Fatigue Test

The prone plank to fatigue test began with the subject lying prone with arms bent and positioned so that elbows were directly below shoulders and upper arms were perpendicular to the floor and with feet together (Figure 2). Time started when the subject then lifted their hips off the floor so that body weight was entirely supported by forearms and toes. The goal was to maintain a straight line from the shoulders to the ankles with the line running through the hips [11, 12]. Time to failure was measured in seconds and was defined as the point when the subject could no longer maintain the straight-back posture or hips returned to the ground. Verbal cues were given to the subject alerting them when hips began to drop from the required position. Reliability testing produced an ICC(3,1) = 0.949 and SEM = 9.907 seconds.

Lateral Musculature Endurance Test

The lateral musculature test began with the subject lying in full side-bridge position. Subject positioning consisted of legs extended, and the top foot placed in front of the lower foot for support. Subjects supported themselves on one elbow and feet while lifting their hips off the floor (Figure 3). The uninvolved arm was held with hand placed on hip. Time to failure was measured in seconds and failure occurred when the subject lost the straight-back posture or hips returned to the ground [13-15]. Verbal cues were given to the subject alerting them when hips began to drop from the required position. Reliability testing for this test produced an ICC(3, 1) = 0.764 and SEM = 11.650 seconds.

Quadruped Arm Leg Raise

The quadruped arm leg raise test began with the subject on hands and knees, with hands positioned directly below shoulders, knees directly below hips, and back straight. The subject then slowly lifted one arm and the opposite leg and raised them until they were parallel to the floor (Figure 4). The position was held for ten seconds. This was then repeated with the other arm and leg. The tester was positioned behind the subject and observed for signs of instability characterized by the line of the shoulders or hips becoming unparallel with the floor. Failure was defined as shoulder or hip rotation upon the removal of the sturdy base of support. The quadruped arm leg raise test had an intersession reliability of 0.75, describing the percent agreement between day 1 and day 2.

Data Processing and Reduction

A global coordinate system was created for use during the single leg squat. The global coordinate system was set up with the x-axis corresponding to the AP axis of the subject, the y-axis corresponding to the ML axis of the subject, and the z-axis corresponding to the longitudinal axis of the subject. The local coordinate system of the shank, thigh, pelvis, and trunk was defined based on a right-hand coordinate system: the positive x-axis corresponded with the anterior direction, the positive y-axis corresponded with the medial direction, and the positive z-axis pointed superiorly. The same coordinate system was applied for subjects who performed the single leg squat on their left leg in which the positive y-axis corresponded with the lateral direction. This factor was corrected for during data processing for frontal and transverse plane kinematics for left leg subjects to maintain continuity in the output of angle sign conventions.

Motion about the knee was defined in terms of the shank relative to the thigh. The knee joint center was located at the midpoint between the medial and lateral femoral condyles. Motion about the hip was defined in terms of the thigh relative to the sacrum. The hip joint center was estimated using the Bell method and the left and right anterior superior iliac spines. Motion of the trunk was defined as the thorax relative to the world axis system. Euler angles were used to calculate the knee and trunk angles in an order of rotations of 1.)

flexion-extension about the y-axis, 2.) varus-valgus of the knee and lateral flexion of the trunk about the x-axis, and 3.) internal-external rotation about the z-axis.

All kinematic and kinetic data were collected and processed using the Motion Monitor Software (Innovative Sports Training, Inc., Chicago, IL). A low pass 4th order Butterworth filter was applied to all kinematic data at a cutoff frequency of 10 Hz using a custom Matlab program (The Mathworks, Inc., Natick, MA). The same program was used to define the descent phase of each squat, select three trials for analyses per subject, and reduce all variables of interest. Squat trials were selected based on visualization of the data to confirm no extraneous noise and confirm that the target knee flexion angle of 60 degrees was achieved. Using standard inverse dynamics the internal knee valgus moment was calculated during the descending phase of the single leg squat [52]. We identified the peak internal knee valgus moment for each trial. The internal knee valgus moments were then normalized to body weight multiplied by height.

Statistical Analysis

Pearson correlation coefficients were calculated to define the association among trunk and knee biomechanics during a single leg squat and time to failure for the prone plank and lateral musculature endurance tests. Because they are non-parametric measures, a Spearman's rho correlation was calculated to determine if relationships existed between trunk and knee biomechanics and the abdominal hollowing maneuver and quadruped arm leg raise. Independent sample t-tests were then performed to assess for between-group differences. For the abdominal hollowing maneuver, subjects were divided into two groups: those who committed zero errors and those who committed 1 or more errors. For the quadruped arm leg raise, subjects were also divided into two groups: those who displayed rotation during the test and those who did not. Statistical analyses was set a-priori at $\alpha \leq 0.05$ and Statistical Package for the Social Sciences v. 15.0 (SPSS Inc, Chicago, IL) was used for all analyses.

CHAPTER 4

RESULTS

Thirty five subjects were tested, however only thirty one fulfilled all of the requirements of the study. Subject 1 did not meet the inclusion criteria for physical activity, subject 8 had unfixable spikes in the data, and subjects 18 and 22 were unable to perform successful single leg squat trials. Of the remaining thirty one subjects (9 males and 22 females, age = 22.1 ± 2.9 years, height = 169.7 ± 9.1 cm, weight = 68.4 ± 10.5 kg) the core stability data for subjects 32, 33, 34, and 35 were not included in the analysis. Subject demographics are presented in Table 1.

Descriptive Data

Means and standard deviations for the seven biomechanical variables as well as the four core stability tests are presented in Table 2.

Correlational Analyses

Pearson correlation coefficients and p-values for kinematic and kinetic data with both prone plank to fatigue and lateral musculature endurance test scores are presented in Table 3. There was a significant correlation between trunk flexion displacement and prone plank to fatigue scores ($r = 0.366$, $p = 0.043$) (Figure 5). The positive relationship between trunk flexion displacement and prone plank to fatigue times indicate that increased endurance times are associated with greater trunk flexion displacement; as prone plank to fatigue test scores increase, trunk flexion displacement increases. There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, peak trunk flexion angle, or peak normalized knee valgus moment and prone plank to fatigue scores ($p > 0.05$).

There was a significant correlation between trunk flexion displacement and lateral musculature endurance test scores ($r = 0.398$, $p = 0.027$) (Figure 6). As the endurance test scores increase, trunk flexion displacement increases as well. There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, peak trunk flexion angle, or peak normalized knee valgus moment and lateral musculature endurance test scores ($p > 0.05$).

Spearman's rho correlation coefficients and p-values for kinematic and kinetic data with both abdominal hollowing maneuver and quadruped arm leg raise scores are presented in Table 4. There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, trunk flexion displacement, peak trunk flexion angle, or peak normalized knee valgus moment and abdominal hollowing maneuver scores ($p > 0.05$).

There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, trunk flexion displacement, peak trunk flexion angle, or peak normalized knee valgus moment and quadruped arm leg raise scores ($p > 0.05$).

Group Comparisons

Eight subjects committed 1 or more errors on the abdominal hollowing maneuver; nineteen subjects committed zero errors. There were no statistically significant differences between those subjects who committed errors on the abdominal hollowing maneuver and those who did not for any of the biomechanical variables. Means, standard deviations, confidence intervals, t-values and p-values are presented in Table 5.

Nineteen subjects displayed rotation and therefore failed the quadruped arm leg raise; eight subjects did not display any rotation and therefore passed the quadruped arm leg raise. There were no statistically significant differences between those subjects who passed the quadruped arm leg raise and those who did not on any of the biomechanical variables. Means, standard deviations, confidence intervals, t-values and p-values are presented in Table 6.

CHAPTER 5

DISCUSSION

Correlational Findings

The aim of this study was to determine the association between core stability and trunk and knee biomechanics. The most important finding was the observed correlation between trunk flexion displacement and two of the clinical measures of core stability. There was a significant positive relationship between trunk flexion displacement and the prone plank to fatigue test as well as the lateral musculature endurance test; as trunk flexion displacement increased, core stability (measured in seconds) increased as well.

Although these findings are contrary to our original hypothesis, they may be in line with previous research that describes a position of increased trunk flexion creating beneficial contributions at the knee [7, 37-39]. Farrokhi et al found that increased trunk flexion during performance of a lunge increased hip extensor muscle involvement [53]. The increase in trunk flexion may not be the result of an unstable core but rather a compensatory mechanism utilized to promote optimal kinematic motion at the knee. Our findings suggest that improved core stability may results in greater control of the trunk which would allow for a greater amount of trunk flexion to occur.

Trunk flexion is an essential component in creating optimal movement patterns when considering knee injuries. Ireland et al described a “position of no return” in which limited knee flexion contributed to the dangerous posture that often resulted in non-contact ACL injuries [6]. Previous research has investigated the association between trunk flexion and lower extremity motion in an effort to prevent these types of injuries. Blackburn and Padua found that increased trunk flexion, compared to a more erect posture, produced an increase in hip and knee flexion during a drop landing task [7]. Additionally, they found that a less erect landing posture reduced landing forces and quadriceps activity [54]. These results suggest that trunk motion is associated with knee kinematics, specifically that increased trunk flexion is related to increased knee flexion. This supports that trunk flexion is, therefore, a good compensation for ACL injury risk.

There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, peak trunk flexion angle, or peak normalized knee valgus moment and core stability. These findings were contrary to our original hypotheses and were not supported by any current literature concerning this topic.

The core stability tests were chosen in part because they focused on different aspects of the core musculature, that when combined, provided a fairly good representation of the whole. The abdominal hollowing maneuver was included in this study because it targets the transverse abdominis. Previous research has shown that the transverse abdominis is involuntarily contracted in preparation for lower extremity motion [16, 43, 46]. It was hypothesized that greater control of the transverse abdominis would result in fewer errors committed on the abdominal hollowing maneuver and would translate to greater control and less overall trunk motion. Increased trunk control would in turn cause less motion to occur at the knee. Our data suggest that voluntary control of the transverse abdominis may have little to do with the muscle's ability to involuntarily contract and stabilize the trunk during activity.

During data collection, the results of the abdominal hollowing maneuver were observed to be less an assessment of core stability than a statement about whether or not the subject had previously been exposed to the maneuver. The most common error was being unable to breathe normally while maintaining the contraction. Those subjects who were familiar with abdominal hollowing performed the maneuver without any difficulty while those who were inexperienced were unable to do so. Even though all subjects were given sufficient time to practice, previous knowledge of the abdominal hollowing maneuver had an overwhelming effect on the outcome and is a possible explanation for the lack of correlation found between this test and any of the kinematic measures.

Additionally, the method of quantifying transverse abdominis contraction may not have been valid. For the purposes of this study, transverse abdominis contraction was verified by palpating slightly medial to the anterior superior iliac spine. Though this method is commonly used in clinical settings, it may not be valid when compared to ultrasound measures. Without visual confirmation, it is possible that the tester was palpating the contraction of other muscles, such as the internal or external obliques, instead of the transverse abdominis. Subjects may have inadvertently been scored as having successfully performed the abdominal hollowing maneuver without actually producing a transverse abdominis contraction.

The prone plank to fatigue test and the quadruped arm leg raise both target multiple muscles including the rectus abdominis, internal and external obliques, erector spinae, and the gluteal muscles [55-57]. The ability to maintain the plank position for longer period of time and the ability to perform the quadruped maneuver without rotation were thought to indicate greater core stability. It was therefore hypothesized that a higher score on the prone plank to fatigue test or the ability to pass the quadruped arm leg raise would correspond with a greater ability to maintain trunk stability exemplified by less trunk motion in general which would then translate to less knee motion. However, this was not supported by the data.

Potential problems were observed during data collection for the quadruped arm leg raise. It was noted that the majority of the subjects failed this test, meaning that rotation at the shoulders or the hips (or both) was observed during the movement. Though this test proved to be reliable and the results repeatable, a simple assignment of pass or fail may not have been the best way to assess this measure of core stability. This grading system allowed no room for degrees of instability, only a dichotomous outcome. It might have been more beneficial to assign a scale such as no rotation, mild, moderate, or severe rotation based on the number of degrees rotated or the number of times rotation occurred during the 10 second assessment period. The lack of information regarding how to accurately assess this test may be one reason why no correlations were found between this measure of core stability and any of the kinematic variables.

The lateral musculature endurance test targets mainly the quadratus lumborum but also involves the internal and external obliques [55]. It was thought that a greater ability to maintain this side plank position would indicate stronger lateral core muscles, so it was hypothesized that a higher score on this test would translate into less lateral trunk flexion motion and, because lateral trunk flexion is believed to be an indicator of knee valgus motion [40, 41], less knee valgus motion.

Limitations

One limitation of this study was the sample population. A majority of the subjects were female, 71 percent compared to 29 percent male. It has been shown that females have significantly different movement patterns compared to their male counterparts [23, 38, 58]. It is possible that the sample was too much alike and consequently did not create enough spread in the data. An increase in the number of male subjects could have resulted in greater sample diversity and therefore more observed differences. Similarly, all of the subjects tested were healthy. Introducing an injured population into the study would have provided more variety and, again, the possibility for greater differences to be detected.

Another limitation of this study was the single leg squat task the subjects performed in order to provide the kinematic data. The single leg squat is less physically demanding and, therefore, may not have accurately represented the motions created during more dynamic activities. Previous studies have used drop landing, running, cutting, and sidestepping tasks in order to better simulate the actual movements occurring in a sport setting [7, 37-41, 59]. Overall, there was little motion occurring at the trunk and knee during the single leg squat task. It is possible that because the single leg squat is slower and more controlled that the resulting trunk and knee kinematics and kinetics were not as extreme as they might have been if using a different task.

Future Research Considerations

Future research should focus foremost on developing accurate ways to evaluate core stability. Though several authors have attempted to do just that [13, 15, 49], their methods and results are not universally agreed upon. The benefits of such evaluation tools would be evident in literature concerning low back pain, which is where most core research is currently focused, any forthcoming studies regarding non-contact knee injuries, as well as being an invaluable asset in clinical practice.

It is of interest to determine the role of the core in preventing non-contact ACL injuries because core strength and stability can be modified through the use of a training program. It is logical to believe that gross movements of the trunk would impact motions at the knee as they are connected along the kinematic chain. Future research should investigate the same relationship questions in this study using more established core stability tests and a more dynamic task in order to further evaluate the association between core stability and trunk and knee kinematics.

Conclusions

This study attempted to identify relationships between trunk and knee biomechanics and clinical measures of core stability. Based on the results, we can only conclude that trunk flexion displacement is positively related to core stability. The clinical relevance of this study is limited due to few significant findings; more research needs to be done in order to propose a direct relationship between core stability and non-contact ACL injury prevention.

Table 1: Subject demographics

	Mean ± SD	Minimum Value	Maximum Value
Age (years)	22.1 ± 2.9	18	30
Height (cm)	169.7 ± 9.1	152	194.6
Weight (kg)	68.4 ± 10.5	46.8	95.2

Table 2: Descriptive statistics for kinematic and kinetic data and core stability tests

Variable	Mean	SD	Minimum Value	Maximum Value
Knee Valgus Displacement	-2.562	± 2.43	-8.18	0.00
Peak Knee Valgus Angle	-2.431	± 3.71	-10.46	4.47
Lateral Trunk Flexion Displacement	3.507	± 2.34	0.56	9.30
Peak Lateral Trunk Flexion Angle	3.342	± 5.28	-9.54	15.62
Trunk Flexion Displacement	11.832	± 6.25	0.63	26.37
Peak Trunk Flexion Angle	109.439	± 11.67	-90.69	136.67
Peak Normalized Knee Valgus Moment	-0.003	± 0.00	-0.01	0.00
Abdominal Hollowing Maneuver	0.482	± 0.85	0.00	3.00
Prone Plank to Fatigue Test	105.571	± 44.62	27.44	216.47
Lateral Musculature Endurance Test	71.727	± 27.247	15.53	150.54
Quadruped Arm Leg Raise	-	-	-	-

Table 3: Pearson correlation coefficients and p-values for kinematic data with prone plank to fatigue test and lateral musculature endurance test scores

	Prone Plank to Fatigue Test		Lateral Musculature Endurance Test	
	Pearson r value	p value	Pearson r value	p value
Knee Valgus Displacement	-0.092	0.621	-0.083	0.659
Peak Knee Valgus Angle	0.056	0.763	0.163	0.380
Lateral Trunk Flexion Displacement	-0.192	0.302	-0.253	0.170
Peak Lateral Trunk Flexion Angle	-0.114	0.540	-0.185	0.318
Trunk Flexion Displacement	0.366	0.043	0.398	0.027
Peak Trunk Flexion Angle	0.248	0.179	0.327	0.073
Peak Normalized Knee Valgus Moment	-0.059	0.753	-0.092	0.624

Table 4: Spearman's rho correlation coefficients and p-values for kinematic data with abdominal hollowing maneuver and quadruped arm leg raise scores

	Abdominal Hollowing Maneuver		Quadruped Arm Leg Raise	
	Spearman's rho value	p value	Spearman's rho value	p value
Knee Valgus Displacement	0.277	0.163	0.047	0.816
Peak Knee Valgus Angle	0.315	0.110	0.052	0.796
Lateral Trunk Flexion Displacement	-0.004	0.984	0.135	0.501
Peak Lateral Trunk Flexion Angle	0.031	0.878	0.281	0.155
Trunk Flexion Displacement	-0.162	0.419	-0.073	0.718
Peak Trunk Flexion Angle	0.026	0.897	0.125	0.535
Peak Normalized Knee Valgus Moment	-0.141	0.484	0.312	0.113

Table 5: Means, standard deviations, t-values, p-values, and confidence intervals for independent samples t-test between abdominal hollowing maneuver groups

Variable	Group	Mean	SD	t value	p value	95% Confidence Intervals	
Knee Valgus Displacement	0 errors	-3.116	± 2.662	1.687	0.104	-0.381	3.827
	1 or more errors	-1.393	± 1.664				
Peak Knee Valgus Angle	0 errors	-3.263	± 3.889	1.082	0.289	-1.537	4.943
	1 or more errors	-1.560	± 3.297				
Lateral Trunk Flexion Displacement	0 errors	3.346	± 2.113	0.067	0.947	-2.033	2.169
	1 or more errors	3.414	± 3.073				
Peak Lateral Trunk Flexion Angle	0 errors	3.098	± 5.534	-0.042	0.967	-4.849	4.655
	1 or more errors	3.001	± 5.317				
Trunk Flexion Displacement	0 errors	11.676	± 6.281	-0.513	0.612	-6.473	3.890
	1 or more errors	10.385	± 5.083				
Peak Trunk Flexion Angle	0 errors	109.297	± 11.803	0.187	0.853	-9.151	10.983
	1 or more errors	110.213	± 11.053				
Peak Normalized Knee Valgus Moment	0 errors	-0.003	± 0.001	-0.001	0.999	-0.001	0.001
	1 or more errors	-0.003	± 0.000				

Table 6: Means, standard deviations, confidence intervals, t-values, and p-values for independent samples t-test between quadruped arm leg raise groups

Variable	Group	Mean	SD	t value	p value	95% Confidence Intervals	
Knee Valgus Displacement	Rotation	-2.320	± 2.136	-0.909	0.372	-3.149	1.221
	No Rotation	-3.283	± 3.301				
Peak Knee Valgus Angle	Rotation	-2.740	± 3.831	-0.039	0.969	-3.378	3.252
	No Rotation	-2.802	± 3.789				
Lateral Trunk Flexion Displacement	Rotation	3.553	± 2.626	-0.624	0.538	-2.717	1.453
	No Rotation	2.921	± 1.696				
Peak Lateral Trunk Flexion Angle	Rotation	3.950	± 5.860	-1.333	0.194	-7.564	1.619
	No Rotation	0.978	± 3.412				
Trunk Flexion Displacement	Rotation	10.958	± 6.059	0.450	0.657	-4.055	6.321
	No Rotation	12.091	± 5.761				
Peak Trunk Flexion Angle	Rotation	109.985	± 9.709	-0.288	0.776	-11.463	8.651
	No Rotation	108.579	± 15.396				
Peak Normalized Knee Valgus Moment	Rotation	-0.003	± 0.001	-0.481	0.635	-0.001	0.001
	No Rotation	-0.003	± 0.001				

Figure 1: Abdominal Hollowing Maneuver (in crook-lying position)

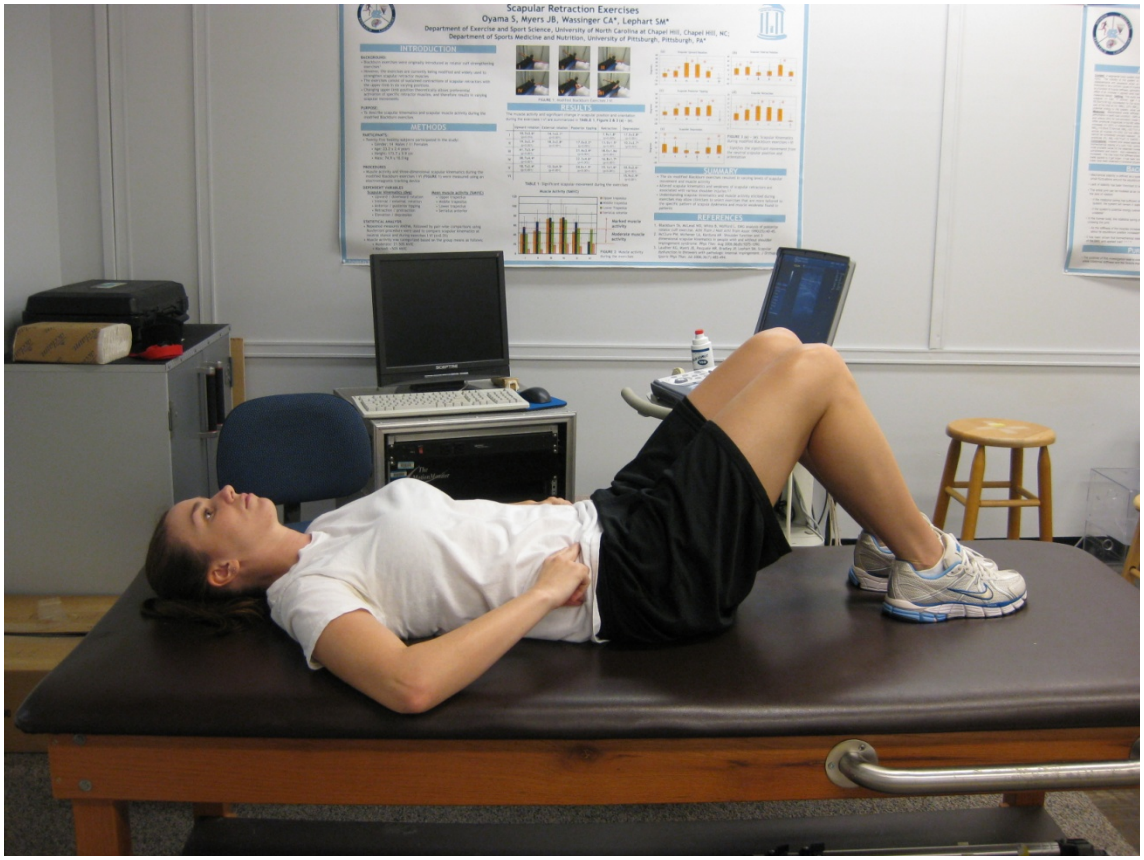


Figure 2: Prone Plank to Fatigue Test

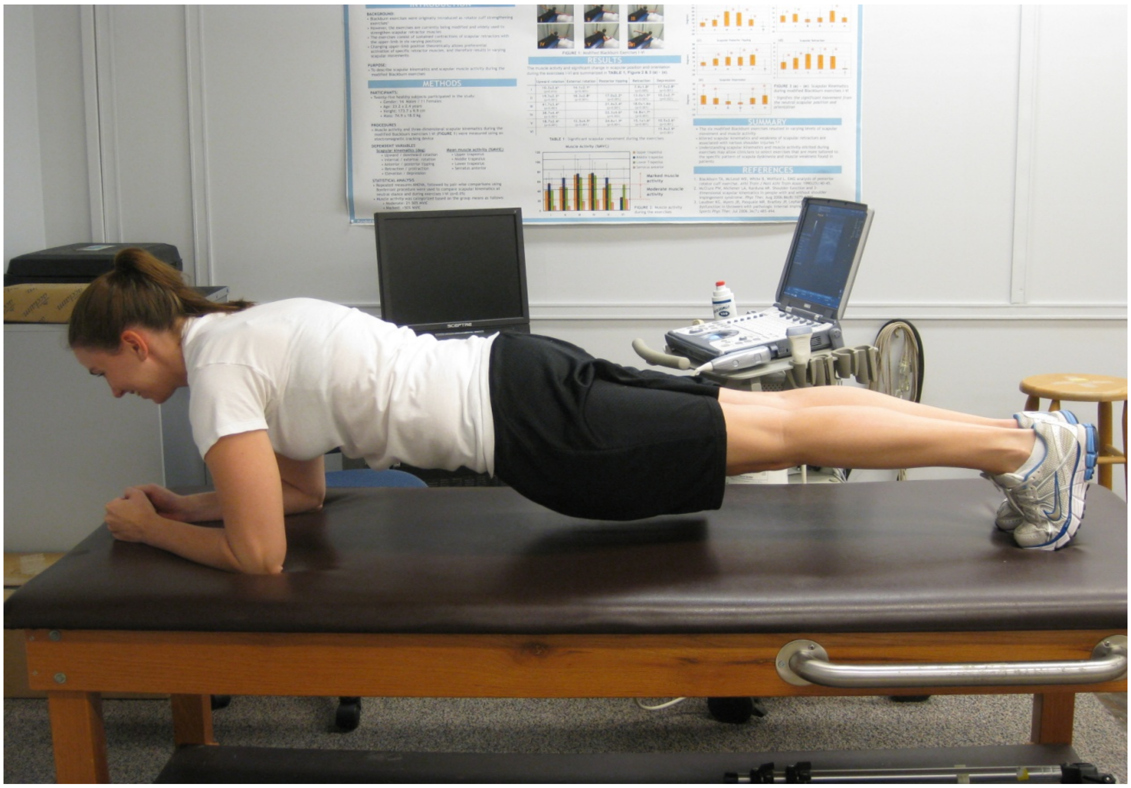


Figure 3: Lateral Musculature Endurance Test

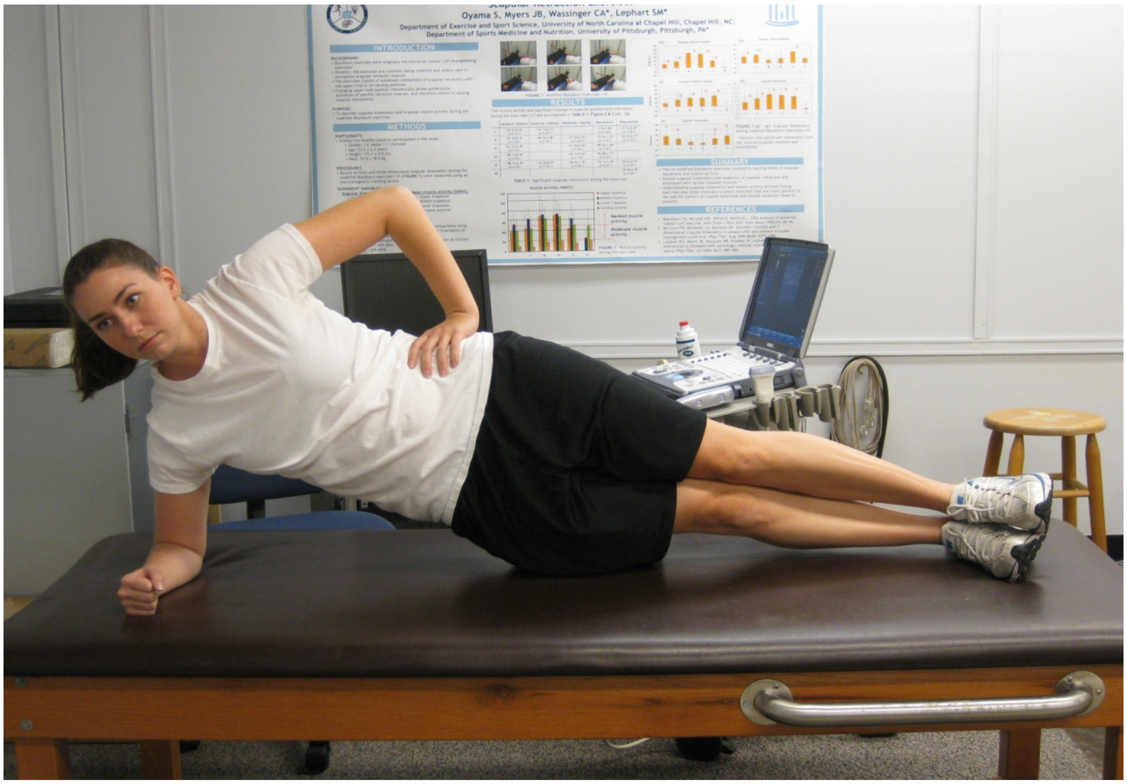


Figure 4: Quadruped Arm Leg Raise

Figure 5: Correlational graph for trunk flexion ROM and prone plank to fatigue scores

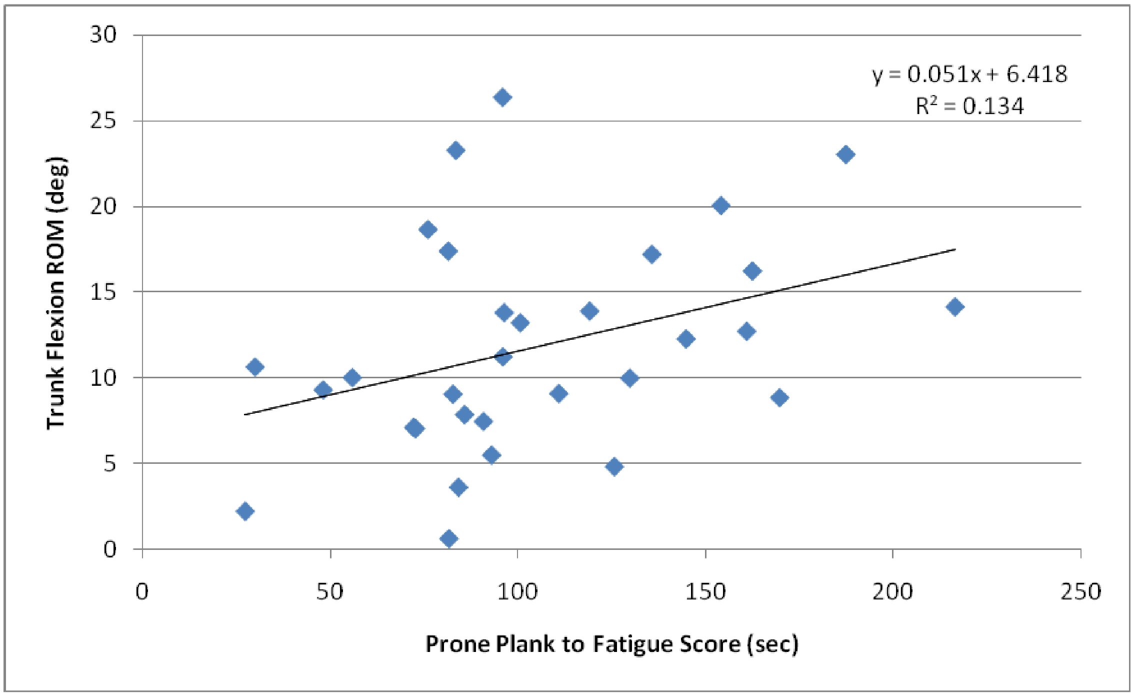
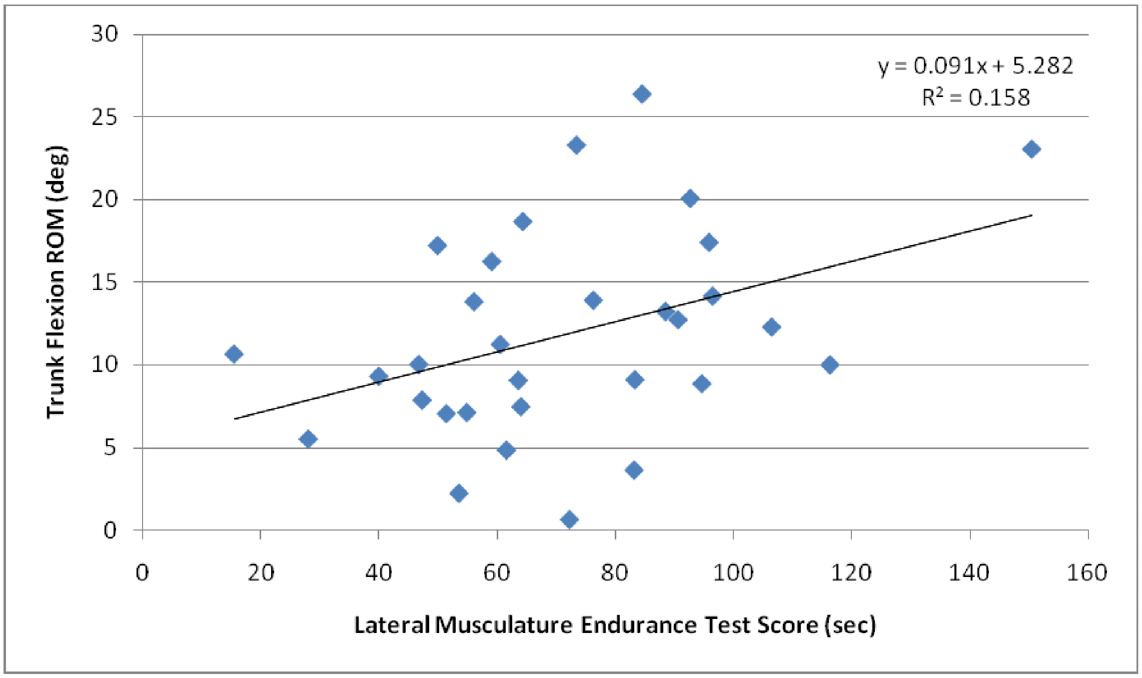


Figure 6: Correlational graph for trunk flexion ROM and lateral musculature endurance test scores



APPENDIX A

MANUSCRIPT

The Association Between Measures of Core Stability and Biomechanics of the Trunk and Knee During a Single Leg Squat

It has been estimated that there are over 100,000 anterior cruciate ligament (ACL) injuries in the United States annually [1, 2]. Treatment usually necessitates surgical intervention, painful rehabilitation, and considerable time lost from sports. The cost of treating these injuries adds up to almost one billion dollars per year [3]. Of all ACL injuries, 70% occur in non-contact situation [3]. There is immense interest in discovering ways to reduce the number of non-contact ACL tears since many of the risk factors associated with this injury are believed to be modifiable.

Several risk factors for non-contact ACL injuries have been identified and divided into 4 categories: environmental, hormonal, anatomical, and biomechanical [3, 4]. Environmental factors include any equipment, such as knee braces, as well as the type of shoes worn by the athlete. Hormonal factors refer to the theorized changes that take place in the mechanical properties of ligaments based on the levels of estrogen and progesterone present throughout the different phases of the female menstrual cycle [5]. Anatomical factors include an increased Q angle, the size and shape of the femoral notch, excessive tibial rotation, and excessive pronation [4]. Biomechanical factors include muscle activation patterns and alterations in joint angles. The biomechanical risk factors are commonly focused on in research because they are the most easily modifiable.

Certain kinematic patterns have been proposed to predispose athletes to ACL injury. Ireland et al described a "position of no return" in regards to understanding the biomechanics behind the mechanism for non-contact ACL injury [6]. This position consists of trunk forward flexion and rotation to the opposite side, hip adduction and internal rotation, decreased knee flexion, knee valgus, external tibial rotation, and foot pronation. She suggested that neuromuscular training of muscles proximal to the knee may prevent athletes from adopting this dangerous posture during athletic activity.

Trunk positioning has been shown to have an influence on lower extremity kinematics which may play a role in ACL injury risk [7]. Blackburn and Padua found that increased trunk flexion, as compared to a more erect posture, produced an increase in knee flexion during a drop landing task. These results suggest that trunk motions do affect knee kinematics and can, therefore, potentially affect the risk for ACL injury.

The trunk is a very large body of mass that has to be controlled and manipulated during athletic activity. Any lack of control may increase the moment requirements and kinematic demands of the lower extremity musculature; these changes may insult the system, thereby causing injury. Core stability is, therefore, believed to be an important aspect to athletic performance and injury risk.

Research has identified the ability to control trunk motion following perturbation and trunk proprioception as factors that may predispose individuals to non-contact ACL injury [8, 9]. Zazulak et al demonstrated that athletes who sustained a knee ligament injury had greater trunk displacement following an unexpected perturbation compared to those who did not experience an injury [8]. Trunk displacement was assessed using a customized perturbation device that measured trunk displacement after the release of a sustained force. Subjects were then tracked for injuries over a 3 year period. Of the 277 subjects initially tested, 25 sustained knee injuries. They were able to determine that trunk displacement was greater in ACL injured athletes compared to uninjured athletes, and that lateral displacement was the strongest predictor of knee ligament injury. Based on these results, they concluded that core stability was an important factor related to the risk of knee injuries. Unfortunately the method of assessing core stability in this study is not applicable in the clinical setting. Thus, it is not known if clinical measures of core stability may provide insight into risk of injury. A significant amount of research has been devoted to identifying factors that predispose individuals to non-contact knee injuries. However, little research has focused on how core stability may be related to the risk of injury. It is possible that decreased core stability may allow for excessive and uncontrolled trunk motions, which may in turn impact knee position and loading. Specifically, the inability to control lateral trunk flexion and rotation may facilitate increased knee valgus alignment and loading and poor sagittal plane trunk control can influence knee flexion angle and moments. It seems reasonable that core stability may influence the risk of injury due to core stability's influence on knee joint position and loading; however, research has not investigated the relationship between core stability and knee joint position and loading.

The purpose of this study was to determine the relationship between clinical measures of core stability and trunk and knee kinematics during a single leg squat. Specifically, we investigated whether or not there was an association between the number of errors committed during an abdominal hollowing maneuver, the time to failure during a prone plank to fatigue test, the time to failure during a lateral musculature endurance test, or the pass or failure of a quadruped arm leg raise and knee valgus diisplacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion, trunk flexion displacement, peak trunk flexion angle, or peak normalized knee valgus moment during the descent phase of a single leg squat.

METHODS

Subjects

Thirty five recreationally active males and females between the ages of 18-30 years participated in this study. Recreationally active was defined as physical activity 3 times per week for at least 30 minutes. Exclusion criteria included any known history of knee surgery, lower extremity injury or episodes of back pain for at least 3 months prior to testing. Prior to the start of data collection, subjects read and signed an informed consent form approved by the Institutional Review Board of the School of Medicine at the University of North Carolina at Chapel Hill.

Instrumentation

An electromagnetic motion tracking system (Ascension Technologies, Inc., Burlington, VT) was used to measure knee kinematics at a sampling rate of 100 Hz. A non-conductive forceplate (Bertec Corp., Columbus, OH) was used to collect kinetic data at a sampling rate of 1000 Hz. The Motion Monitor software system (Innovative Sports Training, Inc., Chicago, IL) was used to record the measurements. A standard digital stop watch was used to measure time (seconds) during 3 of the 4 core stabilization tests.

Procedures

All testing was conducted in the Sports Medicine Research Laboratory at the University of North Carolina at Chapel Hill. All testing for each subject was performed during a single session lasting approximately 1 hour. Subjects were dressed in a t-shirt and shorts with their own athletic shoe. Subjects filled out a general health questionnaire. Subjects then completed a self-paced five minute warm up on a stationary bike.

Four electromagnetic tracking sensors, placed on the spinous process of C7, sacrum, lateral thigh, and shank, defined the trunk, pelvis and dominant leg. The dominant leg was defined as the leg used to kick a ball for maximal distance. Sensors were secured with double-sided tape, pre-wrap, and athletic tape in order to minimize movement during the trials. Additional landmarks were then digitized and included the spinous process of T12, medial femoral condyle, lateral femoral condyle, medial malleolus, lateral malleolus, left anterior superior iliac spine, and right anterior superior iliac spine.

Single Leg Squat Task

Subjects were given a standard set of instructions on how to perform the single leg squat. Subjects began standing on their dominant leg with the toes pointing straight ahead and hands on the hips. Subjects were instructed to squat as if they were sitting in a chair. Additional instructions included not allowing the knee to go over the toes, not allowing the heel to come off the ground, and not allowing the non-dominant leg to touch the dominant leg during the task. Subjects squatted to approximately 60 degrees of knee flexion and then returned to the start position. Subjects were allowed practice until they indicated that they were comfortable with the task and then testing began. Each subject performed 5 successful and consecutive single leg squat trials. A successful trial was defined as the subject maintaining balance and squatting at least 60 degrees of knee flexion while also keeping the heel on the ground, the hands on the hips, and not allowing the knee to go past the toes.

Core Stability Testing

Core stability was assessed via a battery of 4 clinical tests: the abdominal hollowing maneuver, the prone plank to fatigue test, the lateral musculature endurance test, and the quadruped arm leg raise. In attempts to control for an effect of fatigue, the order of the tests was randomized, determined by the subject drawing slips of paper. Subjects were given time to familiarize themselves with each test prior to data collection. Each test was performed once and subjects were allowed 2 minutes of rest in between each test.

Abdominal Hollowing Maneuver

The abdominal hollowing maneuver began with the subject in the crook-lying position; the subject lay supine with both knees flexed to 90 degrees (Figure 1). The subject was instructed to draw their belly button in and up towards their spine [10]. Failure was measured in the number of errors committed during the contraction. The tester palpated one side of the abdomen just medial to the anterior superior iliac spine to ensure transverse abdominis contraction. Possible errors included: 1.) the inability to maintain a neutral spine 2.) movement of the pelvis 3.) movement of the rib cage 4.) movement of the shoulders 5.) the inability to breathe normally during the contraction and 6.) the inability to hold the contraction for at least 10 seconds.

Prone Plank to Fatigue Test

The prone plank to fatigue test began with the subject lying prone with arms bent and positioned so that elbows were directly below shoulders and upper arms were perpendicular to the floor and with feet together (Figure 2). Time started when the subject then lifted their hips off the floor so that body weight was entirely supported by forearms and toes. The goal was to maintain a straight line from the shoulders to the ankles with the line running through the hips [11, 12]. Time to failure was measured in seconds and was defined as the point when the subject could no longer maintain the straight-back posture or hips returned to the ground. Verbal cues were given to the subject alerting them when hips began to drop from the required position.

Lateral Musculature Endurance Test

The lateral musculature test began with the subject lying in full side-bridge position. Subject positioning consisted of legs extended, and the top foot placed in front of the lower foot for support. Subjects supported themselves on one elbow and feet while lifting their hips off the floor (Figure 3). The uninvolved arm was held with hand placed on hip. Time to failure was measured in seconds and failure occurred when the subject lost the straight-back posture or hips returned to the ground [13-15]. Verbal cues were given to the subject alerting them when hips began to drop from the required position.

Quadruped Arm Leg Raise

The quadruped arm leg raise test began with the subject on hands and knees, with hands positioned directly below shoulders, knees directly below hips, and back straight. The subject then slowly lifted one arm and the opposite leg and raised them until they were parallel to the floor (Figure 4). The position was held for ten seconds. This was then repeated with the other arm and leg. The tester was positioned behind the subject and observed for signs of instability characterized by the line of the shoulders or hips becoming unparallel with the floor. Failure was defined as shoulder or hip rotation upon the removal of the sturdy base of support.

Data Processing and Reduction

A global coordinate system was created for use during the single leg squat. The global coordinate system was set up with the x-axis corresponding to the AP axis of the subject, the y-axis corresponding to the ML axis of the subject, and the z-axis corresponding to the longitudinal axis of the subject. The local coordinate system of the shank, thigh, pelvis, and trunk was defined based on a right-hand coordinate system: the positive x-axis corresponded with the anterior direction, the positive y-axis corresponded with the medial direction, and the positive z-axis pointed superiorly. The same coordinate system was applied for subjects who performed the single leg squat on their left leg in which the positive y-axis corresponded with the lateral direction. This factor was corrected for during data processing for frontal and transverse plane kinematics for left leg subjects to maintain continuity in the output of angle sign conventions.

Motion about the knee was defined in terms of the shank relative to the thigh. The knee joint center was located at the midpoint between the medial and lateral femoral condyles. Motion about the hip was defined in terms of the thigh relative to the sacrum. The hip joint center was estimated using the Bell method and the left and right anterior superior iliac spines. Motion of the trunk was defined as the thorax relative to the world axis system. Euler angles were used to calculate the knee and trunk angles in an order of rotations of 1.) flexion-extension about the y-axis, 2.) varus-valgus of the knee and lateral flexion of the trunk about the x-axis, and 3.) internal-external rotation about the z-axis. All kinematic and kinetic data was collected and processed using the Motion Monitor Software (Innovative Sports Training, Inc., Chicago, IL). A low pass 4th order Butterworth filter was applied to all kinematic data at a cutoff frequency of 10 Hz using a custom Matlab program (The Mathworks, Inc., Natick, MA). The same program was used to define the descent phase of each squat, select three trials for analyses per subject, and reduce all variables of interest. Squat trials were selected based on visualization of the data to confirm no extraneous noise and confirm that the target knee flexion angle of 60 degrees was achieved.

Statistical Analysis

Pearson correlation coefficients were calculated to define the association among trunk and knee biomechanics during a single leg squat and time to failure for the prone plank and lateral musculature endurance tests. Because they are non-parametric measures, a Spearman's rho correlation was calculated to determine if relationships existed between trunk and knee biomechanics and the abdominal hollowing maneuver and quadruped arm leg raise. Independent sample t-tests were then performed to assess the between-group differences for subjects committing errors on the abdominal hollowing maneuver and those that did not, as well as subjects that passed the quadruped arm leg raise and those that failed it. Statistical analyses was set a-priori at $\alpha \leq 0.05$ and Statistical Package for the Social Sciences v. 15.0 (SPSS Inc, Chicago, IL) was used for all analyses.

RESULTS

Thirty five subjects were tested, however only thirty one fulfilled all of the requirements of the study. Of the remaining thirty one subjects (9 males and 22 females, age = 22.1 ± 2.9 years, height = 169.7 ± 9.1 cm, weight = 68.4 ± 10.5 kg) the core stability data for subjects 32, 33, 34, and 35 were not included in the analysis. Subject demographics are presented in Table 1.

Descriptive Data

Means and standard deviations for the seven biomechanical variables as well as the four core stability tests are presented in Table 2.

Correlational Analyses

Pearson correlation coefficients and p-values for kinematic and kinetic data with both prone plank to fatigue and lateral musculature endurance test scores are presented in Table 3. There was a significant correlation between trunk flexion displacement and prone plank to fatigue scores ($r = 0.366$, $p = 0.043$) (Figure 5). The positive relationship between trunk flexion displacement and prone plank to fatigue times indicate that increased endurance times are associated with greater trunk flexion displacement; as prone plank to fatigue test scores increase, trunk flexion displacement increases. There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, peak trunk flexion angle, or peak normalized knee valgus moment and prone plank to fatigue scores ($p > 0.05$).

There was a significant correlation between trunk flexion displacement and lateral musculature endurance test scores ($r = 0.398$, $p = 0.027$) (Figure 6). As the endurance test scores increase, trunk flexion displacement increases as well. There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, peak trunk flexion angle, or peak normalized knee valgus moment and lateral musculature endurance test scores ($p > 0.05$).

Spearman's rho correlation coefficients and p-values for kinematic and kinetic data with both abdominal hollowing maneuver and quadruped arm leg raise scores are presented in Table 4. There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, trunk flexion displacement, peak trunk flexion angle, or peak normalized knee valgus moment and abdominal hollowing maneuver scores ($p > 0.05$).

There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, trunk flexion displacement, peak trunk flexion angle, or peak normalized knee valgus moment and quadruped arm leg raise scores ($p > 0.05$).

Group Comparisons

Eight subjects committed 1 or more errors on the abdominal hollowing maneuver; nineteen subjects committed zero errors. There were no statistically significant differences between those subjects who committed errors on the abdominal hollowing maneuver and those who did not for any of the biomechanical variables. Means, standard deviations, confidence intervals, t-values and p-values are presented in Table 5.

Nineteen subjects displayed rotation and therefore failed the quadruped arm leg raise; eight subjects did not display any rotation and therefore passed the quadruped arm leg raise. There were no statistically significant differences between those subjects who passed the quadruped arm leg raise and those who did not on any of the biomechanical variables. Means, standard deviations, confidence intervals, t-values and p-values are presented in Table 6.

DISCUSSION

Correlational Findings

The aim of this study was to determine the association between core stability and trunk and knee biomechanics. The most important finding was the observed correlation between trunk flexion displacement and two of the clinical measures of core stability. There was a significant positive relationship between trunk flexion displacement and the prone plank to fatigue test as well as the lateral musculature endurance test; as trunk flexion displacement increased, core stability (measured in seconds) increased as well.

Although these findings are contrary to our original hypothesis, they may be in line with previous research that describes a position of increased trunk flexion creating beneficial contributions at the knee [7, 37-39]. Farrokhi et al found that increased trunk flexion during performance of a lunge increased hip extensor muscle involvement [53]. The increase in trunk flexion may not be the result of an unstable core but rather a compensatory mechanism utilized to promote optimal kinematic motion at the knee. Our findings suggest that improved core stability may results in greater control of the trunk which would allow for a greater amount of trunk flexion to occur.

Trunk flexion is an essential component in creating optimal movement patterns when considering knee injuries. Ireland et al described a "position of no return" in which limited knee flexion contributed to the dangerous posture that often resulted in non-contact ACL injuries [6]. Previous research has investigated the association between trunk flexion and lower extremity motion in an effort to prevent these types of injuries. Blackburn and Padua found that increased trunk flexion, compared to a more erect posture, produced an increase in hip and knee flexion during a drop landing task [7]. Additionally, they found that a less erect landing posture reduced landing forces and quadriceps activity [54]. These results suggest that trunk motion is associated with knee kinematics, specifically that increased trunk flexion is related to increased knee flexion. This supports that trunk flexion is, therefore, a good compensation for ACL injury risk.

There were no significant correlations found between knee valgus displacement, peak knee valgus angle, lateral trunk flexion displacement, peak lateral trunk flexion angle, peak trunk flexion angle, or peak normalized knee valgus moment and core stability. These findings were contrary to our original hypotheses and were not supported by any current literature concerning this topic.

The core stability tests were chosen in part because they focused on different aspects of the core musculature, that when combined, provided a fairly good representation of the whole. The abdominal hollowing maneuver was included in this study because it targets the transverse abdominis. Previous research has shown that the transverse abdominis is involuntarily contracted in preparation for lower extremity motion [16, 43, 46]. It was hypothesized that greater control of the transverse abdominis would result in fewer errors committed on the abdominal hollowing maneuver and would translate to greater control and less overall trunk motion. Increased trunk control would in turn cause less motion to occur at the knee. Our data suggest that voluntary control of the transverse abdominis may have little to do with the muscle's ability to involuntarily contract and stabilize the trunk during activity.

During data collection, the results of the abdominal hollowing maneuver were observed to be less an assessment of core stability than a statement about whether or not the subject had previously been exposed to the maneuver. The most common error was being unable to breathe normally while maintaining the contraction. Those subjects who were familiar with abdominal hollowing performed the maneuver without any difficulty while those who were inexperienced were unable to do so. Even though all subjects were given sufficient time to practice, previous knowledge of the abdominal hollowing maneuver had an overwhelming effect on the outcome and is a possible explanation for the lack of correlation found between this test and any of the kinematic measures.

Additionally, the method of quantifying transverse abdominis contraction may not have been valid. For the purposes of this study, transverse abdominis contraction was verified by palpating slightly medial to the anterior superior iliac spine. Though this method is commonly used in clinical settings, it may not be valid when compared to ultrasound measures. Without visual confirmation, it is possible that the tester was palpating the contraction of other muscles, such as the internal or external obliques, instead of the transverse abdominis. Subjects may have inadvertently been scored as having successfully performed the abdominal hollowing maneuver without actually producing a transverse abdominis contraction.

The prone plank to fatigue test and the quadruped arm leg raise both target multiple muscles including the rectus abdominis, internal and external obliques, erector spinae, and the gluteal muscles [55-57]. The ability to maintain the plank position for longer period of time and the ability to perform the quadruped maneuver without rotation were thought to indicate greater core stability. It was therefore hypothesized that a higher score on the prone plank to fatigue test or the ability to pass the quadruped arm leg raise would correspond with a greater ability to maintain trunk stability exemplified by less trunk motion in general which would then translate to less knee motion. However, this was not supported by the data.

Potential problems were observed during data collection for the quadruped arm leg raise. It was noted that the majority of the subjects failed this test, meaning that rotation at the shoulders or the hips (or both) was observed during the movement. Though this test proved to be reliable and the results repeatable, a simple assignment of pass or fail may not have been the best way to assess this measure of core stability. This grading system allowed no room for degrees of instability, only a dichotomous outcome. It might have been more beneficial to assign a scale such as no rotation, mild, moderate, or severe rotation based on the number of degrees rotated or the number of times rotation occurred during the 10 second assessment period. The lack of information regarding how to accurately assess this test may be one reason why no correlations were found between this measure of core stability and any of the kinematic variables.

The lateral musculature endurance test targets mainly the quadratus lumborum but also involves the internal and external obliques [55]. It was thought that a greater ability to maintain this side plank position would indicate stronger lateral core muscles, so it was hypothesized that a higher score on this test would translate into less lateral trunk flexion motion and, because lateral trunk flexion is believed to be an indicator of knee valgus motion [40, 41], less knee valgus motion.

Limitations

One limitation of this study was the sample population. A majority of the subjects were female, 71 percent compared to 29 percent male. It has been shown that females have significantly different movement patterns compared to their male counterparts [23, 38, 58]. It is possible that the sample was too much alike and consequently did not create enough spread in the data. An increase in the number of male subjects could have resulted in greater sample diversity and therefore more observed differences. Similarly, all of the subjects tested were healthy. Introducing an injured population into the study would have provided more variety and, again, the possibility for greater differences to be detected.

Another limitation of this study was the single leg squat task the subjects performed in order to provide the kinematic data. The single leg squat is less physically demanding and, therefore, may not have accurately represented the motions created during more dynamic activities. Previous studies have used drop landing, running, cutting, and sidestepping tasks in order to better simulate the actual movements occurring in a sport setting [7, 37-41, 59]. Overall, there was little motion occurring at the trunk and knee during the single leg squat task. It is possible that because the single leg squat is slower and more controlled that the resulting trunk and knee kinematics and kinetics were not as extreme as they might have been if using a different task.

Future Research Considerations

Future research should focus foremost on developing accurate ways to evaluate core stability. Though several authors have attempted to do just that [13, 15, 49], their methods and results are not universally agreed upon. The benefits of such evaluation tools would be evident in literature concerning low back pain, which is where most core research is currently focused, any forthcoming studies regarding non-contact knee injuries, as well as being an invaluable asset in clinical practice.

It is of interest to determine the role of the core in preventing non-contact ACL injuries because core strength and stability can be modified through the use of a training program. It is logical to believe that gross movements of the trunk would impact motions at the knee as they are connected along the kinematic chain. Future research should investigate the same relationship questions in this study using more established core stability tests and a more dynamic task in order to further evaluate the association between core stability and trunk and knee kinematics.

Conclusions

This study attempted to identify relationships between trunk and knee biomechanics and clinical measures of core stability. Based on the results, we can only conclude that trunk flexion displacement is positively related to core stability. The clinical relevance of this study is limited due to few significant findings; more research needs to be done in order to propose a direct relationship between core stability and non-contact ACL injury prevention.

REFERENCES

1. Dugan SA. Sports-related knee injuries in female athletes: what gives? *Am J Phys Med Rehabil.* Feb 2005;84(2):122-130.

2. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy.* Dec 2007;23(12):1320-1325 e1326.

3. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* May-Jun 2000;8(3):141-150.

4. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg.* Jan 2005;18(1):82-88.

5. Chandrashekar N, Mansouri H, Slauterbeck J, Hashemi J. Sex-based differences in the tensile properties of the human anterior cruciate ligament. *J Biomech.* 2006;39(16):2943-2950.

6. Ireland ML. Anterior Cruciate Ligament Injury in Female Athletes: Epidemiology. *J Athl Train.* Apr 1999;34(2):150-154.

7. Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon).* Mar 2008;23(3):313-319.

8. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* Jul 2007;35(7):1123-1130.

9. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med.* Mar 2007;35(3):368-373.

10. Richardson CA, Jull GA. Muscle control-pain control. What exercises would you prescribe? *Man Ther.* Nov 1995;1(1):2-10.

11. Fredericson M, Moore T. Muscular balance, core stability, and injury prevention for middle- and long-distance runners. *Phys Med Rehabil Clin N Am.* Aug 2005;16(3):669-689.

12. Cowley PM, Fitzgerald S, Sottung K, Swensen T. Age, weight, and the front abdominal power test as predictors of isokinetic trunk strength and work in young men and women. *J Strength Cond Res.* May 2009;23(3):915-925.

13. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil.* Aug 1999;80(8):941-944.

14. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* Jun 2004;36(6):926-934.

15. Tse MA, McManus AM, Masters RS. Development and validation of a core endurance intervention program: implications for performance in college-age rowers. *J Strength Cond Res.* Aug 2005;19(3):547-552.

16. Willson JD, Dougherty CP, Ireland ML, Davis IM. Core stability and its relationship to lower extremity function and injury. *J Am Acad Orthop Surg.* Sep 2005;13(5):316-325.

17. Moore KL, Dalley, A.F. *Clinically Oriented Anatomy*. Fourth ed. Baltimore: Lippincott Williams & Wilkins; 1999.

18. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med.* Nov-Dec 1995;23(6):694-701.

19. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* Sep 2006;34(9):1512-1532.

20. Boden BP, Dean GS, Feagin JA, Jr., Garrett WE, Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* Jun 2000;23(6):573-578.

21. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* Oct 2003;35(10):1745-1750.

22. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med.* Jun 2004;32(4):1002-1012.

23. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* Apr 2005;33(4):492-501.

24. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. *Am J Sports Med.* Feb 2006;34(2):299-311.

25. Arms SW, Pope MH, Johnson RJ, Fischer RA, Arvidsson I, Eriksson E. The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. *Am J Sports Med.* Jan-Feb 1984;12(1):8-18.

26. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med.* Jan-Feb 1995;23(1):24-34.

27. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med.* Mar 2004;32(2):477-483.

28. Draganich LF, Jaeger RJ, Kralj AR. Coactivation of the hamstrings and quadriceps during extension of the knee. *J Bone Joint Surg Am.* Aug 1989;71(7):1075-1081.

29. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* Nov 1995;13(6):930-935.

30. Berns GS, Hull ML, Patterson HA. Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res.* Mar 1992;10(2):167-176.

31. Kanamori A, Woo SL, Ma CB, et al. The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test: A human cadaveric study using robotic technology. *Arthroscopy.* Sep 2000;16(6):633-639.

32. Kanamori A, Zeminski J, Rudy TW, Li G, Fu FH, Woo SL. The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. *Arthroscopy.* Apr 2002;18(4):394-398.

33. Fung DT, Hendrix RW, Koh JL, Zhang LQ. ACL impingement prediction based on MRI scans of individual knees. *Clin Orthop Relat Res.* Jul 2007;460:210-218.

34. Fung DT, Zhang LQ. Modeling of ACL impingement against the intercondylar notch. *Clin Biomech (Bristol, Avon).* Dec 2003;18(10):933-941.

35. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* Mar 2007;35(3):359-367.

36. Devita P, Skelly WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc.* Jan 1992;24(1):108-115.

37. Chappell JD, Creighton RA, Giuliani C, Yu B, Garrett WE. Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. *Am J Sports Med.* Feb 2007;35(2):235-241.

38. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon).* Jun 2001;16(5):438-445.

39. McLean SG, Walker KB, van den Bogert AJ. Effect of gender on lower extremity kinematics during rapid direction changes: an integrated analysis of three sports movements. *J Sci Med Sport.* Dec 2005;8(4):411-422.

40. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. *Med Sci Sports Exerc.* Oct 2007;39(10):1765-1773.

41. Chaudhari AM, Hearn BK, Andriacchi TP. Sport-dependent variations in arm position during single-limb landing influence knee loading: implications for anterior cruciate ligament injury. *Am J Sports Med.* Jun 2005;33(6):824-830.

42. Fukuda Y, Woo SL, Loh JC, et al. A quantitative analysis of valgus torque on the ACL: a human cadaveric study. *J Orthop Res.* Nov 2003;21(6):1107-1112.

43. Akuthota V, Ferreiro A, Moore T, Fredericson M. Core stability exercise principles. *Curr Sports Med Rep.* Feb 2008;7(1):39-44.

44. Bergmark A. Stability of the lumbar spine. A study in mechanical engineering. *Acta Orthop Scand Suppl.* 1989;230:1-54.

45. Akuthota V, Nadler SF. Core strengthening. *Arch Phys Med Rehabil.* Mar 2004;85(3 Suppl 1):S86-92.

46. Barr KP, Griggs M, Cadby T. Lumbar stabilization: core concepts and current literature, Part 1. *Am J Phys Med Rehabil.* Jun 2005;84(6):473-480.

47. Barr KP, Griggs M, Cadby T. Lumbar stabilization: a review of core concepts and current literature, part 2. *Am J Phys Med Rehabil.* Jan 2007;86(1):72-80.

48. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.

49. Lanning CL, Uhl T, L, Ingram CL, Mattacola CG, English T, Newsom S. Baseline values of trunk endurance and hip strength in college athletes. *Journal of Athletic Training.* 2006;41(4):427-434.

50. Liemohn WP, Baumgartner TA, Gagnon LH. Measuring core stability. *J Strength Cond Res.* Aug 2005;19(3):583-586.

51. Chanthapetch P, Kanlayanaphotporn R, Gaogasigam C, Chiradejnant A. Abdominal muscle activity during abdominal hollowing in four starting positions. *Man Ther.* Dec 2009;14(6):642-646.

52. Gagnon D, Gagnon M. The influence of dynamic factors on triaxial net muscular moments at the L5/S1 joint during asymmetrical lifting and lowering. *J Biomech.* Aug 1992;25(8):891-901.

53. Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, Powers CM. Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. *J Orthop Sports Phys Ther.* Jul 2008;38(7):403-409.

54. Blackburn JT, Padua DA. Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *J Athl Train.* Mar-Apr 2009;44(2):174-179.

55. Lehman GJ, Hoda W, Oliver S. Trunk muscle activity during bridging exercises on and off a Swiss ball. *Chiropr Osteopat.* Jul 30 2005;13:14.

56. Nuzzo JL, McCaulley GO, Cormie P, Cavill MJ, McBride JM. Trunk muscle activity during stability ball and free weight exercises. *J Strength Cond Res.* Jan 2008;22(1):95-102.

57. Behm DG, Leonard AM, Young WB, Bonsey WA, MacKinnon SN. Trunk muscle electromyographic activity with unstable and unilateral exercises. *J Strength Cond Res.* Feb 2005;19(1):193-201.

58. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon).* Aug 2003;18(7):662-669.

59. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc.* Jul 2001;33(7):1168-1175.