A COMPARISON OF GLUTEUS MEDIUS, GLUTEUS MAXIMUS, AND HAMSTRINGS ACTIVATION DURING FIVE COMMONLY USED PLYOMETRIC EXERCISES

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ABSTRACT

AARON HOWARD STRUMINGER: A Comparison of Gluteus Medius, Gluteus Maximus, and Hamstrings Activation during Five Commonly Used Plyometric Exercises
(Under the direction of Dr. Troy Blackburn)

Anterior Cruciate Ligament (ACL) injuries occur frequently in athletics, and plyometric exercises may aid in preventing these injuries. The purpose of this study was to determine which plyometric exercises produce the greatest activation of the gluteal and hamstrings muscles and the medial-to-lateral hamstrings activation ratio. Forty-one subjects performed 5 plyometric exercises while muscle activity was recorded. Subjects displayed the most hamstrings and gluteal muscle activity during the single-leg sagittal plane hurdle hops, the least muscle activity during the 180^{o} hops, and the greatest preparatory medial-to-lateral hamstrings ratio during the double-leg sagittal plane hurdle hops and split squat jumps. Therefore, 180^{o} hops are not as effective as other plyometric exercises at targeting gluteal and hamstrings activation. Frontal or sagittal plane exercises are needed to enhance medial-to-lateral hamstrings activation and gluteal activation, respectively. Future research should examine the effects of frontal versus sagittal plane plyometric exercise intervention programs on knee biomechanics.

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CHAPTER I

INTRODUCTION

OVERVIEW

Anterior Cruciate Ligament (ACL) injuries are common in athletics. As more youth are encouraged to become active and participate in sports, more ACL injuries will occur, purely because of increased exposure. ACL injuries can affect athletes from all age groups and can result in both short-term consequences including pain, loss of function, and surgery or long term consequences including increased risk of another ACL injury and a 70% risk of developing arthrosis in the knee (Gillquist & Messner, 1999; Hootman, Dick, & Agel, 2007; Salmon, Russell, Musgrove, Pinczewski, & Refshauge, 2005; Shea, Pfeiffer, Wang, Curtin, & Apel, 2004). In order to prevent the numerous consequences that result from ACL injuries, clinicians should first understand the mechanisms of ACL injury and then design programs to prevent those mechanisms.

Despite the growing number of ACL injuries that occur during athletics each year, no clear mechanism of injury has been identified. Hewett et al. (2006) determined that 70% of ACL injuries occur with no contact to the lower extremity during landing and cutting tasks, likely due to certain biomechanical errors that predispose an athlete to injury. For example, Ireland (1999) described the kinematic events associated with ACL injury as resulting in a “position of no return” where limited activity and/or weakness of the hip abductors, external rotators, and extensors results in uncontrolled hip and pelvis motion, leading to altered knee alignment. This altered knee alignment, known specifically as knee valgus, results from a combination of hip adduction and internal rotation along with tibial external rotation and knee abduction and may predict injury in female athletes (Hewett et al., 2006; Hewett et al., 2005). Similarly, delayed preparatory co-activation of the hamstrings and quadriceps contributes ACL loading by altering sagittal, frontal, and transverse plane forces upon the knee (Hashemi et al., 2010; McLean, Borotikar, & Lucey, 2010; Palmieri-Smith, Wojtys, & Ashton-Miller, 2008). These findings, as well as various cadaver models, suggest that forces in the sagittal, frontal, and transverse planes all contribute to ACL injury (Durselen, Claes, & Kiefer, 1995; Li et al., 1999).

To prevent ACL injuries, clinicians aim to develop injury prevention programs that aid in correcting the errors suggested by Ireland (1999) and Hashemi et al. (2010). To prevent these errors, clinicians must alter the forces acting upon the knee joint. Strengthening of the gluteus medius, gluteus maximus, and hamstrings is a common treatment used by clinicians to promote movement patterns which avoid biomechanical errors known to increase ACL loading. Increases in gluteus medius, gluteus maximus, and hamstrings strength would theoretically limit hip adduction and internal rotation (contributors to knee valgus) and anterior tibial translation. However, altering the strength of the gluteal muscles does not affect the amount of knee valgus or knee flexion exhibited by an individual when landing from a jump (Herman et al., 2008). Since strengthening the hamstrings and gluteal muscles does not alter knee biomechanics and because tasks in which ACL injuries occur do not likely require maximal effort from the gluteals and hamstrings, clinicians should find other ways to alter the function of hamstrings and gluteal muscles to produce biomechanical changes which may reduce loading and ACL injury risk.

An alternate way of producing changes to prevent biomechanical errors at the knee is altering the activation of the gluteal and hamstrings muscles. Unlike greater strength of the gluteal and hamstrings muscles, greater activation of these muscles both before and after initial ground contact has been found to aid in the correction of the biomechanical errors that lead to ACL injury (Jacobs, Uhl, Mattacola, Shapiro, & Rayens, 2007; McLean et al., 2010; Palmieri-Smith et al., 2008; Preece et al., 2008). Increasing muscle activation may be more important than increasing strength in preventing biomechanical errors, as landing and cutting tasks do not require maximal muscular strength. Subjects who exhibit earlier and greater medial hamstrings activity and lesser lateral hamstrings activity during both the preparatory and loading phases of jump landing display lesser knee valgus forces and angles than their counterparts (McLean et al., 2010; Palmieri-Smith et al., 2008). Unlike the direct correlation between hamstrings activity and knee valgus, greater gluteal muscle activation has only been correlated to lesser knee valgus indirectly. Specifically, subjects exhibiting greater gluteus maximus activation while walking display greater deceleration of tibial external rotation, and a less active gluteus medius results in greater femoral adduction upon the completion of a landing task (Jacobs et al., 2007; Preece et al., 2008). Since tibial external rotation and femoral adduction are components that lead to knee valgus, one could surmise that increases in gluteal muscle activation could lead to a reduction in knee valgus. Therefore, instead of focusing on increasing strength of the gluteal and hamstrings muscles to prevent ACL injury, clinicians might want to focus on increasing the activation of those muscles.

One way clinicians are able to alter the activation of musculature is through the use of plyometric exercises (Potteiger et al., 2005). Plyometric training programs are designed to enhance neuromuscular effectiveness by improving muscle performance in targeted muscles, but they do not improve muscle performance by changing muscle fiber type or area (Markovic & Mikulic, 2010; Potteiger et al., 2005). Instead, changes in neuromuscular effectiveness after a plyometric training program seem to come from enhancements in motor unit recruitment in targeted muscles (Potteiger et al., 2005). An enhancement in motor unit recruitment would enhance the neural drive to the muscles, thus leading to increased activation of those muscles. If these increases in activation are evident in the gluteal muscles and medial hamstrings during specific plyometric exercises, clinicians may be able to use exercises that increase the activation of the gluteal and hamstrings muscles to create a process of feed-forward neuromuscular control by which the athlete is able to increase activation of the gluteal and hamstrings muscles during functional activities both before and after initial ground contact.

Plyometric exercise programs are an important component of injury prevention because they can reduce risk factors that lead to ACL injury, such as knee valgus and knee flexion moments and angles (Lephart et al., 2005; Myer, Ford, McLean, & Hewett, 2006; Myer, Ford, Palumbo, & Hewett, 2005). Plyometric exercises have also been identified as one of the most important elements in an ACL injury prevention program (Markovic & Mikulic, 2010). However, the results of ACL prevention programs that incorporate plyometrics are contradictory. Some injury prevention programs which include plyometrics have resulted in significant reductions in ACL injury risk (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Mandelbaum et al., 2005) while other programs show little-to-no effect (Myklebust et al., 2003; Pfeiffer, Shea, Roberts, Grandstrand, & Bond, 2006; Steffen, Myklebust, Olsen, Holme, & Bahr, 2008). A potential cause for this equivocal body of literature is the fact that these investigations included a wide variety of plyometric exercises. The most common exercises included in these prevention programs are double leg sagittal plane cone hops, single leg sagittal plane cone hops, double leg frontal plane cone hops, split squat jumps, and 180° jumps (Hewett et al., 1999; Mandelbaum et al., 2005; Myer, Ford, Brent, & Hewett, 2006; Myer et al., 2005; Myklebust et al., 2003; Pfeiffer et al., 2006; Steffen et al., 2008). However, these common exercises were included at different phases of each prevention program and in different frequencies and intensities during each prevention program. Also, none of these studies provided rationale for why they included or excluded specific plyometric exercises.

If ACL injury prevention programs that include plyometric exercises are truly designed to prevent ACL injuries, they should be aimed at decreasing the biomechanical errors that lead to ACL injury. Altering the activation of the gluteal and hamstrings muscles seems to be one way to decrease knee biomechanical errors, so plyometric exercises should be aimed at increasing the activation of those muscles. One plyometric training program has been able to increase activity of the gluteus medius in both phases of a jump landing trial, but this program was extremely broad and did not identify exercises which caused this change (Lephart et al., 2005). Previous research has shown that step-up exercises performed in the frontal plane increase gluteus medius activity to a greater extent than exercises completed in the sagittal plane (Mercer, Gross, Sharma, & Weeks, 2009). This difference in muscle activation when performing exercises in different planes is also seen in the medial hamstrings, as cutting tasks in the frontal and transverse planes produce higher muscle activation in the medial hamstrings when compared to an equivalent sagittal plane task (Houck, 2003). Therefore, exercises performed in the frontal and transverse planes, such as a 180° jump or a frontal plane hurdle hop, may be more effective in activating the medial hamstrings and gluteals compared to exercises performed in the sagittal plane, such as a double leg sagittal plane hurdle hop.

If clinicians implement programs that target increased activation of the gluteal and hamstrings muscles and remove exercises that do not target the gluteal and hamstrings muscles, they may be able to begin refining ACL prevention programs. Also, finding plyometric exercises that activate the gluteals and hamstrings may lead to future research which examines whether performing a plyometric program with only the exercises that are most effective for activating the gluteal and hamstrings muscles produces greater biomechanical changes or a greater reduction in ACL injury risk than a general plyometric program which includes a variety of plyometric exercises. Therefore, the purpose of this study was to determine which plyometric exercises produce the greatest mean EMG amplitudes of the gluteus medius, gluteus maximus, lateral hamstrings, and medial hamstrings muscles as well as medial hamstrings to lateral hamstring co-activation ratio.

RESEARCH QUESTIONS AND HYPOTHESES

RQ1: Are there differences in preparatory and loading electromyographic (EMG) amplitudes of the following muscles between 5 commonly used plyometric exercises?

RQ1a) Gluteus Maximus

RH1a) The split squat jump will produce the greatest mean amplitude of gluteus maximus muscle activation, and all activities will produce a larger mean amplitude compared to double leg sagittal plane hurdle hops.

RQ1b) Gluteus Medius

RH1b) The single leg hurdle hops and frontal plane hurdle hops will produce the greatest mean amplitude of gluteus medius muscle activation, and all activities will produce a larger mean amplitude compared to double leg sagittal plane hurdle hops.

RQ1c) Medial Hamstrings

RH1c) The frontal plane double leg hurdle hops will produce the greatest mean amplitude of medial hamstrings muscle activation, and all activities will produce a larger mean amplitude compared to double leg sagittal plane hurdle hops.

RQ1d) Lateral Hamstrings

RH1d) Single leg sagittal plane hurdle hops will produce the greatest mean amplitude of lateral hamstrings muscle activation.

RQ2: Is there a difference in the ratio of medial to lateral hamstrings EMG amplitude between 5 commonly used plyometric exercises during the preparatory and loading phases?

RH2) The frontal plane hurdle hops will produce the greatest ratio of mean amplitude of the medial hamstrings versus mean amplitude of the lateral hamstrings.

OPERATIONAL DEFINITIONS

Plyometric Activities: Exercises in which lower extremity muscles are stretched and shortened in rapid sequence

180^{O} Jump: Exercise in which a subject jumps and performs 180^{O} turn in the transverse plane, lands, and continues to repeat process

Double Leg Frontal Plane Hurdle Hop: Exercise in which a subject jumps over a hurdle in the frontal plane towards his non-dominant leg pushing off the both legs, lands on both legs, and jumps back over the hurdle

Double Leg Sagittal Plane Hurdle Hop: Exercise in which a subject jumps forward over a hurdle in the sagittal plane pushing off the both legs, lands on both legs, and jumps backwards over the hurdle

Single Leg Sagittal Plane Hurdle Hop: Exercise in which a subject jumps forward over a hurdle in the sagittal plane pushing off his dominant leg, lands on the dominant leg, and jumps backwards over the hurdle

Split Squat Jump: Exercise in which a subject begins in a lunge position with his non-dominant leg forward, jumps as high as he can in the air, lands in a lunge position with his dominant leg forward, and continues to repeat the process

Electromyography (EMG): A technique used to evaluate the electrical signal produced by a muscle

Physically active: Person who completes at least 30 minutes of exercise a minimum of 3 times per week

VARIABLES

Independent variable

Plyometric Exercise:

Sagittal Plane Hurdle Hop

Frontal Plane Hurdle Hop

One Leg Sagittal Plane Hurdle Hop

180^{O} Jump

Split Squat Jump

Dependent variables:

Mean activity of the gluteus medius during the preparatory phase

Mean activity of the gluteus medius during the loading phase

Mean activity of the gluteus maximus during the preparatory phase

Mean activity of the gluteus maximus during the loading phase

Mean activity of the medial hamstrings during the preparatory phase

Mean activity of the medial hamstrings during the loading phase

Mean activity of the lateral hamstrings during the preparatory phase

Mean activity of the lateral hamstrings during the loading phase

Ratio of mean activity of the medial hamstrings to mean activity of the lateral hamstrings during the preparatory phase

Ratio of mean activity of the medial hamstrings to mean activity of the lateral hamstrings during the loading phase

DELIMITATIONS

1) Physically active population

2) No Lower extremity or lower back injury within the past 6 months

3) No history of grade 3 ligament injury in the lower extremity or lower extremity fracture

4) No weight lifting 48 hours prior to testing protocol

5) No previous history of chronic ankle instability

LIMITATIONS

1) Effort given during testing protocol

2) Laboratory jumping tests may be restricted by EMG wires

3) EMG activity was only collected with the subject jumping in only one direction

ASSUMPTIONS

1) EMG accurately measures muscle activation

2) EMG is placed over true muscle belly

3) Rest time between plyometric activities is sufficient to prevent fatigue

4) Subjects will not become fatigued during testing protocol

5) Participants will perform plyometric exercises correctly

6) The subjects in the study are representative of the entire recreationally active population

CHAPTER II

REVIEW OF THE LITERATURE

INTRODUCTION

Anterior cruciate ligament (ACL) injuries can be devastating injuries for athletes. This injury can restrict an athlete's participation in a sport for months, cause short term pain, produce psychological stress, lead to increased risk for another ACL injury, and contribute to long term degenerative changes in the knee joint (Gillquist & Messner, 1999; Griffin et al., 2000; Salmon et al., 2005). The best way to avoid the short-term and long-term stresses that are experienced by an athlete who suffers an ACL rupture is preventing the initial injury. In order to prevent ACL injuries, clinicians attempt to change the biomechanical factors that contribute to injury including excessive peak knee valgus angles, relatively small peak knee flexion angles upon cutting or landing, greater ground reaction forces upon landing, and weakness or reduced activation of the musculature in the thigh and hip. Traditionally, prevention programs have been implemented to attempt to change an athlete's lower extremity biomechanics by increasing the strength of the gluteus maximus, gluteus medius, and hamstrings. However, basic strength training does not seem to produce any changes in lower extremity biomechanics (Herman et al., 2008), so researchers have begun to focus on neuromuscular programs that include plyometric exercises in order to produce these biomechanical changes. Plyometric training does seem to produce lower extremity biomechanical changes, but specific mechanisms by which plyometric exercises produce these biomechanical changes have not been determined (Chappell & Limpisvasti, 2008; Lephart et al., 2005; Myer, Ford, McLean, et al., 2006). The purpose of this review is to highlight the need for an investigation on muscle activation patterns during different plyometric exercises so that plyometric programs can become more effective in preventing ACL injuries.

EPIDEMIOLOGY AND LONG TERM RISK

ACL rupture can be a debilitating injury for an athlete from both a physical and psychological standpoint. With the introduction of modern surgical techniques, ACL injury is no longer considered career threatening but can still result in short-term and long-term physiological effects. ACL injuries can affect athletes both young and old. The vast majority of ACL injuries occur in individuals between the ages of 15 and 45 years, and it is estimated that one in every 1,750 people in that age range will sustain an ACL injury (Griffin et al., 2000). When looking at a youth population, ACL injuries accounted for 7% of insurance claims in a youth soccer population over a period of five years with a rapid increase in injuries between 11 and 12 years of age (Shea et al., 2004). As these athletes grow older and the number of athletes competing at the National Collegiate Athletic Association (NCAA) level continues to rise, ACL injury rates will also continue to rise from the estimated 2,000 ACL injuries that occur in NCAA participants every year (Hootman et al., 2007). These ACL tears in a collegiate population are up to six times more prevalent in women and can occur once out of every 385 activity sessions in men’s soccer and once out of every 161 activity session sessions in women’s soccer (Arendt & Dick, 1995).

In addition to the psychological and physical impacts, ACL injuries can have an economic impact as well. ACL injuries cost injured athletes up to almost $1 billion each year because of the rehabilitation visits and possible reconstructive surgery that are required after injury (Griffin et al., 2000). That figure also does not take into account the cost of future care of the degenerative changes that occur at the knee, so the long-term cost of ACL injury might be even higher, as 70% of ACL deficient knees show signs of knee arthrosis (Daniel et al., 1994; Gillquist & Messner, 1999; Griffin et al., 2000). Surgical repair may be able to reduce the risk of arthrosis in the knee, but initial injury of the ACL remains the major determinant in future knee arthrosis, especially if the initial ACL injury is associated with a meniscus tear (Gillquist & Messner, 1999).

Future arthrosis in the knee joint is not the only long term risk for an athlete who suffers an ACL tear. An athlete who previously torn an ACL has at least a 9% chance to tear his/her ACL in either knee no matter what kind of graft was used (Salmon et al., 2005; Shelbourne, Gray, & Haro, 2009). That risk is immense when considering that the uninjured/healthy population only has a 1.7% chance of suffering an ACL injury in either knee (LaPrade & Burnett, 1994). It is important to note that this increased risk of injury is not just present in the knee in which the ACL has already been torn. An athlete is actually just as likely to tear his/her ACL in a knee which is surgically repaired as he/she is to tear the ACL on the contralateral knee (Salmon et al., 2005). The equal injury rate in either knee following ACL injury may indicate a biomechanical fault that is not corrected during the traditional ACL rehabilitation process. If clinicians are able to recognize and correct these biomechanical faults, rate of injury in both healthy and previously injured populations might decrease. This decrease in injury rate would also decrease the costs and long-term consequences associated with ACL injury.

ACL ANATOMY

In order to understand ACL injuries, one must first understand the anatomy of the ACL. The ACL consists of two different bundles that run from the posterior femur to the anterior intercondylar space of the tibia (Neumann, 2010). These bundles, the anterior-medial bundle and the posterior-lateral bundle, are named for the locations at which they attach on the tibia (Neumann, 2010). Because of the presence of the two bundles, some fibers of the ACL remain relatively taut throughout flexion and extension of the knee (Neumann, 2010). The primary purpose of the ACL is limiting anterior translation of the tibia on the femur. However, the slight oblique orientation of the bundles of the ACL allow it to become a secondary restraint to internal rotation of the knee joint, as shown in cadaver studies where an internal rotation stress that simulates knee valgus significantly increases ACL strain (Durselen et al., 1995). The ACL becomes even further stressed when force is applied in multiple planes (Markolf et al., 1995). More specifically, if an anterior tibial force is combined with a valgus load, the ACL experiences an additive stress that is greater than the stress experienced by any other possible force combinations applied to the knee (Markolf et al., 1995).

ACL INJURY RISK FACTORS

Sagittal Plane

Some biomechanical faults that lead to ACL injuries may be the result of altered kinematics. One kinematic error that can lead to an increased risk of ACL injury is lesser knee flexion when landing from a jump (Koga et al., 2010; Taylor et al., 2010). Lesser knee flexion angles upon jump landing result in both a longer ACL and greater anterior tibial translation, which also creates a longer ACL (Podraza & White, 2010; Taylor et al., 2010). Since ligaments have no contractile properties, an increase in length must result in an increase in tension of the ACL. On the other hand, greater knee flexion angles result in a shorter ACL, which means that less strain is put on the ACL throughout the entire landing process, thus reducing the risk of an ACL tear (Taylor et al., 2010). This knee flexion and ACL tension relationship is confirmed by video analysis of landings in which jump landings which resulted in ACL injury exhibited a relatively straight knee flexion angle of 23 degrees (Koga et al., 2010). Even though these sagittal plane forces alone cannot cause an ACL rupture (McLean, Huang, Su, & Van Den Bogert, 2004), the increased tension on the ACL might allow a lesser force in either the frontal or transverse plane to cause the ligament to rupture.

Lesser knee flexion upon landing does not only affect the tension of the ACL but also affects the shear force produced by the quadriceps contraction. When the quadriceps contracts, the strain on the ACL increases (Li et al., 1999; Renstrom, Arms, Stanwyck, Johnson, & Pope, 1986). In cadavers, the strain on the ACL from a quadriceps contraction becomes significantly greater than normal passive strain on the ACL when the knee flexion angle is between 0 and 30 degrees (Li et al., 1999). The greater strain occurs with lesser knee flexion angles because the angle of insertion of the patellar tendon increases in extension (Zheng, Fleisig, Escamilla, & Barrentine, 1998). Since the anterior component of the quadriceps force is calculated as the sine of the angle of insertion of the patellar tendon, increasing the angle of the patellar tendon would produce an increase of anterior tibial shear force (Blackburn & Padua, 2008). This greater moment arm leads to a greater mechanical advantage for the quadriceps. If the quadriceps produces a greater force, the anterior tibial translation will increase based on the direction of pull of the quadriceps, thereby causing a greater strain on the ACL. Therefore, landing from a jump with lesser knee flexion causes strain on the ACL because of the anatomical position of the ACL as well as the force produced by the quadriceps.

Lesser peak knee flexion angles both upon initial ground contact and during the stance phase of landing can result in sagittal plane kinetic errors which increase the risk of ACL injury (Hewett et al., 2005). One example of this relationship is demonstrated by the association between knee flexion angle, vertical ground reaction force (vgrf), and energy absorption (Norcross, Blackburn, Goerger, & Padua, 2010). Both greater knee flexion and lesser vgrf contribute to greater absorption of forces during the terminal phase of landing, a fact which is important because later in landing muscles are in a better mechanical position to absorb the impact forces caused by landing from a jump (Norcross et al., 2010). Athletes who limit early absorption of forces during jump landing may be able to reduce the strain on the ACL because the muscles will be able to absorb more force from the landing impact, thereby allowing the ACL to absorb less force and not become as taut (Norcross et al., 2010). Landing with lower vgrf also diminishes the amount of force that needs to be absorbed by the body. In a prospective study, athletes who went on to tear their ACLs displayed significantly greater peak vgrf than the uninjured cohort (Hewett et al., 2005). This greater vgrf upon landing has also been positively correlated with kinematic errors such as decreased knee flexion angles in athletes who go on to suffer ACL injuries (Hewett et al., 2005). Therefore, landing with small knee flexion angles may decrease the lower extremity muscles' ability to absorb force. This decrease in force absorption of the muscles would cause increased stress on the ligaments of the lower extremity, including the ACL.

Frontal and Transverse Planes

Other biomechanical errors that increase stress on the ACL and could possibly lead to ACL rupture can occur in the frontal and transverse planes. The most common frontal and transverse plane kinematic error that leads to ACL injury is dynamic knee valgus, which results from a combination of hip adduction, femoral internal rotation, knee abduction, and tibial external rotation (Hewett et al., 2006). Since the ACL helps stabilize the knee during excessive internal rotation of the femur and acts as a secondary stabilizer when the knee moves into abduction, a valgus position would theoretically lead to increased stress on the ACL. The theory of dynamic knee valgus leading to ACL stress seems to be validated when observing ACL injuries in cadavers and on videotape (Koga et al., 2010; Meyer & Haut, 2008). In cadavers, internal rotation torque was able to induce an ACL tear (Meyer & Haut, 2008). This internal rotation torque was also associated with knee valgus in all tests before failure of the ACL (Meyer & Haut, 2008). If femoral internal rotation is associated with knee valgus and can lead to an ACL tear in cadavers, knee valgus should also be associated with ACL injury in athletes. Upon video analysis athletes who suffer an ACL injury show a rapid increase in knee abduction angle during the first 40 milliseconds after landing from a jump (Koga et al., 2010). The same injured athletes also show a rapid increase in knee internal rotation angle of the tibia during the first 40 milliseconds after landing (Koga et al., 2010). These video data seem to indicate that dynamic knee valgus is associated with increased strain on the ACL because increases in the knee abduction and internal rotation angles are able to cause enough strain to produce an ACL tear. Females, who suffer ACL injuries at a greater frequency than males, experience greater dynamic knee valgus angles upon initial ground contact and throughout the landing phase than males (Arendt & Dick, 1995; Ford, Myer, & Hewett, 2003; Russell, Palmieri, Zinder, & Ingersoll, 2006). These two factors suggest that dynamic knee valgus at initial contact and throughout the landing phase may contribute to the discrepancy in injury rate between males and females (Hewett et al., 2005).

Knee valgus moments also place increased strain on the ACL (Shin, Chaudhari, & Andriacchi, 2009; Withrow, Huston, Wojtys, & Ashton-Miller, 2006). Increased internal knee adduction moment causes rapid increase in shear force on the structures that attempt to control knee valgus including the ACL. As the shear force becomes too great, the ACL may rupture (Beynnon, Johnson, Abate, Fleming, & Nichols, 2005). Upon computer simulation, peak strain on the ACL significantly increased when a simulated valgus moment was applied to the knee (Shin et al., 2009). Even though this simulated peak strain was not enough to cause ACL injury, additional perturbations could further increase ACL strain and cause injury (Shin et al., 2009). Knee valgus moments also significantly increase ACL strain in cadavers (Withrow et al., 2006). This increase in ACL strain was independent of the impulsive force upon landing, so the increases in ACL strain can be directly attributed to increases in knee valgus (Withrow et al., 2006). External knee valgus moments are also observed to be useful when trying to predict future knee injury (Hewett et al., 2005). Knee valgus moments may predict ACL injury with up to 78% specificity and 73% sensitivity and suggest that the athlete has a lack of control of the knee in the frontal plane (Hewett et al., 2005). This high sensitivity and specificity suggest that knee valgus moments are the key component in predicting ACL injury risk.

Muscular ACL Injury Risk Factors

Hamstrings

Athletic movements require large dynamic contributions from the lower extremity musculature in order to prevent ACL injury. If an athlete's muscles are weak, at a mechanical disadvantage, or not activated properly, he will be unable to control the dynamic movement of the knee during athletic activity. One muscle group that is commonly trained in order to protect the ACL is the hamstrings, which provide a posterior force on the tibia when contracted. When the hamstrings are contracted as the primary knee flexor, the sagittal plane force on the ACL decreases significantly (O'Connor, 1993). As the magnitude of hamstrings contraction changes, the load on the ACL also changes (Baratta et al., 1988). An increase in contraction strength of the hamstrings has been shown to contribute to greater joint stiffness and decreased anterior laxity (Baratta et al., 1988). Greater stiffness and less anterior laxity help reduce strain on the ACL by controlling the anterior movement of the tibia, which in turn keeps some slack in the ACL. Even when the knee is being extended, the hamstrings are still able to decrease peak strain of the ACL by up to 70% (Withrow, Huston, Wojtys, & Ashton-Miller, 2008). Therefore, the hamstrings seem to provide a dynamic support for the ACL during both the eccentric and concentric phases of muscle contraction.

Strength of the hamstrings is also important in preventing the anterior shear force to the tibia applied by the quadriceps (Baratta et al., 1988). Quadriceps contraction, which is influenced by both quadriceps strength and knee flexion angle, provides an anterior shear force to the knee, and a deficiency in hamstrings strength can result in excessive anterior tibial translation (Isaac et al., 2005). However, if the quadriceps and hamstrings contract at the same time, also called co-contraction, with equal magnitude the ACL will not be stressed (O'Connor, 1993). Also, if the knee joint is placed in a relatively extended position, the moment arm and insertion angle of the hamstrings are altered (Baratta et al., 1988; Blackburn & Padua, 2008). This alteration would alter the pull of the hamstrings and cause the hamstrings to pull more superiorly than posteriorly. Thus the hamstrings would not be able to properly counteract the anterior tibial shear force that has been increased because the angle of insertion of the patellar tendon (Blackburn & Padua, 2008; Zheng et al., 1998). All of these factors that reduce the force from the hamstrings could lead to an increased anterior tibial shear force and increase the risk of an ACL injury. Hamstring and quadriceps co-activation is also important in protecting the ACL when landing from a jump (Hashemi et al., 2010). During a jump landing, the quadriceps must contract strongly in order to stabilize the body and prevent the loss of balance. Therefore, the hamstrings must contract as well to limit anterior shear force. After the peak strain on the ACL occurs during a jump, the knee flexes just before landing in order to improve knee stability (Taylor et al., 2010). If the hamstrings are not co-activated with the quadriceps during landing, increased risk for ACL injury may occur because of excessive anterior tibial shear force or reduction in knee flexion angles.

Gluteus Medius and Gluteus Maximus

Weakness or insufficient activation of muscles that do not directly attach to the knee may also increase the risk of ACL injury. The gluteus medius, by abduction, and gluteus maximus, by extension and external rotation, directly affect the motion of the femur. Since the femur is one of the bones that makes up the knee joint and is a rigid body, hip musculature that affects the proximal femur will move the entire femur and affect movement at the knee. If the hip musculature is weak or relatively inactive, an athlete can experience a lack of stability at the knee (Leetun, Ireland, Willson, Ballantyne, & Davis, 2004). Weakness at the hip can leave the athlete exposed to large external forces, especially in the frontal and transverse planes (Leetun et al., 2004). Seeing that the ACL helps restrict frontal and transverse plane motions at the knee, these forces may place enough stress on the ACL to cause a rupture. These frontal and transverse plane motions at both the knee and the hip can be controlled by the gluteus medius, which abducts the hip, the adductors, which adduct and internally rotate the hip, the hip flexors, which flex the hip, and the gluteus maximus which extends and externally rotates the hip. When applied to athletes, hip weakness, more specifically weakness in hip abduction and external rotation, most closely predicts injury rates over an entire season compared to other core stability measures (Leetun et al., 2004). These deficits seem to indicate that weakness in the gluteus medius and gluteus maximus might be a risk factor for ACL injury.

EFFECT OF MUSCLE STRENGTH AND ACTIVATION ON ACL INJURY RISK FACTORS

Previous research has shown that many kinetic and kinematic factors increase ACL injury risk and that weakness of certain muscles can result in ACL tear (Baratta et al., 1988; Hewett et al., 2005; Leetun et al., 2004; Norcross et al., 2010; Taylor et al., 2010). However, to design a program to prevent injuries, researchers and clinicians must know how the body functions in order to prevent these biomechanical faults. Biomechanists cannot directly influence previous injury or anatomical factors, but they may be able to influence the activation or strength of the muscles acting on the knee joint in order to correct for these biomechanical errors. In this section, the influence of muscle activation and strength on ACL risk factors will be explored.

Gluteus Medius

The gluteus medius acts as a prime abductor of the thigh. If the gluteus medius is not activated properly, the femur will not be restricted when it goes into adduction. As femur adduction is one of the motions associated with knee valgus, proper strength and contraction of the gluteus medius have been suggested to help prevent knee valgus. This relationship between valgus knee angle and concentric abduction strength is also found in subjects performing a single leg squat (Claiborne, Armstrong, Gandhi, & Pincivero, 2006). During a jump landing task, fatigue of the gluteus medius led to increases in hip adduction, which is associated with greater knee valgus angles (Jacobs et al., 2007). The results of this study led the authors to suggest that individuals with greater hip abduction strength may have more beneficial landing mechanics than individuals who have lesser hip abduction strength (Jacobs et al., 2007). However, other authors found a different relationship between knee valgus and hip abductor strength (Hollman et al., 2009; Patrek, Kernozek, Willson, Wright, & Doberstein, 2011). These studies found that subjects who had lesser hip abduction strength, whether naturally or induced by fatigue, exhibited no differences in knee valgus or even exhibited lower knee valgus angles when compared to either a population with greater hip abduction strength or when compared to their pre-fatigue state (Hollman et al., 2009; Patrek et al., 2011). The discrepancy between the studies might be the result of unmeasured differences in hip flexion angles between the studies (Hollman et al., 2009). As the hip flexes, the internal rotation moment arm of the gluteus medius increases. Therefore, greater gluteus medius strength could cause greater internal rotation of the femur if the hip enters a higher degree of flexion. Another reason for the difference between the studies may be the difference in the activation levels of the gluteus medius after the fatigue protocol. Jacobs et al. (2007) noted that the increase in knee valgus angles might be due to a decrease in gluteus medius activation rather than a decrease in strength whereas Patrek et al. (2011) did not see a difference between gluteus medius activation after the fatigue protocol.

Unlike studies on gluteus medius strength, studies on gluteus medius activation seem to consistently suggest that increases in gluteus medius activation are able to limit knee frontal plane motion (Patrek et al., 2011; Zazulak et al., 2005). Even though fatigue through repetitive hip abduction decreases the strength of the gluteus medius, fatigue does not affect the activation of the gluteus medius as measured by surface electromyography (EMG) (Patrek et al., 2011). As only minimal changes in knee and hip biomechanics resulted after the fatigue protocol, one can infer that gluteus medius activation is more important in controlling frontal plane knee motion than gluteus medius strength (Patrek et al., 2011). Additionally, when landing on a single leg, men activate their gluteus medii 25% more than women during the same task (Zazulak et al., 2005). This diminished activation of gluteus medius activity exhibited by women might contribute to greater knee valgus angles and moments in women compared to men (Zazulak et al., 2005).

Gluteus Maximus

The gluteus maximus acts as a prime extensor and external rotator of the thigh. The gluteus maximus should help control femoral internal rotation, which is associated with knee valgus. Like the gluteus medius, the effect of the strength of the gluteus maximus on ACL risk factors is debated. Fatigue of the gluteus maximus leads to an increase in the anterior tilt of the pelvis in a standing position (Alvim, Peixoto, Vicente, Chagas, & Fonseca, 2010). The prevention of anterior tilt is important because when the pelvis is anteriorly tilted, the moment arms of the muscles that internally rotate the thigh become larger and the moment arms of the muscles that in externally rotate the thigh become smaller (Neumann, 2010). Therefore, a change in tilt of the pelvis should increase femoral internal rotation, thereby potentially increasing knee valgus. However, increasing the strength of the gluteus maximus by 48% with a strength training program neither enhances nor prevents any factors that cause knee valgus during a jump landing task (Herman et al., 2008).

Even if strength of the gluteus maximus is not related to knee valgus, activation of the gluteus maximus seems to have a direct impact on the prevention of knee valgus. When examining kinematics, subjects with lower gluteus maximus recruitment displayed greater knee valgus angles (Hollman et al., 2009). Hollman et al. (2009) further found that gluteus maximus recruitment accounted for 20% of the variance in knee valgus angle. Gluteus maximus activation may have been able to limit knee valgus angles by eccentrically controlling femoral internal rotation (Hollman et al., 2009). The gluteus maximus must contract eccentrically because the hip goes into flexion during a jump landing. Gluteus maximus recruitment also seems to have an effect on the kinetic factors that lead to an increased risk of ACL injuries. Larger gluteus maximus activation is correlated with greater internal rotation deceleration of the tibia during walking (Preece et al., 2008). This increase in tibial deceleration might have an even larger impact on injury prevention in a more stressful task such as jump landing. Landing from a jump creates a greater magnitude of forces, which can lead to even faster tibial internal rotation. If the gluteus maximus is able to contract and control tibial internal rotation velocity, the ACL will not experience as much shear force, relieving the strain and reducing risk of injury.

Hamstrings

The hamstrings are the primary flexors of the knee and can aid the ACL in preventing anterior tibial translation (Krogsgaard, Dyhre-Poulsen, & Fischer-Rasmussen, 2002). Since the hamstrings are knee flexors, increases in strength should increase knee flexion angles. In a cross-sectional study, hamstring strength was positively correlated with knee flexion angle (Salci, Kentel, Heycan, Akin, & Korkusuz, 2004). Greater hamstrings strength may also limit knee valgus motion and moment, as greater knee flexion peak torque produced a lesser valgus knee angle, and knee flexion torque explained over 18% of the variability when predicting frontal plane knee movement (Claiborne et al., 2006). Even though knee flexor strength may be correlated with knee valgus and greater knee extension, increases in knee flexor strength may not produce biomechanical changes. Herman et al. (2008) found that a 25% increase in hamstrings strength did not produce any changes in sagittal or frontal plane knee movement when landing from a jump. The results of these studies seem to indicate that a confounding variable might be present in the cross-sectional studies that produce a relationship between hamstrings strength and landing mechanics.

The confounding variable present in the previous studies of hamstrings strength might be hamstrings activation. When the hamstrings are activated alone, the strain of the ACL decreases relative to normal passive strain of the ACL in a cadaveric model (Renstrom et al., 1986). This decreased strain from increased hamstrings activation seems to affect knee valgus angles. Higher preparatory lateral hamstring, or lateral hamstrings, activation measured by EMG analysis produced higher knee valgus angles in subjects who performed a forward hopping task (Palmieri-Smith et al., 2008). Higher activation of the lateral hamstrings may cause higher knee valgus angles because the line of pull by the lateral hamstrings muscle may be able to provide a small internal adduction force on the knee. Unlike the lateral hamstrings, the line of pull of the medial hamstrings, the semimembranosis and semitendinosis may cause a slight adduction torque on the knee and help prevent knee valgus. Subjects who exhibit delayed activation of the medial hamstrings also exhibit greater knee valgus torques (McLean et al., 2010). This delay in medial hamstrings activation accounted for over 35% of knee valgus during an anticipated single-leg landing task and 60% of the variance in knee valgus torques during an unanticipated singe-leg landing task respectively (McLean et al., 2010). These results indicate that if the medial hamstrings muscles contract to a greater extent than the lateral hamstrings muscles prior to landing, knee valgus angles and torques might be prevented.

TRADITIONAL REHABILITATION

Even though strength does not seem to influence risk factors associated with ACL injuries, a basic resistance program for the gluteal muscles can still provide athletes with an understanding of how to contract their gluteal muscles. Previous literature suggests that a resistance exercise must produce muscle activity greater than 50% MVIC (Atha, 1981). Using this criterion, the best exercises to strengthen the gluteus maximus seem to be a quadruped opposite arm and leg reach, single leg squat, and single leg dead lift (Distefano, Blackburn, Marshall, & Padua, 2009; Ekstrom, Donatelli, & Carp, 2007). It appears that a large hip extensor torque is needed in order to produce strength gains, which is consistent with the action of the gluteus maximus. When trying to gain strength in the gluteus medius, the strength exercises needed either use frontal plane movement or stabilization of the body with one leg. Based on the greater than 50% MVIC needed to produce strength gains, the best rehabilitation exercises to produce increases in gluteus medius strength seem to be side bridges, single leg abduction, single leg squats, lateral band walks, single leg dead lifts, and sideways hops (Atha, 1981; Distefano et al., 2009; Ekstrom et al., 2007).

These basic exercises are able to give an athlete a solid base of strength, but another form of exercise may be necessary to produce biomechanical changes and further reduce the risk of ACL injury. If an athlete builds strength in the hamstrings and gluteal muscles but activates those muscles improperly, the increased strength might actually lead to an increase of the risk factors that contribute to ACL injury. For example, if the gluteus maximus and gluteus medius are both strong but the gluteus maximus activates too late, an athlete will have an anterior tilt of the pelvis causing the gluteus medius to have a greater internal rotation moment arm. If the gluteus medius has a strong internal rotation contraction, the femur will internally rotate to a greater extent contributing to knee valgus and potential ACL injury. Therefore, in addition to basic strength exercises, a program that trains the neuromuscular system to contract muscles properly would be advantageous in order to prevent ACL injuries.

PHYSIOLOGICAL EFFECTS OF PLYOMETRIC EXERCISES

Plyometric exercise programs attempt to train the neuromuscular system and have the potential to prevent injuries. Plyometric exercises are defined as activities in which muscles are stretched and then shortened in rapid sequence. Plyometric exercise takes advantage of the series elastic component of a muscle fiber that is able to store energy during eccentric contraction. If the change in direction is quick enough, the new agonist will already have stored energy to use in contraction. In using this stretch-shortening cycle, plyometrics can influence muscle characteristics such as fiber size and power. Although plyometric exercises do not change fiber type, they are able to increase muscle fiber size, possibly by up to 30% (Malisoux, Francaux, Nielens, & Theisen, 2006; Potteiger et al., 2005). Increases in fiber size indicate that individual muscle fibers are getting stronger through plyometric exercise and may add supplemental strength benefits when added to a basic resistance program. Plyometric exercises can also improve the velocity of muscle fiber contraction by up to 29% depending on the fiber type (Malisoux et al., 2006). Since the individual muscle fibers are larger and are able to contract more quickly, peak power of every fiber type increases by over 25% (Malisoux et al., 2006). This increase in power is important because muscles would be able to create more force in less time, potentially improving their ability to prevent kinematic and kinetic factors that are associated with ACL injury.

Plyometric exercises not only produce changes in the muscles and tendons but can also alter motor unit recruitment patterns (Potteiger et al., 2005). One of these changes in motor unit recruitment patterns is an increase in the activation levels of the muscles that are trained. This increase is apparent during running, as triathletes who completed a plyometric program exhibited increases in activation of the tibialis anterior, lateral gastrocnemius, rectus femoris, and lateral hamstrings when compared to baseline testing (Bonacci et al., 2011). Increases in activation are also seen in subjects who complete jumping activities after a plyometric program (Chimera, Swanik, Swanik, & Straub, 2004; Wu et al., 2010). After participation in a plyometric program, subjects increased activation of their hip abductors, hip adductors, and the triceps surae complex during a vertical jump test (Chimera et al., 2004; Wu et al., 2010). This increase in muscle activation is one of the rationales that has been used by researchers to explain the increase in jump height and agility performance that is observed by subjects who have completed a plyometric training program (McBride, McCaulley, & Cormie, 2008; Miller, Herniman, Ricard, Cheatham, & Michael, 2006).

Plyometric exercises also have the ability to change the timing of muscle activation. This change is evident in subjects who underwent a plyometric training program and subsequently were able to decrease the time to peak reactivity (i.e. the time that a muscle takes to reach peak activation) of the medial hamstrings (Lephart et al., 2005). This change seems to be unique to plyometric training because athletes who completed only basic resistance exercises did not experience any changes in medial hamstrings activation (Lephart et al., 2005). Changes to the timing of muscle activation also seem to be apparent in the quadriceps muscle after plyometric training (Mikkola, Rusko, Nummela, Paavolainen, & Hakkinen, 2007). Cross-country skiers who underwent an 8-week plyometric program in addition to their endurance training regimen exhibited an significant increase in vastus lateralis and vastus medialis force production in the early activation period (0-100ms) when compared to a control group who only completed endurance training (Mikkola et al., 2007). Therefore, plyometric programs seem to be able to improve a muscle’s ability experience early activation, thereby increasing the total force produced by a muscle over time. As the motor recruitment patterns become more efficient, the muscle is able to contract earlier and in better synergy with other muscles in the body. This change in motor unit recruitment patterns could help the lower extremity muscles contract with proper timing in order to prevent ACL injuries.

PLYOMETRIC EFFECTS ON KINEMATICS

Because of the changes that are produced in both the elasticity of the tendons and the improvement in motor unit recruitment patterns, plyometric exercise programs should be able to impact the musculature and consequently the movements that affect an athlete's risk for sustaining an ACL injury. Plyometric training programs are able to increase knee flexion angles at initial ground contact as well as peak knee flexion during jumping and landing tasks (Chappell & Limpisvasti, 2008; Lephart et al., 2005; Myer, Ford, McLean, et al., 2006). This increase in knee flexion angles occurs regardless of the plane in which the plyometric exercises were performed (Arabatzi, Kellis, & Saez-Saez De Villarreal, 2010; Chappell & Limpisvasti, 2008; Lephart et al., 2005; Myer, Ford, McLean, et al., 2006). This increase in knee flexion angles has been attributed to an increase peak hamstrings torque as measured by an isokinetic testing device (Hewett, Stroupe, Nance, & Noyes, 1996; Wilkerson et al., 2004). However, these changes in peak torque might actually be related to increased activation that occurs when a subject begins a training program (Tillin, Pain, & Folland, 2011). Theoretically, an increase in activation should lead to an increase in peak torque because enhanced neural activity would allow more muscle fibers to be depolarized. The fact that plyometric programs are also able to decrease the time to peak reactivity of the hamstrings might explain the ability of plyometrics to increase knee flexion angles (Lephart et al., 2005). This decrease in time to peak reactivity could cause knee flexion to occur earlier in the landing process, which would increase knee flexion angles upon contact.

Plyometric programs also seem to be able to influence knee valgus angles. Plyometric exercises could have an effect on knee valgus because of the decreased time to reach peak reactivity of the medial hamstrings and the increased co-activation of the abductor and adductor muscles (Chimera et al., 2004; Lephart et al., 2005). As previously discussed, the decrease in time to peak reactivity could help provide a varus force to the knee while the increase in co-activation of the abductor and adductor muscles could place the knee in a more neutral frontal plane position (Chimera et al., 2004). Because of the changes in muscle activation, a change in knee valgus should occur upon completion of a plyometric program. However, changes in knee valgus from ACL prevention protocols seems to be affected by the type of plyometric exercises that are incorporated into those programs. A program primarily focused on sagittal plane plyometric exercises did not have any effect on either knee valgus angle at ground contact or at peak valgus angles (Chappell & Limpisvasti, 2008), but a program which included multi-planar exercises did decrease initial ground contact and maximal knee valgus angles (Myer, Ford, McLean, et al., 2006). These differences would seem to suggest that plyometric exercises performed in multiple planes induce changes in the activation of muscle that help prevent knee valgus that plyometric exercises performed only in the sagittal plane do not produce. Therefore, plyometric exercises performed in the sagittal plane may not change the activation of the gluteus medius, gluteus maximus, or medial hamstrings.

PLYOMETRIC EFFECTS ON KINETICS

Seeing that plyometric exercise programs are able to influence an athlete’s kinematics, they should also be able to produce changes in kinetics. The first change in kinetics that is produced by a plyometric program is a change in vgrf. After participation in ACL prevention programs which include plyometric exercises, subjects can reduce their peak impact forces upon landing (Hewett et al., 1996; Irmischer et al., 2004). This reduction in forces is extremely important as athletes are trained to jump higher. When athletes jump higher, higher forces are generated (Irmischer et al., 2004). Since no clinician can control forces added by an increase in jumping height, they must instead control the forces present at landing (Irmischer et al., 2004). If forces are decreased at landing, the amount of stress placed on the lower extremity will decrease. This reduction in stress should decrease the risk of lower extremity injury, including injury to the ACL.

Since certain plyometric programs are able to decrease knee valgus angles and vgrf (Chappell & Limpisvasti, 2008; Irmischer et al., 2004; Myer, Ford, McLean, et al., 2006), one could surmise that plyometrics are also able to decrease knee valgus moments. This assumption does appear to be true as ACL prevention programs that include plyometric exercises can reduce knee valgus torques upon completion of a drop jump by up to 28% in a general population and up to 13% in a high ACL injury risk population (Hewett et al., 1996; Myer, Ford, Brent, & Hewett, 2007; Myer et al., 2005). Even though plyometric exercises aided in the ability of the high risk population to decrease knee valgus moments, that decrease did not reduce knee valgus angles in these individuals such that they were no longer categorized as high risk (Myer et al., 2007). However, these decreases in knee valgus moments might still be clinically significant because any decrease in knee valgus moment should reduce ACL stress.

PLYOMETRIC PREVENTION PROGRAMS' EFFECTS ON ACL INJURIES

If plyometric programs are able to decrease the kinetics and kinematics associated with increased risk of ACL injury, they should be able to actually prevent injuries when applied to a population of athletes. These prevention programs that use plyometrics to aid in the prevention of ACL injury seem to produce mixed results. Some studies on female athletes have shown that completion of a prevention program that includes plyometrics successfully reduces ACL injury risk (Hewett et al., 1999; Mandelbaum et al., 2005). However, others show that the completion of an ACL injury prevention program does not prevent the occurrence of ACL or lower extremity injuries (Pfeiffer et al., 2006; Steffen et al., 2008). One study even showed an insignificant reduction in ACL injuries with the completion of an ACL prevention program during one season and a significant reduction in the next season (Myklebust et al., 2003).

One reason for the discrepancy in effectiveness seems to be compliance rate. Many studies that incorporate a warm-up that is given to coaches have low compliance (Myklebust et al., 2003; Pasanen et al., 2008; Pfeiffer et al., 2006; Steffen et al., 2008). Of the two plyometric programs which did not work, one had only 26% of teams complete the compliance criteria and the other had an average of 20 training sessions completed in two years (Pfeiffer et al., 2006; Steffen et al., 2008). When only considering teams with higher compliance, athletes who complete prevention programs which include plyometric exercises have even lower risk of lower extremity injury, including severe knee injuries, than teams who did not complete the prevention program or had low compliance (Pasanen et al., 2008; Steffen et al., 2008).

Another major reason for the ineffectiveness of plyometric programs in preventing

ACL injury may also be the exercises that were completed during the plyometric program. In a plyometric program that had success in preventing ACL injury, Mandelbaum et al. (2005) explained that the program was designed to address the feed-forward mechanism to anticipate external forces and emphasize gluteal muscle strength. This reasoning seems to be sound because most of the plyometric exercises were performed in the frontal plane or on one leg, but no other data collected seem to indicate any focus on the gluteal muscles. Plyometric programs that did not have success in preventing ACL injury did not include many repetitions of frontal plane or single leg exercises (Myklebust et al., 2003; Pfeiffer et al., 2006; Steffen et al., 2008). In fact, only one of these programs (Pfeiffer et al., 2006), included more than one frontal plane and one single leg exercise during the entire program (Myklebust et al., 2003; Steffen et al., 2008). Frontal plane and single leg exercises have been shown to enhance activation of the gluteus medius, one of the muscles that helps prevent knee valgus (Distefano et al., 2009; Houck, 2003; Mercer et al., 2009). Therefore, targeting more muscles responsible for preventing ACL risk factors, the gluteals and hamstrings, should help improve the efficacy of plyometric programs. This increase in efficacy of the programs could also lead to increased athlete compliance with these programs because exercises which do not help change biomechanics that lead to ACL injury would be eliminated. This streamlining of ACL injury prevention programs would lead to a decrease in the time that the prevention program requires as well as minimizing the burden on coaches to use practice time or remember all of the exercises that the athletes need to complete.

CONCLUSION

Many factors contribute to the risk of ACL injuries in an athletic population.

Activation of the medial hamstrings, gluteus medius, and gluteus maximus seem to help prevent some of the risk factors that lead to ACL injuries, while the effects of the strength of those muscles are still debated. Plyometric exercises seem to be effective in reducing both the risk factors associated with ACL injury and ACL injuries themselves. Previous research has attempted to quantify muscle activity during plyometric exercises, but the exercises were primarily performed in the sagittal or vertical plane, and the muscle activity of the gluteus medius and the gluteus maximus has not been included (Ebben, Simenz, & Jensen, 2008). If increases in gluteus medius, gluteus maximus, and medial hamstrings activity decrease ACL injury risk, clinicians should attempt to find plyometric activities that elicit greater activation of those muscles. Therefore, the purpose of this study is to determine which plyometric exercises produce the greatest mean amplitude of the gluteus medius, gluteus maximus, lateral hamstrings, and medial hamstrings muscles both prelanding and during the loading phase. By determining the plyometric exercises that activate these muscles most effectively, ACL prevention programs may be able to be more concise and efficient in preventing ACL injuries.

CHAPTER III

METHODOLOGY

SUBJECTS

Forty-one subjects (20 males, 21 females) between the ages of 18 and 30 were recruited from the University of North Carolina-Chapel Hill campus. Subjects were eligible to be included in the study if they self-reported participation in physical activity for a minimum of 30 minutes per day, 3 times per week for the past six months. Subjects were excluded if they suffered a lower extremity or lower back injury within the six months prior to participation, or had a previous history of surgery in either lower extremity. Subjects were instructed to stop resistance training within the 48 hours prior to testing.

INSTRUMENTATION

Electromyography

A surface electromyography (EMG) system (DelSys, Inc., Boston, MA, USA: interelectrode distance 10 mm; amplification factor 1,000 (20 – 450 Hz); CMMR @ 60 Hz > 80 dB; input impedance > 10^{15}//0.2 Ω//pF) was applied to the subject to record muscle activity of the gluteus medius, gluteus maximus, medial hamstrings, and lateral hamstrings.

Kinetic Data

One conductive force plate (Bertec 4060, Columbus, OH) was used to collect vertical ground reaction forces to properly identify the beginning and end of both the preparatory and loading phases.

PROCEDURES

Subjects reported to the Neuromuscular Research Laboratory wearing athletic shoes, shorts, and a t-shirt for testing. Each subject read and signed an informed consent document approved by the University of North Carolina Biomedical Institutional Review Board. Demographic information and injury history were collected prior to data collection to determine whether a subject qualified for participation in the study. Eligible subjects then completed a five minute warm-up on a stationary cycle ergometer at a self-selected pace. After the warm-up, subjects were were asked to report their dominant leg as the leg that they would use to kick a soccer ball for maximum distance. Then, the primary researcher explained and demonstrated one repetition of each exercise as follows:

***180° jump*:** The subject was instructed to stand with the non-dominant foot on the force plate and the dominant foot off of the force plate. The subject then jumped in rhythm with a metronome set at 76 beats per minute while performing a 180° turn in the transverse plane toward the non-dominant shoulder, landing with the non-dominant foot off the force plate and the dominant foot on the force plate. On the next beat of the metronome, the subject jumped and completed another 180° turn over the dominant shoulder, returning to the starting position. This sequence occurred a total of three times.

***Frontal Plane Hurdle Hop*:** The subject was instructed to start standing, feet straddling a line, with the dominant foot at a distance of 50% of the subject's height from the center of one of the force plates and the non-dominant leg closest to the force plate. A 10.16cm tall hurdle was placed halfway between the subject's dominant leg and the center of the force plate. The subject then jumped laterally in rhythm with a metronome set at 76 beats per minute metronome over the hurdle towards his/her non-dominant leg and landed with the dominant foot on the force plate and the non-dominant foot off of the force plate. On the next beat of the metronome, the subject jumped in the opposite direction over the hurdle and returned to the initial starting position. This sequence occurred a total of three times.

***Double Leg Sagittal Plane Hurdle Hop*:** The subject was instructed to start standing behind a line with the feet at a distance 50% of his/her height from the center of the force plates. A 10.16cm tall hurdle will be placed halfway between the subject's feet and the center of the force plates. With the metronome again set at 76 beats per minute, the subject jumped forward over the hurdle in the sagittal plane and landed with the dominant foot on the force plate and the non-dominant foot off the force plate. On the next beat of the metronome, the subject jumped backward over the hurdle and return to the initial starting position. This sequence occurred a total of three times.

***Single Leg Sagittal Plane Hurdle Hop*:** The subject was instructed to start standing on the dominant foot behind a line a distance 30% of his/her height from the center of the force plate. A 10.16cm tall hurdle was placed halfway between the subject's feet and the center of the force plate. With the metronome set at 76 beats per minute, the subject jumped forward over the hurdle in the sagittal plane and land with the dominant foot on the force plate. On the next beat of the metronome, the subject jumped backward over the hurdle and return to the initial starting position. This sequence occurred a total of three times.

***Split Squat Jump*:** The subject was instructed to begin in a lunge position with the non-dominant leg immediately lateral to the force plate and the dominant limb behind the force plate. With the metronome set at 76 beats per minute, the subject jumped in the air while moving the non-dominant limb backward and immediately the dominant limb forward onto the force plate, landing in a lunge position. On the next beat of the metronome, the subject jumped as high as possible and switched the legs back to the starting position. This sequence occurred a total of three times.

After the exercises were explained, the subject was allowed to practice each exercise until he/she felt comfortable with each exercise. Each subject was required to practice each exercise a minimum of two times.

Following the completion of practice trials, surface EMG electrodes were placed on each subject's dominant leg. Before the electrodes were placed on the subject, the skin was shaved if necessary, abraded, and cleaned with isopropyl alcohol to maximize the electrode adherence to the skin and minimize skin impedance. A differential parallel-bar surface EMG sensor (DE-2.1 Delsys, Inc., Boston, MA: interelectrode distance=10mm; sensor material; nickel-silver) was placed on each muscle using a double-sided adhesive skin interface (Delsys, Inc., Boston MA). Electrode placements were determined based on the SENIAM guidelines and are as follows:

***Gluteus Maximus*:** The electrode for the gluteus maximus was placed at the greatest prominence of the middle of the buttocks at a distance of 50% on the line between the sacral vertebrae and the greater trochanter with the subject lying prone (Hermens et al., 2000).

<u>Gluteus medius:</u> The electrode for the gluteus medius was placed at a distance of 50% on the line from the iliac crest to the greater trochanter with the subject lying on his contralateral side (Hermens et al., 2000).

***<u>Medial hamstrings</u>*:** The electrode for the medial hamstrings was be placed at a distance of 50% on the line between the ischial tuberosity and the medial epicondyle the of tibia with the subject lying supine (Hermens et al., 2000).

***<u>Lateral hamstrings</u>*:** The electrode for the lateral hamstrings was placed at a distance of 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia with the subject lying supine (Hermens et al., 2000).

Each electrode was placed approximately parallel to the muscle fiber orientation. The placement of the electrodes on the gluteus maximus, gluteus medius, medial hamstrings, and lateral hamstrings was confirmed with observation of the muscle activity on an oscilloscope during isometric hip extension, hip adduction, and knee flexion against resistance applied by the investigator. The wires and sensors were secured to the skin with elastic wrap to prevent motion artifact.

Following electrode placement, each subject performed three block randomized trials of maximum voluntary isometric contraction (MVIC) for the gluteus maximus, gluteus medius, and hamstrings for five seconds against a handheld dynamometer. EMG amplitudes during these contractions were used as normalization criteria for EMG activity during the plyometric exercises. MVIC for each muscle was tested in the following positions:

***<u>Gluteus Maximus</u>*:** The subject lay prone with his knee flexed to 90° and extended his hip off of the table and attempted to extend the hip while the researcher, who stood on an elevated box, provided a downward force on the thigh. Before contraction, a strap was placed around the patient's lower back to prevent accessory motion (Hislop & Montgomery, 1995).

***Gluteus Medius*:** The subject lay on his non-dominant side with the hip in a neutral position. The researcher, standing on an elevated box behind the patient, provided a downward force while the subject attempted to abduct his hip. Before contraction, a strap was placed around the patient's lower back to prevent accessory motion (Hislop & Montgomery, 1995).

***Hamstrings*:** The subject lay prone with the knee flexed to 90°. The researcher provided manual resistance in the direction of knee extension while the subject flexed the knee. Before contraction, a strap was placed around the patient's hips to hip extension and other accessory motion (Hislop & Montgomery, 1995).

Once the EMG sensors were set on the subject, EMG activity of the gluteus maximus, gluteus medius, and hamstrings was collected during all five plyometric exercises. The plyometric exercises were completed in a block randomized order to avoid an order effect. A one minute rest period was given between each exercise to reduce the likelihood of fatigue. If a subject did not land on the force plate, touched the hurdle with his/her foot, lost balance at any point, did not perform the exercises with proper technique as assessed by the primary researcher, did not complete the trial within 9 beats of the metronome, or if the subject's movement was impeded by cables, the trial was discarded and repeated. Subjects were excluded from the study if they performed 5 bad trials throughout the testing protocol or could not properly complete the exercises during the practice trials.

DATA REDUCTION

All EMG data was bandpass filtered between 20 and 350 Hz and notch filtered between 59.5 and 60.5 Hz with a 4^{th} order Butterworth filter and smoothed using a 15ms root mean squared sliding window. All kinetic data were collected at 1,000 Hz and low pass filtered with a 4^{th} order Butterworth filter at 60 Hz.

The kinetic and EMG data were reduced using a custom LabVIEW software program (National Instruments, San Antonio, TX). Mean EMG of the gluteus maximus, gluteus medius, and hamstrings across all three trials was calculated for both the preparatory and loading phases. The preparatory phase was defined as the 150ms before initial contact (Lephart et al., 2005). The loading phase will be defined as the time from initial ground contact to 50% of the ground contact interval. Initial ground contact will be defined as the point at which the vertical ground reaction force exceeds 10 N after the participants contact the force plate.

All EMG data were normalized to the mean EMG amplitude during MVIC. The mean EMG amplitude for each subject's MVIC was calculated during the middle three seconds of the five second MVIC contraction. All data analysis was performed on normalized EMG (%MVIC) values. After normalization, EMG data was averaged across all three trials completed by each participant before analysis. The medial hamstrings to lateral hamstrings ratio was calculated by dividing the normalized EMG of the medial hamstrings by the normalized EMG of the lateral hamstrings.

STATISTICAL ANALYSES

All statistical analyses were performed using SPSS 18.0 (SPSS Inc. Chicago, IL). The reduced EMG amplitudes were compared between exercises using ten separate one-way repeated measures ANOVAs, one for each of the four muscles during the preparatory and loading phases and one for medial hamstrings/lateral hamstrings co-activation ratio during the preparatory and lading phase. All significant ANOVA values were evaluated *post hoc* via Tukey's HSD post-hoc test. A priori alpha levels were set at 0.05. *A priori* power analysis from a t-test model predicted an effect size of 0.6, so 40 subjects were necessary to produce a power level above 0.8.

CHAPTER IV

RESULTS

Forty-one subjects (height = 173.2±10.24cm mass =70.32 ±13.44kg), twenty-one females and twenty males, completed the plyometric exercise protocol. One subject's data were excluded from statistical analysis because she could not complete the plyometric exercise protocol without making mistakes on 5 or more trials. Two subjects' lateral hamstrings and medial hamstrings data were excluded from the statistical analysis because the EMG electrodes fell off during testing. Other subjects' EMG data were excluded from the statistical analysis because they were statistical outliers, which were defined by values more than 3sd's beyond mean. For the preparatory phase, the number of subjects excluded from statistical analysis was: 4 subjects from the lateral hamstrings, 7 subjects from the medial hamstrings, 5 subjects from the gluteus medius, 5 subjects from the gluteus maximus, and 6 subjects from the medial to lateral hamstrings co-activation ratio. For the loading phase, the number of subjects excluded from statistical analysis was: 6 from the lateral hamstrings, 6 from the medial hamstrings, 5 from the gluteus medius, 7 from the gluteus maximus, and 6 from the medial to lateral hamstrings co-activation ratio. Many of these subjects excluded from the statistical analysis were excluded from both the preparatory and loading phase analyses for multiple muscles.

Significant main effects between exercises ($p < 0.01$) were found for each muscle during the preparatory phase (Table 2 and Figures 1-4). Upon post-hoc analysis, the single leg sagittal plane hurdle hop demonstrated significantly greater preparatory activation of the lateral hamstrings, medial hamstrings, gluteus medius, and gluteus maximus than any other exercise (Table 2 and Figures 1-4). Additionally, for the medial hamstrings, the double leg sagittal plane hurdle hop displayed significantly greater preparatory activation (20.65 ± 12.31%) than both the frontal plane hurdle hop (16.04 ± 10.35%) and the 180^{o} jump (13.46 ± 8.16%), and the split squat jump (19.36 ± 11.33%) displayed significantly greater preparatory activation than the 180^{o} jump (13.46 ± 8.16%) (Table 2,Figure 2).

Significant differences main effects between exercises ($p < 0.01$) were also found for each muscle during the loading phase (Table 3, Figures 1-4). Upon post-hoc analysis, the single leg sagittal plane hurdle hop resulted in significantly greater loading phase activation of the gluteus medius and gluteus maximus than all other exercises (Table 2, Figures 3,4). The single leg sagittal plane hurdle hop also displayed significantly greater loading phase activation of the lateral hamstrings than the double leg sagittal plane hurdle hop (40.87±23.95%), frontal plane hurdle hop (37.95±22.85%), and 180^{0} jump (33.11±20.11%) as well as significantly greater loading phase activation of the medial hamstrings than the split squat jump (22.90±13.25%) and 180^{o} jump (16.37±8.83%) (Table 3, Figures 1,2). More differences in loading phase activation were also present in the medial hamstrings with the double leg sagittal plane hurdle hop (24.70±15.07%), frontal plane hurdle hop (24.06±12.97%), and split squat jump (22.90±13.25%) showing greater activation than the 180^{o} jump (16.37±8.83%) (Table 3, Figure 2). For the gluteus medius during the loading phase, the split squat jump (62.44±24.07%) showed greater activation than both the 180^{o} jump (46.47±18.12%) and frontal plane hurdle hop (34.91±14.11%), and both the double leg sagittal plane cone hop (58.72±20.80) and 180^{o}

jump (46.47±18.12%) showed greater activation than the frontal plane hurdle hop (34.91±14.11%) (Table 3, Figure 3). For the gluteus maximus during the loading phase, the double leg sagittal plane hurdle hop (54.01±30.75) and split squat jump (50.93±24.02) displayed greater activation during the loading phase than both the frontal plane hurdle hop (37.06±21.78%) and 180^{o} jump (24.18±16.40%) with the frontal plane hurdle hop (37.06±21.78%) also showing greater activation than the 180^{o} jump (24.18±16.40%) (Table 3, Figure 4).

Finally, a significant difference between the medial hamstrings to lateral hamstrings ratio was found for both the preparatory ($p<.01$) and loading phases($p=.019$) (Table 2,3, Figure 5). Specifically, the double leg sagittal hurdle hop (1.169±0.763) and split squat jump (1.128±0.061) showed a greater medial to lateral hamstrings ratio during the preparatory phase than the single leg sagittal hurdle hop (0.750±0.400) (Table 2, Figure 5). During the loading phase, the frontal plane hurdle hop (0.686±0.342) displayed a significantly greater medial to lateral hamstrings ratio than the 180^{o} jump (0.548±0.266) (Table 3, Figure 5). EMG activity for each muscle during each exercise were rank ordered and are presented in tables 2 and 3.

CHAPTER V

DISCUSSION

Our investigation demonstrated that the single leg sagittal plane hurdle hops produced the greatest mean activation of the gluteus medius, gluteus maximus, medial hamstrings, and lateral hamstrings during both the preparatory and loading phases compared to all other plyometric exercises. Conversely, the 180^{o} jumps consistently produced the lowest activation of all muscles and exercises with one exception: the gluteus medius during the loading phase of the frontal plane hurdle hop. Additionally, the double leg sagittal plane hurdle hops and split squat jumps produced a medial hamstrings to lateral hamstrings co-activation ratio of greater than one during the preparatory phase, indicating that the medial hamstrings were more active than the lateral hamstrings during the preparatory phase of those exercises.

To our knowledge, this study was the first to examine preparatory and loading phase muscle activation of the hamstrings, gluteus medius and gluteus maximus during plyometrics performed in multiple planes. One previous study examined lateral hamstrings EMG during plyometric exercises, but no differences in EMG activity were observed between exercises even though single-leg hopping was included in the exercise protocol (Ebben et al., 2008). The cause of this difference in hamstrings activity between our study and the study by Ebben et al. (2008) may be twofold. First, hamstrings EMG in the study by Ebben et al. (2008) was variable in people with different landing strategies, leading to a lack of power in a smaller sample size. Secondly, different exercises were included in each study, and the three of the exercises in this study required a subject to jump a distance of 30-50% of his height contrary to the study by Ebben et al. (2008) where subjects jumped in the vertical plane or a short distance off of a box. Since the primary actions of the hamstrings are to flex the knee, extend the hip, and provide a restraint to anterior tibial momentum, a larger hopping distance would place a greater load on the hamstrings because of the increased sagittal plane momentum created by the plyometric task (Ebben et al., 2008). This greater distance hopped could also create greater activation of the hamstrings because the hamstrings help propel the body posteriorly during a sagittal plane plyometric exercise. Hamstrings activation could have been altered by posterior propulsion of the body even though it was measured only during the loading phase because the dynamic nature of plyometric exercises required the subjects to control their momentum and immediately produce momentum in the opposite direction. Therefore, the hamstrings activation observed during the loading phase of sagittal plane exercises might be a combination of both momentum absorption and production.

Even though the primary action of the hamstrings occurs in the sagittal plane, the hamstrings can control varus and valgus motion at the knee (Lloyd, Buchanan, & Besier, 2005). With regard to ACL injury, the medial hamstrings have a substantial moment arm that can create knee varus motion and moment (Lloyd et al., 2005). Therefore, higher activation of the medial hamstrings relative to the lateral hamstrings may limit valgus knee movement and ACL loading (Lloyd et al., 2005; Palmieri-Smith et al., 2008). In our study, the sagittal plane exercises provided the greatest activation of the medial hamstrings before initial ground contact, with both the double leg sagittal plane hurdle hops and split squat jumps producing a medial hamstrings to lateral hamstrings co-activation ratio of greater than one during the preparatory phase. A medial to lateral hamstrings co-activation ratio greater than one is indicative of greater activity in the medial hamstrings relative to the lateral hamstrings and may be beneficial in terms of ACL loading because activation of the medial hamstrings helps resist valgus forces placed on the knee while activation of the lateral hamstrings can introduce a valgus knee moment (Zhang & Wang, 2001).

During the loading phase, the medial hamstrings became more active during the frontal plane hurdle hops, and this exercise produced the third greatest activation of the medial hamstrings during the loading phase (not significantly different than the two exercises which produced greater medial hamstrings activation). Additionally, the frontal plane hurdle hops produced the greatest medial to lateral hamstrings co-activation ratio of all exercises during the loading phase (significantly greater than the 180^{o} jumps). This activity of the medial hamstrings during the loading phase is similar to findings by Houck (2003) who observed that frontal plane exercises produced greater medial hamstrings activity than an equivalent sagittal plane task. Even though the loading phase frontal plane ratio is less than one, and knee valgus motion still occurs, a greater ratio may still be important because it may still help limit the extremes of knee valgus. Also, both medial and lateral hamstrings activity increased during the loading phase of the frontal plane hurdle hops, so overall knee joint stability may have improved because of greater joint compression and overall muscle stiffness. This activation of the medial hamstrings during the loading phase is most likely a feed-forward mechanism that is pre-programmed to occur after landing. During fast movements such as plyometrics, feed-forward neuromuscular control is used to produce specific movements (Enoka, 2002). Since the medial hamstrings can provide a varus moment (Lloyd et al., 2005) and presumably limit ACL loading, frontal plane hurdle hops may result in better activation patterns after landing based on the ratios observed in this study. However, these loading phase activation patterns might not attenuate ACL loading due to the fact that ACL injuries occur early in the loading phase (Koga et al., 2010). Even though the medial hamstrings became more active during the loading phase of the frontal plane hurdle hops, the lateral hamstrings also became more active, and the observed medial to lateral hamstrings co-activation ratio decreased. This change in co-activation ratio may contribute to greater valgus knee angles during the loading phase compared to initial ground contact as observed in previous literature (Ford et al., 2003; Lephart et al., 2005).

Activation of the gluteus medius was significantly less during the frontal plane hurdle hop than any of the other exercises. This finding is unexpected and contrary to our hypotheses because the gluteus medius would seemingly be more active during this task to prevent excessive frontal plane hip motion. Our findings also differ from previous literature demonstrating that the gluteus medius is most active during frontal plane step-ups compared to sagittal plane step ups and active to similar levels during frontal plane hop-to-stabilization exercises compared to transverse and sagittal plane hop to stabilization exercises (Distefano et al., 2009; Mercer et al., 2009). The difference in gluteus medius activation between our study and other studies may also exist because of the data collection process. During the frontal plane hurdle hops, each subject jumped toward the non-dominant limb, landed with the dominant limb on the force plate and the non-dominant limb off the force plate, and then jumped back to the starting position.

Because of the position of the force plate and its necessity for identification of landing phases, EMG data were collected only as the subject jumped toward the non-dominant limb. During this direction of the plyometric exercise, subjects may have used their non-dominant limbs rather than their dominant limbs to absorb and produce force to change directions and may have experienced a pelvic shift toward the non-dominant leg. Upon landing, this use of the non-dominant limb may have concentrically activated the gluteus medius on the non-dominant limb or eccentrically activated the adductors on the dominant limb rather than the gluteus medius on the dominant limb to limit the pelvic shift towards the non-dominant limb that may occur during the frontal plane hurdle hop. However, this theory cannot be confirmed because no EMG activity was measured on the non-dominant limb.

In addition to differences in the data collection process, our results may have differed from previous studies (Distefano et al., 2009; Mercer et al., 2009) because other muscles not measured in this study may have been active to control or produce frontal plane motion. One of these muscle groups, the hip adductors, may have contracted eccentrically to control frontal plane hip motion. Also, the hip adductors may have been active to propel the body in the opposite direction during the landing phase. If the adductors were more active during the gluteus medius during the early loading phase, greater knee valgus could have occurred at the beginning of the loading phase as greater hip adductor activity correlates to greater knee valgus angles (Jacobs et al., 2007). These increases in valgus angles may increase ACL injury risk (Hewett et al., 2005). Because of the lesser activation of the gluteus medius observed during the exercise, frontal plane hurdle hops may not be a good plyometric exercise to change biomechanics that lead to

ACL injury. Given that frontal plane hurdle hops seem to be an important component in plyometric programs aimed at ACL injury prevention (Hewett et al., 1999; Mandelbaum et al., 2005), a further investigation is needed on why gluteus medius EMG was not higher during the frontal plane hurdle hops.

The finding of lesser gluteus medius activity in the frontal plane hurdle hops compared to other plyometric exercises also differs from previous literature demonstrating that the gluteus medius is most active during frontal plane step-ups compared to sagittal plane step ups and active to similar levels during frontal plane hop-to-stabilization exercises compared to transverse and sagittal plane hop to stabilization exercises (Distefano et al., 2009; Mercer et al., 2009).

Gluteus maximus activation during the preparatory and loading phases was greatest during the single leg sagittal plane hurdle hop, and the values were only slightly greater than previously observed gluteus maximus activation values observed during single leg landings (Zazulak et al., 2005). In the loading phase, gluteus maximus activity during the double leg sagittal plane hurdle hops and split squat jumps was significantly higher than gluteus maximus activation during the frontal plane hurdle hops and split squat jumps. The observation that gluteus maximus activity is greater during sagittal plane exercises may be explained by the fact that the primary action of the gluteus maximus is to extend the hip, and the secondary action is to produce external rotation of the femur. These actions of the gluteus maximus would suggest that more muscle fibers are recruited to perform hip extension than to perform femoral external rotation during this task. The gluteus maximus also must contract eccentrically to limit hip flexion moments and anterior pelvic tilt (Alvim et al., 2010). Even though all the plyometric exercises included during this study involved hip flexion, the hip flexion moments during the sagittal plane exercises were most likely greater than the hip flexion angles observed in frontal or transverse plane exercises. This difference in hip flexion angle may exist because higher hip flexion angles were most likely needed to counteract the anterior momentum created during the sagittal plane exercises compared to frontal or transverse plane exercises. Also, greater hip flexion angles were required to complete the split squat jump, so high activation of the gluteus maximus may have been needed to control those high hip flexion angles.

Muscle activation is an important factor in determining which exercises should be used in the clinical setting. At first glance, the results of this study suggest that a single leg sagittal plane hurdle hop may be an important plyometric exercise to include in an ACL prevention program because the activation of the medial hamstrings, gluteus medius, and gluteus maximus during the preparatory phase is greater than all other exercises included in this study. These results are similar to other studies on dynamic strengthening exercises in which the gluteus medius and gluteus maximus are activated more during a single leg squat than during a double leg squat (Lubahn et al., 2011; McCurdy et al., 2010). High activation of the hamstrings during the single leg sagittal plane hurdle hop may also be important in increasing stability at the knee joint. If the medial and lateral hamstrings become more active, the knee will experience an increase in stability because of the increase in dynamic stabilization of the knee. Hamstrings activity is also important in restraining the anterior translation of the tibia (Baratta et al., 1988). Because of the increased hamstrings activity found in this study, anterior translation of the tibia should be restricted, and the single leg sagittal plane hurdle hops may decrease sagittal plane risk factors for ACL injury (Podraza & White, 2010; Taylor et al., 2010).

The single leg sagittal plane hurdle hop also exhibited a significantly lower medial to lateral hamstrings co-activation ratio compared to the double leg sagittal plane hurdle hop and split squat jump. This lower co-activation ratio may have been observed because of the higher lateral hamstrings activity needed to perform the single leg sagittal plane hurdle hops compared to the double leg plyometric exercises. Higher lateral hamstrings activity during single leg dynamic exercises has been documented in previous literature (McCurdy et al., 2010) and may be detrimental to knee mechanics because the lateral hamstrings may produce a valgus moment about the knee. High lateral hamstrings activity during single leg plyometric exercises may be required because of the increased lower extremity stability and force demands of single leg versus double leg exercises, as single leg sagittal plane hops produce greater time-to stabilization compared to double leg exercises (Ebben, Vanderzanden, Wurm, & Petushek, 2010). Single leg sagittal plane hurdle hops require the dominant limb to resist full ground impact compared to the other exercises where the dominant limb is only required to resist about half of the ground impact. Because of this increase in forces and decrease in stability, the muscles of the thigh must increase co-activation for a subject to perform the exercise correctly and stay balanced. One might expect that the medial hamstrings would increase activity to match the increase lateral hamstrings activity for balance to occur and excessive knee valgus to be avoided. However, that increase may not occur because the increase gluteus medius activation or a potential increase in lateral gastrocnemius activity may aid the medial hamstrings in limiting the knee valgus created by increased lateral hamstrings activation.

Because of the high activation of all muscles and low medial to lateral hamstrings ratio, clinicians may want to use an exercise progression to prepare their athletes for single leg sagittal plane hurdle hops (Hewett et al., 1996; Myer, Ford, McLean, et al., 2006; Myklebust et al., 2003).

On the other hand, the 180^o jumps produced either the smallest or 2^{nd} smallest activation of each muscle during both phases of the all of the exercises. This exercise also resulted in the lowest medial to lateral hamstrings co-activation ratio during the loading phase and the 2^{nd} lowest co-activation ratio during the preparatory phase. We expected the gluteus maximus to be more active during the 180^o hops to control internal rotation of the hip. However, these results suggest that the 180^o jump requires less gluteus maximus activity to control and produce transverse plane movement than to control and produce sagittal plane movement. Also, other muscles that cannot be measured with surface EMG because of their depth (e.g. the piriformis, obturators, quadratus femoris, and gamelli) may aid the gluteus maximus in controlling femoral internal rotation during the 180^o plyometric exercise, thus requiring less gluteus maximus activity. Another reason that the gluteus maximus may not be as active in the 180^o jump may be the way subjects perform 180^o jumps. When performing the 180^o jumps, subjects had essentially completed the rotation of their bodies early during the flight phase. Because the rotation was essentially completed, subjects were observed to have little rotational momentum when they contacted the ground. This limited rotation would produce less internal rotation momentum of the femur and require less external rotation of the hip to control the internal rotation moment. Because of the lesser activity of the gluteus maximus in the 180^o jumps and the greater activity of the all muscles during other exercises, 180^{o} jumps may not be an important exercise to include in plyometric programs aimed at preventing ACL injury.

LIMITATIONS

We acknowledge that the current study has several limitations. First, the subjects included were only recreationally active, so conclusions drawn from this study can only be applied to others who are recreationally active and not necessarily athletes. Also, the type of exercise may be only one component of muscle activation during plyometric exercises. Other factors not examined, such as cueing and jump distance, may affect muscle activation strategies during plyometric exercises and could have changed the results of this study. Other limitations of this study were that data were only collected while the subjects were jumping in one direction, so all conclusions drawn from this study are based on half of the landings performed by each subject. Also, EMG data were only obtained from one limb during double limb exercises, so we could not assess the contributions of the non-dominant limb during the plyometric exercises.

FUTURE RESEARCH

Since plyometrics are an important component in ACL injury prevention programs (Markovic & Mikulic, 2010), further research should be performed to determine the long-term effects of different types of plyometric programs on muscle activation and biomechanics. Since our study found that single-leg plyometric exercise produce greater gluteal and hamstrings muscle activation than double leg exercises but a lower medial to lateral hamstrings activation ratio, future research should examine the changes in muscle activation and knee biomechanics from a plyometric program including all single leg exercises versus a plyometric program including double leg exercises. Similarly, since gluteal and hamstrings muscle activation were variable during sagittal plane and frontal plane exercises, researchers may want to examine if a plyometric program including only sagittal plane exercises alters muscle activation or knee biomechanics differently from a plyometric program including only frontal plane exercises. Future research should also focus on how other exercises, verbal cuing, and jump distance affect gluteal and hamstrings activation. Future research should also examine gluteal and hamstrings activation during plyometric exercises that were not included in this study.

CONCLUSION

Our results suggest that single leg sagittal plane plyometric exercises produce the greatest activation of the gluteus medius, gluteus maximus, and hamstrings and that the 180 ^{o} jumps produce the least activation of those muscles during both the preparatory and loading phases. Additionally, double leg sagittal plane plyometric exercises produced the greatest preparatory medial to lateral hamstrings co-activation ratio while single leg sagittal plane hurdle hops produce the lowest preparatory medial to lateral hamstrings co-activation ratio. Therefore, clinicians may want to be careful when including single leg sagittal plane exercises into ACL prevention programs and may be able to exclude 180^{o} jumps from ACL prevention programs because other exercises are more effective at targeting the gluteus medius, gluteus maximus, and hamstrings muscles.

TABLES

Table 1: Research Questions and Statistical Analysis

Question	Description	Data Collection	Comparison	Method
1	Is there a difference in the mean amplitude of lower extremity muscle activation between 5 commonly used plyometric exercises during the preparatory and loading phases?	EMG - Glute med - Glute max - Lateral hamstrings - Medial Hamstrings	Between Plyometric Exercises: - Double leg sagittal plane cone hop - Single leg sagittal plane cone hop - Split squat jmp - Double leg frontal plane cone hop - 180 degree jump	Eight one-way within subjects ANOVAs
2	Is there a difference between the ratios of the mean amplitude of lower extremity muscle activation for 5 commonly used plyometric exercises during the preparatory and loading phases?	EMG Ratios -Medial Hamstrings/ Lateral Hamstrings	Between Plyometric Exercises: - Double leg sagittal plane cone hop - Single leg sagittal plane cone hop - Split squat jmp - Double leg frontal plane cone hop - 180 degree jump	Two one-way within subjects ANOVA

Table 2 EMG Rank Orders for the Preparatory Phase

	dlsag	frontal	180	slsag	splitsquat
Lateral Hamstrings	2	4	5	1[*]	3
Medial Hamstrings	2[†]	4	5	1[*]	3[‡]
Gluteus Medius	3	2	4	1[*]	5
Gluteus Maximus	3	2	5	1[*]	4
Medial /Lateral Hamstrings Ratio	1[‡]	4	5	5	2[‡]

dlsag= double leg sagittal plane hurdle hops; frontal= frontal plane hurdle hops; 180= 180^{o} hops; slsag= single leg sagittal plane hurdle hops; splitsquat= split squat jumps

[*]Significantly different from DLS, SS, FP, and 180

[†]Significantly different from FP and 180

[‡]Significantly different from 180

Table 3 EMG Rank Orders for the Loading Phase

	dlsag	frontal	180	slsag	splitsquat
Lateral Hamstrings	3	4	5	1*	2†
Medial Hamstrings	2†	3†	5	1‡	4†
Gluteus Medius	3§	5	4§	1#	2‡
Gluteus Maximus	2‡	4†	5	1#	3‡
Medial/Lateral Hamstrings Ratio	2	1†	5	3	4

dlsag= double leg sagittal plane hurdle hops; frontal= frontal plane hurdle hops; 180= 180^o hops; slsag= single leg sagittal plane hurdle hops; splitsquat= split squat jumps

*Significantly different from DLS, FP, and 180

†Significantly different from 180

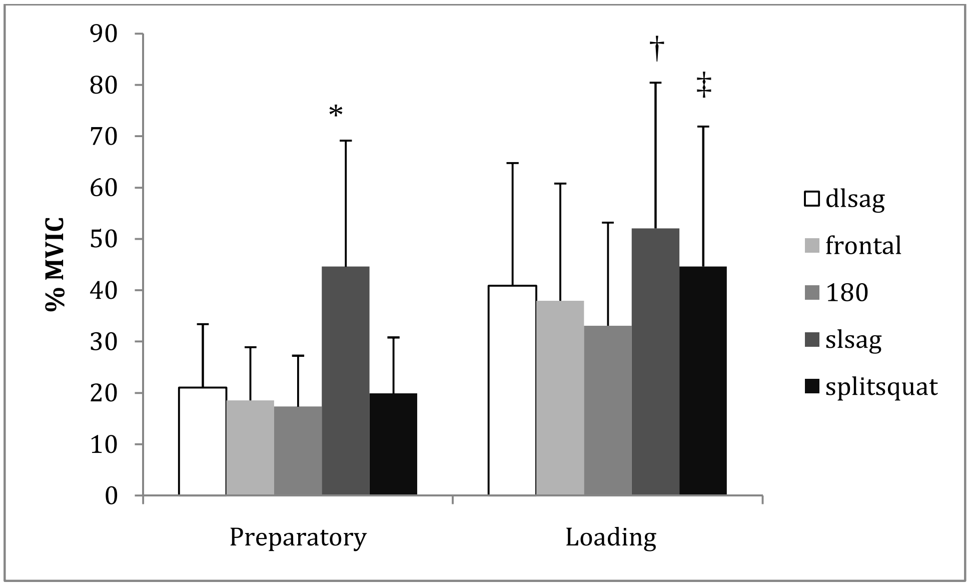
‡Significantly different from FP and 180

#Significantly different from DLS, SS, FP, and 180

§Significantly different from FP

FIGURES

Figure 1 Lateral Hamstrings Activation



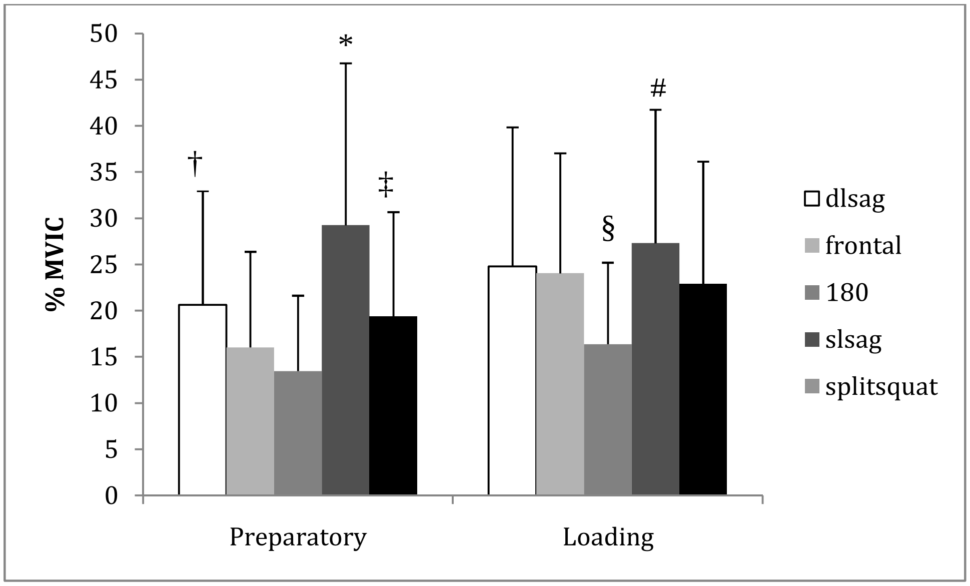
dlsag= double leg sagittal plane hurdle hops; frontal= frontal plane hurdle hops; 180= 180^{o} hops; slsag= single leg sagittal plane hurdle hops; splitsquat= split squat jumps

[*]Significantly greater than preparatory dlsag, frontal, 180, and splitsquat

[†]Significantly greater than loading dlsag, frontal, and 180

[‡]Significantly greater than 180

Figure 2 Medial Hamstrings Activation



dlsag= double leg sagittal plane hurdle hops; frontal= frontal plane hurdle hops; 180= 180^{o} hops; slsag= single leg sagittal plane hurdle hops; splitsquat= split squat jumps

[*]Significantly greater than preparatory dl sag, frontal, 180, splitsquat

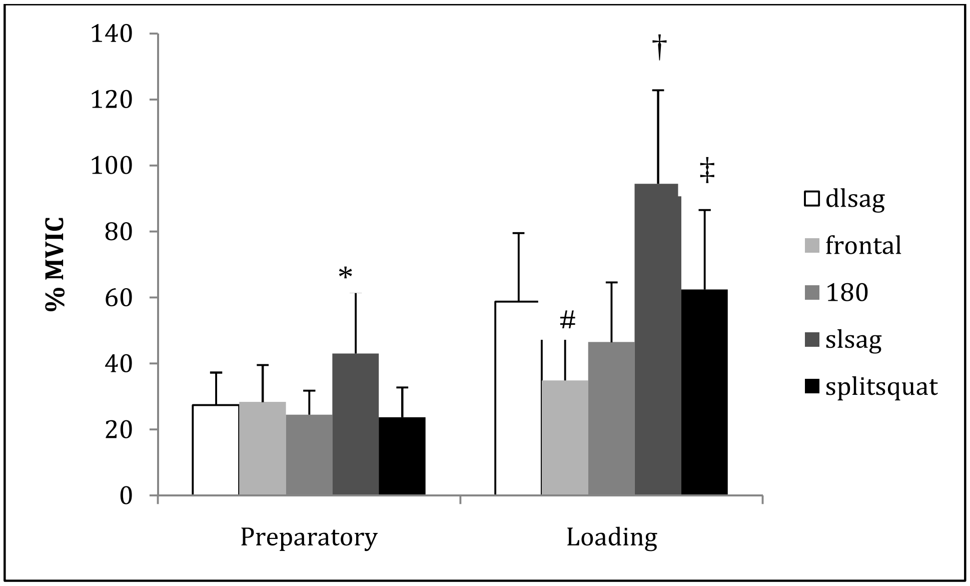
[†]Significantly greater than preparatory frontal and 180

[‡]Significantly greater than preparatory 180

[#]Significantly greater than loading 180 and splitsquat

[§]Significantly less than loading dl sag, frontal, slsag, and splitsquat

Figure 3 Gluteus Medius Activation



dlsag= double leg sagittal plane hurdle hops; frontal= frontal plane hurdle hops; 180= 180° hops; slsag= single leg sagittal plane hurdle hops; splitsquat= split squat jumps

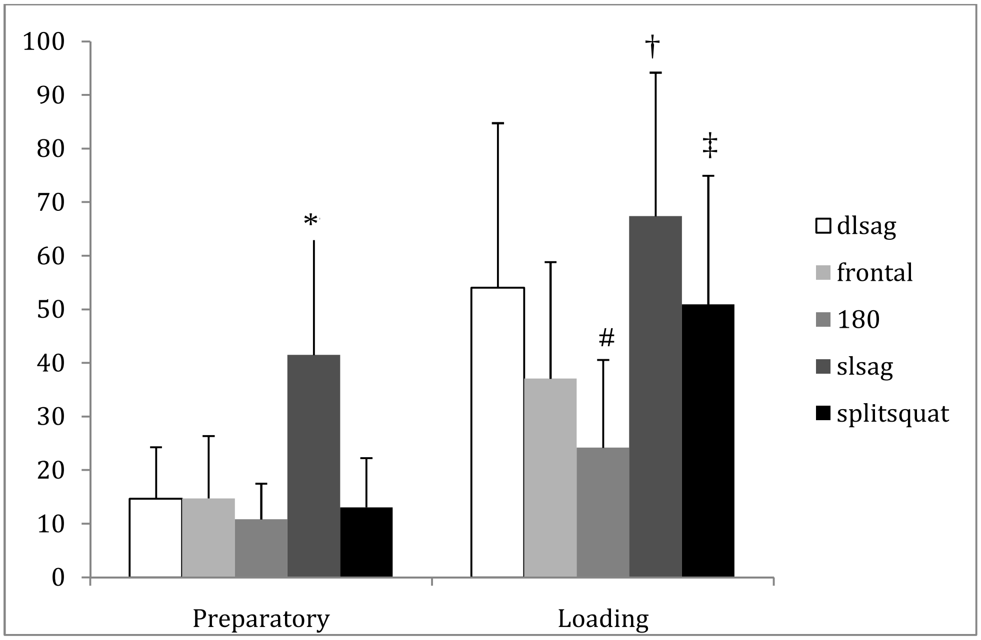
*Significantly greater than preparatory dl sag, frontal, 180, splitsquat

†Significantly greater than loading dl sag, frontal, 180, splitsquat

‡Significantly greater than loading frontal and 180

#Significantly less than loading dlsag, 180, slsag, and splitsquat

Figure 4 Gluteus Maximus Activation



dlsag= double leg sagittal plane hurdle hops; frontal= frontal plane hurdle hops; 180= 180° hops; slsag= single leg sagittal plane hurdle hops; splitsquat= split squat jumps

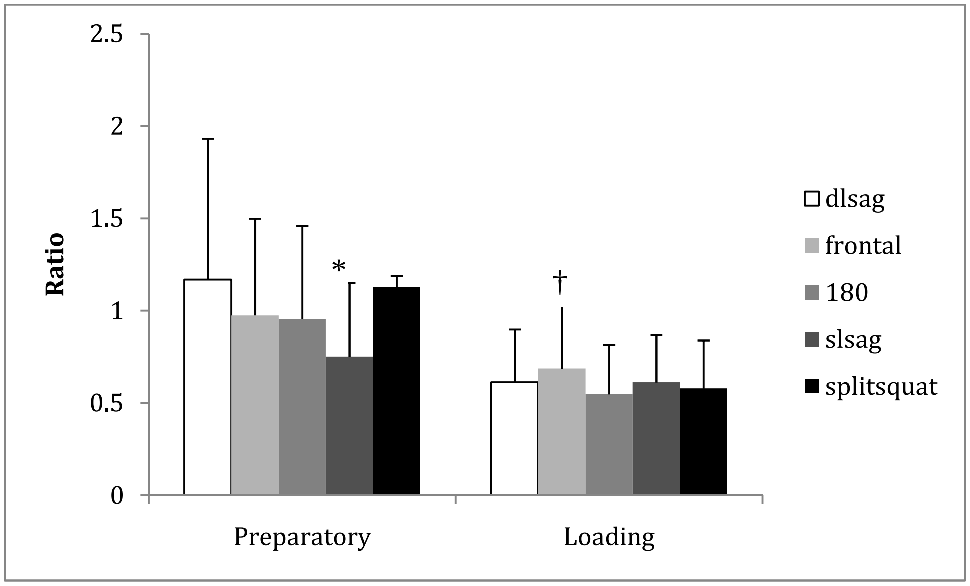
*Significantly greater than preparatory dl sag, frontal, 180, splitsquat

†Significantly greater than loading dl sag, frontal, 180, splitsquat

‡Significantly less than loading dlsag, slsag, and splitsquat

#Significantly less than loading dlsag, frontal, slsag, and splitsquat

Figure 5 Medial Hamstrings to Lateral Hamstrings Co-activation Ratio



dlsag= double leg sagittal plane hurdle hops; frontal= frontal plane hurdle hops; 180= 180^{o} hops; slsag= single leg sagittal plane hurdle hops; splitsquat= split squat jumps

*Significantly less than preparatory dl sag, and splitsquat

†Significantly greater than loading 180

APPENDIX A COMPARISON OF GLUTEUS MEDIUS, GLUTEUS MAXIMUS, AND HAMSTRINGS ACTIVATION DURING FIVE COMMONLY USED PLYOMETRIC EXERCISES

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I. Introduction

Anterior cruciate ligament (ACL) injuries affect athletes from all age groups and result in long-term consequences including increased risk of subsequent ACL injury and knee osteoarthritis (Gillquist & Messner, 1999; Hootman et al., 2007; Shea et al., 2004). While no clear mechanism of injury has been identified (Hootman et al., 2007), knee valgus motion has received considerable attention in the literature as an ACL loading mechanism, and Hewett et al. (2005) reported that peak knee valgus angle prospectively predicted ACL injury risk in adolescent female athletes. Therefore, limiting knee valgus motion may reduce ACL injury risk.

Knee valgus motion results from hip adduction and internal rotation, tibial external rotation, and knee abduction. Numerous investigators have evaluated the roles of hip musculature in limiting knee valgus during dynamic tasks. Higher EMG activation of the gluteus medius and gluteus maximus limits knee valgus motion by controlling hip adduction and hip internal rotation, respectively (Hollman et al., 2009; Patrek et al., 2011; Zazulak et al., 2005). Earlier activation of the medial hamstrings has also been shown to decrease knee valgus torques, potentially by applying a varus force to the knee over a longer period of time (McLean et al., 2010; Palmieri-Smith et al., 2008). Therefore, enhancing activation of the gluteals and hamstrings should be effective to help prevent ACL injury.

Plyometric exercises are common techniques used to enhance muscle activation and improve neuromuscular effectiveness (Potteiger et al., 2005). These exercises are important elements of ACL prevention programs due to the fact that they can influence knee valgus moments and angles (Markovic & Mikulic, 2010; Myer, Ford, McLean, et al., 2006; Myer et al., 2005). However, the literature regarding the efficacy of plyometrics in ACL injury prevention is equivocal, as some investigations reported significant decreases in ACL injury risk (Hewett et al., 1999; Mandelbaum et al., 2005) while others reported little-to-no effect (Myklebust et al., 2003; Pfeiffer et al., 2006; Steffen et al., 2008).

A potential cause for this equivocal body of literature is the fact that these investigations included a wide variety of plyometric exercises. Interventions that did not reduce ACL injury risk also did not emphasize frontal plane or single leg plyometric exercises (Myklebust et al., 2003; Pfeiffer et al., 2006; Steffen et al., 2008). Conversely, a program which included plyometric exercises designed to target the gluteal and hamstrings musculature via single leg and frontal plane exercises resulted in a significant reduction in ACL injury risk (Mandelbaum et al., 2005). As exercises which promote motion in the frontal plane increase gluteus medius and hamstrings activity to a greater extent than those in the sagittal plane (Houck, 2003; Mercer et al., 2009), this discrepancy may partially explain the varied results. Therefore, the purpose of this study was to compare five different plyometric exercises to determine which produce the greatest activation of the gluteus medius, gluteus maximus, biceps femoris, and medial hamstrings muscles.

II. Methods

Subjects

Forty-one volunteers (20 males, 21 females) participated in this investigation. Subjects were physically active (participation in physical activity at least 30 minutes per day, 3 days per week), and had no history of lower extremity or back injury within the 6 months prior to participation or of surgery in either lower extremity. Subjects read and signed an approved informed consent document and were asked to cease resistance training within the 48 hours prior to testing. Subject demographics are detailed in Table 1.

Experimental Procedures

Subjects first completed a five minute warm-up on a stationary cycle ergometer at a self-selected pace. The primary researcher then explained each plyometric exercise, and subjects completed at least two practice trials to ensure that they understood and could perform each task. Surface electromyography (EMG) electrodes were used to measure activation of the gluteus medius, gluteus maximus, and medial and lateral hamstrings as subjects performed each exercise in a randomized order. One set of each exercise included three repetitions, and subjects performed 3 sets of each exercise with one minute of rest between sets.

During each exercise, the subject jumped and landed with his/her dominant foot on a force plate (Bertec 4060, Columbus, OH), which was used to identify ground contact and landing phases. Subjects were asked to report their dominant leg as the leg that he/she would use to kick a ball for maximum distance. The specific plyometric exercises were chosen by reviewing the literature and identifying the most common exercises used to alter biomechanical factors associated with ACL loading or ACL injury risk (Arabatzi et al., 2010; Chappell & Limpisvasti, 2008; Chimera et al., 2004; Hewett et al., 1996; Irmischer et al., 2004; Lephart et al., 2005; Myer, Ford, Brent, et al., 2006; Myklebust et al., 2003; Pasanen et al., 2008; Pfeiffer et al., 2006; Steffen et al., 2008; Wilkerson et al., 2004) and are detailed in Figure 1. Hurdle hops were performed over a 10cm hurdle. Plyometric exercises were completed to the beat of a 76 beats per minute metronome such that each landing occurred on a subsequent beat. A metronome was used to to standardize jumping during plyometric exercises and the frequency was determined through pilot testing. If a subject touched the hurdle with his/her foot, lost balance at any point, or did not perform the exercises with proper technique as assessed by the primary researcher, the trial was discarded and repeated. Subjects were excluded from the study if they perform 5 unacceptable trials throughout the testing protocol.

Electromyography

Differential surface EMG electrodes (DelSys, Inc., Boston, MA, USA: interelectrode distance 10 mm; amplification factor 1,000 (20 – 450 Hz); CMMR @ 60 Hz > 80 dB; input impedance > 10^{15}//0.2 Ω//pF) were placed over the gluteus maximus, gluteus medius, medial hamstrings, and lateral hamstrings of the dominant limb approximately parallel to the muscle fiber orientation (Hermens et al., 2000) using a double-sided adhesive skin interface (Delsys, Inc., Boston MA). Electrode sites were shaved if necessary, abraded, and cleaned with isopropyl alcohol to maximize the electrode adherence to the skin and minimize skin impedance, and were confirmed via observation of the EMG on an oscilloscope during isometric contractions against manual resistance.

Data Reduction

EMG data were bandpass (20-350 Hz) and notch (59.5-60.5 Hz) filtered (4^{th} order Butterworth), and smoothed using a 15ms root mean squared sliding window. Force plate data were collected at 1000Hz and lowpass filtered at 60 Hz (4^{th} order Butterworth).

Data were reduced using a custom LabVIEW software program (National Instruments, San Antonio, TX). Mean EMG of the gluteus maximus, gluteus medius, and medial and lateral hamstrings was calculated for both the pre-activation and loading phases . The pre-activation phase was defined as the 150ms before initial contact (Lephart et al., 2005). The loading phase was defined as the time from initial ground contact to 50% of the ground contact interval. Initial ground contact was defined as the point at which the vertical ground reaction force exceeded 10 N.

EMG amplitudes were normalized to the mean EMG amplitude during a maximum voluntary isometric contraction (MVIC). MVICs were completed for each muscle after the practice trials and before the plyometric exercises in a counterbalanced order and included hip extension, hip abduction, and knee flexion for the gluteus maximus, gluteus medius, and hamstrings, respectively (Hislop & Montgomery, 1995). A 1 second moving average of mean EMG amplitude was taken for each MVIC trial, and the highest 1 second mean EMG amplitude was used for analysis. After normalization, EMG data were averaged across trials for statistical analyses. The medial hamstrings to lateral hamstrings activation ratio was calculated by dividing the normalized EMG of the medial hamstrings by the normalized EMG of the lateral hamstrings.

Statistical Analyses

EMG amplitudes were compared across exercises using separate one-way repeated-measures ANOVA. Separate analyses were conducted for each muscle and phase of landing, resulting in a total of 10 analyses: two for each of the four muscles, and two for the hamstring activation ratio. One subject's data were excluded from statistical analysis because she could not complete the plyometric exercise protocol without making mistakes on 5 or more trials. Two females' biceps femoris and medial hamstrings data were excluded from the statistical analysis because the EMG electrodes fell off during testing. Other subjects' EMG data were excluded from the statistical analysis because they were statistical outliers, which were defined as values more than 3sd's beyond mean. These statistical outliers were a combination of males and females, and most subjects whose data were excluded from analysis were excluded from analyses of multiple muscles. The maximum number of subjects excluded from a particular ANOVA was 7. Significant ANOVA models were be evaluated *post hoc* via Tukey's HSD test. Statistical significance was established *a priori* $\alpha \leq 0.05$.

Results

Significant differences ($p < 0.01$) between exercises were found for each muscle during the preparatory phase (Table 2 and Figures 2-5). Upon post-hoc analysis, the single leg sagittal plane hurdle hop demonstrated significantly greater preparatory activation of the lateral hamstrings, medial hamstrings, gluteus medius, and gluteus maximus than any other exercise (Table 2 and Figures 2-5). Additionally, for the medial hamstrings, the double leg sagittal plane hurdle hop (20.65 ± 12.31%) displayed significantly greater preparatory activation than both the frontal plane hurdle hop (16.04 ± 10.35%) and the 180^{o} jump (13.46 ± 8.16%), and the split squat jump (19.36 ± 11.33%) displayed significantly greater preparatory activation than the 180^{o} jump (13.46 ± 8.16%) (Table 2,Figure 2).

Significant differences ($p < 0.01$) between exercises were also found for each muscle during the loading phase (Table 3, Figures 2-5). Upon post-hoc analysis, the single leg sagittal plane hurdle hop resulted in significantly greater loading phase activation of the gluteus medius and gluteus maximus than all other exercises (Table 2, Figures 4,5). The single leg sagittal plane hurdle hop also displayed significantly greater loading phase activation of the lateral hamstrings than the double leg sagittal plane hurdle hop (40.87±23.95%), frontal plane hurdle hop (37.95±22.85%), and 180^{0} jump (33.11±20.11%) as well as significantly greater loading phase activation of the medial hamstrings than the split squat jump (22.90±13.25%) and 180^{o} jump (16.37±8.83%) (Table 3, Figures 2,3). More differences in loading phase activation were also present in the medial hamstrings with the double leg sagittal plane hurdle hop (24.70±15.07%), frontal plane hurdle hop (24.06±12.97%), and split squat jump (22.90±13.25%) showing greater activation than the 180^{o} jump (16.37±8.83%) (Table 3, Figure 3). For the gluteus medius during the loading phase, the split squat jump (62.44±24.07%) showed greater activation than both the 180^{o} jump (46.47±18.12%) and frontal plane hurdle hop (34.91±14.11%), and both the double leg sagittal plane cone hop (58.72±20.80) and 180^{o}

jump (46.47±18.12%) showed greater activation than the frontal plane hurdle hop (34.91±14.11%) (Table 3, Figure 4). For the gluteus maximus during the loading phase, the double leg sagittal plane hurdle hop (54.01±30.75) and split squat jump (50.93±24.02) displayed greater activation during the loading phase than both the frontal plane hurdle hop (37.06±21.78%) and 180^{o} jump (24.18±16.40%) with the frontal plane hurdle hop (37.06±21.78%) also showing greater activation than the 180^{o} jump (24.18±16.40%) (Table 3, Figure 5).

Finally, a significant difference between the medial hamstrings to lateral hamstrings ratio was found for both the preparatory ($p<.01$) and loading phases ($p=.019$) (Table 2,3, Figure 6). Specifically, the double leg sagittal hurdle hop (1.169±0.763) and split squat jump (1.128±0.061) showed a greater medial to lateral hamstrings ratio during the preparatory phase than the single leg sagittal hurdle hop (0.750±0.400) (Table 2, Figure 6). During the loading phase, the frontal plane hurdle hop (0.686±0.342) displayed a significantly greater medial to lateral hamstrings ratio than the 180^{o} jump (0.548±0.266) (Table 3, Figure 6). EMG activity for each muscle during each exercise were rank ordered and are presented in tables 2 and 3.

Discussion

The most important findings in our investigation were that demonstrated that the single leg sagittal plane hurdle hops produced the greatest activation while 180^{o} jumps consistently produced the least activation of the gluteus medius, gluteus maximus, medial hamstrings, and lateral hamstrings during both the preparatory and loading phases compared to all other plyometric exercises. Additionally, the double leg sagittal plane hurdle hops and split squat jumps produced a medial hamstrings to lateral hamstrings co-activation ratio of greater than one during the preparatory phase, indicating that the medial hamstrings were more active than the lateral hamstrings during the preparatory phase of those exercises.

To our knowledge, this study was the first to examine muscle activation of the hamstrings, gluteus medius and gluteus maximus during plyometrics performed in multiple planes. One previous study examined lateral hamstrings EMG during plyometric exercises, but no differences in EMG activity were observed between exercises even though single-leg hopping was included in the exercise protocol (Ebben et al., 2008). The cause of this difference in hamstrings activity between studies may be twofold. First, hamstrings EMG can be variable in people with different landing strategies leading to a lack of power in a smaller sample size (Ebben et al., 2008). Secondly, the distance covered by the jumps of the plyometric exercises may have influenced the results of each study. Since the primary actions of the hamstrings are to flex the knee, extend the hip, and provide a restraint to anterior tibial momentum, a larger hopping distance would place a greater load on the hamstrings to both absorb and produce the sagittal plane momentum needed to accomplish the plyometric task, thereby increasing EMG activity (Ebben et al., 2008). Even though hamstrings activation was measured only during the loading phase, the dynamic nature of plyometric exercises required the subjects to control their momentum and immediately produce momentum in the opposite direction. Therefore, the data collected during the loading phase might be a combination of both momentum absorption and production.

Even though the primary action of the hamstrings occurs in the sagittal plane, the hamstrings can control varus and valgus motion at the knee (Lloyd et al., 2005). With regard to ACL injury, the medial hamstrings have a substantial moment arm that can create knee varus motion and moment (Lloyd et al., 2005). Therefore, higher activation of the medial hamstrings relative to the lateral hamstrings may limit valgus knee movement and ACL loading (Lloyd et al., 2005; Palmieri-Smith et al., 2008). The sagittal plane exercises provided the greatest activation of the medial hamstrings before initial ground contact, with both the double leg sagittal plane hurdle hops and split squat jumps producing a medial hamstrings to lateral hamstrings co-activation ratio of greater than one during the preparatory phase. A medial to lateral hamstrings co-activation ratio greater than one is indicative of greater activity in the medial hamstrings relative to the lateral hamstrings and may be beneficial in terms of ACL loading because activation of the medial hamstrings helps resist valgus forces placed on the knee while activation of the lateral hamstrings can introduce a valgus knee moment (Zhang & Wang, 2001). Because of this higher pre-contact co-activation ratio, the double leg sagittal plane hurdle hops and split squat jumps may be best for enhancing medial to lateral hamstring ratios and potentially limiting knee valgus loading and ACL injury risk.

In contrast to the activation patterns during the preparatory phase, the medial hamstrings became more active during the loading phase of the frontal plane hurdle hops, and this exercise produced the third greatest activation of the medial hamstrings during the loading phase (not significantly different than the two exercises which produced greater medial hamstrings activation). Additionally, the frontal plane hurdle hops produced the greatest medial to lateral hamstrings co-activation ratio of all exercises during the loading phase (significantly greater than the 180^{o} jumps). This activity of the medial hamstrings during the loading phase is similar to findings by Houck (2003) who observed that frontal plane exercises produced greater medial hamstrings activity than an equivalent sagittal plane task. This activation of the medial hamstrings during the loading phase is most likely a feed-forward mechanism that is pre-programmed to occur after landing. During fast movements such as plyometrics, feed-forward neuromuscular control is used to produce specific movements (Enoka, 2002). Since the medial hamstrings can provide a varus moment (Lloyd et al., 2005) and presumably limit ACL loading, frontal plane hurdle hops may result in better activation patterns after landing based on the ratios observed in this study. However, these loading phase activation patterns might not attenuate ACL loading due to the fact that ACL injuries occur early in the loading phase (Koga et al., 2010).

Activation of the gluteus medius was significantly less during the frontal plane hurdle hop than any of the other exercises. This finding is surprising because the gluteus medius would seemingly be active during this task to prevent excessive frontal plane hip motion. If the gluteus medius is not as active as other muscles, such as the adductors, during the early loading phase, greater knee valgus could occur at the beginning of the loading phase as greater hip adductor activity correlates to greater knee valgus angles (Jacobs et al., 2007). These greater valgus angles may increase ACL injury risk (Hewett et al., 2005). Because of the lesser activation of the gluteus medius observed during the exercise, frontal plane hurdle hops may not be a good plyometric exercise to change biomechanics that lead to ACL injury.

The finding of lesser gluteus medius activity in the frontal plane hurdle hops compared to other plyometric exercises also differs from previous literature which demonstrates that the gluteus medius is most active during frontal plane step-ups compared to sagittal plane step ups and active to similar levels during frontal plane hop-to-stabilization exercises compared to transverse and sagittal plane hop to stabilization exercises (Distefano et al., 2009; Mercer et al., 2009). The difference in gluteus medius activation between our study and other studies may exist because of the times over which data were collected during the plyometric exercises. During the frontal plane hurdle hops, each subject jumped toward the non-dominant limb, landed with the dominant limb on the force plate and the non-dominant limb off the force plate, and then jumped back to the starting position. Because of the position of the force plate and its necessity for identification of landing phases, EMG data were collected only as the subject jumped toward the non-dominant limb. During this direction of the plyometric exercise, subjects may have used their non-dominant limbs rather than their dominant limbs to absorb and produce force to change directions and may have experienced a pelvic shift toward the non-dominant leg. Upon landing, this use of the non-dominant limb may have concentrically activated the gluteus medius on the non-dominant limb or eccentrically activated the adductors on the dominant limb rather than the gluteus medius on the dominant limb to limit the pelvic shift towards the non-dominant limb that may occur during the frontal plane hurdle hop. However, this theory cannot be confirmed because no EMG activity was measured on the non-dominant limb.

Muscle activation is an important factor in determining which exercises should be used in the clinical setting. At first glance, the results of this study suggest that a single leg sagittal plane hurdle hop may be an important plyometric exercise to include in an ACL prevention program because the activation of the medial hamstrings, gluteus medius, and gluteus maximus during the preparatory phase is greater than all other exercises included in this study. These results are similar other studies on dynamic strengthening exercises in which the gluteus medius and gluteus maximus are activated more during a single leg squat than during a double leg squat (Lubahn et al., 2011; McCurdy et al., 2010). However, the single leg sagittal plane hurdle hop also exhibited a significantly lower medial to lateral hamstrings co-activation ratio compared to the double leg sagittal plane hurdle hop and split squat jump. This lower co-activation ratio was most likely observed because of the higher lateral hamstrings activity needed to perform the single leg dynamic exercises than double leg dynamic exercises (McCurdy et al., 2010) and may be required because of the higher lower extremity force demands and stability demands of single leg versus double leg exercises (Ebben et al., 2010). Because of this increase in forces and decrease in stability, the muscles of the thigh must increase co-activation for a subject to perform the exercise correctly and stay balanced. One might expect that the medial hamstrings would increase activity to match the increase lateral hamstrings activity for balance to occur. However, that increase may not occur because the increase gluteus medius activation or a potential increase in lateral gastrocnemius activity may aid the medial hamstrings in limiting the knee valgus created by increased lateral hamstrings activation. Because of the high activation of all muscles and low medial to lateral hamstrings ratio, clinicians may want to use an exercise progression to prepare their athletes for single leg sagittal plane hurdle hops (Hewett et al., 1996; Myer, Ford, McLean, et al., 2006; Myklebust et al., 2003).

On the other hand, the 180^{o} jumps produced either the smallest or 2nd smallest activation of each muscle during both phases of the all of the exercises. This exercise also resulted in the lowest medial to lateral hamstrings co-activation ratio during the loading phase and the 2^{nd} lowest co-activation ratio during the preparatory phase. We expected the gluteus maximus to be more active during the 180^{o} hops to control internal rotation of the hip. However, these results suggest that the 180^{o} jump requires less gluteus maximus activity to control and produce transverse plane movement than to control and produce sagittal plane movement. This observation may have occurred because of the primary action of the gluteus maximus is to extend the hip, and the secondary action is to produce external rotation of the femur, thus control internal rotation of the femur. These actions of the gluteus maximus would suggest that more muscle fibers are recruited to perform hip extension than to perform femoral external rotation during this task. Also, other muscles that cannot be measured with surface EMG because of their depth (e.g. the piriformis, obturators, quadratus femoris, and gamelli) may aid the gluteus maximus in controlling femoral internal rotation during the 180^{o} plyometric exercise, thus requiring less gluteus maximus activity. Because of the inactivity of the gluteus maximus in the 180^{o} jumps and the greater activity of the all muscles during other exercises, 180^{o} jumps may not be an important exercise to include in plyometric programs aimed at preventing ACL injury.

We acknowledge that the current study has several limitations. First, the subjects included were only recreationally active, so conclusions drawn from this study can only be applied to others who are recreationally active and not necessarily athletes. Also, the type of exercise may be only one component of muscle activation during plyometric exercises. Other factors not examined, such as cueing and jump distance, may affect muscle activation strategies during plyometric exercises and could have changed the results of this study. Other limitations of this study were that data were only collected while the subjects were jumping in one direction, so all conclusions drawn from this study are based on half of the landings performed by each subject. Also, EMG data were only obtained from one limb during double limb exercises, so we could not assess the contributions of the non-dominant limb during the plyometric exercises.

Conclusion

Our results suggest that single leg sagittal plane plyometric exercises produce the greatest activation of the gluteus medius, gluteus maximus, and hamstrings and that the 180 ^{o} hurdle hops produce the least activation of those muscles during both the preparatory and loading phases. Additionally, double leg sagittal plane plyometric exercises produced the greatest medial to lateral hamstrings co-activation ratio. Since plyometrics are an important component in ACL prevention programs (Markovic & Mikulic, 2010), further research should be performed to determine the long-term effects of muscle activation resulting from plyometric exercises and whether these changes in muscle activation lead to changes in biomechanics after the program is completed.

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