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Effects of Single-Leg Neuromuscular Training on ACL Risk Factors in Female Collegiate Soccer Players

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EFFECTS OF SINGLE-LEG NEUROMUSCULAR TRAINING ON ACL RISK FACTORS IN FEMALE COLLEGIATE SOCCER PLAYERS

BY

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Signature Page

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Abstract

Introduction. Non-contact anterior cruciate ligament (ACL) injuries typically occur during activities that involve cutting, pivoting, sudden deceleration, and landing from a jump, movements that are prevalent in soccer (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle et al., 2009; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). Female soccer players, due to both intrinsic and extrinsic factors, are up to six times more likely to sustain a non-contact ACL tear (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Myer et al., 2006; Pantano et al., 2005; Youdas et al., 2007, Zeller et al., 2003). Coaches, strength and conditioning specialists, and rehabilitation specialists have built on the present body of knowledge to begin creating preventative neuromuscular training programs, with some success of reducing ACL injury risk (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Kernozek et al., 2008; McLean et al., 2007; Myer et al., 2006; and Myer et al., 2005; Yoo et al., 2009). The purpose of this study was to compare the effects of a single-leg neuromuscular training program (NTP-SL) and a double-leg neuromuscular training program (NTP-DL) on ACL injury risk factors. **Methods.** Triple-hop test (THT) distance, vertical jump (VJ) height, predicted maximal back squat strength (BS 1-RM), and six kinetic and kinematic measures of a jump-landing and cut maneuver (JLC) in ten healthy female collegiate soccer players were compared before and after the six-week training period. **Results.** In the BS1RM, there was no significant Test x Group interaction (*F*(1,8) = .694, *p* > .05), nor was there a significant main effect for Group (*F*(1,8) = 1.134, *p* > .05). A significant main effect for Test was found (*F*(1,8) = 14.727, *p* < .05), indicating that when groups were combined, post-test 1RM was significantly higher. The VJ saw no significant Test x Group interaction (*F*(1,8) = 4.082, *p* > .05), nor was there a significant main effect for Group (*F*(1,8) = .030, *p* > .05). A significant main effect for Test was found (*F*(1,8) = 5.878, *p* < .05), indicating that when groups were combined, post-test VJ was significantly higher than the pre-test. Three separate 2 x 2 (Time x Group) MANOVAs were calculated for hip flexion angle (HFA) and knee flexion angle (KFA); knee anterior shear (KAS); and knee adduction moment (KAdM), hip abduction moment (HAbM), and hip external rotation moment (HERM). Each variable was examined at three different periods of stance: initial contact (IC), peak vertical ground reaction force (PVGRF), and 25% of stance phase (QS). For HFA and KFA, no significant Test x Group interaction or main effect was found for Test or Group. No significant Test x Group interaction or main effect was found for Test or Group for KAS. For KAdM and HAbM, no significant Test x Group interaction or main effect was found for Test or Group. There was no significant Test x Group interaction or main effect for Group for HERM during a side-cut to the right, nor was there a significant Test x Group interaction or main effect for Test or Group for HERM during a side-cut to the left. The main effect for Test for HERM during a side-cut to the right approached significance (*F*(3,6) = .747, *p* = .050). Follow-up univariate tests did not show significant effects for Test at any particular phase of stance (IC: *F*(3,6) = .363, *p* > .05; PVGRF: *F*(3,6) = .433, *p* > .05; QS: *F*(3,6) = 2.202, *p* > .05). **Discussion.** Single-leg training did not produce strength or power performance deficits. However, neither the NTP-SL nor NTP-DL groups experienced significant changes in THT distance or any biomechanical ACL risk factor. This is similar to previous research which showed that 9 weeks of training with resistance bands did not alter at-risk biomechanics in female recreational athletes (Herman et al., 2008). Further research is need to understand the role of strength training in ACL prevention and to identify reliable training approaches that consistently improve performance and lower injury risk.

Chapter One: Introduction

Soccer, as it is known in America, is the most commonly played sport in the world (Alentorn-Geli et al., 2009a). Though typically a male-dominated sport, the continued rise in participation in soccer stems from an increase in female athletes. Defined as a contact sport, soccer is nonetheless considered relatively safe. However, the risk of injury still exists.

Non-contact anterior cruciate ligament (ACL) injuries typically occur during activities that involve cutting, pivoting, sudden deceleration, and landing from a jump, movements that are prevalent in soccer (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle et al., 2009; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). This is especially true for females, who, due to both intrinsic and extrinsic factors (Zeller, McCrory, Kibler, & Uhl, 2003), are up to six times more likely to sustain a non-contact ACL tear (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Myer, Ford, McLean & Hewett, 2006; Pantano, White, Gilchrist, & Leddy, 2005; Youdas, Hollman, Hitchcock, Hoyme, & Johnsen, 2007). The reported incidence rate of ACL injury ranges from 0.06 to 3.7 per 1,000 hours of match play and competitive practice (Alentorn-Geli et al., 2009a). This adds up to thousands of ACL tears every year, leading to substantially high costs for treatment and rehabilitation and untold lost opportunities for participation. Though intrinsic risk factors are person-specific, identifying modifiable extrinsic factors may be a major step toward reducing the incidence rate of non-contact ACL tears.

As an identifiable extrinsic risk factor, biomechanical positioning has recently gained attention as improved technology allows for the quantification of at-risk movement patterns. Measurements of angles, forces, and moments in the joints of the lower extremity have given practitioners insight as to how their combined effects may influence ACL strain. Several risky positions have been identified. Multiple studies are in agreement that out-of-plane knee and hip movements, particularly hip adduction angle (Imwalle, Myer, Ford, & Hewett, 2009; Myer et al., 2006; Wilson, Ireland, & Davis, 2006; Zeller et al., 2003) and knee abduction angle (Borotikar, Newcomer, Koppes, & McLean, 2008; Imwalle et al., 2009; Kernozek, Torry, & Iwasaki, 2008; Myer et al., 2006; Pantano et al., 2005; Wilson et al., 2006; Zeller et al., 2003), can increase the risk of ACL injury. Muscle-firing patterns and magnitudes have been shown to change under fatigue in both males and females (with females exhibiting greater changes than their male counterparts) that lead to previously identified risky biomechanical patterns (Chappell et al., 2005; McLean et al., 2007; McLean & Samorezov, 2009).

Despite some remaining questions regarding ACL injury in the current body of knowledge, coaches, strength and conditioning specialists, and rehabilitation specialists have built on the present findings and begun to create preventative neuromuscular training programs (Alentorn-Geli et al., 2009a; Kernozek et al., 2008; McLean et al., 2007; Myer et al., 2006; and Myer, Ford, Palumbo, & Hewett, 2005). These programs have seen moderate success under specific circumstances (Alentorn-Geli et al., 2009b; Yoo et al., 2009). Though many causes of non-contact ACL injuries are not yet fully understood and must continue to be investigated, the high cost of injury (in both financial and future health outcomes) creates a need to implement protocols which empirically reduce injury rates (Borotikar et al., 2008; Imwalle et al., 2009).

Statement of the Problem

Some current neuromuscular training programs designed to prevent ACL injury show moderate improvement in at-risk biomechanics, particularly in female participants (Alentorn-Geli et al., 2009b; Lim et al., 2009; Myer et al., 2006; Myer et al., 2005; Yoo et al., 2009). These programs are typically multidisciplinary in approach, including several or all of the following training stimuli: progressive warm-up, plyometrics, agility, balance training, resistance training, and conditioning. Of these factors, the plyometric aspect has, thus far, appeared to be the most effective due to the emphasis on the stretch-shortening cycle in accepting and redirecting force and the similarity of the movements to athletic situations (Alentorn-Geli et al., 2009a; Lim et al., 2009; Myer et al., 2006). These protocols are lacking in uniformity, and therefore not yet fit for widespread adoption, as evidenced by the recent finding that the rate of force development during landing and the forces placed on the knee can differ depending on the type and intensity of the plyometric exercise (Jensen & Ebben, 2007).

Though there is preliminary evidence that plyometric training is effective, especially when coupled with skilled reinforcement from trained coaches, the role of resistance training is not yet clear. Of the protocols that included a resistance training portion, the lifting program was often identical for all participants while other factors (plyometric intensity, for instance) were manipulated (Alentorn-Geli et al., 2009b; Myer et al., 2006). Additionally, resistance training programs were either not clearly described in the literature (Myer et al., 2005), or else they were total-body, “cookie cutter” programs that addressed overall strength, but lacked a clear goal (i.e., improving quadriceps-hamstring ratio, strengthening hip musculature, or improving core strength).

Importantly, resistance training programs included in the literature lack sport-specific and injury-specific movements, including single-leg exercises. Considering that many sport-related activities involve single-leg cutting, bounding, and landing, and ACL injury has been linked to poor hip muscular stability and control during these movements (Borotikar et al., 2008; Imwalle et al., 2009; Kernozek et al., 2008; McLean et al., 2007; McLean & Samorezov, 2009;

Myer et al., 2006; Myer et al., 2005; Willson et al., 2006; Yu, Lin, & Garrett, 2006; Zeller et al., 2003), the specificity of training principle indicates that dynamic resistance training should include a robust single-leg component. To the author's knowledge, no research on a single-leg specific resistance training program for non-contact ACL injury prevention has been executed.

Purpose

The purpose of this research study was to compare functional performance measures and lower-extremity biomechanics during simulated sports tasks in healthy female collegiate soccer players subjected to six weeks of either a predominantly single-leg (NTP-SL) or predominantly double-leg (NTP-DL) neuromuscular training protocol. Triple-hop test (THT) distance, vertical jump (VJ) height, predicted maximal back squat strength (BS 1-RM), and kinetic and kinematic measures of a jump-landing and cut maneuver (JLC) were assessed pre- and post-training for each respective group.

Significance of the Study

Injury to the ACL is responsible for significant and well-documented short- and long-term debilitations in athletes (Alentorn-Geli et al., 2009a; Borotikar et al., 2007). At-risk biomechanics in sport movements appears to be positively affected by neuromuscular training programs with an emphasis on plyometrics and strengthening exercises (Yoo et al., 2009). However, these programs have thus far not resulted in a widespread decrease in ACL injury rates, indicating that while they may modify risk factors in a laboratory setting for certain participants, there is still a gap in providing effective training that carries over onto the field of play. Single-leg neuromuscular training may provide an added benefit that can be translated into game situations due to the specificity of the movement preparation.

Research Hypotheses

Both groups (NTP-SL and NTP-DL) in this study were subjected to a neuromuscular training protocol. Some aspects of the program were identical, such as upper-body and core strength exercises, to control for the outside influence of these potentially confounding activities. The resistance training portion, however, differed dependent on group assignment. Thus, it was expected that both groups would experience a significant increase in VJ height, THT distance, and predicted BS 1-RM mass from pre-test to post-test. It was further hypothesized that, at post-test, the groups would not significantly differ in VJ height or predicted BS 1-RM mass, but that the SL group would have a significantly farther THT distance than the DL group.

For the JLC maneuver, the kinematic and kinetic variables recorded were compared pre-test to post-test and between the NTP-SL and NTP-DL group at predetermined points (initial contact [IC], 25% of stance phase [QS] and peak vertical ground reaction force [PVGRF]) during the stance phase of the movement. It was hypothesized that both groups would experience a significant increase in hip and knee flexion angles (HFA and KFA, respectively), a significant increase in hip external rotation moment (HERM) and hip abduction moment (HAbM), a significant decrease in knee adduction moment (KAdM), and a significant decrease in knee anterior shear force (KAS).

There were 5 specific hypotheses in this study:

1. Six weeks of neuromuscular training will significantly increase vertical jump height in both groups.
2. Six weeks of neuromuscular training will significantly increase predicted back squat 1-RM mass in both groups.

3. Six weeks of single-leg neuromuscular training will result in significantly greater triple-hop distance than six weeks of double-leg neuromuscular training.
4. Six weeks of single-leg neuromuscular training will result in significantly higher hip flexion angle and knee flexion angle at initial contact, 25% of stance-phase, and peak vertical ground reaction force than six weeks of double leg neuromuscular training.
5. Six weeks of single-leg neuromuscular training will result in significantly higher hip external rotation moment and hip abduction moment and significantly lower knee abduction moment and knee anterior shear force at initial contact, 25% of stance-phase, and peak vertical ground reaction force than six weeks of double leg neuromuscular training.

Variables

The three functional tests, the THT for distance (in meters), VJ height (in inches), and predicted BS 1-RM mass (in kilograms) were compared from pre- to post-test and between the NTP-SL and NTP-DL group at post-test.

During the JLC maneuver, the following kinematic and kinetic variables were measured at initial contact (IC), 25% of stance phase (QS), and peak vertical ground reaction force (PVGRF): hip flexion angle (HFA) in degrees, knee flexion angle (KFA) in degrees, hip external rotation moment (HERM) in Nm, hip abduction moment (HAbM) in Nm, knee adduction moment (KAdM) in Nm, and knee anterior shear force (KAS) in N. These variables were also compared from pre- to post-test and between the NTP-SL and NTP-DL group at post-test.

Limitations

Though every participant was a member of a collegiate varsity NCAA Division II soccer team for a minimum of one season, there was a possibility of variability regarding years of previous resistance training experience and familiarity with the testing measures employed in this study. Additionally, variations in body morphology may have led to inherent biomechanical differences during specific tasks. During testing, individuals received standard coaching, including a demonstration and explanation of the task and the opportunity to practice. No further coaching was allowed. During the intervention, however, all individuals in each group were consistently coached on proper biomechanical form of the selected exercises with constant reinforcement of accepted coordination patterns and limb alignment. For example, participants performing a double-leg back squat were instructed to push the hips posteriorly, flex the knees and hips, and keep an upright torso while the entire foot maintained contact with the floor. Throughout the movement, the athlete was reminded to keep the knee joint in-line with the ankle joint, preventing a knee valgus angle from occurring. Despite such a method, however, some individual training approaches and techniques were undertaken due to unique anatomical features (e.g., range-of-motion limitations) that were outside the practitioner’s control. Every effort was made to limit these exceptions.

The length of the intervention (six weeks) may be a limitation. Six weeks has been shown to be a sufficient time-frame for increasing motor recruitment (Lim et al., 2009), but it does not correlate with the ability to achieve muscle hypertrophy or improved endurance. However, Lim et al. (2009) were able to successfully achieve significant changes in biomechanics following a six-week neuromuscular program, possibly because such a program trains nerve-muscle factors, making six weeks an adequate time-frame.

The athletes who participated in this study were part of Barry University's varsity women's soccer team. The study intervention occurred during their spring season, which involved several days a week of practice and occasional games. Due to this schedule, it was not possible to completely control the outside activity of the participants. However, because of the team nature of the activities, all participants were exposed to the same practice and game regimen, negating this as a confounding variable.

Delimitations

Participants were required to complete the entire six weeks, totaling twelve workout sessions, of neuromuscular training and participate in both the pre- and post-test to be included in this study. Criteria for exclusion included: prior ACL injury (<1yrs post-reconstruction), current lower-extremity injury of a muscular, tendinous, or ligamentous nature, neuromuscular disease, or an inability to perform any part of the testing protocols or the neuromuscular training program. Female participants from the Barry University NCAA Division II collegiate soccer program, age 18-22, were recruited.

To prevent the confounding effects of other exercise modalities, power exercises, core rotational stability exercises, and core rotational strength exercises were excluded. Plyometric training, balance training, agility training, and aerobic conditioning were not explicitly included in the neuromuscular training protocol, though each may have inherently existed to a small extent in conjunction with the selected strength training exercises and dynamic warm-up.

Assumptions

It was assumed that all individuals were in good health and had the good-faith intention of completing all testing procedures and the neuromuscular training protocol to the best of their abilities. It was additionally assumed that there would be no significant differences between the NTP-SL and the NTP-DL group in any variable at pre-test.

Definition of Terms

Balance Training: Training designed to create movement symmetry between the right and left sides of the body and to promote a balance of mobility and stability within the body (Cook, 2003).

Dynamic Warm-up: A general warm-up period of 5 to 10 minutes of slow activity such as jogging or skipping, or low-intensity sport-specific actions, designed to increase heart rate, blood flow, deep muscle temperature, respiration rate, and perspiration and to decrease viscosity of joint fluids; followed by a specific warm-up period of 8 to 12 minutes of movements similar to the movements of the athlete's sport and includes dynamic stretching focusing on movements that work through the range of motion required for the sport (Baechle & Earle, 2004).

Genu recurvatum: Hyperextension, or posterior bowing of the knee (Anderson, Hall & Martin, 2004).

Kinematic: Motion examined from a spatial and temporal perspective without reference to the forces causing the motion, including position, velocity, and acceleration (Hamill & Knutzen, 2003).

Kinetic: Measurement of the forces acting on a system (Hamill & Knutzen, 2003).

Moment: The product of the magnitude of a force and the perpendicular distance from the line of action of the force to the axis of rotation (Hamill & Knutzen, 2003).

Neuromuscular Training Program: An exercise program consisting of one or all of the following components: warm-up, stretching, agility, plyometrics, balance training, and resistance training (Alentorn-Geli et al., 2009b; Lim et al., 2009).

Non-Contact Anterior Cruciate Ligament Tears: Injuries that occur with no physical contact with other players at the time of injury (Alentorn-Geli et al., 2009a).

Plyometric Training: The purpose of plyometric exercise is to increase the power and subsequent movements by using both the natural elastic components of muscle and tendon and the stretch reflex (Baechle & Earle, 2004)

Power: The time-rate of doing work, where “work” is defined as the product of the force exerted on an object and the distance the object moved in the direction in which the force is exerted (Work = Force * Distance; Power = Work/Time) (Baechle & Earle, 2004).

Resistance Training: A technique used to increase muscular strength and stability. Varying forms of resistance are applied to the body to produce an overload on the musculature. For the purposes of this study, “resistance training” will encompass any exercise not already classified as “plyometric” or “balance” in which the participant uses, at minimum, the resistance of body-weight or the added resistance of free-weights.

Shear force: A force applied parallel to the surface of an object, creating deformation internally in an angular direction (Hamill & Knutzen, 2003).

Strength: The maximal force that a muscle or muscle group can generate at a specified velocity (Baechle & Earle, 2004).

Stretching: Stretching requires movement of a body segment to a point of resistance in the range of motion, followed by applying a force. This stretching movement can be done either actively (the person stretching supplies the force of the stretch) or passively (a partner or stretching machine provides external force to cause or enhance a stretch). A dynamic stretch is a type of functionally based stretching exercise that uses sport-specific movements to prepare the body for activity. Dynamic stretching places an emphasis on the movement requirements of the sport or activity rather than on individual muscles (Baechle & Earle, 2004).

Subtalar pronation: Calcaneal eversion, foot abduction, and dorsiflexion during weight-bearing at mid-stance (Anderson, Hall & Martin, 2004).

Tibial torsion: Medial torsion is associated with genu varum, in which the feet point toward each other; lateral torsion is associated with genu valgum, in which the feet point outward (Anderson, Hall & Martin, 2004).

Vertical ground reaction force (VGRF): The vertical component of a force acting on the center of mass of an individual (Hamill & Knutzen, 2003).

Chapter Two – Literature Review

Male and female soccer players experience high rates of ACL injury, with females suffering a 6-fold higher rate than their male counterparts. This prevalence has led to investigations into the mechanisms of non-contact ACL injury, including intrinsic and extrinsic factors. Though differences between men and women do exist that predispose women to higher rates of injury, men are also susceptible to the mechanisms that characterize non-contact ACL injuries. Therefore, the purpose of this study was to compare two strength training protocols (a predominantly single-leg variation or a predominantly double-leg variation) for their effect on functional performance measures and lower-extremity biomechanics during simulated sports tasks in healthy collegiate soccer players.

Given the high cost of injury, recent research has focused on modifiable risk factors and preventative neuromuscular programs. Though moderate success has been realized in reducing the risk factors associated with injury, actual rates of injury do not appear to have ebbed. It is unclear if this is because effective programs have yet to be implemented on a widespread basis, or if there is a dearth of effective programs to implement. Despite a lack of consensus, individual aspects of training programs have shown to be more promising than others. Each of these factors is discussed in detail in the following sections.

Prevalence of Non-Contact ACL Injury

Injury to the ACL remains one of the most common injuries in sports (Kernozek et al., 2008). Both men and women experience ACL tears, with the majority occurring in men due to their higher rates of sport participation (Yoo et al., 2009). However, women experience a relative rate of injury that is up to six times higher than their male counterparts (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Myer, Ford, McLean & Hewett, 2006; Pantano, White, Gilchrist, & Leddy, 2005; Youdas, Hollman, Hitchcock, Hoyme, & Johnsen, 2007), accounting for approximately 38,000 cases annually (Yoo et al., 2009). This difference in injury rate between men and women participating in all sports has not been reported for any other acute knee injury except for torn meniscus, which is often concomitant with an ACL injury (Chaudhari & Andriacchi, 2006). Of all ACL tears in both sexes, a majority are considered “non-contact” injuries whereby the injury occurs without any physical contact with other players or objects (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Kernozek et al., 2008).

The cost of any injury, particularly one requiring surgical intervention, is likely to be substantial. Injuries to the ACL have the highest economic cost among all soccer injuries (Alentorn-Geli et al., 2009). This can have a deleterious effect on one’s life; absence from school, work, or sports, temporary or permanent disability, and a negative impact on an athlete’s activity level and quality of life (Alentorn-Geli et al., 2009b; Lim et al., 2009; Yoo et al., 2009). ACL tears often occur with concomitant injuries, such as the aforementioned meniscus tears and medial ligament sprains (Alentorn-Geli et al., 2009a). Reconstructive surgery and long rehabilitation periods do not mitigate the increased post-traumatic injury risk of developing knee osteoarthritis (Alentorn-Geli et al., 2009b). These factors in combination provide a clear incentive for any athlete to employ prophylactic measures in order to avoid sustaining an ACL injury.

Men’s and women’s soccer, unlike many other sports in which both genders participate, has identical rules. Ball size, field size, game length, substitution rules, and player-contact rules are the same for each sex at matched levels of competition. Thus, the difference in ACL injury rates for males and females in soccer is not likely inherent to the game (Alentorn-Geli et al., 2009a). Researchers have identified several intrinsic (person-specific) and extrinsic (potentially modifiable) risk factors for ACL injury, many of which present differently in men and women and may explain the gender disparity in injury rate.

Mechanisms of Injury

Injury to the ACL occurs in one of two ways. First, the athlete may come into contact with an object or a player that causes an anteriorly-directed force on the tibia with the femur in a fixed position, or a posteriorly-directed force on the femur with the tibia in a fixed position, causing the ACL to rupture. This mechanism is involved in a minority of ACL injuries. More commonly, a non-contact event occurs, usually during high-risk maneuvers such as cutting, pivoting, sudden deceleration, or landing from a jump (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle et al., 2009; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). These motions reportedly involve knee valgus, varus, internal rotation, and external rotation moments, as well as anterior translation force (Alentorn-Geli et al., 2009a).

It is not the high-risk actions described above, or even necessarily the existence of an anterior translation force, which the ACL directly resists, that results in an injury. This is illustrated by the continued investigation into reported risk-factors in which participants perform these movements and demonstrate the aforementioned moments and forces, yet injuries rarely, if ever, occur during the research. Therefore, the magnitude, timing, and the actions that preclude detrimental forces and moments may play a large role in determining whether or not an injury occurs (Alentorn-Geli et al., 2009a).

During a jump-landing, the body is required to absorb the forces imposed on it by the ground. One of the most commonly referenced mechanisms of injury is an extended knee and hip position during landing (Alentorn-Geli et al., 2009a; Chaudhari & Andriacchi, 2006; Lim et al., 2009; Yoo et al., 2009). This, like most biomechanical risk factors, is more common in women than in men. During cutting, excessive knee valgus, especially when coupled with hip adduction and internal rotation of the femur, also leads to high knee adduction moments and increased stress on the ACL (Alentorn-Geli et al., 2009; Chaudhari & Andriacchi, 2006; McLean et al., 2007; Zeller et al., 2003). Combined with external tibial rotation on a pronated, externally rotated foot, the ACL may become impinged against the lateral femoral trochlea or experience compromised integrity (Pantano et al., 2005; Willson et al., 2006; Zeller et al., 2003). Identifying the full gamut of risk factors allows practitioners to determine the best methods with which to reduce the incidence of ACL injury.

Intrinsic Risk Factors

Alentorn-Geli et al. (2009a) note that, "There is no definitive evidence that any anatomical risk factors are directly correlated with an increased rate of non-contact ACL injury with respect to age and gender." (p. 708). Nonetheless, several factors exist which may predispose an athlete to injury, even in the absence of a direct correlation to the injury itself. Intrinsic factors have previously been defined as individual, physical, and psychosocial aspects that are sex-specific and less likely to be changeable (Zeller et al., 2003). In females, joint laxity, anterior pelvic tilt, genu recurvatum, excessive navicular drop, excessive subtalar pronation, increased tibial torsion, a low ACL fibril concentration and a lower percent area occupied by collagen fibrils, sex hormones, and a greater hip width-to-femoral length ratio as compared to males may preclude other extrinsic risk factors that contribute to an elevated risk of non-contact ACL tear (Alentorn-Geli et al., 2009; Chaudhari & Andriacchi, 2006; Lim et al., 2009; Pantano et al., 2005).

Generalized joint laxity has been demonstrated to significantly increase the risk of leg injuries in female soccer players, though not specifically ACL injuries (Alentorn-Geli et al., 2009a). Anterior-posterior knee joint laxity, however, was correlated with a higher risk of ACL tears in female United State Military Academy cadets as compared to their male peers, and varus-valgus and internal-external rotation knee laxity results in an increased functional valgus collapse that may put female athletes at a higher risk of injury (Alentorn-Geli et al., 2009a). Knee joint laxity is heightened by the female sex hormones progesterone and estrogen, which have receptor sites in human ACL cells (Alentorn-Geli et al., 2009a). However, the evidence for an increased risk of injury is equivocal; Chaudhari and Andriacchi (2006) note that static knee laxity measurements do not relate to dynamic ones, like peak knee flexion moments during walking and jogging. Though laxity in the knee may create risky joint positions, it appears there is no accompanying increase in joint loading that would produce an injury.

An anteriorly-tilted pelvis places the hip into a relatively internally rotated, anteverted (resulting in a toe-in posture), and flexed position (Alentorn-Geli et al., 2009a). This puts the hamstrings in a lengthened, and therefore weakened, position and changes the moment arms of the gluteal muscles, causing them to be less effective as hip stabilizers (Alentorn-Geli et al., 2009a). In the absence of a stable hip in females, the quadriceps will increase their workload in an attempt to control knee position during dynamic tasks (Zeller et al., 2003). The weakened hamstring muscles are unable to counteract the quadriceps work, resulting in an increase in anterior translation force in the knee (Borotikar et al., 2008; Chappell et al., 2005; McLean & Samorezov, 2009; Youdas et al., 2007). Therefore, an inability to resist hip adduction and a high quadriceps to hamstring ratio are likely contributors to ACL injury risk in females (Herman et al., 2008; Imwalle et al., 2009).

The role of the foot-ankle complex in ACL injury is not fully understood (Alentorn-Geli et al., 2009a). In a study on the combined effects of fatigue and decision-making in lower-limb landing postures in females, Borotikar et al. (2008) postulated that altered ankle strategies in the presence of fatigue may exist to reduce, rather than promote, fatigue-induced changes in hip and knee positions that increase the potential for ACL injury. Navicular drop or excessive pronation may be a force-dispersing strategy, much in the way that muscular activity at the ankle may influence the loads that are transferred to the knee (Chaudhari & Andriacchi, 2006). In contrast, Alentorn-Geli et al. (2009a) report that knee recurvatum (genetic knee hyperextension) and excessive navicular drop and subtalar joint pronation were significant discriminators between participants with and without injured ACLs. Additionally, subtalar pronation and internal tibial rotation at the knee may produce an increased internal femoral rotation and valgus angle at the knee (Alentorn-Geli et al., 2009a), though hip internal rotation has not been found to be a significant predictor of knee valgus (Imwalle et al., 2009). More research must be done to elicit the role of the foot-ankle complex in heightening or mitigating non-contact ACL injury risk.

Female ACLs have a lower fibril concentration and lower percent area occupied by collagen fibrils compared to their male counterparts (Alentorn-Geli et al., 2009a). The ability of females' ACLs to resist detrimental forces is highly correlated to their fibril concentration, whereas failure in males was highly correlated to the percent area occupied by collagen fibrils (Alentorn-Geli et al., 2009a). There is also a significant correlation between ACL cross-sectional area and the intracondylar notch surface area, resulting in a smaller cross-sectional area at the mid-substance of the ACL in females with a small intracondylar notch (Alentorn-Geli et al., 2009a). The relationship between a small notch and the increased risk of ACL injury, however, is not yet fully understood and should continue to be investigated.

For many years, the increased quadriceps-angle (Q-angle) present in females as compared to males was thought to be a contributing factor to knee valgus positions during dynamic movements, making it a risk factor for ACL injury (Pantano et al., 2005). This idea has since been refuted, and the idea of a wider female pelvis has come into question (Alentorn-Geli et al., 2009a; Chaudhari & Andriacchi, 2006; Pantano et al., 2005). The Q-angle is more a measure of patellofemoral alignment, rather than genu valgus, and therefore may contribute to patellofemoral pain issues (Pantano et al., 2005). However, another anatomical variation at the hip differentiates males and females and may influence ACL risk. A greater hip width-to-femoral length ratio exists in females, which could lead to excessive knee valgus (Pantano et al., 2005). Unlike Q-angle, which can be corrected for by the participant during dynamic movements, the hip width-to-femoral length ratio appears unalterable (Pantano et al., 2005).

Extrinsic Risk Factors.

Extrinsic factors contributing to the risk of non-contact ACL injury are, in general, modifiable in nature. Though no one has yet harnessed control over weather conditions, advances in field technology and the use of domed stadiums have greatly reduced weather-related injury risk. Likewise, equipment such as footwear and protective braces have been designed to mitigate potential hazards, though more research should be conducted to gain a further understanding of their effectiveness (Alentorn-Geli et al., 2009; Zeller et al., 2003). The major extrinsic risk factors, however, fall into three broad categories: lower-extremity biomechanics, neuromuscular fatigue, and strength and conditioning.

Lower-extremity biomechanics.

Current research has identified detrimental lower-limb positions and torques in the sagittal, coronal, and transverse planes (Alentorn-Geli et al., 2009a). Though interrelated, these motions do not always correlate with one another (Imwalle et al., 2009) but together result in a “position of no return” for non-contact ACL injury (Zeller et al., 2003). These combinations of risky postures rarely occur in every-day life or even in a majority of athletic situations. Rather, forces detrimental to the integrity of the ACL occur during certain high-risk motions, such as sudden changes in direction (cutting), rapid deceleration, and landing from a jump (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle et al., 2009; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). Additionally, women appear to be more susceptible to these biomechanical risk factors than their male counterparts (Alentorn-Geli et al., 2009a; Willson et al., 2006; Zeller et al., 2003).

Sagittal plane biomechanics of the lower extremity include flexion/extension at the hip and knee and plantar/dorsiflexion at the ankle. Multiple studies have concluded that increased knee, hip, and trunk flexion angles during landings from a jump or during a cutting maneuver have a protective effect on the ACL and that females tend to land in a more extended knee and hip position compared to males (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Kernozek et al., 2008; Lim et al., 2009; McLean & Samorezov, 2009; Myer et al., 2006; Myer et al., 2005; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). The speed of flexion during landing also plays a role in injury prevention through a decrease in posterior and vertical ground reaction forces associated with a faster hip and knee flexion angular velocity (Alentorn-Geli et al., 2009a; Yu et al. 2006). However, McLean et al. (2007) note that recent modeling studies have shown that an increase in anterior tibial shear force during an extended landing is not, in isolation, enough to produce an ACL rupture. Nonetheless, reducing anterior shear will lessen the stress on the ACL, which may prove important in the presence of other high-risk biomechanics.

In their recent review article on the prevention of non-contact ACL injuries in soccer players, Alentorn-Geli et al. (2009a) discuss at length the effect sagittal plane biomechanics has on ACL strain. In addition to energy absorption through hip and knee flexion and a reduction in the peak landing force that is transmitted up the lower extremity, ACL elevation angle, the angle of insertion of the hamstrings, and the patellar tendon-tibial shaft angle all serve as a protective mechanism in a deeper landing posture. A perpendicular position of the ACL relative to the tibial plateau line lessens the ligament's ability to resist an anteriorly-directed force. Rather than resisting a tensile force along the long-axis of the ligament, a greater elevation angle puts the ACL in a shear loading condition, under which it is more likely to fail. This is similarly true of the hamstring muscles, which are able to produce a counteractive posterior force when parallel to the tibial plateau, at knee angles greater than 100° of flexion. An extended position lessens the protective abilities of the hamstrings to counteract the anterior tibial strain on the ACL. Concurrently, an extended knee position increases the patellar tendon insertion angle with respect to the tibial longitudinal axis. This allows the quadriceps to exert a high anteriorly-directed force that is weakly offset by the hamstrings and ACL.

Despite the detrimental conditions described above, isolated sagittal-plane forces are reportedly not high enough to cause ACL rupture (Alentorn-Geli et al., 2009a; Kernozek et al., 2008). Investigators have therefore focused on the contributions of the coronal (frontal) and transverse planes to non-contact ACL injury risk. Hip adduction and knee abduction positions are highly correlated and are present during 45° and 90° cutting maneuvers (Imwalle et al., 2009). Knee abduction is a common mechanism of ACL injury; the increase in knee abduction that occurs in concert with hip adduction during cutting places the athlete at a higher risk of injury (Imwalle et al., 2009). Therefore, the ability to resist hip adductions could be an important factor in reducing ACL injury rates. This theory has been supported by the finding that athletes who demonstrated greater hip abduction strength and stiffness were less likely to experience a lower-extremity injury (Chaudhari & Andriacchi, 2006; Imwalle et al., 2009).

A varus/valgus opening of the knee by as little as 2° significantly affects the ability of the ACL to resist rupture (Chaudhari & Andriacchi, 2006). Furthermore, when a valgus loading is combined with the at-risk landing position of knee extension, the ACL becomes tense before the MCL does, increasing the likelihood of injury (Chaudhari & Andriacchi, 2006; Myer et al., 2006). The aforementioned correlation between hip adduction and knee abduction (Imwalle et al., 2009) is strong enough that these positions, along with hip adduction moments, have been shown to predict ACL injury in young female athletes (Myer et al., 2006).

It has previously been hypothesized that the static measure Q-angle was correlated with knee valgus angles. Females tend to have a higher Q-angle than males (Pantano et al., 2005). The higher rate of ACL injury in females and the relation of injury risk to knee valgus positions and moments led many to conclude that a higher Q-angle may be an intrinsic risk factor for non-contact ACL injury in women (Pantano et al., 2005). Many recent studies, however, suggest otherwise (Alentorn-Geli et al., 2009a; Pantano et al., 2005). A different measure, pelvic width-to-femoral length ratio (PW/FL) has also been shown to significantly differ between men and women (Pantano et al., 2005). Furthermore, unlike Q-angle, PW/FL contributes to a greater knee valgus in both static and dynamic measures (Pantano et al., 2005). This may partially explain why neuromuscular training programs designed to prevent ACL injury are often successful in reducing risky biomechanics in females but are not able to produce results in which male and female athletes do not still significantly differ (Myer et al., 2006).

While coronal plane biomechanics appear to play an important role in non-contact ACL injury risk, the impact of transverse plane movements is less understood. The few studies that have been conducted have focused on the hip and knee joints (Alentorn-Geli et al., 2009a). Many studies cite the role of potentially injurious transverse plane biomechanics – specifically, tibial external rotation and hip internal rotation – in combination with coronal plane movements (Pantano et al., 2005; Willson et al., 2006). However, there is conflicting evidence regarding the occurrence of hip transverse plane motions during cutting and landing maneuvers (Alentorn-Geli et al., 2009a). For example, Borotikar et al. (2008) notes a direct correlation between initial contact hip internal rotation and resultant peak stance phase knee abduction moments. Conversely, Imwalle et al. (2009) found that hip internal rotation is not correlated to, and therefore not predictive of, knee valgus motions. In cutting angles of 45 and 90, hip internal rotation increased as the cut angle increased, but without an associated increase in knee abduction angles. The study by Borotikar et al. (2008) notes forces in the knee, while Imwalle et al. (2009) only discusses knee and hip kinematics. Regardless, this apparent discrepancy in findings supports the need for further research.

Similarly, a review article by Alentorn-Geli et al. (2009a) reports both an increase in hip external rotation and an increase in hip internal rotation during side-cut tasks in two different studies. McLean et al. (2009) found an increase in hip internal rotation postures during unanticipated versus anticipated and fatigued versus non-fatigued states during a jump-landing task. They report that the subsequent increase in hip internal rotation during landing promotes suboptimal biarticular quadriceps and hamstring lengths. However, as discussed in the section on intrinsic risk factors, anterior pelvic tilt places the hip into a relatively internally rotated, anteverted, and flexed position (Alentorn-Geli et al., 2009a). Therefore, the finding that hip internal rotation increases in females during the aforementioned landing situations may in fact be due to lumbo-pelvic instability and an anteriorly tilted pelvic girdle rather than an actual increase in hip internal rotation. This may explain why hip internal rotation postures are likely not correlated with an increase in knee valgus. Support for this theory can be found in a report by Zeller et al. (2003), which describes a hip external rotation posture in females during a single-leg squat. However, the authors note that during the performance of the single-leg squat, female participants had a tendency to rotate their pelvis away from the dominant leg in order to maintain their center of gravity. This instance of relative pelvic rotation on a fixed femur could very likely occur during other movement tasks.

A clear picture of tibial transverse plane motions is also lacking. McLean et al. (2007) is currently the only study to find a gender difference in knee axial rotation biomechanics. The authors observed that while internal tibial rotation motions and torques are known contributors to ACL loading, the occurrence and magnitude of tibial internal or external rotation may be task-specific.

Despite contradictory findings in the literature, it is presumable that a lack of consistent transverse plane joint displacement does not mean that the transverse plane is irrelevant. Any activity performed on a single-limb, as cutting and jump-landings typically are, requires adequate neuromuscular control to counteract the ground-reaction force that acts to collapse weight-bearing lower-extremity joints in all three planes of motion (Youdas et al., 2007). Therefore, a lack of motion in the transverse plane, especially at the hip, may be the desirable outcome.

The sagittal, coronal, and transverse planes of motion each play a role in non-contact ACL injury to varying degrees(Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle et al., 2009; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). Increased knee, hip, and trunk flexion – especially when performed with a high angular velocity - may serve to increase the body's ability to absorb and disperse ground reaction forces during cutting and landing postures (Alentorn-Geli et al., 2009a; Yu et al., 2006). This may help minimize the negative forces associated with the coronal plane motions of hip adduction and knee abduction (Pantano et al., 2005; Willson et al., 2006). Though a high knee valgus moment is considered to be a loading force on the ACL, the negative impact of this force may be mitigated by sagittal plane biomechanics that lessen anterior shear forces in the knee through optimal alignments of the ACL, hamstrings, and patellar tendon angle (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Kernozek et al., 2008; Lim et al., 2009; McLean & Samorezov, 2009; Myer et al., 2006; Myer et al., 2005; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). Finally, the contribution of transverse plane biomechanics is not yet fully understood. Tibial internal rotation certainly puts the ACL in a strained position and may occur in increased amounts during landing and cutting movements (McLean et al., 2007). However, conflicting findings regarding hip rotations during at-risk movements suggest that there may be contributions from elsewhere, such as the lumbo-pelvic complex, that have yet been unaccounted for (Alentorn-Geli et al., 2009a; Borotikar et al., 2008; Imwalle et al., 2009; McLean et al., 2009; Zeller et al., 2003). Further research should seek to clarify the role of pelvic and trunk biomechanics on hip and knee actions during jumping and cutting maneuvers.

Neuromuscular fatigue.

The major mechanisms of non-contact ACL injury are risky biomechanical positions that lead to excessive anterior shear force, valgus force unhindered by the MCL, and rotational force that puts a high level of strain on the ACL. Researchers have long suspected that fatigue may play a role in at-risk biomechanics, leading to an increase in injury incidence and prevalence. With regard to soccer, significantly more injuries occur in the final 15 minutes of the first half and the final 30 minutes of the second half of regulation matches, with 17% of these injuries occurring at the knee with a non-contact mechanism (Kernozek et al., 2008). Replicating in-game or in-practice neuromuscular fatigue in a laboratory setting can be difficult to do, making research on the effects of fatigue on injury challenging (Chappell et al., 2005). However, several studies examining the biomechanics of cutting and landing in fatigued conditions have given researchers a better understanding of the contribution of fatigue to injury.

Effects of fatigue.

Fatigue is a likely contributor to established biomechanical risk factors, but it may not be an isolated risk factor in and of itself (Alentorn-Geli et al., 2009a). In their discussion of muscular fatigue, Alentorn-Geli et al. (2009a) point out that fatigued muscles are able to absorb less energy, resulting in increased energy being transferred to passive structures such as ligament and bone. This typically occurs in conjunction with an increase in vertical ground reaction force during landings and changes of direction (Kernozek et al., 2008). In addition, fatigued conditions lead to a multitude of at-risk biomechanical positions, especially in females: a decreased knee flexion angle during landing, increased tibial internal rotation during impact-force absorption, and a general increase in anterior tibial translation and peak knee abduction motions (Alentorn-Geli et al., 2009a). These postures result in an increase in peak knee internal rotation and abduction moments, putting the ACL at further risk for injury (Alentorn-Geli et al., 2009a).

The findings in the Alentorn-Geli et al. (2009a) study are supported by many other recent investigations. Borotikar et al. (2008) found a substantial decrease in hip control under a fatigued condition, resulting in decreased hip flexion and increased hip internal rotation during jump landings. The hip and knee extensors were fatigued during repetitive squatting tasks, making it difficult for these muscle groups to control eccentric loading during landing. Therefore, the extended position found by the authors may be an attempt to prevent the lower-limb collapse that could occur as a result of the muscles' inability to generate the force or power necessary to control the landing posture. Interestingly, the authors note that this change in sagittal plane hip control has not been observed in two-legged landings, but is consistently found during single-leg tasks. Therefore, the contribution of hip motions and musculature may be task-specific (Borotikar et al., 2008). An extended knee position, in contrast, is found during fatigued double-leg stop-jump landings (Chappell et al., 2005). Both extended hip and knee positions during landing are associated with increased peak proximal tibial anterior shear force, placing stress on the ACL in a position in which it is less able to safely absorb such a force (Borotikar et al., 2008; Chappell et al., 2005). Furthermore, both single-leg and double-leg landings during fatigued states appear to increase peak stance knee abduction and internal rotation positions and increase knee valgus moments in females, known risk factors for non-contact ACL injury (Borotikar et al., 2008; Chappell et al., 2005; McLean et al., 2007). However, some authors have noted tibial external rotations during other movement tasks, suggesting that this finding may be task-specific, as well (McLean et al., 2007).

Temporal effects.

The temporal characteristics of landing and cutting maneuvers may greatly influence the load borne by the ACL in women (McLean et al., 2007). Borotikar et al. (2008) used a fatigue model that was employed concurrently with their data collection during jump-landing trials. This allowed the researchers to preliminarily examine the time frame of fatigue; in this case, data were compared at the 50% and 100% fatigue levels. Intriguingly, the detrimental effects of fatigue were present at the 50% mark, and did not significantly differ at the 100% mark.

Additionally, work by McLean et al., (2007) found a temporal shift in peak knee abduction moments (occurring much closer to initial contact) in females while fatigued, whereas male participants saw no change in the timing of peak knee abduction moments. However, females additionally experienced a large, posteriorly directed tibial load that coincided with the early-onset peak knee abduction moment. The authors suggest that this landing strategy may in fact be an adaptive rather than a predisposing one.

In order to further understand the role of timing in fatigue, McLean and Samorezov (2009) examined lower-extremity kinetic and kinematic variables in female collegiate athletes during single-leg landing trials at five points during the fatigue protocol: pre-fatigue and 25%, 50%, 75%, and 100% of fatigue. The main effect of fatigue level elicited significant decreases in initial contact knee flexion angles and increases in peak-stance hip internal rotation and knee abduction angles. In agreement with the findings of Borotikar et al. (2009), the authors found that lower-limb biomechanical modifications occurred at fatigue levels that were well below maximum. Furthermore, the altered biomechanics did not change as fatigue progressed further, suggesting that fatigue-induced risks associated with ACL rupture may occur much earlier than previously thought (McLean & Samorezov, 2009). While it appears that the onset of a fatigued-state, as well as the timing of muscle firing patterns and dynamic lower-extremity coordination patterns, may contribute to ACL loading, further research needs to be conducted in order fully understand the roles of each factor.

Central and peripheral contributions.

Neuromuscular fatigue may involve both a central and a peripheral component. The central component consists of a gradual exercise-induced reduction in the level of voluntary muscle activation that occurs at sites above the neuromuscular junctions (Kernozek et al., 2008;

McLean & Samorezov, 2009). The peripheral component, on the other hand, refers to exercise-induced processes involving muscle and contractile elements occurring at or below the neuromuscular junction that lead to a reduction in the force-generating capability of a muscle (Kernozek et al., 2008; McLean and Samorezov, 2009). Most research has focused on the peripheral component of fatigue, believing it to be the most amenable to changes with neuromucular training (Alentorn-Geli et al., 2009; Borotikar et al., 2008; Chappell et al., 2005; Kernozek et al., 2008; McLean et al., 2007). However, one study linking fatigue-induced ACL injury risk to a degradation in central control suggests that from an injury prevention standpoint, peripheral fatigue may be harder to combat (McLean & Samorezov, 2009). Training that increases muscle fatigue resistance typically mirrors an increased effort on behalf of the athlete, making peripheral fatigue inevitable. Balance and proprioceptive training to decrease central fatigue, which is known to enhance motor performance, may therefore be a more effective means of negating high-risk fatigue responses (McLean & Samorezov, 2009).

Neuromuscular fatigue may increase injury risk through changes in biomechanics caused by inadequate joint stabilization, which stems from a suboptimal muscle activation strategy (McLean & Samorezov, 2009). Central fatigue may play a role in this degradation of neuromuscular control, both at the spinal level via muscle spindle and golgi tendon organ reflex inhibition and at the supraspinal level where adaptations in cortical excitability may reduce the volitional drive of the descending motor pathways (Borotikar et al., 2008). In their study involving single-limb landing tasks, McLean & Samorezov (2009) measured the biomechanics of the landing technique on each leg, but implemented a fatigue protocol on only one limb. The authors observed a crossover effect whereby biomechanical changes occurred in the non-fatigued limb during unanticipated tasks. This led the investigators to conclude that central fatigue may be a dominant mechanism in fatigued landing biomechanics. It is also likely that the risk of injury is heightened when substantial peripheral fatigue exists in combination with central fatigue, such that an injury may even occur during anticipated tasks (McLean & Samorezov, 2009).

Since peripheral fatigue leads to the reduction in the force-generating capacity of a muscle, it is possible that other muscles will attempt to replace the lost power of the fatigued muscle (Alentorn-Geli et al., 2009a). For example, quadriceps fatigue from eccentric work produced early activation of the gastrocnemius and delayed activation of the rectus femoris during cutting maneuvers in female athletes as compared to controls (Alentorn-Geli et al., 2009a). The gastrocnemius appears to act as a compensatory knee stabilizer in closed-kinetic chain movements when the quadriceps fatigue, but this possible knee stabilization technique may actually serve to increase ACL strain (Alentorn-Geli et al., 2009a). Hamstring fatigue, meanwhile, creates decreased transverse plane knee control, resulting in increased tibial internal rotation during the force-absorption phase of a movement and an additional strain to the ACL that is poorly counteracted by the hamstrings and possibly heightened by the over-active gastrocnemius (Alenteorn-Geli et al., 2009).

Further evidence for peripheral fatigue mechanisms lie in studies assessing reflex latencies and muscle activity using surface electromyography (EMG). Though fatigue produced a significantly longer latency for the monosynaptic reflex latencies, there was also a significant reduction in EMG amplitudes for other latency components (Alentorn-Geli et al., 2009a). The investigators concluded that reduced motor activity, rather than extended latency of the first hamstring response, is responsible for the increased risk of ACL failure (Alentorn-Geli et al., 2009a). A peripheral contribution to fatigue is also suggested by the finding that poor muscular conditioning can increase injury rates and alter athletic performance during landing and stop-jump tasks (Kernozek et al., 2008). Currently, however, there is no direct correlation between pre-determined conditioning levels and peripheral fatigue. Like fatigue, decision-making (anticipated versus unanticipated tasks) is, in isolation, directly related to ACL injury risk (Alentorn-Geli et al., 2009a). For example, lower extremity muscle activation during cutting has been shown to be significantly different between anticipated and unanticipated conditions (Alentorn-Geli et al., 2009a). These effects are heightened by the combination of fatigue and decision-making, as evidenced by the finding that fatigue-induced increases in initial contact hip internal rotations and peak knee abduction angle – two known ACL risk factors – were significantly more pronounced during unanticipated landings (Alentorn-Geli et al., 2009a). Borotikar et al., (2008) suggested that the reduced central control due to fatigue in combination with the reduced reaction time of an unanticipated movement serves to compromise an already depleted central nervous system, resulting in potentially injurious kinesthetic adjustments. Furthermore, since successful neuromuscular control strategies exhibited during landings are largely pre-planned, exaggerated postures during unanticipated trials may be due to a delayed initiation of an appropriate central response (Borotikar et al., 2008; McLean & Samorezov, 2009). It is also likely that metabolic changes in fatigued muscle groups become large enough to elicit an anticipatory down-regulation in central control, meaning that an already taxed central nervous system that cannot provide the increased activation needed to maintain force production is overwhelmed by the unanticipated nature of a movement, resulting in an altered biomechanical response (McLean & Samorezov, 2009). The combination of fatigued states and unanticipated actions, as are prevalent during sport competitions, may present a “worst case scenario” for high-risk dynamic cutting and landing strategies (Alentorn-Geli et al., 2009a; Borotikar et al., 2008; McLean & Samorezov, 2009).

Strength and conditioning.

In addition to neuromuscular fatigue, poor biomechanical strategies during cutting and jump-landing maneuvers occur due to inadequate muscular strength (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Chaudhari & Andriacchi, 2006; Herman et al., 2008; Imwalle et al., 2009; Myer et al., 2006; Myer et al., 2005; Willson et al., 2006; Zeller et al., 2003), stiffness (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Chaudhari & Andriacchi, 2006; Willson et al., 2006), or balance (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Herman et al., 2006; Imwalle et al., 2009; Myer et al., 2006; Myer et al., 2005; Newton et al., 2006; Shields et al., 2005; Yoo et al., 2009; Youdas et al., 2007; Zeller et al., 2003). While each factor is cited to some extent as a contributor to biomechanical risk factors for non-contact ACL injury, the extent to which modifications of muscular strength, stiffness, and balance have on cutting and landing strategies is poorly understood. Nonetheless, current ACL injury prevention programs based on neuromuscular training are built on improving these factors (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Herman et al., 2008; Myer et al., 2006; Myer et al., 2005; Willson et al., 2006; Yoo et al., 2009).

Quadriceps dominance, often described as a high quadriceps-to-hamstring ratio, is a frequently cited risk factor for increased ACL strain (Alentorn-Geli et al., 2009a; Youdas et al., 2007). As discussed earlier, high quadriceps activation, particularly in the presence of weak hamstrings, leads to an increase in anterior tibial shear force (Alentorn-Geli et al., 2009a; Shields et al., 2005). Though not strong enough to cause the ACL to rupture on its own, in combination with coronal and transverse plane motions and torques a dominant quadriceps can predispose one to injury (Alentorn-Geli et al., 2009a; Imwalle et al., 2009; Kernozek et al., 2008; Willson et al., 2006). Therefore, a focus in many neuromuscular training programs is improving the quadriceps-to-hamstring ratio by improving hamstring strength (Alentorn-Geli et al., 2009a; Myer et al., 2006; Willson et al., 2006). At this time, there does not appear to be a consensus on the best way to increase measures of hamstring strength, nor is there consistency among authors as to appropriate strength measures (e.g., isometric or isokinetic knee flexion or hip extension torques, mass used during hamstring- or hip-dominant exercises, or EMG activity relative to the quadriceps) (Alentorn-Geli et al., 2009b; Herman et al, 2008; Willson et al., 2006).

The quadriceps-to-hamstring ratio is a commonly studied muscular imbalance that is intra-limb. However, Newton et al. (2006) recently focused on inter-limb imbalances that may result in an increased injury risk. The authors reference a study examining contralateral lower-extremity imbalances in female collegiate athletes that revealed a trend for higher injury rates associated with knee flexor or hip extensor strength imbalances of 15% or more on either side of the body. However, it was not clear what sort of injuries (musculotendinous, ligamentous, bone, or other) were more likely to occur. Though the results of the investigation by Newton et al. (2006) failed to elucidate a significant difference between limbs with regard to strength, it was noted that comparing right and left legs of people who may be either right-leg dominant or left-leg dominant could nullify strength differences when averaged across a group. This was supported by the finding that there was a considerable variation in right and left leg dominance across the various tests. Most intriguing, however, was the finding that extensive training with bilateral squats, vertical jumps, and other leg extensor training exercises was not enough to overcome significant contralateral imbalances. Thus, symmetrical bilateral activities are not enough to diminish significant differences between legs. The previously discussed cross-over effect of fatigue (McLean & Samorezov, 2009) may provide some further insight into this phenomenon. If one leg is truly weaker than another, the fatigue experienced in that limb will have a cross-over effect into the stronger limb, limiting the total amount of work that can be accomplished. Though it is yet unclear how such imbalances may play a role in injury or injury prevention, from a sport-performance standpoint it could be beneficial to focus training unilaterally to ensure that both limbs are doing the same amount of work.

Intra-limb and inter-limb strength imbalances appear to predispose athletes, particularly females, to non-contact ACL injury (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Herman et al., 2006; Imwalle et al., 2009; Myer et al., 2006; Myer et al., 2005; Newton et al., 2006; Shields et al., 2005; Yoo et al., 2009; Youdas et al., 2007; Zeller et al., 2003). Alentorn-Geli et al. (2009a) discuss a prospective comparison of female soccer and basketball players with matched male athletes who did and did not go on to experience an ACL injury. Female athletes who sustained a ligament rupture had a combination of similar quadriceps strength and decreased hamstring strength compared to the males, indicating a high quadriceps-to-hamstring ratio in these females. In contrast, those female athletes who did not experience subsequent ACL injury were found to have decreased quadriceps strength and similar hamstring strength compared to the males, indicating lower quadriceps-to-hamstring ratio in the uninjured females (Alentorn-Geli et al., 2009a). The authors do not mention any injury rates or incidences in the male group of athletes. However, it is worth noting that the group of uninjured females exhibited similar hamstring strength but lower quadriceps strength than their male counterparts, meaning that they had a relatively lower quadriceps-to-hamstring ratio. Therefore, it may not be solely the quadriceps-to-hamstring ratio that serves a preventative purpose; absolute hamstring strength may itself be the most important factor. In addition to a perpendicular angle-of-pull to the tibial plateau during positions of increased knee flexion, the hamstrings serve to limit anterior tibial translation through knee joint compression, allowing more of the valgus load to be carried by articular contact forces such as the medial tibial plateau (Alentorn-Geli et al., 2009a). Evidence that hamstring muscles are activated by ACL receptors when the ligament is placed under stress further supports this tenet (Alentorn-Geli et al., 2009a).

Though a low quadriceps-to-hamstring ratio and higher absolute hamstring strength are likely both contributors to preventing an ACL injury from occurring, still another factor regarding the role of these biarticular muscles may be at issue. Related to strength is muscular activity, which is typically lower in females than males, and lower in the hamstrings than the quadriceps in at-risk female athletes (Alentorn-Geli et al., 2009a). Muscular coordination patterns in which hamstring activity is delayed or submaximal, regardless of overall strength of the muscles, may allow high anterior tibial shear forces to occur before the preventative action of the hamstrings can be realized (Alentorn-Geli et al., 2009a). This is supported by McLean et al. (2007) who report that non-contact ACL injuries likely occur within the first 50 ms of ground contact, a time frame that negates the impact of ACL receptor feedback on hamstring activation.

In addition to the hip and knee flexor and extensor groups, the gluteals are important stabilizers of the pelvis and help to maintain proper hip and knee alignment in single-leg stance (Alentorn-Geli et al., 2009b; Imwalle et al., 2009; Zeller et al., 2003). Athletes who exhibit significantly greater hip abduction strength, indicating strong postero-lateral hip musculature (abductors, extensors, and external rotators) as compared to antero-medial hip musculature (flexors and adductors), are less likely to sustain a lower-extremity injury (Alentorn-Geli et al., 2009b; Imwalle et al., 2009). Likewise, weakness of the postero-lateral hip musculature combined with increased hip flexion, either via hip flexor tightness or increased anterior pelvic tilt, could limit the gluteal muscles' ability to stabilize the pelvis and maintain a neutral alignment of the hip and knee during single-limb stance static or dynamic activities (Alentorn-Geli et al., 2009b). The inability of the gluteals to stabilize the pelvis perpetuates anterior pelvic tilt and, subsequently, hip flexor and erector spinae tightness, serving to weaken, elongate, and inhibit the abdominal muscles (Alentorn-Geli et al., 2009b). The ensuing trunk weakness may be an ACL injury risk factor on its own since trunk musculature and positioning has an influence on hamstring activation (Alentorn-Geli et al., 2009b).

Besides proper limb alignment during dynamic movements, muscular strength contributes to the prevention of injury by increasing the stiffness, or the resistance to dynamic stretch, of the joint on which the muscles act (Alentorn-Geli et al., 2009a). This could be relevant to ACL injury prevention in that a more balanced agonist-antagonist muscle activation pattern and higher joint stiffness results in an improvement in dynamic knee stabilization (Alentorn-Geli et al., 2009b). For example, the quadriceps and hamstrings provide anterior-posterior joint stiffness, limiting tibial translation and tibial rotational forces (Alentorn-Geli et al., 2009a). Additionally, Willson et al. (2006) found that the axial force needed to collapse the knee in the frontal plane was sensitive to the level of hip muscle stiffness.

As with many other biomechanical risk factors for non-contact ACL injury, females tend to show less muscular stiffness than their male counterparts, placing them at increased risk for rupture (Alentorn-Geli et al., 2009a). Several authors have hypothesized that females are more prone to at-risk biomechanics due to decreased control of the knee joint musculature and an associated decrease in knee joint stiffness (Willson et al., 2006). Research has supported this idea, showing that males activate their lower-extremity muscles earlier and have longer activation periods in muscles that initiate and maintain dynamic knee and lower extremity stiffness than their female counterparts (Alentorn-Geli et al., 2009a).

The correlation between hip adduction and knee abduction indicates that hip joint stiffness may also play a role in neuromuscular control at the knee (Imwalle et al., 2009; Willson et al., 2006). Stiffening of the hip joint may aid stability of the knee joint through the tendency of the body to act as a linked system, where the constraint of one joint helps to stabilize another, allowing the rest of the body to resist femoral adduction, as well (Imwalle et al., 2009). Support for this theory is found in evidence that females place greater demands on hip musculature during weight bearing than their male counterparts, but possess a decreased capacity to generate muscular stiffness in the hip, thus allowing for a collapse into hip adduction (Alentorn-Geli et al., 2009a; Willson et al., 2006). The role of the proximal joint in providing stability is especially important in that the hip is responsible for transferring upper-body loads to the lower-limb during dynamic movements (Chaudhari et al., 2006; Zeller et al., 2003). While it may also seem likely that the ankle joint would contribute to knee joint stability through attenuation of vertical ground reaction force, a modeling study conducted by Imwalle et al. (2009) concluded that ankle stiffness did not have any discernable effect on knee stability.

A common focus, therefore, of neuromuscular training programs is to improve muscular strength and stiffness at the knee and hip and subsequently improve knee joint stability (Alentorn-Geli et al., 2009b). Though this might be accomplished through a number of mechanisms, two commonly researched techniques are plyometric training and proprioceptive training (Alentorn-Geli et al., 2009b). Plyometric training may achieve enhanced dynamic stiffening through the utilization of the stretch-shortening cycle in order to activate and improve neural, muscular, and elastic components (Alentorn-Geli et al., 2009b). Proprioceptive training, on the other hand, stimulates the somatosensory system, improving co-activation and, with it, joint stiffness (Alentorn-Geli et al., 2009b). The ability of the ACL to sense elongation or a torque and subsequently activate the hamstrings supports the inclusion of proprioceptive elements into neuromuscular programs (Alentorn-Geli et al., 2009a). However, isolated proprioceptive training only improves agonist-antagonist muscle contraction and does not decrease the peak ground reaction force or dynamic valgus collapse at landing, nor does it modify high-risk dynamic positioning the way plyometric training does (Alentorn-Geli et al., 2009b). This is especially true when plyometric training is combined with a resistance training component, resulting in a decrease in muscle activation time and an increase in the force generated by the relevant musculature (Alentorn-Geli et al., 2009b). The improved force-generating capacity during dynamic movements enables an athlete to use active musculature to better accept and redirect the forces created by their body during directional changes or jump-landings, limiting the stress on passive structures such as the ACL (Alentorn-Geli et al., 2009b).

Prevention of Non-Contact ACL Injury

Injuries to the ACL have the highest economic cost among all soccer injuries (Alentorn-Geli et al., 2009a). Non-contact ACL tears often occur with concomitant injuries, such as meniscus tears and medial collateral ligament sprains (Alentorn-Geli et al., 2009a). Reconstructive surgery and long rehabilitation periods have not served to reduce the post-traumatic injury risk of developing knee osteoarthritis (Alentorn-Geli et al., 2009b). The economic and health costs associated with ACL injuries have therefore resulted in the creation of prevention programs designed to modify ACL injury risk factors and reduce non-contact ACL injury rates (Alentorn-Geli et al., 2009b).

This is not to say that other prophylactic measures may not be beneficial. There is currently a dearth of information on the usefulness of knee braces and the role of ground and shoe-surface interaction modifications (Alentorn-Geli et al., 2009b). With regard to knee braces, there have been contradictory findings concerning their effectiveness in reducing ACL injury rates in American football players; nonetheless, many players continue to use them due to the possibility that they may limit injurious ranges-of-motion at the knee (Alentorn-Geli et al., 2009b). Understanding the influence of knee braces on neuromuscular control, knee and whole-body kinematics, and knee kinetics will enable players, coaches, and sports medicine personnel to make informed decisions about their use. Studies using brace interventions that control for outside factors (player position, conditioning level, skills, experience, gender, age, etc.) are highly desirable (Alentorn-Geli et al., 2009b). The same is true for prospective studies on the effects of footwear on the biomechanics of at-risk movements during varying conditions (turf or grass field, weather, spike length, etc.) (Alentorn-Geli et al., 2009b).

Preventative neuromuscular training programs have gained popularity in research facilities primarily due to the purported ability of such programs to alter biomechanical risk factors that contribute to non-contact ACL injury (Alentorn-Geli et al., 2009b; Borotikar et al., 2008; Herman et al., 2008; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Myer et al., 2005; Yoo et al., 2009; Youdas et al., 2007; Zeller et al., 2003). Athletic venues, meanwhile, have begun adopting these programs for the performance enhancement benefits of speed, agility, and strength training (Alentorn-Geli et al., 2009b). This latter point may be the most salient; adherence rates to preventative neuromuscular training programs are two to three times higher when the program is also shown to enhance athletic performance, with compliance as high as 80-90% (Alentorn-Geli et al., 2009b; Myer et al., 2005; Yoo et al., 2009). In order to provide injury-reducing benefits, the athletes must complete the program. Thus, maximizing rates of compliance becomes an extremely important consideration in program design (Alentorn-Geli et al., 2009b), and it appears that this can be accomplished through a balance of injury-reducing and performance-enhancing components (Alentorn-Geli et al., 2009b; Yoo et al., 2009).

Components of Preventative Programs

There is currently little consensus as to which components of neuromuscular training programs, in combination or in isolation, and to what degree, are the most effective at non-contact ACL injury prevention (Alentorn-Geli et al., 2009b; Herman et al., 2008; Lim et al., 2006; Myer et al., 2005; Yoo et al., 2009). Multi-component programs may be more effective than any solitary component on its own (Alentorn-Geli et al., 2009b; Yoo et al., 2009), though the mechanism by which multi-component programs are superior is as yet undefined. Successful preventative interventions appear to have elements of stretching, strengthening, aerobic, plyometric, risk-awareness, and proprioceptive training in varying amounts (Alentorn-Geli et al., 2009b; Lim et al., 2009).

Though stretching has been identified as a component of successful ACL injury prevention programs, there is no direct evidence to support its incorporation. The commonly understood purpose of stretching is to increase the range-of-motion of a joint by increasing the length of the muscle(s) that act on the joint. However, there are not currently any studies that have correlated a stretching program or increased range-of-motion about any specific joint to a decrease in non-contact ACL injury risk (Alentorn-Geli et al., 2009b). It is plausible that stretching is included in prevention programs simply because increased range-of-motion is generally considered to be a beneficial asset and therefore is incorporated into nearly every sport performance program.

Like stretching, the effect of aerobic performance on non-contact ACL injury risk is poorly researched. One possible reason for this is an inconsistency in terminology. Though “aerobic fitness” (Alentorn-Geli et al., 2009b) and “conditioning” (Alentorn-Geli et al., 2009b; Chappell et al., 2005; Yoo et al., 2009) have been identified as integral to preventative neuromuscular training programs, the terms are often used interchangeably and are rarely, if ever, strictly defined. The term “conditioning” could refer to the ability to delay peripheral or central fatigue (or both), as is inferred in some studies (Chappell et al., 2005). However, aerobic conditioning is also related to several different aspects of fitness, such as maximal oxygen uptake, running economy, or lactate threshold. This disparity leads to a poor understanding of conditioning and its possible role in injury prevention.

Proprioceptive training, as discussed previously, stimulates the somatosensory system, improving muscle co-activation and joint stiffness (Alentorn-Geli et al., 2009b). Proprioceptive training is another fitness term that is referenced through many pseudonyms, most commonly “dynamic stabilization” or “balance training” (Myer et al., 2006; Oliver & DiBezzo, 2009). Proprioceptive training typically refers to exercises designed to increase kinesthetic awareness, muscular strength, and core strength and are often performed with the goal of resisting movement during unstable conditions (Oliver & DiBezzo, 2009). This differs from traditional strength training, in which a specific range-of-motion is performed against some form of resistance. Though proprioceptive training can lead to increases in postural control (Oliver & DeBezzo, 2009), the benefits are task-specific (Myer et al., 2006) and do not include a reduction in peak ground reaction force or valgus collapse during dynamic movements (Alentorn-Geli et al., 2009b). Furthermore, plyometric and strength-training components of preventative neuromuscular training programs have been found to significantly reduce ACL injury risk as compared to balance training alone (Yoo et al., 2009). Specific proprioceptive training adaptations have been identified in the sagittal plane during medial and lateral movements, allowing for increased knee flexion, and possibly force absorption, during these tasks (Myer et al., 2006). These results indicate that proprioceptive training is an appropriate compliment to other training methods but is not sufficient at reducing the risk of non-contact ACL injury on its own (Myer et al., 2006).

Plyometric exercises reportedly increase muscular power, strength, and speed (Yoo et al., 2009). The utilization of the stretch-shortening cycle during plyometrics activates and improves neural, muscular, and elastic components of muscles and tendons, resulting in increased dynamic stiffening in the affected joints, decreased muscle activation time, increased force-generating capacity of the relevant musculature, reduced knee abduction and adduction moments, reduced peak vertical ground reaction forces and increased hamstring torques during landing and cutting tasks (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b). Taken together, such adaptations result in a decrease in biomechanical risk factors for ACL injury (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Yoo et al., 2009). Current evidence, however, suggests that isolated plyometric protocols may not be beneficial to at-risk athletes (Myer et al., 2006; Yoo et al., 2009), but combined plyometric/strength-training protocols show the most promise for reducing risk factors and incidence rates of non-contact ACL injury (Alentorn-Geli et al., 2009b; Herman et al., 2008; Lim et al., 2009; Myer et al., 2006; Myer et al., 2005; Yoo et al., 2009).

Strength training, like plyometric training, is often cited as non-beneficial to the reduction of at-risk biomechanics in isolation (Herman et al., 2008; Lim et al., 2009). However, there has only been one study, conducted by Herman et al. (2008), that has compared a strength training program purported to alter at-risk biomechanics with a control group. The protocol used in this study involved single joint movements designed to increase strength in the quadriceps, hamstrings, gluteus maximus, and gluteus medius. The resistance used to elicit strength gains was rubber tubing, and strength measures were quantified by isometric contractions against a hand-held dynamometer. Biomechanical risk-factors for ACL injury were measured during a stop-jump task. Though the processes used to improve and measure strength, as well as the stop-jump task protocol, are methodologically reliable, this protocol may have produced misleading conclusions. Anecdotal evidence regarding strength training is that it is task-specific; that is, the greatest benefits are achieved when the training methods mimic the on-field activities (Cook, 2003). This is called "specificity of training" (Cook, 2003). Therefore, it is not surprising that supported, single-joint exercises did not elicit changes in a dynamic, total-body movement pattern.

It seems evident that further research should focus on the contribution of a performance-enhancing strength training protocol to changes in at-risk biomechanics during cutting and jump-landing tasks. Strength training on its own likely reduces injury due to the beneficial adaptations that occur in bones, ligaments, and tendons (Myer et al., 2005). Those studies that did not examine a strength training protocol directly, but that included one in their neuromuscular training protocol (in addition to stretching, agility, plyometrics, or balance training), included functional exercises for the entire body, much like a performance-enhancing strength training protocol would (Lim et al., 2009; Myer et al., 2006; Myer et al., 2005). Furthermore, current results indicate that training should include both single-leg and double-leg components in order to mimic athletic situations and continue to improve hip strength and stiffness, two commonly identified modifications that will decrease ACL injury risk (Myer et al., 2005). Single-limb strength training exercises have the combined benefits of strength training and dynamic stabilization/proprioceptive training, enabling athletes to experience greater biomechanical improvements with fewer total exercises. However, the preventative strength training protocols in existence include lower-extremity exercises that are almost entirely double-legged in nature (Lim et al., 2009; Myer et al., 2006; Myer et al., 2005).

This study was the first in which two strength training protocols designed to increase athletic performance and decrease non-contact ACL risk factors were compared. The protocols were identical in nature with regard to core and upper-extremity exercises. The lower-extremity exercises (identified as hip-dominant and knee-dominant movements) differed between the two groups. One group performed all hip- and knee-dominant exercises with double-leg support, whereas the second group performed all hip- and knee-dominant exercises with single-leg support. The results of this study add to the current literature regarding the importance and efficacy of strength training protocols on reducing at-risk biomechanics in soccer players, as well as increase the current body of knowledge as to the impact of strength training exercises that mimic on-field postures and movements.

Chapter Three – Methods

The purpose of this research study was to compare functional performance measures and lower-extremity biomechanics during simulated sports tasks in healthy female collegiate soccer players subjected to either a predominantly single-leg (SL) or predominantly double-leg (DL) six-week neuromuscular training protocol. Triple-hop test (THT) distance, vertical jump (VJ) height, maximal back squat strength (BS 1-RM), and kinetic and kinematic measures of a jump-landing and cut maneuver (JLC) were assessed pre- and post-training for each respective group. The participants, measures, and interventions are described in the sections that follow.

Participants

Thirteen players were recruited from the Barry University women's soccer team. Alpha was set at 0.05 with a power of 0.80, which gives an estimated effect size of 0.30. This effect size is based on previous research with similar variables (Borotikar et al., 2008). Criteria for exclusion included current lower-extremity injury, ACL reconstruction <1 years old, and any neurological disease or muscular or cartilaginous injury that would preclude completion of all testing procedures and a six week neuromuscular training program. Ten participants were subsequently accepted into the study. Participants were randomly assigned to one of two groups: a single-leg, or experimental, group (NTP-SL) or a double-leg, or control, group (NTP-DL). As indicated by their names, each group performed all major hip- and knee-dominant resistance training exercises in either a single-leg or double-leg variation. Further details are included below.

Approval for the use of human subjects was granted from the Barry University Institutional Review Board, and participants were required to read and sign an Informed Consent.

Instrumentation

Data Collection

A Vicon seven-camera three-dimensional motional analysis system (Centennial, CO) was used to measure kinematic data during the JLC movement. Data was collected at 240Hz. Two 2400Hz six-channel AMTI force platforms (Watertown, MA) measured force data during the stance phase of the JLC. Data was synced directly through the Vicon MX hardware and recorded and processed with Vicon Nexus software (Centennial, CO).

Neuromuscular Training Program (NTP)

The athletes recruited for this study were in the midst of a soccer off-season training program. Their practices were conducted several times weekly in conjunction with a light spring schedule of exhibition games. Additionally, the team participated in a plyometric conditioning program once per week and an abdominal muscle-intensive workout once per week, both conducted by the Barry University Strength and Conditioning Coach.

The strength and conditioning program implemented as a part of this study included a dynamic warm-up and range-of-motion exercises and a neuromuscular training (resistance training) protocol (NTP). With the exception of the hip- and knee-dominant exercises, all aspects of the NTP (warm-up, range-of-motion, upper-body and core strength exercises) were identical. Hip- and knee-dominant exercises differed only between groups, which were determined by random assignment. All NTP workouts were designed and supervised by the Principle Investigator, a nationally certified Strength and Conditioning Coach.

Procedures

Pre- and post-testing for each individual took place on one day with adequate rest periods in place to avoid the confounding effect of fatigue. An estimated back squat 1-RM test, rather than a maximal test, was chosen for this reason (Kernozek et al., 2008; LeSuer, McCormick, Mayhew, Wasserstein & Arnold, 1997). On the day of testing, the athletes performed a repetitions-to-fatigue back squat test as previously described in the literature (LeSuer et al., 1997) to predict their back squat 1-RM weight. Additionally, the participants completed the THT, VJ, and JLC tests. The order of the testing was randomized, with a minimum of 10 minutes of rest following the 1-RM and JLC tests and a minimum of 5 minutes of rest following the THT and VJ tests. Prior to beginning the testing procedures, each participant was given five minutes to perform a self-directed, generalized warm-up. Each test is described in detail below.

Triple-Hop Test (THT)

A tape measure was affixed to the ground perpendicular to a pre-determined starting line. The test was conducted in the participants' self-selected athletic footwear. Participants balanced on one leg and performed three consecutive maximal hops forward on this limb without losing balance or allowing any other part of their body touch the floor or a supporting structure. The landing of the last jump was held in a controlled manner for a period of 3 seconds to be considered a valid trial. The distance traveled was measured from the starting line to the point where the participant's heel struck the ground on the landing of the third hop. This process was then repeated with the contralateral limb. Three trials were performed on each limb with each participant, and the farthest distance traveled for both right and left legs were recorded and used for analysis (Hamilton et al., 2008).

Vertical Jump (VJ)

The vertical jump is a reliable and valid measure of power output in athletes (Hamilton et al., 2008). The VJ was performed using a countermovement jump, and jump height was measured, in inches, with a Vertec Jump Measurement System (Gill Athletics, Champaign, IL). The athlete stood beneath the Vertec system, feet shoulder-width apart and with preferred reach-hand positioned closest to the device. While keeping shoulders level, the reaching arm was flexed 180-degrees and the height of this static reach was recorded. The participant then performed as many countermovement jumps with a reach as she could while still increasing the height of each jump. Once jump height remained constant for three consecutive trials, the maximum height reached was subtracted from the original static reach height to obtain the VJ height. This height was recorded for analysis.

Predicted Back Squat 1-RM (BS 1-RM)

In a predictive back squat 1-RM test, the athlete must select a weight that he or she can squat more than one repetition but less than 10 repetitions. This weight is estimated through 2-3 increasingly heavy warm-up sets. To minimize fatigue, warm-up sets were kept to a maximum of 6 repetitions, regardless of weight lifted, and had a 1-2 minute rest period between each set. During the test set, the athlete squatted the given weight as many times as possible. The test was successful if the athlete performed each repetition in the correct manner, bringing the thighs parallel to the floor on each descent, and if she was able to perform at least 2, but no more than 10, repetitions. If the test was unsuccessful, the weight was adjusted and the test re-attempted after a 3-5 min rest period.

Once a successful test was performed, the weight and number of repetitions completed was recorded. The following formula, originally described by Wathan (1994) and found to be a valid and reliable predictor (*r* = 0.969) of the back squat 1-RM (LeSuer et al., 1997), was used to obtain the 1-RM value for each participant:

$$\text{1-RM} = 100 \times \mathit{rep\ wt} \,/\, (48.8 + 53.8 \times \qquad\qquad)$$

Jump-Landing and Cut (JLC)

Two of the most common mechanisms of non-contact ACL injury are landing from a jump (i.e., rapid deceleration) and cutting (i.e., a rapid change in direction). These two movements result in previously identified high-risk biomechanics (Imwalle, Myer, Ford, & Hewett, 2009). Since these movements, and therefore the risks, are a natural occurrence in most sporting events, limiting the extent to which these motions result in biomechanical risk-factors is paramount.

In order to ascertain if the NTP-SL group results in superior biomechanics (less risk) over the NTP-DL group, participants performed a jump-landing and cut maneuver. The athletes stood behind a line that was 1 meter behind two force plates. When given a signal, the participant jumped forward onto the force plates, landing on two feet, under one of two conditions: landing and making a 90° cutting maneuver quickly and forcefully to their right, or landing making a 90° cutting maneuver quickly and forcefully to their left. All trials were randomized and unanticipated, such that the participant did not know which direction to cut until she had begun her jump onto the force plates. While in the air, the direction in which to cut was indicated by the Principle Investigator or a trained research assistant. The directional indication consisted of turning one's shoulders to the left or the right, as if about to make an athletic move in that direction. The participants were instructed to cut in the same direction as researcher. A total of 10 successful trials (5 per condition/leg) were recorded for analysis.

Neuromuscular Training Program (NTP)

Single-leg training program (NTP-SL).

The hip- and knee-dominant portions of the NTP-SL program featured a back-loaded rear-foot-elevated squat (RFE squat), slideboard lunge, single-leg Romanian deadlift (SL RDL), single-leg squats (SL squats) and rear-foot-elevated jumps (RFE jumps). The full program, along with the exercise progressions, can be found in Appendix A.

Double-leg training program (NTP-DL).

The hip- and knee-dominant portions of the NTP-DL program featured back squats (BS), stability ball leg curls (SB leg curls), trap-bar deadlifts (TBDL), and dumbbell Romanian deadlifts (DB RDL). The full program, along with the exercise progressions, can be found in Appendix A.

Data Analysis

THT, VJ, and predicted BS 1-RM were analyzed as a separate mixed-model 2 x 2 (TIME x GROUP) ANOVAs. Each test examined differences in distance (meters), height (inches), and mass (kilograms), respectively, with an alpha level of .05.

From the JLC maneuver, six dependent variables were analyzed at various phases of STANCE (IC, 25%, and PVGRF) and between groups (NTP-SL and NTP-DL). Therefore, three separate 2 x 2 (TIME x GROUP) MANOVAs were calculated at each stance phase for: HFA (deg) and KFA (deg); HERM (Nm), HAbM (Nm), KAdM (Nm); and KAS (N). All kinetic measures were normalized to body weight.

Chapter Four – Results

Ten participants were randomly assigned to the NTP-SL group (height: 165.32 cm (157.48-172.72); weight: 59.79 kg (54.1-68.0) and the NTP-DL group (height: 165.39 cm (157.48-170.18); weight: 61.18 kg (53.64-67.7). All athletes completed the 12 training sessions and were included in the data analysis. Three sport performance tests were used to evaluate each participant pre- and post-intervention. The vertical jump (VJ), triple hop test (THT), and back squat 1-RM (BS1RM) measured lower-extremity power, agility and balance, and strength, respectively. These tests were not significantly correlated, and therefore were calculated as separate 2 x 2 (Test x Group) mixed-model ANOVAs. The descriptive statistics can be found in Table 1.

In the BS1RM, there was no significant Test x Group interaction ($F(1,8) = .694$, $p > .05$), nor was there a significant main effect for Group ($F(1,8) = 1.134$, $p > .05$). However, a significant main effect for Test was found ($F(1,8) = 14.727$, $p < .05$). When groups were combined, post-test 1RM was significantly higher. The VJ, similar to the BS1RM, saw no significant Test x Group interaction ($F(1,8) = 4.082$, $p > .05$), nor was there a significant main effect for Group ($F(1,8) = .030$, $p > .05$). There was, however, a significant main effect for Test ($F(1,8) = 5.878$, $p < .05$). When groups were combined, post-test VJ was significantly higher than the pre-test.

In the THT, a significant Test x Group interaction was found ($F(1,8) = 5.937$, $p < .05$). Follow-up ANOVAs showed no significant Test x Group interaction for THT on the right ($F(1,8) = 5.012$, $p > .05$) or left ($F(1,8) = .134$, $p > .05$) legs from pre-test to post-test. There was no significant main effect for Group ($F(2,7) = .677$, $p > .05$) or Test ($F(2,7) = 1.572$, $p > .05$) during the THT.

Table 1

Descriptive Statistics for Athletic Performance Tests Pre- and Post-Test by Group

	Single-Leg		Double-Leg	
	Pre-test	Post-test	Pre-test	Post-test
BS1RM	76.08 +/- 4.71	88.78 +/- 12.72	77.52 +/- 6.66	97.26 +/- 12.93
VJ	49.8 +/- 3.52	50.0 +/- 3.66	48.0 +/- 5.49	50.8 +/- 5.75
THTright	480.2 +/- 25.13	471.7 +/- 43.47	453.6 +/- 36.78	480.4 +/- 35.85
THTleft	492.5 +/- 19.56	491.2 +/- 21.25	470.7 +/- 45.41	475.1 +/- 22.80

Note: BS1RM = Back squat one-repetition maximum (kg); VJ = Vertical jump height (cm); THTright = Triple-hop test distance, right leg (cm); THTleft = Triple-hop test distance, left leg (cm)

Six variables were examined from the jump landing and cut (JLC) maneuver. Since the side-cut movement was performed at a 90-degree angle in both the left and right direction, yielding five trials in each direction, kinetic and kinematic variables were examined either for the right leg (in the case of a cut to the left) or the left leg (in the case of a cut to the right). Descriptive statistics for NTP-SL and NTP-DL can be found in Table 2.

Table 2

Descriptive Statistics for Kinematic and Kinetic Variables in the NTP-SL Group

	Single-leg		Double-leg	
	Pre-test	Post-test	Pre-test	Post-test
LICHFA	37.84 +/- 4.16	37.77 +/- 3.78	38.07 +/- 13.03	37.70 +/- 12.31
RICHFA	38.86 +/- 5.90	41.88 +/- 4.97	40.95 +/- 8.78	37.39 +/- 10.71
LPVGRFHFA	39.83 +/- 6.41	40.14 +/- 3.87	39.78 +/- 11.29	37.59 +/- 8.41
RPVGRFHFA	42.68 +/- 8.91	41.63 +/- 7.26	43.88 +/- 12.00	37.32 +/- 7.43
LQSHFA	49.36 +/- 8.73	46.80 +/- 2.26	43.72 +/- 11.03	39.98 +/- 5.97
RQSHFA	50.72 +/- 9.44	48.80 +/- 9.98	48.51 +/- 11.75	40.74 +/- 6.52
LICKFA	14.71 +/- 3.11	12.49 +/- 4.34	16.21 +/- 8.53	19.52 +/- 8.39
RICKFA	11.51 +/- 3.60	12.26 +/- 1.36	14.21 +/- 7.80	17.78 +/- 10.36
LPVGRFKFA	32.27 +/- 5.76	37.17 +/- 9.45	34.38 +/- 14.19	36.38 +/- 14.11
RPVGRFKFA	29.29 +/- 8.74	32.61 +/- 9.96	30.56 +/- 22.24	32.59 +/- 16.40
LQSKFA	55.96 +/- 7.84	53.67 +/- 4.27	53.06 +/- 12.67	52.73 +/- 16.24
RQSKFA	53.99 +/- 4.79	52.76 +/- 6.55	49.45 +/- 21.66	49.10 +/- 17.99
LICKAS	-1.10 +/- 1.20	-2.06 +/- 1.32	-1.78 +/- 1.89	-1.37 +/- 2.11
RICKAS	-0.64 +/- 2.12	-1.41 +/- 1.21	-1.01 +/- 1.76	-1.65 +/- 0.86
LPVGRFKAS	6.75 +/- 2.39	7.72 +/- 1.48	7.89 +/- 4.30	9.97 +/- 2.66
RPVGRFKAS	2.98 +/- 3.55	5.02 +/- 3.30	5.12 +/- 4.49	6.59 +/- 3.70
LQSKAS	7.69 +/- 2.42	8.09 +/- 0.70	10.23 +/- 2.58	11.63 +/- 1.65
RQSKAS	6.63 +/- 2.03	7.27 +/- 1.59	8.11 +/- 1.83	9.26 +/- 4.15
LICKAdM	136.94 +/- 160.06	57.88 +/- 134.87	53.85 +/- 233.44	108.24 +/- 218.46
RICKAdM	116.66 +/-	37.33 +/- 185.28	149.82 +/- 323.22	-6.91 +/- 286.59

	136.53			
LPVGRFKAdM	156.68 +/- 518.24	322.36 +/- 313.47	247.91 +/- 704.97	543.63 +/- 820.73
RPVGRFKAdM	-2144.71 +/- 983.93	-1735.11 +/- 210.39	-1163.22 +/- 1081.37	-1693.17 +/- 778.68
LQSKAdM	599.60 +/- 300.80	703.99 +/- 187.83	714.24 +/- 596.52	1293.00 +/- 225.23
RQSKAdM	-886.16 +/- 491.98	-1218.19 +/- 416.98	-562.22 +/- 1325.04	-823.29 +/- 504.25
LICHAbM	365.05 +/- 328.80	318.24 +/- 518.56	181.51 +/- 792.49	495.17 +/- 1048.00
RICHAbM	308.58 +/- 445.44	93.84 +/- 287.92	739.15 +/- 635. 03	400.54 +/- 717.56
LPVGRFHAbM	394.18 +/- 692.45	-98.78 +/- 346.06	966.27 +/- 852.29	23.08 +/- 1283.89
RPVGRFHAbM	-2348.92 +/- 517.88	-1758.79 +/- 605.16	-1619.60 +/- 1471.71	-1957.90 +/- 1153.52
LQSHAbM	532.03 +/- 467.67	488.93 +/- 398.62	362.95 +/- 415.95	351.64 +/- 349.47
RQSHAbM	-685.68 +/- 435.07	-1212.98 +/- 625.65	-870.61 +/- 738.51	-1612.56 +/- 1195.70
LICHERM	40.89 +/- 63.12	42.49 +/- 12.25	5.89 +/- 44.27	52.17 +/- 73.48
RICHERM	27.29 +/- 41.69	52.91 +/- 38.57	3.46 +/- 69.45	6.58 +/- 41.32
LPVGRFHERM	8.95 +/- 112.66	-16.80 +/- 106.61	-106.62 +/- 304.22	-116.11 +/- 437.00
RPVGRFHERM	983.22 +/- 533.76	732.25 +/- 125.51	371.53 +/- 271.54	842.44 +/- 720.86
LQSHERM	-138.80 +/- 202.64	-52.61 +/- 138.83	-137.75 +/- 411.37	-235.28 +/- 299.78
RQSHERM	593.54 +/- 145.02	660.13 +/- 238.42	489.75 +/- 221.20	900.62 +/- 657.78

Note: L = Left; R = Right; IC = Initial contact; PVGRF = Peak vertical ground reaction force; QS = 25% of stance phase; HFA = Hip flexion angle; KFA = Knee flexion angle; KAS = Knee anterior shear force; KAdM = Knee adduction moment; HAbM = Hip abduction moment; HERM = Hip external rotation moment

Three separate 2 x 2 (Time x Group) MANOVAs were calculated for HFA and KFA, KAS, and KAdM, HAbM, and HERM. Each variable was examined at three different periods of stance: IC, PVGRF, and QS. For HFA and KFA, no significant Test x Group interaction or main effect was found for Test or Group. Similarly, no significant Test x Group interaction or main effect was found for Test or Group for KAS. For KAdM and HAbM, no significant Test x Group interaction or main effect was found for Test or Group. There was no significant Test x Group interaction or main effect for Group for HERM during a side-cut to the right, nor was there a significant Test x Group interaction or main effect for Test or Group for HERM during a side-cut to the left. However, the main effect for Test for HERM during a side-cut to the right approached significance ($F(3,6) = .747$, $p = .050$). Follow-up univariate tests did not show significant effects for Test at any particular phase of stance (IC: $F(3,6) = .363$, $p > .05$; PVGRF: $F(3,6) = .433$, $p > .05$; QS: $F(3,6) = 2.202$, $p > .05$).

Chapter Five – Discussion

Female soccer players experience ACL tears at a rate of up to 6 times that of their male counterparts (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Myer et al., 2006; Pantano et al., 2005; Youdas et al., 2007), resulting in significant short- and long-term co-morbidities (Alentorn-Geli et al., 2009a; Borotikar et al., 2007). At-risk biomechanics, such as an extended knee posture during landing and out-of-sagittal- plane hip and knee moments, have been positively affected by neuromuscular training programs that consist of plyometric and strength training exercises (Yoo et al., 2009). The current research aimed to elicit the contribution of strength training to the resulting alterations in biomechanical approaches to a side-cut maneuver in healthy female collegiate soccer players. Further, a comparison was made between more traditional double-leg and the purportedly more athletically-based single-leg closed-chain hip and knee exercises.

Participants were subjected to six weeks of either a predominantly single-leg (NTP-SL) or predominantly double-leg (NTP-DL) neuromuscular training protocol. Triple-hop test (THT) distance, vertical jump (VJ) height, predicted maximal back squat strength (BS 1-RM), and six kinetic and kinematic measures of a jump-landing and side-cut maneuver (JLC) were assessed pre- and post-training for each respective group. Given the test-retest nature of the research design and the utilization of a six-week neuromuscular training program, it was expected that both the NTP-SL and NTP-DL groups would experience a significant increase in BS 1-RM mass, VJ height, and THT distance. Due to the inherent balance and stability training that accompanies single-limb stance, it was further hypothesized that the NTP-SL intervention group would achieve significantly farther results in the THT test than the NTP-DL group at post-test, but that the groups would not differ in BS 1-RM mass or VJ height.

For the JLC maneuver, the kinematic and kinetic variables recorded were compared pre-test to post-test and between the NTP-SL and NTP-DL group at predetermined points (initial contact [IC], 25% of stance phase [QS] and peak vertical ground reaction force [PVGRF]) during the stance phase of the movement. It was hypothesized that both groups would experience a significant increase in hip and knee flexion angles (HFA and KFA, respectively), a significant increase in hip external rotation moment (HERM) and hip abduction moment (HAbM), a significant decrease in knee adduction moment (KAdM), and a significant decrease in knee anterior shear force (KAS).

Performance Measures

As expected, both groups experienced a significant increase in BS 1-RM mass and VJ height. Additionally, there were no significant differences between the NTP-SL and NTP-DL groups at post-test for either measure. A concern with single-limb training is the use of less overall mass. A person who has a back squat 1-RM of 100kg on two legs cannot be expected to do the same on one leg. Similarly, performance of the VJ on two legs should result in a higher jump than a VJ performed on one leg. Jensen & Ebben (2007) report that unilateral jump heights result in approximately 58% of the bilateral equivalent. Though higher than the 50% of bilateral jump height one might expect, it is nevertheless an overall decrease in force in absolute terms. This has led to speculation that the use of lighter weights will result in a decrease in overall lower-extremity strength and power. The participants in this study did not suffer this feared decrease, with both groups instead experiencing the gains in BS 1-RM mass and VJ height that would be expected with participation in a strength training program.

The aforementioned 58% of bilateral VJ height attained by a single-limb may explain why this decrease does not occur. The person squatting 100kg would be subjecting each leg to roughly a 50kg load. Conversely, when performed one leg at a time, the same individual should be able to squat 58kg with each leg, a 16% increase in mass. Since maximal strength has a strong influence on power production (Chaouachi et al., 2009), the increase in mass carried by each limb individually could increase bilateral power to the point where it would result in increases in VJ performance above and beyond that achieved with traditional bilateral strength training. The use of EMG to measure muscle activity and temporal aspects of single-limb versus double-limb hip- and knee-dominant exercises may further illuminate these hypotheses. Additionally, future research should compare measurements of work in each limb during single- and double-limb exercises.

Participants did not experience significant gains in THT distance, regardless of the group to which they were randomly assigned. The THT, which is performed on one leg and is a measure of balance, agility, and power, was expected to improve for both groups after training, with the NTP-SL group seeing significantly greater increases in distance than the NTP-DL group. Though single-limb hops were not a part of the NTP-SL training protocol, multiple exercises were performed under loaded conditions while balancing on one leg. Such postures are thought to increase the work done by the hip rotators in order to stabilize the pelvis and maintain balance during movement. It is possible, however, that such exercises are still not specific enough to a single-limb hopping activity as to have functional carry-over.

There are other possibilities for the THT results. An examination of the means for each group (Table 1) shows a moderate decrease in THT distance for the right leg and a slight decrease for the left leg in the NTP-SL group from pre- to post-test. Conversely, the NTP-DL group experienced a substantial gain in distance in the right limb and a small gain in distance in the left limb. Small group size, a wide range in values, large standard deviations, and insufficient power likely contributed to the lack of statistical significance in THT distance comparisons. However, the distances achieved here, as well as the large standard deviations and ranges, are in agreement with previously reported results. Hamilton et al. (2008) subjected 40 participants to the THT with their right leg, yielding a mean distance of 547.2cm with a standard deviation (SD) of 97.0cm and a range of 383 – 781cm as compared to a mean of 466.9cm, SD of 32.8387cm and range of 395.5 – 511cm on the right leg at pre-test in the current study. Therefore, small group size and the concurrent lack of statistical power may be the sole reason for non-significant results.

It is interesting to note that while the NTP-DL group experienced gains in both limbs, the dominant limb (in this case, the right leg for all participants) experienced a markedly larger increase than the non-dominant limb. This was not the case for the NTP-SL group, which saw a small decrease in the distance attained by the dominant limb. It is possible that the training undertaken by the NTP-DL group caused an increase in limb dominance, whereas the NTP-SL group, by design, could not compensate the non-dominant limb by having the dominant limb perform more work. Previous literature has reported similar findings. Newton et al. (2006) examined force production during a back squat at 80% of 1-RM and the VJ under three conditions: bilateral jumping, right-limb only, and left-limb only. Participants had between one and five years of strength training at the collegiate level, which the authors report featured extensive bilateral squat, vertical jump, and other leg extensor training. Despite such training, significant contralateral imbalances in strength and power persisted. This was observed through a 6% difference in force production between limbs during the back squat and double-leg VJ and an 8% difference in force production between the dominant and non-dominant leg during the single-limb VJ. The authors hypothesized that these imbalances are perpetuated by dominance of one side of the body during skills training and competition and that specific resistance training targeting the weaker side may be required to address this issue. These findings are echoed by Kernozek et al. (2008), who report that unilateral asymmetries in kinematic and kinetic measures frequently occur between legs during double-leg landings. Whether double-limb training reinforces limb dominance and compensation movement patterns or single-limb training is able to reduce disparities between limbs is a topic for continued research.

Kinematic and Kinetic Measures

Non-contact ACL injuries typically occur during movements involving high-risk biomechanics, such as cutting, pivoting, sudden deceleration, or landing from a jump (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle et al., 2009; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). These motions result in knee valgus, varus, internal rotation, and external rotation moments, as well as anterior translation force (Alentorn-Geli et al., 2009a). The risk of injury is magnified when these forces occur at greater degrees of hip and knee extension, a common posture for female athletes as compared to their male counterparts, resulting in less shock attenuation and higher forces experienced at the knee (Alentorn-Geli et al., 2009a; Chaudhari & Andriacchi, 2006; Lim et al., 2009; Yoo et al., 2009).

Though HFA and KFA in the NTP-SL and NTP-DL groups were non-significant from pre-test to post-test at all three phases of stance, the importance of increasing these angles during at-risk movements should not be overlooked. Current ACL neuromuscular training programs aim to lower the risk of injury by reinforcing proper postures and creating the strength and endurance necessary to maintain correct biomechanics. Increasing hip and knee angles during cutting maneuvers or jump-landings helps to absorb force through the more elastic muscles, rather than through the less-forgiving ligaments at ankle and knee joints. This decreases anterior shear force in the knee, lessening the strain on the ACL, while placing the hamstrings at an optimal angle-of-pull to assist in resisting anterior translation of the tibia (Alentorn-Geli et al., 2009a). Importantly, though statistically non-significant, both the NTP-SL and NTP-DL groups trended toward a consistent increase in KFA at PVGRF after training. However, this increase in KFA may be mitigated by a concurrent trend toward a decrease in HFA at PVGRF at post-test, also exhibited in both groups.

The NTP-SL and NTP-DL training protocols incorporated hip- and knee-dominant exercises that aimed to strengthen the extensor muscle groups. Increased strength during hip and knee eccentric flexion allows athletes to use sagittal plane motions to absorb the forces exerted on the body without risk of collapse in the frontal or transverse planes, putting more strain on the ACL. As such, if the athletes in the present study experienced the expected increase in lower-limb strength, there should have been a concomitant increase in hip and knee flexion angles at post-test. However, similar to the THT, it is possible that the exercises selected were not dynamic enough to have carry-over to the JLC, which is essentially a plyometric movement. As discussed in Chapter Two, plyometric programs, particularly when paired with a strength training regimen, had the most success at reducing at-risk biomechanics during jump-landing and cutting maneuvers (Alentorn-Geli et al., 2009a; Alentorn-Geli et al., 2009b; Myer et al., 2006; Yoo et al., 2009). This could be because an increase in strength seen with just a resistance training protocol may not be specific enough to carry over to the ballistic deceleration experienced during plyometric, cutting, and landing maneuvers.

Once again, small group size and insufficient statistical power may have contributed to the lack of significant differences in KFA and HFA from pre-test to post-test. Additionally, twelve training sessions that occur over a six-week period may not be enough to elicit true neuromuscular changes. As noted by Lim et al. (2009), six weeks does not correlate with the time frame needed to produce muscle hypertrophy or improved endurance. However, that should be a sufficient time frame in which to increase motor unit recruitment. Further studies should attempt to implement neuromuscular training programs over a longer period of time, allowing both neurological and morphological changes to take place.

Considering there was no significant increase in HFA or KFA, it is of little surprise that there were also no significant changes in KAS in either group from pre-test to post-test. Another look at trends among means of the NTP-SL and NTP-DL groups shows that both groups experienced a similar training effect. In this case, KAS tended to decrease slightly at IC – and, in fact, be a posteriorly-directed force – in the NTP-SL group, but was higher at both PVGRF and QS phases. The same trend occurred during a side-cut to the right in the NTP-DL group, but not during a side-cut to the left, during which KAS tended to increase at all phases of stance from pre- to post-test.

Though KAS alone is not enough to rupture the ACL, when experienced in combination with coronal and transverse plane torques the risk of ACL rupture is elevated (Alentorn-Geli et al., 2009a; Imwalle et al., 2009; Kernozek et al., 2008; Willson et al., 2006). KAS is bound to occur during movements involving quick changes in direction, such as side-cut maneuvers and jump-landings, but reducing the amount of shear force at the knee is still a desirable outcome. In female athletes, a predisposition toward quadriceps dominance increases the amount of this anteriorly-directed shear force (Alentorn-Geli et al., 2009a; Shields et al., 2005; Youdas et al., 2007). Though hip-dominant exercises are designed to increase hamstring strength and decrease the quadriceps-to-hamstring ratio, their incorporation into the strength training protocols used during this study did not elicit the intended effect. As previously discussed, six weeks of training is not enough to create muscle hypertrophy, making it likely that there was not enough time for the protocols to meaningfully impact either hamstring strength or the quadriceps-to-hamstring ratio. An additional six weeks may have resulted in the desired muscular changes; future research with longer training protocols will enable investigators to further examine the impact of strength training on reducing KAS.

In addition to linear forces at the knee, coronal plane hip and knee moments and transverse plane moments at the hip add to the increased risk of ACL rupture in female soccer players (Imwalle et al., 2009). In the present study, the widest variation between participants existed in KAdM, HAbM, and HERM data. In all three variables, at all phases of stance, and in each group, no significant differences were observed, nor were there any consistent trends. This variability among participants may be what makes these motions the most risky. During the force absorption that occurs during the eccentric phase of cutting or landing from a jump, extended hip and knee postures in female athletes mean that compensatory motions must occur in order to execute the movement. Instead of collapsing in the sagittal plane, these athletes instead experience excessive out-of-plane motions, placing them at higher risk of ACL injury. Based on the current data, these compensatory movements do not appear to be universal in nature and are probably very person-specific. This is an added challenge when attempting to condition the athlete to avoid certain movement patterns and adopt others.

Despite the dissimilarity among coronal and transverse plane kinetics in each participant, altering the moments experienced at the knee and hip is an important factor in reducing ACL injury. Athletes who exhibit increased hip stiffness, as characterized by an increase in hip abduction and external rotation moments, are less likely to experience a lower-extremity injury (Chaudhari & Andriacchi, 2006; Imwalle et al., 2009). Female athletes, who consistently exhibit reduced hip stiffness as compared to male athletes, stand to greatly benefit from strength programs that address hip musculature. Research has shown that women experience excessive hip external rotation when performing dynamic closed-chain movements on one limb (Zeller et al., 2003). However, it is probable that this posture results in pelvic rotation away from the stance leg as a mechanism of maintaining center of gravity. This places the hip external rotators in a shortened position during these movements, decreasing their workload and placing increased responsibility for knee control on the quadriceps. Single-limb exercises, when performed correctly, work to correct this compensatory action through gradual loading of the rotators as pelvic stabilizers.

Limitations

Many of the limitations of this study have already been touched upon. Due to the nature of the strength training protocols, the access to female soccer players, and the time constraints of the spring season, only ten athletes were available to participate. In addition to decreasing the statistical power, and therefore the ability to obtain significant findings if any exist, small group sizes also threaten the external validity of the results. Ideally, future research should aim to incorporate several teams of female soccer players in order to gauge the true effect of the different training programs. If possible, three days a week of training, as well as a total of twelve weeks in the protocol, should be used to ensure that both neurological and morphological changes occur in the participants.

Another limitation to the current research is the time of year during which the testing and intervention occurred. The participants who were included performed their pre-tests prior to the university's spring break and at the start of an abbreviated spring schedule of games and practices. Though not as taxing as the regular season, spring season included an average of a game per week and team practices between 3-5 days a week in addition to the training protocol that was a part of this study. It is possible that fatigue became a factor in the participants by the time post-testing occurred. Furthermore, post-testing fell during the week before final exams. Many athletes reported having interrupted sleep patterns and high levels of stress, both of which could have affected the outcomes of all tests. Though it would be difficult to mitigate this issue entirely in this population, care should be taken in future investigations to reduce the chances of a fatigue-effect over the course of the training protocol, as well as scheduling pre- and post-testing for times where sleep patterns and stress levels would be roughly equal.

The participants recruited in this study had a minimum of one year of collegiate-level strength and conditioning experience, but it was limited to largely machine-based exercises, body-weight calisthenics, and abdominal work. Many of the hip- and knee-dominant exercises chosen for both groups were foreign to a majority of the athletes. There was an extremely large learning curve, particularly in the single-leg group, with regard to proper form during the execution of these movements. Even at the end of six weeks, it was not apparent that the participants had mastered the correct biomechanics for each exercise. This could be another reason why results were not as expected. Though a certain amount of athleticism is assumed with Division II varsity athletes, it was apparent that the focus of their previous training was centered around on-field skills training and not strength and conditioning for athletic performance or injury prevention. Therefore, six weeks may not have been sufficient time to train coordination patterns for the eccentric, amortization, and concentric phases of the chosen exercises, ensuring that there would be no significant biomechanical changes during testing modalities.

To the author's knowledge, no examinations of the effects of single-limb exercises have been published. Of the neuromuscular training protocols in existence that purport to reduce ACL injury risk, there is a wide variety in exercise selection and volume. In order to have two protocols that weren't inherently different, great care was taken to select both single-limb and double-limb exercises that were similar in nature. Further, no power exercises were utilized due to the author's prior knowledge of the participants' inexperience with such training methods. All athletes, regardless of group, performed two hip-dominant and two knee-dominant exercises during every training session, and all athletes performed the same upper-body and core exercises. No existing protocols met the requirements outlined above, and thus the NTP-SL and NTP-DL programs were created from scratch. In an effort to control for confounding variables, the resulting training programs did not necessarily reflect "best practices" with regard to a well-rounded strength and conditioning program. However, rather than continue to create new protocols, future research should build on the current body of literature by first expanding the time frame during which intervention occurs, and then by increasing the exercise selection, as warranted. This will enable comparisons across investigations and aid researchers in discovering the best ways in which to utilize strength training to decrease ACL injury risk.

Future Research

The results of the current study echo findings that strength training alone is not enough to produce the desired changes in biomechanics that represent a reduced risk of ACL injury. A wide variety of strength and conditioning approaches in neuromuscular training interventions has made it difficult to compare programs from study to study. Researchers should continue to build upon the programs outlined here by increasing the length of intervention and adding in other strength training modalities, such as power exercises. It is suggested that plyometric programs are the most effective at reducing biomechanical ACL injury risk factors, but this has only been the case when a plyometric program has been performed in conjunction with a strength training protocol (Myer et al., 2006; Yoo et al., 2009). Therefore, the contribution of strength training to this effect continues to warrant further inquiry.

There were no significant differences elicited between the NTP-SL and NTP-DL groups for the training intervention undertaken in this study. Due to the limitations previously discussed, the effect of single-leg training, and its place in an ACL injury prevention program, should continue to be explored. A comparison of muscle activation patterns and forces during single-leg versus double-leg hip- and knee-dominant exercises may indicate whether or not differences in these approaches exist that would result in neuromuscular changes.

Conclusions

Improved technology over the past 30 years has allowed researchers to gain extensive knowledge regarding ACL injury. In female athletes, the higher incidence rate can likely be attributed to intrinsic factors, such as hormone levels and pelvic width, as well as extrinsic factors, including increased quadriceps dominance, decreased hip stiffness, decreased hip and knee flexion angles at initial ground contact, and increased hip adduction and knee valgus during high-risk movements. These extrinsic factors appear to be modifiable and should continue to be the focus of current research.

While we continue to increase our understanding of the causes of ACL injury, there is a dearth of knowledge regarding ACL injury prevention. A handful of published studies that have examined the effects of combined plyometric and strength exercise programs have determined that it is possible to alter at-risk biomechanics through training. However, the mechanism by which this occurs is still unknown. Additionally, it is still not clear which behaviors exhibited by female athletes during at-risk movements serve to increase the risk of ACL injury and which occur as a coping mechanism to prevent ACL injury. For example, the role of the foot-ankle complex and the increased pronation that occurs in women as compared to men continues to be investigated as researchers attempt to tease out differences in those who eventually experience ACL injury versus those who do not. It is possible that the increased pronation is a form of shock attenuation, reducing the risk of injury, rather than an injurious motion in and of itself. The continued investigation of these issues will lead to improved practices regarding ACL injury prevention techniques.

The use of single-limb training in this study did not reduce gains in strength or power as measured by back squat and vertical jump over the six-week intervention period when compared to double-leg training. However, the expected improvements in hip and knee angles, forces, and moments during a side-cut maneuver did not occur. Therefore, it cannot be definitively concluded that single-limb training plays either a beneficial or a detrimental role in sport performance or ACL injury prevention programs when compared to double-limb training. Where single-limb training may be necessary, though, is in reducing inter-limb strength imbalances and challenging the athlete to reduce compensatory movement patterns. The trend of the NTP-DL group to experience such large improvements in their dominant leg during the THT lends credence to the hypothesis by Newton et al. (2006) that extensive training using double-leg support may only serve to increase deficiencies already present. Over time, such imbalances may increase the risk of injury, despite the use of these exercises to increase strength, power, and endurance and thereby reduce ACL injury risk.

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APPENDIX A

Barry University Neuromuscular Training Program

Single-Leg Group: PHASE 1 (Weeks 1-2)

Code:

Back Squat 1-RM

Est. RFE Squat 1-RM

Day 1	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**	**Day 2**	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**
		Wt.		**Wt.**				**WT**		**WT**	
Back Loaded	1/0/1		x8ea		x8ea	**Single-Leg**	1/0/exp		x8ea		x8ea
Rear-Foot			x8ea		x8ea	**Squat**			x8ea		x8ea
Elevated Squat			x8ea		x8ea				x8ea		x8ea
SA DB Row	1/0/exp		x8ea		x8ea	**Pull-ups/**	Exp/0/1		x8		x8
			x8ea		x8ea	**Pull-downs**			x8		x8
			x8ea		x8ea				x8		x8
Stretch: *Box*	5 sec hold		x3ea		x3ea	**Stretch: *Toe***			x8		x8
Hip Flexor			x3ea		x3ea	***Touch Squat***			x8		x8
Stability Ball	1/0/exp		x8ea		x8ea	**Reaching**	1/1/1		x8ea		x8ea
Lunge			x8ea		x8ea	**Single-Leg**			x8ea		x8ea
			x8ea		x8ea	**Romanian DL**			x8ea		x8ea
Bench Press	1/0/exp		x8		x8	**Dumbbell**	1/0/exp		x8		x8
			x8		x8	**Incline Press**			x8		x8
			x8		x8				x8		x8
Straight-Leg			x10		x10	**Single-Leg**	2 sec hold		x10ea		x10ea
Sit-Up			x10		x10	**Bench Hip Lift**			x10ea		x10ea

Barry University Neuromuscular Training Program **Single-Leg Group: PHASE 2 (Weeks 3-4)**

Code:

Back Squat 1-RM

Est. RFE Squat 1-RM

Day 1	**Tempo**	**WK1** **Wt.**	**Reps**	**WK2** **Wt.**	**Reps**	**Day 2**	**Tempo**	**WK1** **WT**	**Reps**	**WK2** **WT**	**Reps**
Back Loaded	1/0/1		x5ea		x5ea	**Single-Leg**	1/0/exp		x5ea		x5ea
Rear-Foot			x5ea		x5ea	**Squat**			x5ea		x5ea
Elevated Squat			x5ea		x5ea				x5ea		x5ea
SA DB Row	1/0/exp		x5ea		x5ea	**Pull-ups/**	Exp/0/1		x5		x5
			x5ea		x5ea	**Pull-downs**			x5		x5
			x5ea		x5ea				x5		x5
Stretch: *Box*	5 sec hold		x3ea		x3ea	**Stretch: *Toe***			x8		x8
Hip Flexor			x3ea		x3ea	***Touch Squat***			x8		x8
Stability Ball	1/0/exp		x5ea		x5ea	**2 Dumbbell**	1/1/exp		x5ea		x5ea
Lunge			x5ea		x5ea	**Single-Leg**			x5ea		x5ea
			x5ea		x5ea	**Romanian DL**			x5ea		x5ea
Bench Press	1/0/exp		x5		x5	**Standing**	1/0/exp		x8		x8
			x5		x5	**Dumbbell Press**			x8		x8
			x5		x5				x8		x8
Straight-Leg			x12		x12	**Single-Leg**	2 sec hold		x12ea		x12ea
Sit-Up			x12		x12	**Bench Hip Lift**			x12ea		x12ea

Barry University Neuromuscular Training Program **Single-Leg Group: PHASE 3 Weeks 5-6)**

Code:

Back Squat 1-RM

Est. RFE Squat 1-RM

Day 1	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**	**Day 2**	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**
		Wt.		**Wt.**				**WT**		**WT**	
Back Loaded	1/0/1		x3ea		x3ea	**Rear-Foot**	Exp		x5ea		x5ea
Rear-Foot			x3ea		x3ea	**Elevated**			x5ea		x5ea
Elevated Squat			x3ea		x3ea	**Jumps**			x5ea		x5ea
SA DB Row	1/0/exp		x3ea		x3ea	**Pull-ups/**	Exp/0/1		x3		x3
			x3ea		x3ea	**Pull-downs**			x3		x3
			x3ea		x3ea				x3		x3
Stretch: *Box*	5 sec hold		x3ea		x3ea	**Stretch: *Toe***			x8		x8
Hip Flexor			x3ea		x3ea	***Touch Squat***			x8		x8
Stability Ball	1/0/exp		x5ea		x5ea	**1 Dumbbell**	1/1/exp		x5ea		x5ea
Lunge			x5ea		x5ea	**Single-Leg**			x5ea		x5ea
			x5ea		x5ea	**Romanian DL**			x5ea		x5ea
Bench Press	1/0/exp		x3		x3	**Alternating**	1/0/exp		x5ea		x5ea
			x3		x3	**Standing**			x5ea		x5ea
			x3		x3	**Dumbbell Press**			x5ea		x5ea
Straight-Leg			x14		x14	**Single-Leg**	2 sec hold		x14ea		x14ea
Sit-Up			x14		x14	**Bench Hip Lift**			x14ea		x14ea

Barry University Neuromuscular Training Program | **Double-Leg Group: PHASE 1 (Weeks 1-2)**

Code: | **Back Squat 1-RM**

Est. RFE Squat 1-RM

Day 1	**Tempo**	**WK1 Wt.**	**Reps**	**WK2 Wt.**	**Reps**	**Day 2**	**Tempo**	**WK1 WT**	**Reps**	**WK2 WT**	**Reps**
Back Squats	1/0/Exp		x8		x8	**Trap Bar**	Exp/1/1		x8		x8
			x8		x8	**Deadlift**			x8		x8
			x8		x8				x8		x8
SA DB Row	1/0/exp		x8ea		x8ea	**Pull-ups/**	Exp/0/1		x8		x8
			x8ea		x8ea	**Pull-downs**			x8		x8
			x8ea		x8ea				x8		x8
Stretch: *Box*	5 sec hold		x3ea		x3ea	**Stretch: *Toe***			x8		x8
Hip Flexor			x3ea		x3ea	***Touch Squat***			x8		x8
Stability Ball	1/0/exp		x10		x10	**Dumbbell**	1/0/exp		x8		x8
Leg Curls			x10		x10	**Romanian**			x8		x8
			x10		x10	**Deadlift**			x8		x8
Bench Press	1/0/exp		x8		x8	**Dumbbell**	1/0/exp		x8		x8
			x8		x8	**Incline Press**			x8		x8
			x8		x8				x8		x8
Straight-Leg			x10		x10	**Double-Leg**	2 sec hold		x10		x10
Sit-Up			x10		x10	**Bench Hip Lift**			x10		x10

Barry University Neuromuscular Training Program						**Double-Leg Group: PHASE 2 (Weeks 3-4)**					
Code:						**Back Squat 1-RM**					
						Est. RFE Squat 1-RM					
Day 1	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**	**Day 2**	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**
		Wt.		**Wt.**				**WT**		**WT**	
Back Squats	1/0/Exp		x5		x5	**Trap Bar**	Exp/1/1		x5		x5
			x5		x5	**Deadlift**			x5		x5
			x5		x5				x5		x5
SA DB Row	1/0/exp		x5ea		x5ea	**Pull-ups/**	Exp/0/1		x5		x5
			x5ea		x5ea	**Pull-downs**			x5		x5
			x5ea		x5ea				x5		x5
Stretch: *Box*	5 sec hold		x3ea		x3ea	**Stretch: *Toe***			x8		x8
Hip Flexor			x3ea		x3ea	***Touch Squat***			x8		x8
Stability Ball	1/0/exp		x12		x12	**Dumbbell**	1/0/exp		x5		x5
Leg Curls			x12		x12	**Romanian**			x5		x5
			x12		x12	**Deadlift**			x5		x5
Bench Press	1/0/exp		x5		x5	**Standing**	1/0/exp		x8		x8
			x5		x5	**Dumbbell Press**			x8		x8
			x5		x5				x8		x8
Straight-Leg			x12		x12	**Double-Leg**	2 sec hold		x12		x12
Sit-Up			x12		x12	**Bench Hip Lift**			x12		x12

Barry University Neuromuscular Training Program

Double-Leg Group: PHASE 3 (Weeks 5-6)

Code:

Back Squat 1-RM

Est. RFE Squat 1-RM

Day 1	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**	**Day 2**	**Tempo**	**WK1**	**Reps**	**WK2**	**Reps**
		Wt.		**Wt.**				**WT**		**WT**	
Back Squats	1/0/Exp		x3		x3	**Trap Bar**	Exp/1/1		x3		x3
			x3		x3	**Deadlift**			x3		x3
			x3		x3				x3		x3
SA DB Row	1/0/exp		x3ea		x3ea	**Pull-ups/**	Exp/0/1		x3		x3
			x3ea		x3ea	**Pull-downs**			x3		x3
			x3ea		x3ea				x3		x3
Stretch: *Box*	5 sec hold		x3ea		x3ea	**Stretch: *Toe***			x8		x8
Hip Flexor			x3ea		x3ea	***Touch Squat***			x8		x8
Stability Ball	1/0/exp		x14		x14	**Dumbbell**	1/0/exp		x3		x3
Leg Curls			x14		x14	**Romanian**			x3		x3
			x14		x14	**Deadlift**			x3		x3
Bench Press	1/0/exp		x3		x3	**Alternating**	1/0/exp		x5		x5
			x3		x3	**Standing**			x5		x5
			x3		x3	**Dumbbell Press**			x5		x5
Straight-Leg			x14		x14	**Double-Leg**	2 sec hold		x14		x14
Sit-Up			x14		x14	**Bench Hip Lift**			x14		x14

APPENDIX B

Barry University
Research with Human Participants
Protocol Form

PROJECT INFORMATION

1. Effect of single-leg neuromuscular training on ACL risk factors in collegiate soccer players

2. **Principal Investigator** (please type or print)

Student Number or Faculty Number: 1795429
Name: Erin C. Learoyd
School – Department: HPLS – Biomechanics
Mailing Address: 4025 N Federal Hwy Apt B322, Fort Lauderdale, FL 33308
Telephone Number: (603) 801-8104
E-Mail Address: erinlearoyd@gmail.com; erin.learoyd@mymail.barry.edu

*NOTE: You **WILL NOT** receive any notification regarding the status of your proposal unless accurate and complete contact information is provided at the time the proposal is submitted.*

3. **Faculty Sponsor** (If Applicable)

Name: Dr. Kathryn Ludwig
School – Department: HPLS – Biomechanics
Mailing Address:
Telephone Number: (305) 899-4077
E-Mail Address: kludwig@mail.barry.edu

Faculty Sponsor Signature:__________________________________ Date: ______________

4. **Is an IRB Member on your Dissertation Committee? Yes __X__ No: ________**

5. **Funding Agency or Research Sponsor**
Not Applicable

6. **Proposed Project Dates**
Start ____02/19/2010____
End ____06/19/2010____

Note: It is appropriate to begin your research project (i.e., the data collection process) only *after* you have been granted approval by this board. Proposals that list starting dates occurring before the date of submission will be returned without review. Please allow time for approval when determining your start date. It is best if the end date you choose is one year after the start date.

Please Provide the Information Requested Below

A. Project activity STATUS is: (Check one of the following three as appropriate.)

_X_ NEW PROJECT
___ PERIODIC REVIEW ON CONTINUING PROJECT
___ PROCEDURAL REVISION TO PREVIOUSLY APPROVED PROJECT
(Please indicate in the **PROTOCOL** section the way in which the project has been revised.

B. This project involves the use of an **INVESTIGATIONAL NEW DRUG (IND) OR AN APPROVED DRUG FOR AN UNAPPROVED USE** in or on human participants.
___ YES _X_ NO
Drug name, IND number and company: ____

C. This project involves the use of an **INVESTIGATIONAL MEDICAL DEVICE (IMD)** or an **APPROVED MEDICAL DEVICE FOR AN UNAPPROVED USE.**
___ YES _X_ NO

D. This project involves the use of **RADIATION** or **RADIOISOTOPES** in or on human participants.
___ YES _X_ NO

E. This project involves the use of Barry University students as participants. (If any students are minors, please indicate this as well.)
_X_ YES Barry Students will be participants (Will minors be included? ___ YES _X_ NO)
___ NO Barry Students will participate

F. **HUMAN PARTICIPANTS** from the following population(s) would be involved in this study:

___ Minors (under age 18)
___ Abortuses
___ Prisoners
___ Mentally Disabled
___ Other institutionalized persons (specify)
___ Other (specify) ____

___ Fetuses
___ Pregnant Women
___ Mentally Retarded

G. Total Number of Participants to be Studied: ____40___

Description of Project

1. **Abstract** (200 words or less)

Non-contact ACL ruptures account for 70% of ACL injuries in soccer, with women experiencing incidence rates six times that of their male counterparts. Current neuromuscular training programs have been able to change at-risk biomechanics during cutting and jumping tasks. However, the role of strength training in these protocols is not fully understood. The purpose of this research study is to compare functional performance measures and lower-extremity biomechanics during simulated sports tasks in collegiate soccer players subjected to either a predominantly single-leg (NTP-SL) or predominantly double-leg (NTP-DL) neuromuscular training protocol. Triple-hop test (THT) distance, vertical jump (VJ) height, predicted maximal back squat strength (BS 1-RM), and kinetic and kinematic measures of a jump-landing and cut maneuver (JLC) will be assessed pre- and post-training for each respective group. Forty participants will be recruited and randomly assigned to the NTP-SL or NTP-DL groups. Each group will participate in a six-week strength training protocol designed to enhance sport performance and decrease ACL injury risk. It is expected that all participants will significantly improve in the THT, VJ, BS 1-RM, and JLC measures, with the NTP-SL group performing significantly better than the NTP-DL group at the THT and JLC measures at post-test.

2. **Recruitment Procedures**

This study will begin near the halfway point of the semester, just prior to spring break, and will continue through the second-to-last week of classes. We will attempt to recruit male and female soccer players from the Barry University varsity teams. The athletes will be educated on the purpose of this study through team meetings prior to or following practice or a work-out session. Once the IRB has approved the use of human participants, the players will be approached again by the Principle Investigator and given a written consent form and a detailed explanation of the study. The athletes will, at that time, indicate their willingness to volunteer in the study by completing the consent form and giving permission to the Principle Investigator to contact them regarding scheduling. Recruitment will not take place in the classroom or directly through the coaches, and the Principle Investigator does not have access to the participants through the virtue of her position at Barry.

Current student-athlete soccer players who have played out their eligibility but are still attending classes at Barry will be contacted via email to extend the opportunity to participate. A copy of this email is attached.

3. **Methods**

There will be a pre-test and a post-test comparison in this study that will take place 8 weeks apart. The necessary tests will be performed in one day and should take no more than 1.5 hours. Participants will have to complete all tests to be included in the study; a description of all test procedures is given below. We will notify the participants about scheduling for post-testing a minimum of one week prior to the available dates.

Pre- and Post-Test Protocols

The four tests described below will be performed in a randomized order. Participants will be assigned the order of testing upon arrival to the lab on the day of data collection. All tests have rest periods built in to minimize the effect of fatigue. Additionally, all tests should be performed in the participants' own athletic footwear and comfortable clothing that allows them to move freely, except during the jump landing and cut (JLC) maneuver, which is described below. Prior to beginning the testing procedures, each participant will be given five minutes to perform a self-directed, generalized warm-up.

Triple-Hop Test (THT) The maximum distance the participant can hop on one leg will be measured in this test. A tape measure will be affixed to the ground perpendicular to a pre-determined starting line. The participant will be asked to balance on one leg and perform three consecutive maximal hops forward on this limb without losing balance or allowing any other part of your body touch the floor or a supporting structure. The landing of their last hop must be held in a controlled manner for a minimum of 3 seconds to be considered a valid trial. The distance traveled will be measured from the starting line to the point where the participant's heel struck the ground on the landing of the third hop. This process will then be repeated with the other leg. Three trials will be performed on each leg, and the farthest distance traveled for both right and left legs will be recorded. Five minutes of rest will be given following this test.

Vertical Jump (VJ) The participants' maximal jump height during a countermovement jump will be measured during this test. They will be asked to stand beneath the Vertec system (see below for picture) with their feet shoulder-width apart and with their dominant hand positioned closest to the device. While keeping shoulders level, the participant will reach their dominant arm up as high as they can, and this reach height will be recorded. They will then perform as many jumps as they can, at their own pace, while reaching as high as they can on the Vertec pegs. This will continue as long as they can still increase the height of each jump and touch a new peg. Once jump height remains constant for three consecutive trials, the maximum height reached will be subtracted from the original static reach height to obtain the VJ height. This height will be recorded for analysis. Five minutes of rest will be given following this test.

Predicted Back Squat One-Repetition Maximum Test (BS 1-RM) This test will estimate the maximal amount of weight with which the participant could perform a back squat for one repetition. In a predictive BS 1-RM test, the participant will be asked to perform the back squat exercise with a weight that they can squat more than one repetition but less than 10 repetitions. This weight and the number of repetitions completed will be entered into an equation designed to estimate their 1-RM weight. A strength and conditioning professional will guide the participant through this test and ensure their safety and the correct technique during the exercise. Participants will be given the opportunity to warm up by performing 2-3 sets of no more than six repetitions of back squats with increasingly heavy weights. They will have a 1-2 minute rest period between each set in order to minimize fatigue. When they are ready, they will select a weight that they think they can squat more than one time but less than ten times. Participants will perform as many squats as they are capable of with this weight. The strength and conditioning professional will assist participants by giving verbal feedback on correct squatting technique and encouragement during the maximal repetition test. If a participant performs only one repetition or more than ten repetitions, the weight will be adjusted and the test will be re-attempted after a 3-5 min rest period. Once a successful test is performed, the weight and number of repetitions completed will be recorded. Ten minutes of rest will be given following this test.

Jump Landing and Cut Maneuver (JLC) This test will simulate a common movement performed on the soccer field. Specific clothing will need to be worn during the data collection. Participants will be asked to dress in tight athletic clothing that allows for free movement but stays close to the skin. Suggested clothing for men is compression shorts or running shorts and a tight, spandex-like shirt (e.g., Under Armor) or no shirt. Females are suggested to wear compression shorts or running shorts and a tight, spandex-like shirt or a sports bra. Participants will wear the same athletic footwear they chose for the other tests. The researchers will use 7 infrared cameras, 16 reflective markers and 2 force plates to measure the actions and forces in the joints of each participant's lower extremity while they perform this movement. The markers will be placed directly on the participants' skin with hypoallergenic, double-sided tape at predetermined locations on their lower extremity. A more detailed description of marker placement is included below, along with a picture illustrating an example of marker placement and suggested attire. The infrared cameras will be used to record the movement of the reflective markers on the participant; however, the cameras are incapable of recording images, and therefore at no point will the participant be identifiable.

The movement participants will perform is a forward jump onto 2 force plates followed immediately by a 90-degree cut to either the left or the right, as indicated by a researcher. Participants will not know in which direction they should cut until they begin their jump. Five cuts in each direction (left and right) will be performed in a randomized order. As many warm-up repetitions as are necessary for the participant to be comfortable with the movement will be performed. Once data collection begins, the participant will be asked to stand behind a line that is 1 meter away from the 2 force plates. A researcher will give the participant a signal that it is okay to begin, after which they can perform the movement at any time. When they are ready, they will jump forward onto the 2 force plates. While the participant is in the air, a second researcher will indicate in which direction they should perform the cutting maneuver by turning their body in that direction, as if they are an opposing player that the participant is attempting to intercept. Upon landing, the participant will cut in the direction indicated by the second researcher with as much effort as they can. The cutting motion will be a "side cut," and not a "cross-over cut." That is, when asked to cut to the left, the participant should push off their right leg and take their first step off the force plates with their left leg (see below for example). Similarly, when asked to cut to the right, they should push off their left leg and take their first step off the force plates with their right leg. At no time should the participant's legs cross one another during the cutting maneuver.

Vertec device used to measure vertical jump height

Example of marker placement and athletic-wear during biomechanical data collection
(Actual marker placement will vary slightly and is described below)

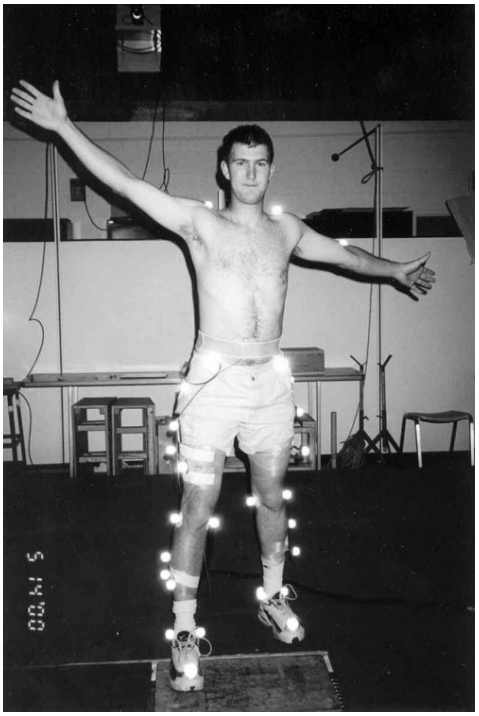
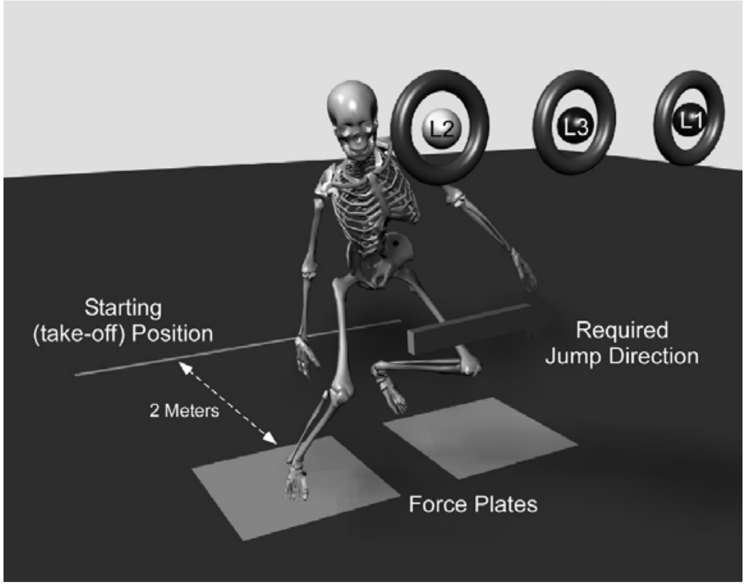


Illustration of cutting maneuver technique
(A researcher will indicate cut-direction in lieu of a light system as illustrated here; take-off position will be 1 meter away from force plates)



Marker placement during JLC maneuver:

4 markers – Anatomical landmarks on the front and back of the pelvis. Specifically, markers will be place on the two bony prominences located just below belly-button height on either side of the front of the torso (anterior superior iliac crests). Two additional markers will be placed on the bony prominences on the back of the pelvis located on either side of the spine (anterior posterior iliac crests).

2 markers – Mid-thigh, along an invisible line from the hip joint to the ankle joint; one on each leg

2 markers – Knee joint, along an invisible line from the hip joint to the ankle joint; one on each leg

2 markers – Mid-lower leg, along an invisible line from the hip joint to the ankle joint; one on each leg

2 markers – On the bony prominence on the outside of the ankle (lateral malleolus); one on each leg

2 markers – On the back of the heel, just below the Achilles tendon; one on each foot

2 markers – On the top of the foot, over the area where the second toe is attached to the rest of the foot (2nd metatarsal head); one on each foot

6-Week Strength and Conditioning Programs

Participants will be randomly assigned to one of two groups who will experience a strength and conditioning program. In one group (NTP-SL), all lower-extremity exercises will be performed one leg at a time. In the other group (NTP-DL), all lower-extremity exercises will be performed with both legs at the same time. All upper-extremity and core exercises, as well as all stretching exercises, will be identical in both groups. Strength training sessions will occur twice a week at agreed-upon times and will last for one hour in length. The duration of the program is six weeks, and will run starting the week of Monday, March 8th, 2010 and ending following the week of Monday, April 12th, 2010. Every training session will be run by the Principle Investigator (Erin Learoyd), who is a Certified Strength and Conditioning coach through the National Strength and Conditioning Association and has more than four years of experience creating and implementing training programs. In order to be included in the study, participants must complete all 12 (6 weeks x 2 days/week) scheduled sessions. If there is ever a scheduling conflict, the participant and the Principle Investigator should work together as soon as possible to determine a time to reschedule to. This flexibility of rescheduling allows participants to continue to receive the benefits of the strength and conditioning program being implemented and enables them to remain a participant in this research study. If scheduling dictates that the final session(s) must occur during week seven (April 19th – 23rd), this is allowable if the participant and the principle investigator are in agreement about the schedule change.

As previously mentioned, the lower-extremity exercises will differ between the two programs. Participants will be randomly assigned to one of these groups. Sets and repetitions have already been determined for every exercise. The weight used (where appropriate) will be determined from a combination of the participant's personal experience and the expertise of the Lead Investigator. The predicted maximal back squat weight will be used to determine training weight for the back squat exercise and the rear-foot elevated squat exercise. Further explanations on the differences between the single-leg and double-leg variations are provided below, and the full exercise programs can be seen on the attached pages.

Single-Leg Neuromuscular Training Program This program is designed to create lower-extremity strength by working one leg at a time. The specific exercises used to accomplish this will be the rear-foot elevated squat (RFE Squat), single-leg squat (SL squat), single-leg Romanian deadlift (SL RDL), slideboard reverse lunge (SB lunge), and single-leg hip lift (SL hip lift). Upper-body exercises will consist of vertical and horizontal pulling and pushing exercises. Core exercises are also included. The program, in its entirety, is included at the end of this protocol form.

Double-Leg Neuromuscular Training Program This program is designed to create lower-extremity strength by working both legs simultaneously. The specific exercises used to accomplish this will be the back squat (BS), trap-bar deadlift (TBDL), Romanian deadlift (RDL), stability ball hamstring curl (SB ham curl), and double-leg hip lift (DL hip lift). Upper-body exercises will consist of vertical and horizontal pulling and pushing exercises. Core exercises are also included. The program, in its entirety, is included at the end of this protocol form.

4. Alternative Procedures

Other than withholding participation, there are no alternative procedures for this study. However, participants are free to discontinue their participation at any time without consequence.

5. Benefits

Several direct benefits to the participant for their participation are likely to occur. Six-weeks of a performance training program designed to lower risk factors involved in non-contact ACL injury will provide each participant with strength increases, better fitness, and a possible decrease in at-risk mechanics during jump-landing and cutting movements.

Additionally, the personal knowledge gained through the functional performance tests may assist them as they continue to improve their athletic abilities as a collegiate athlete and beyond. The knowledge generated as a result of this investigation will also benefit society. This knowledge will contribute to the current body of research regarding prevention of non-contact ACL injuries and may help assist other collegiate soccer players with reducing the biomechanical risk factors associated with this injury. Since the costs, both in economic and in health terms, are high for non-contact ACL rupture, the ability to reduce the risk of this injury is beneficial for both the individual and society at-large.

6. **Risks**

The National College Athletic Association (NCAA) imposes the following rule:

"17.1.5 Mandatory Medical Examination. Prior to participation in any practice, competition or out-of season conditioning activities (or, in Division I, permissible voluntary summer conditioning in basketball and football or voluntary individual workouts pursuant to the safety exception), student-athletes who are beginning their initial season of eligibility shall be required to undergo a medical examination or evaluation administered or supervised by a physician (e.g., family physician, team physician). The examination or evaluation must be administered within six months prior to participation in any practice, competition or out-of-season conditioning activities. In following years, an updated history of the student- athlete's medical condition shall be administered by an institutional medical staff member (e.g., sports medicine staff, team physician) to determine if additional examinations (e.g., physical, cardiovascular, neurological) are required. The updated history must be administered within six months prior to the student-athlete's participation in any practice, competition or out-of-season conditioning activities for the applicable academic year."

Thus, all Barry University athletes must pass a medical exam prior to participation in college sport. The physical examination includes screening for cardiopulmonary disease. An additional requirement for participation in this study is that the participant be free of any musculoskeletal condition that could impede physical activity. The risks of involvement in this study are minimized as much as possible and all exercise tests and the strength and conditioning program will be performed by experienced technicians and coaches. The risks will be no greater than encountered in athletic competition or during any collegiate strength and conditioning program. Risks are further described below:

Triple-Hop Test The participant may feel unsteady when asked to balance on one leg. If he or she has not performed forward hops on a single leg before, they may feel that it is difficult to maintain their balance during this task. In order to maximize the participant's comfort level with the test, they will be given warm-up trials to familiarize themselves with the motion. They may experience a feeling of fatigue, characterized by a slight burning sensation in the muscles or a feeling of "heaviness" in the leg performing the hops. Ample rest periods between trials will be given to minimize the risk of this effect, and any feeling of fatigue should last no more than 3-5 minutes following test completion. The action performed in the THT is similar to ones found the plyometric portion of a collegiate strength and conditioning program. Though unlikely, there is a chance of lower-extremity muscular or joint injury during this movement. The risk of this occurring is no more than would be experienced during athletic competition or a typical strength and conditioning program. This risk will be minimized through the aforementioned familiarization trials and ample rest periods to limit fatigue.

Vertical Jump The participant may experience mild shortness of breath while performing this test, though it will not impact his or her ability to communicate with the researchers or perform the jumps. They may also experience a feeling of fatigue, characterized by a slight burning sensation in the muscles or a feeling of "heaviness" in their lower-extremities following this test. Ample rest periods between trials will be given to minimize the risk of this effect, and any feeling of fatigue should last no more than 3-5 minutes following test completion. The action performed in the VJ is similar to ones found the plyometric portion of a collegiate strength and conditioning program. Though unlikely, there is a chance of lower-extremity muscular or joint injury during this movement. The risk of this occurring is no more than would be experienced during athletic competition or a typical strength and conditioning program. This risk will be minimized through the use of ample rest periods to limit fatigue.

Predicted Back Squat One-Repetition Maximum Test The participant will likely experience mild to moderate shortness of breath, an increase in body temperature, and a significant feeling of lower-extremity fatigue, characterized by a burning sensation in the muscles or a feeling of "heaviness" in their legs following this test. Warm-up trials with lighter weights and ample rest between trials will be used to minimize this risk, and any feeling of fatigue should last no more than 8-10 minutes following test completion. The shortness of breath the participant experiences may be accompanied by a feeling of dizziness or a lightheaded sensation. The strength and conditioning professional administering the test will use verbal feedback to encourage proper breathing techniques to minimize this risk. Rest periods between sets should also serve to minimize this risk. The back squat is an exercise that is commonly used in collegiate strength and conditioning programs. Though unlikely, there is a chance of lower-extremity muscular or joint injury during this movement. The risk of this occurring is no more than would be experienced during athletic competition or a typical strength and conditioning program. This risk will be minimized through the presence of a trained strength and conditioning professional who will provide feedback and supervise the movement. Additionally, the use of ample rest periods to limit fatigue will be employed.

Jump-Landing and Cut Maneuver Participants may experience mild shortness of breath and/or a mild feeling of neuromuscular fatigue, characterized by a burning sensation in the muscles or a feeling of "heaviness" in their legs during this test. Ample rest time between trials will be given in order to minimize these risks. Additionally, the coordination and timing of the entire movement may feel awkward at first; familiarization trials will be used to ensure that participants are comfortable with the movement prior to data collection. Both a jumping motion and a cutting maneuver are commonly researched movements, particularly in collegiate athletes. Though occurring in a controlled laboratory setting, the movements will mimic those experienced on the field of play and in the plyometric and agility portions of collegiate strength and conditioning programs. Though unlikely, there is a chance of lower-extremity muscular or joint injury during this movement. The risk of this occurring is no more than would be experienced during athletic competition, practice sessions, or a typical collegiate strength and conditioning program. This risk will be minimized through the use of practice trials and ample rest periods to limit fatigue.

The intensity of exercise required for each of these tests is not unlike what participants are used to performing on a regular basis for their sport. As with any exercise, however, there is an increased risk of sudden cardiac death and acute myocardial infarction during and immediately after such exercise. These events occur only in individuals with underlying heart disease. Among individuals younger than 35 years of age, such as the recruited participants, the risk of sudden cardiac death during exercise is low due to the low prevalence of disease. Further, because they engage in regular exercise as an athlete, the risk is even lower than in a non-athlete population. Incidence of death during or immediately following sports participation among high school and college-age athletes has been estimated as less than one death per 100,000 participants per year. Thus, these exercise tests present very little risk to the participants.

6-Week Strength and Conditioning Programs The risks of involvement in the strength training portions of this study are minimized as much as possible and all exercises in the strength and conditioning program will be implemented and overseen by an experienced, certified professional (the Principle Investigator). Despite every precaution, some risks do exist. Though unlikely, there is a possibility of muscular or joint injury in any areas of the body that are used to perform the given exercises. These injuries include, but are not limited to, muscular strains, ligament sprains, and cartilage tears. The risk of these injuries will be limited by the direct supervision and constant feedback provided by the Principle Investigator. The intensity of exercise during the training sessions will be similar to what the participants often experience during their athletic participation and school-sanctioned strength and conditioning programs. Therefore, the risk of injury will be no greater than what they already commonly encounter. Furthermore, the participant's experience as an athlete and in strength training programs serves to additionally limit the risk of injury due to familiarity with the exercises being performed. Overall, the risks inherent in this strength training program will be no greater than those encountered in athletic competition or during any collegiate strength and conditioning program. Should the unlikely event of an injury occur, medical costs will be borne by the participant.

7.**Anonymity/Confidentiality**

As a research participant, any information provided will be held in confidence to the extent permitted by law. Only the Principle Investigator and the Faculty Advisor (Dr. Kathryn Ludwig) will have access any personal information provided. All other research assistants will know that the athletes are participating in the study, but will not know anything (e.g., injury history, health history, or age) that goes beyond their presence as assistants during data collection at pre- and post-test. Since many students have access to the program used to collect biomechanical data, participants will be assigned a code, which will be used to reference them in all tests. All data collected via the infrared cameras and force plates will be stored in this manner, and none of this data can be used to physically identify any participant. This will eliminate the participant's name from being on any documents, excepting the Informed Consent, which will be stored under lock and key in the Faculty Advisor's office. Should any published results occur from this investigation, the data will refer to group averages and will not refer to any participant by name. No photos of participants will be taken or used at any time. Data will not be destroyed for a minimum of 7 years, but may remain in the possession of the Principle Investigator indefinitely. Due to the use of coding, this data will in no way be able to be traced back to the participants. Despite all efforts to conceal the identity of the participants, anonymity cannot be guaranteed since they will be undergoing testing and training in public locations.

8. **Consent**

Attach a copy of the consent form(s) to be signed by the participant and/or any statements to be read to the participant or informational letter to be directed to the participant. **(A copy of the consent form should be offered to each participant.)** If this is an anonymous study, attach a cover letter in place of a consent form.

9. Certification

I certify that the protocol and method of obtaining informed consent as approved by the Institutional Review Board (IRB) will be followed during the period covered by this research project. Any future changes will be submitted to IRB review and approval prior to implementation. I will prepare a summary of the project results annually, to include identification of adverse effects occurring to human participants in this study. I have consulted with faculty/administrators of any department or program which is to be the subject of research.

_________________________________ ____________________

Principal Investigator *Date*

Reminder**: Be sure to submit fifteen (15) individually collated and bound (i.e. stapled or paper clipped) copies of this form with your application.**

NOTE: Your proposal ***<u>WILL NOT</u>*** *be reviewed until the completed packet is received in its entirety.*

APPENDIX C

Barry University
Informed Consent Form

Your participation in a research project is requested. The title of the study is "Effects of single-leg neuromuscular training on ACL risk factors in collegiate athletes." The research is being conducted by Erin C. Learoyd, Graduate Student of Biomechanics in Movement Science in the Department of Sport and Exercise Science at Barry University. Three additional graduate students in biomechanics will be assisting with data collection and analyses. There may also be one other exercise science student (who is an athlete and possibly a teammate of yours) who will assist in the data collection but will not have access to your personal information. The aim of the research is to gather information concerning the differences in strength and conditioning protocols with regard to ACL injury risk factors. We anticipate the number of participants to be 40.

There will be a pre-test and a post-test comparison in this study that will take place 8 weeks apart. The necessary tests will be performed in one day and should take no more than 1.5 hours. You will have to complete all tests to be included in the study; a description of all test procedures is given below. We will notify you about scheduling for post-testing a minimum of one week prior to the available dates.

Pre- and Post-Test Protocols

The four tests described below will be performed in a randomized order. You will be assigned the order of testing upon arrival to the lab on the day of data collection. All tests have rest periods built in to minimize the effect of fatigue. Additionally, all tests should be performed in your own athletic footwear and comfortable clothing that allows you to move freely, except during the jump landing and cut (JLC) maneuver, which is described below. Prior to beginning the testing procedures, you will be given five minutes to perform a self-directed, generalized warm-up.

Triple-Hop Test (THT) The maximum distance you can hop on one leg will be measured in this test. A tape measure will be affixed to the ground perpendicular to a pre-determined starting line. You will be asked to balance on one leg and perform three consecutive maximal hops forward on this limb without losing balance or allowing any other part of your body touch the floor or a supporting structure. The landing of your last hop must be held in a controlled manner for a minimum of 3 seconds to be considered a valid trial. The distance traveled will be measured from the starting line to the point where your heel struck the ground on the landing of the third hop. This process will then be repeated with the other leg. Three trials will be performed on each leg, and the farthest distance traveled for both right and left legs will be recorded. Five minutes of rest will be given following this test.

Vertical Jump (VJ) Your maximal jump height during a countermovement jump will be measured during this test. You will be asked to stand beneath the Vertec system (see below for picture) with your feet shoulder-width apart and with your dominant hand positioned closest to the device. While keeping shoulders level, you will reach your dominant arm up as high as you can, and this reach height will be recorded. You will then perform as many jumps as you can, at your own pace, while reaching as high as you can on the Vertec pegs. This will continue as long as you can still increase the height of each jump and touch a new peg. Once jump height remains constant for three consecutive trials, the maximum height reached will be subtracted from the original static reach height to obtain the VJ height. This height will be recorded for analysis. Five minutes of rest will be given following this test.

Predicted Back Squat One-Repetition Maximum Test (BS 1-RM) This test will estimate the maximal amount of weight with which you could perform a back squat for one repetition. In a predictive BS 1-RM test, you will be asked to perform the back squat exercise with a weight that you can squat more than one repetition but less than 10 repetitions. This weight and the number of repetitions completed will be entered into an equation designed to estimate your 1-RM weight. A strength and conditioning professional will guide you through this test and ensure your safety and the correct technique during the exercise. You will be given the opportunity to warm up by performing 2-3 sets of no more than six repetitions of back squats with increasingly heavy weights. You will have a 1-2 minute rest period between each set in order to minimize fatigue. When you are ready, you will select a weight that you think you can squat more than one time but less than ten times. You will perform as many squats as you are capable of with this weight. The strength and conditioning professional will assist you by giving verbal feedback on correct squatting technique and encouragement during the maximal repetition test. If you perform only one repetition or more than ten repetitions, the weight will be adjusted and the test will be re-attempted after a 3-5 min rest period. Once a successful test is performed, the weight and number of repetitions completed will be recorded. Ten minutes of rest will be given following this test.

Jump Landing and Cut Maneuver (JLC) This test will simulate a common movement performed on the soccer field. Specific clothing will need to be worn during the data collection. You will be asked to dress in tight athletic clothing that allows for free movement but stays close to the skin. Suggested clothing for men is compression shorts or running shorts and a tight, spandex-like shirt (e.g., Under Armor) or no shirt. Females are suggested to wear compression shorts or running shorts and a tight, spandex-like shirt or a sports bra. You will wear the same athletic footwear you chose for the other tests. The researchers will use 7 infrared cameras, 16 reflective markers and 2 force plates to measure the actions and forces in the joints of your lower extremity while you perform this movement. The markers will be placed directly on your skin with hypoallergenic, double-sided tape at predetermined locations on your lower extremity. A more detailed description of marker placement is included below, along with a picture illustrating an example of marker placement and suggested attire. The infrared cameras will be used to record the movement of the reflective markers on your body; however, the cameras are incapable of recording images, and therefore at no point will you be identifiable.

The movement you will perform is a forward jump onto 2 force plates followed immediately by a 90-degree cut to either the left or the right, as indicated by a researcher. You will not know in which direction you should cut until you begin your jump. Five cuts in each direction (left and right) will be performed in a randomized order. As many warm-up repetitions as are necessary for you to be comfortable with the movement will be performed.

Once data collection begins, you will be asked to stand behind a line that is 1 meter away from the 2 force plates. A researcher will give you a signal that it is okay to begin, after which you can perform the movement at any time. When you are ready, you will jump forward onto the 2 force plates. While you are in the air, a second researcher will indicate in which direction you should perform the cutting maneuver by turning their body in that direction, as if they are an opposing player that you are attempting to intercept. Upon landing, you will cut in the direction indicated by the second researcher with as much effort as you can. The cutting motion will be a "side cut," and not a "cross-over cut." That is, when asked to cut to the left, you should push off your right leg and take your first step off the force plates with your left leg (see below for example). Similarly, when asked to cut to the right, you should push off your left leg and take your first step off the force plates with your right leg. At no time should your legs cross one another during the cutting maneuver.

Vertec device used to measure vertical jump height

Example of marker placement and athletic-wear during biomechanical data collection (Actual marker placement will vary slightly and is described below)

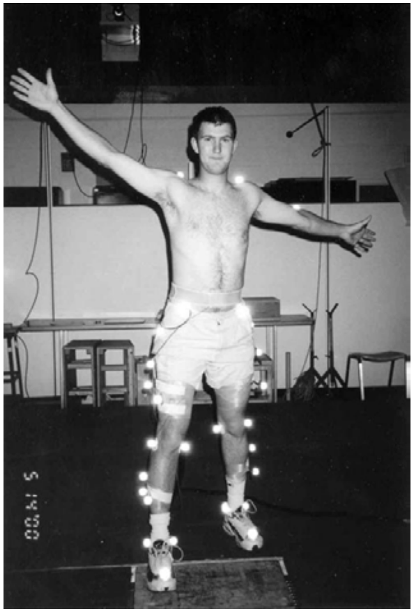
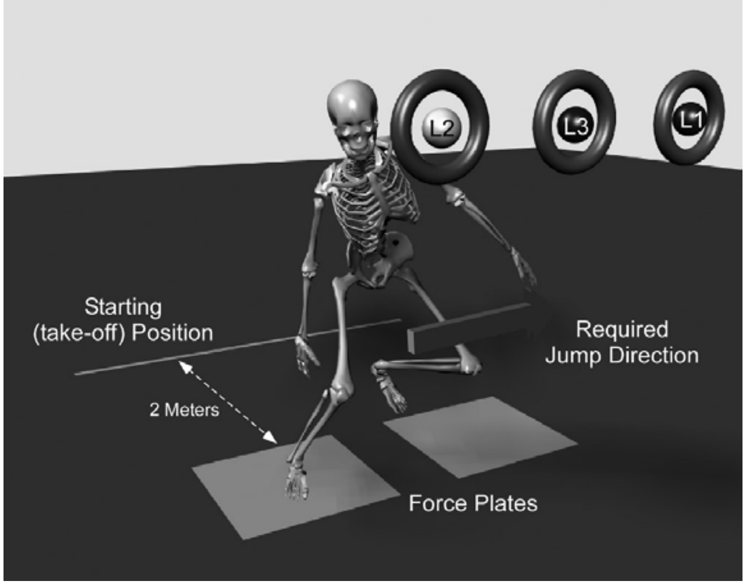


Illustration of cutting maneuver technique
(A researcher will indicate cut-direction in lieu of a light system as illustrated here; take-off position will be 1 meter away from force plates)



Marker placement during JLC maneuver:

4 markers – Anatomical landmarks on the front and back of the pelvis. Specifically, markers will be place on the two bony prominences located just below belly-button height on either side of the front of the torso (anterior superior iliac crests). Two additional markers will be placed on the bony prominences on the back of the pelvis located on either side of the spine (anterior posterior iliac crests).

2 markers – Mid-thigh, along an invisible line from the hip joint to the ankle joint; one on each leg

2 markers – Knee joint, along an invisible line from the hip joint to the ankle joint; one on each leg

2 markers – Mid-lower leg, along an invisible line from the hip joint to the ankle joint; one on each leg

2 markers – On the bony prominence on the outside of the ankle (lateral malleolus); one on each leg

2 markers – On the back of the heel, just below the Achilles tendon; one on each foot

2 markers – On the top of the foot, over the area where the second toe is attached to the rest of the foot (2nd metatarsal head); one on each foot

The risks of involvement in this study are minimized as much as possible and all exercise tests and the strength and conditioning program will be performed by experienced technicians and coaches. The risks will be no greater than encountered in athletic competition or during any collegiate strength and conditioning program. Risks are further described below:

Triple-Hop Test You may feel unsteady when asked to balance on one leg. If you have not performed forward hops on a single leg before, you may feel that it is difficult to maintain your balance during this task. In order to maximize your comfort level with the test, you will be given warm-up trials to familiarize yourself with the motion. You may experience a feeling of fatigue, characterized by a slight burning sensation in the muscles or a feeling of "heaviness" in the leg performing the hops. Ample rest periods between trials will be given to minimize the risk of this effect, and any feeling of fatigue should last no more than 3-5 minutes following test completion. The action performed in the THT is similar to ones found the plyometric portion of a collegiate strength and conditioning program. Though unlikely, there is a chance of lower-extremity muscular or joint injury during this movement. The risk of this occurring is no more than would be experienced during athletic competition or a typical strength and conditioning program. This risk will be minimized through the aforementioned familiarization trials and ample rest periods to limit fatigue.

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Jump-Landing and Cut Maneuver You may experience mild shortness of breath and/or a mild feeling of neuromuscular fatigue, characterized by a burning sensation in the muscles or a feeling of "heaviness" in your legs during this test. Ample rest time between trials will be given in order to minimize these risks. Additionally, the coordination and timing of the entire movement may feel awkward at first; familiarization trials will be used to ensure you are comfortable with the movement prior to data collection. Both a jumping motion and a cutting maneuver are commonly researched movements, particularly in collegiate athletes. Though occurring in a controlled laboratory setting, the movements will mimic those experienced on the field of play and in the plyometric and agility portions of collegiate strength and conditioning programs. Though unlikely, there is a chance of lower-extremity muscular or joint injury during this movement. The risk of this occurring is no more than would be experienced during athletic competition, practice sessions, or a typical collegiate strength and conditioning program. This risk will be minimized through the use of practice trials and ample rest periods to limit fatigue.

The intensity of exercise required for each of these tests is not unlike what you are used to performing on a regular basis for your sport. As with any exercise, however, there is an increased risk of sudden cardiac death and acute myocardial infarction during and immediately after such exercise. These events occur only in individuals with underlying heart disease. Among individuals younger than 35 years of age, such as yourself, the risk of sudden cardiac death during exercise is low due to the low prevalence of disease. Further, because you engage in regular exercise as an athlete, the risk is even lower than in a non-athlete population. Incidence of death during or immediately following sports participation among high school and college-age athletes has been estimated as less than one death per 100,000 participants per year. Thus, these exercise tests present very little risk to you.

6-Week Strength and Conditioning Programs

You will be randomly assigned to one of two groups who will experience a strength and conditioning program. In one group (NTP-SL), all lower-extremity exercises will be performed one leg at a time. In the other group (NTP-DL), all lower-extremity exercises will be performed with both legs at the same time. All upper-extremity and core exercises, as well as all stretching exercises, will be identical in both groups. Strength training sessions will occur twice a week at agreed-upon times and will last for one hour in length. The duration of the program is six weeks, and will run starting the week of Monday, March 8th, 2010 and ending following the week of Monday, April 12th, 2010. Every training session will be run by the Principle Investigator (Erin Learoyd), who is a Certified Strength and Conditioning coach through the National Strength and Conditioning Association and has more than four years of experience creating and implementing training programs. In order to be included in the study, you must complete all 12 (6 weeks x 2 days/week) scheduled sessions. If there is ever a scheduling conflict, you and the Principle Investigator should work together as soon as possible to determine a time to reschedule to. This flexibility of rescheduling allows you to continue to receive the benefits of the strength and conditioning program being implemented and enables you to remain a participant in this research study. If scheduling dictates that the final session(s) must occur during week seven (April 19th – 23rd) this can allowable if you and the principle investigator are in agreement about the schedule change.

As previously mentioned, the lower-extremity exercises will differ between the two programs. You will be randomly assigned to one of these groups. Sets and repetitions have already been determined for every exercise. The weight used (where appropriate) will be determined from a combination of your personal experience and the expertise of the Lead Investigator. The predicted maximal back squat weight will be used to determine training weight for the back squat exercise and the rear-foot elevated squat exercise. None of the exercises included in these protocols are outside the normal selection for an athletic performance program. The full programs are included at the end of this Informed Consent. The differences between the single-leg and double-leg variations are described below.

Single-Leg Neuromuscular Training Program This program is designed to create lower-extremity strength by working one leg at a time. The specific exercises used to accomplish this will be the rear-foot elevated squat (RFE Squat), single-leg squat (SL squat), single-leg Romanian deadlift (SL RDL), slideboard reverse lunge (SB lunge), and single-leg hip lift (SL hip lift). Upper-body exercises will consist of vertical and horizontal pulling and pushing exercises. Core exercises are also included. The program, in its entirety, is included at the end of this consent form.

Double-Leg Neuromuscular Training Program This program is designed to create lower-extremity strength by working both legs simultaneously. The specific exercises used to accomplish this will be the back squat (BS), trap-bar deadlift (TBDL), Romanian deadlift (RDL), stability ball hamstring curl (SB ham curl), and double-leg hip lift (DL hip lift). Upper-body exercises will consist of vertical and horizontal pulling and pushing exercises. Core exercises are also included. The program, in its entirety, is included at the end of this consent form.

The risks of involvement in this study are minimized as much as possible and all exercises in the strength and conditioning program will be implemented and overseen by an experienced, certified professional (the Principle Investigator). Despite every precaution, some risks do exist. Though unlikely, there is a possibility of muscular or joint injury in any areas of the body that are used to perform the given exercises. These injuries include, but are not limited to, muscular strains, ligament sprains, and cartilage tears. The risk of these injuries will be limited by the direct supervision and constant feedback provided by the Principle Investigator. The intensity of exercise during the training sessions will be similar to what you often experience during your athletic participation and school-sanctioned strength and conditioning programs. Therefore, the risk of injury will be no greater than what you already commonly encounter. Furthermore, your experience as an athlete and in strength training programs serves to additionally limit the risk of injury due to familiarity with the exercises being performed. Overall, the risks inherent in this strength training program will be no greater than those encountered in athletic competition or during any collegiate strength and conditioning program. Should the unlikely event of an injury occur, you are responsible for all resulting medical costs.

Your consent to be a research participant is strictly voluntary and should you decline to participate or should you choose to drop out at any time during the study, there will be no adverse effects on your status as a Barry University athlete or student.

Several direct benefits to you for your participation are likely to occur. Six-weeks of a performance training program designed to lower risk factors involved in non-contact ACL injury will provide you with strength increases, better fitness, and a possible decrease in at-risk mechanics during jump-landing and cutting movements. Additionally, the personal knowledge gained through the functional performance tests may assist you as you continue to improve your athletic abilities as a collegiate athlete and beyond. The knowledge generated as a result of this investigation will also benefit society. This knowledge will contribute to the current body of research regarding prevention of non-contact ACL injuries and may help assist other collegiate soccer players with reducing the biomechanical risk factors associated with this injury. Since the costs, both in economic and in health terms, are high for non-contact ACL rupture, the ability to reduce the risk of this injury is beneficial for both you, as an athlete, and society at-large.

As a research participant, any information you provide will be held in confidence to the extent permitted by law. Only the Principle Investigator and the Faculty Advisor (Dr. Kathryn Ludwig) will have access any personal information you provide. All other research assistants will know only that you are participating in the study, but nothing that goes beyond their presence as assistants during data collection at pre- and post-test (e.g., injury history, health history, or age). Since many students have access to the program used to collect biomechanical data, you will be assigned a code, which will be used to reference you in all tests. All data collected via the infrared cameras and force plates will be stored in this manner, and none of this data can be used to physically identify you. This will eliminate your name from being on any documents, excepting this Informed Consent, which will be stored under lock and key in the Faculty Advisor's office. Should any published results occur from this investigation, the data will refer to group averages and will not refer to any participant by name. No photos of you will be taken or used at any time. Data will not be destroyed for a minimum of 7 years, but may remain in the possession of the Principle Investigator indefinitely. Due to the use of coding, this data will in no way be able to be traced back to you. Despite all efforts to conceal your identity, anonymity cannot be guaranteed since you will be undergoing testing and training in public locations.

If you have any questions or concerns regarding the study or your participation in the study, you may contact me, Erin C. Learoyd, at (603) 801-8104, Dr. Kathryn Ludwig at (305) 899-4077 or the Institutional Review Board point of contact, Barbara Cook, at (305) 899-3020. If you are satisfied with the information provided and are willing to participate in this research, please signify your consent by signing this consent form.

Voluntary Consent

I acknowledge that I have been informed of the nature and purposes of this experiment by Erin C. Learoyd and that I have read and understand the information presented above, and that I have received a copy of this form for my records. I give my voluntary consent to participate in this experiment and understand that I may discontinue my participation at any time.

______________________ __________
Signature of Participant *Date*

______________________ __________ ________________________ __________
Researcher *Date* *Witness* *Date*

(Witness signature is required only if research involves pregnant women, children, other vulnerable populations, or if more than minimal risk is present.)

APPENDIX D

Article Format

Introduction

Non-contact anterior cruciate ligament (ACL) injuries typically occur during activities that involve cutting, pivoting, sudden deceleration, and landing from a jump, movements that are prevalent in soccer (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle, Myer, Ford & Hewett, 2009; Kernozek, Torry & Iwasaki, 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer, Ford, McLean & Hewett, 2006; Yoo et al., 2009; Youdas, Hollman, Hitchcock, Hoyme & Johnsen, 2007; Yu, Lin & Garrett, 2006). Females, due to both intrinsic and extrinsic factors, are up to six times more likely to sustain a non-contact ACL tear (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Myer et al., 2006; Pantano, White, Gilchrist, & Leddy, 2005; Youdas, Hollman, Hitchcock, Hoyme, & Johnsen, 2007; Zeller, McCrory, Kibler, & Uhl, 2003). The reported incidence rate of ACL injury ranges from 0.06 to 3.7 per 1,000 hours of match play and competitive practice (Alentorn-Geli et al., 2009a). This adds up to thousands of ACL tears every year, leading to substantially high costs for treatment and rehabilitation and untold lost opportunities for participation. Though intrinsic risk factors are person-specific, identifying modifiable extrinsic factors may be a major step toward reducing the incidence rate of non-contact ACL tears.

As an identifiable extrinsic risk factor, biomechanical positioning has recently gained attention as improved technology allows for the quantification of at-risk movement patterns. Measurements of angles, forces, and moments in the joints of the lower extremity have given practitioners insight as to how their combined effects may influence ACL strain. Several risky positions have been identified. Multiple studies are in agreement that out-of-plane knee and hip movements, particularly hip adduction angle (Imwalle et al., 2009; Myer et al., 2006; Willson, Ireland, & Davis, 2006; Zeller, McCrory, Kibler & Uhl, 2003) and knee abduction angle (Borotikar, Newcomer, Koppes, & McLean, 2008; Imwalle et al., 2009; Kernozek et al., 2008; Myer et al., 2006; Pantano et al., 2005; Willson et al., 2006; Zeller et al., 2003), can increase the risk of ACL injury. Muscle-firing patterns and magnitudes have been shown to change under fatigue in both males and females (with females exhibiting greater changes than their male counterparts) that lead to previously identified risky biomechanical patterns (Chappell et al., 2005; McLean et al., 2007; McLean & Samorezov, 2009).

Coaches, strength and conditioning specialists, and rehabilitation specialists have built on the current body of knowledge to begin creating preventative neuromuscular training programs (Alentorn-Geli et al., 2009a; Kernozek et al., 2008; McLean et al., 2007; Myer et al., 2006; and Myer, Ford, Palumbo, & Hewett, 2005). These programs are typically multidisciplinary in approach, including several or all of the following training stimuli: progressive warm-up, plyometrics, agility, balance training, resistance training, and conditioning. Researchers have shown moderate improvement in at-risk biomechanics, particularly in female participants (Alentorn-Geli et al., 2009b; Lim et al., 2009; Myer et al., 2006; Myer et al., 2005; Yoo et al., 2009). Of the training approaches, the plyometric aspect has, thus far, appeared to be the most effective due to the emphasis on the stretch-shortening cycle in accepting and redirecting force and the similarity of the movements to athletic situations (Alentorn-Geli et al., 2009a; Lim et al., 2009; Myer et al., 2006).

Current plyometric protocols are lacking in uniformity, and therefore not yet fit for widespread adoption, as evidenced by the recent finding that the rate of force development during landing and the forces placed on the knee can differ depending on the type and intensity of the plyometric exercise (Jensen & Ebben, 2007). Though there is preliminary evidence that plyometric training is effective, especially when coupled with skilled reinforcement from trained coaches, the role of resistance training is not yet clear. Of the protocols that included a resistance training portion, the lifting program was often identical for all participants while other factors (plyometric intensity, for instance) were manipulated (Alentorn-Geli et al., 2009b; Myer et al., 2006). Additionally, resistance training programs were either not clearly described in the literature (Myer et al., 2005), or else they were total-body, "cookie cutter" programs that addressed overall strength, but lacked a clear goal (i.e., improving quadriceps-hamstring ratio, strengthening hip musculature, or improving core strength).

Importantly, resistance training programs included in the literature lack sport-specific and injury-specific movements, including single-leg exercises. Considering that many sport-related activities involve single-leg cutting, bounding, and landing, and ACL injury has been linked to poor hip muscular stability and control during these movements (Borotikar et al., 2008; Imwalle et al., 2009; Kernozek et al., 2008; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Myer et al., 2005; Willson et al., 2006; Yu, Lin, & Garrett, 2006; Zeller et al., 2003), the specificity of training principle indicates that dynamic resistance training should include a robust single-leg component. To the author's knowledge, no research on a single-leg specific resistance training program for non-contact ACL injury prevention has been executed. Though many causes of non-contact ACL injuries are not yet fully understood and must continue to be investigated, the high cost of injury (in both financial and future health outcomes) creates a need to implement protocols which empirically reduce injury rates (Borotikar et al., 2008; Imwalle et al., 2009).

The purpose of this research study was to compare functional performance measures and lower-extremity biomechanics during simulated sports tasks in healthy female collegiate soccer players subjected to six weeks of either a predominantly single-leg (NTP-SL) or predominantly double-leg (NTP-DL) neuromuscular training protocol. Triple-hop test (THT) distance, vertical jump (VJ) height, predicted maximal back squat strength (BS 1-RM), and kinetic and kinematic measures of a jump-landing and cut maneuver (JLC) were assessed pre- and post-training for each respective group.

Five specific hypotheses were tested in this study. They were:

1. Six weeks of neuromuscular training will significantly increase vertical jump height in both groups.
2. Six weeks of neuromuscular training will significantly increase predicted back squat 1-RM mass in both groups.
3. Six weeks of single-leg neuromuscular training will result in significantly greater triple-hop distance than six weeks of double-leg neuromuscular training.
4. Six weeks of single-leg neuromuscular training will result in significantly higher hip flexion angle and knee flexion angle at initial contact, 25% of stance-phase, and peak vertical ground reaction force than six weeks of double leg neuromuscular training.
5. Six weeks of single-leg neuromuscular training will result in significantly higher hip external rotation moment and hip abduction moment and significantly lower knee abduction moment and knee anterior shear force at initial contact, 25% of stance-phase, and peak vertical ground reaction force than six weeks of double leg neuromuscular training.

Methods

Participants

Thirteen players were recruited from the Barry University women's soccer team. Criteria for exclusion included current lower-extremity injury, ACL reconstruction <1 years old, and any neurological disease or muscular or cartilaginous injury that would preclude completion of all testing procedures and a six week neuromuscular training program. Ten participants were subsequently accepted into the study. Participants were randomly assigned to one of two groups: a single-leg, or experimental, group (NTP-SL) or a double-leg, or control, group (NTP-DL). As indicated by their names, each group performed all hip- and knee-dominant resistance training exercises in either a single-leg or double-leg variation. Further details are included below. Approval for the use of human subjects was granted from the Barry University Institutional Review Board, and participants were required to read and sign an Informed Consent.

Instrumentation

Data collection.

A Vicon seven-camera three-dimensional motional analysis system (Centennial, CO) was used to measure kinematic data during the JLC movement. Data was collected at 240Hz. Two 2400Hz six-channel AMTI force platforms (Watertown, MA) measured force data during the stance phase of the JLC. Data was synced directly through the Vicon MX hardware and recorded and processed with Vicon Nexus software (Centennial, CO).

Neuromuscular training program (NTP).

The athletes who participated were in the midst of a soccer off-season training program. Their practices were conducted several times weekly in conjunction with a light spring schedule of exhibition games. Additionally, the team participated in a plyometric conditioning program once per week and an abdominal muscle-intensive workout once per week, both conducted by the Barry University Strength and Conditioning Coach.

The strength and conditioning program designed for this study included a dynamic warm-up and range-of-motion exercises and a neuromuscular training (resistance training) protocol (NTP). With the exception of the hip- and knee-dominant exercises, all aspects of the NTP (warm-up, range-of-motion, upper-body and core strength exercises) were identical. Hip- and knee-dominant exercises differed only between groups, which were determined by random assignment. All NTP workouts were designed and supervised by the Principle Investigator, a nationally certified Strength and Conditioning Coach.

Single-leg training program (NTP-SL).

The hip- and knee-dominant portions of the NTP-SL program featured back-loaded rear-foot-elevated squats (RFE squats), slideboard lunges, single-leg Romanian deadlifts (SL RDL), single-leg squats (SL squats), rear-foot-elevated jumps (RFE jumps), and single-leg hip lifts. The upper-body, core, and flexibility exercises were identical between groups.

Double-leg training program (NTP-DL).

The hip- and knee-dominant portions of the NTP-DL program featured back squats (BS), stability ball leg curls (SB leg curls), trap-bar deadlifts (TBDL), dumbbell Romanian deadlifts (DB RDL), and double-leg hip lifts. The upper-body, core, and flexibility exercises were identical between groups.

Procedures

Pre- and post-testing for each individual occurred on one day with adequate rest periods in place to avoid the confounding effect of fatigue. An estimated back squat 1-RM test, rather than a maximal test, was chosen for this reason (Kernozek et al., 2008; LeSuer, McCormick, Mayhew, Wasserstein & Arnold, 1997). On the day of testing, the athletes performed a repetitions-to-fatigue back squat test as previously described in the literature (LeSuer et al., 1997) to predict their back squat 1-RM weight. Additionally, the participants completed the THT, VJ, and JLC tests. The order of the testing was randomized, with a minimum of 10 minutes of rest following the 1-RM and JLC tests and a minimum of 5 minutes of rest following the THT and VJ tests. Prior to beginning the testing procedures, each participant was given five minutes to perform a self-directed, generalized warm-up. Each test is described in detail below.

Triple-hop test (THT).

A tape measure was affixed to the ground perpendicular to a pre-determined starting line. The test was conducted in the participants' self-selected athletic footwear. Participants balanced on one leg and performed three consecutive maximal hops forward on this limb without losing balance or allowing any other part of their body touch the floor or a supporting structure. The landing of the last jump was held in a controlled manner for a period of 3 seconds to be considered a valid trial. The distance traveled was measured from the starting line to the point where the participant's heel struck the ground on the landing of the third hop. This process was then repeated with the contralateral limb. Three trials were performed on each limb with each participant, and the farthest distance traveled for both right and left legs were recorded and used for analysis (Hamilton, Shultz, Schmitz & Perrin, 2008).

Vertical jump (VJ).

The vertical jump is a reliable and valid measure of power output in athletes (Hamilton et al., 2008). The VJ was performed using a countermovement jump, and jump height was measured, in inches, with a Vertec Jump Measurement System (Gill Athletics, Champaign, IL). The athlete stood beneath the Vertec system, feet shoulder-width apart and with preferred reach-hand positioned closest to the device. While keeping shoulders level, the reaching arm was flexed 180-degrees and the height of this static reach was recorded. The participant then performed as many countermovement jumps with a reach as she could while still increasing the height of each jump. Once jump height remained constant for three consecutive trials, the maximum height reached was subtracted from the original static reach height to obtain the VJ height. This height was recorded for analysis.

Predicted back squat 1-RM (BS 1-RM).

In a predictive back squat 1-RM test, the athlete must select a weight that he or she can squat more than one repetition but less than 10 repetitions. This weight is estimated through 2-3 increasingly heavy warm-up sets. To minimize fatigue, warm-up sets were kept to a maximum of 6 repetitions, regardless of weight lifted, and had a 1-2 minute rest period between each set. During the test set, the athlete squatted the given weight as many times as possible. The test was successful if the athlete performed each repetition in the correct manner, bringing the thighs parallel to the floor on each descent, and if she was able to perform at least 2, but no more than 10, repetitions. If the test was unsuccessful, the weight was adjusted and the test re-attempted after a 3-5 min rest period.

Once a successful test was performed, the weight and number of repetitions completed was recorded. The following formula, originally described by Wathan (1994) and found to be a valid and reliable predictor (*r* = 0.969) of the back squat 1-RM (LeSuer et al., 1997), was used to obtain the 1-RM value for each participant:

$$1\text{-RM} = 100 \times rep\ wt\,/\,(48.8 + 53.8 \times \qquad\qquad)$$

Jump-landing and cut (JLC).

Two of the most common mechanisms of non-contact ACL injury are landing from a jump (i.e., rapid deceleration) and cutting (i.e., a rapid change in direction). These two movements result in previously identified high-risk biomechanics (Imwalle et al., 2009). Since these movements, and therefore the risks, are a natural occurrence in most sporting events, limiting the extent to which these motions result in unsafe biomechanical postures is paramount.

In order to ascertain if the NTP-SL protocol results in superior biomechanics (less risk) as compared to the NTP-DL group, participants performed a jump-landing and cut maneuver (JLC). The athletes stood behind a line that was 1 meter behind two force plates. When given a signal, the participant jumped forward onto the force plates, landing on two feet, under one of two conditions: landing and making a 90° cutting maneuver quickly and forcefully to their right, or landing making a 90° cutting maneuver quickly and forcefully to their left. All trials were randomized and unanticipated, such that the participant did not know which direction to cut until she had begun her jump onto the force plates. While in the air, the direction in which to cut was indicated by the Principle Investigator or a trained research assistant. The directional indication consisted of turning one's shoulders to the left or the right, as if about to make an athletic move in that direction. The participants were instructed to cut in the same direction as researcher. A total of 10 successful trials (5 per condition/leg) were recorded for analysis.

Data Analysis

THT, VJ, and predicted BS 1-RM were analyzed as a separate mixed-model 2 x 2 (TIME x GROUP) ANOVAs. Each test examined differences in distance (meters), height (inches), and mass (kilograms), respectively, with an alpha level of .05.

From the JLC maneuver, six dependent variables were analyzed at various phases of STANCE (IC, 25%, and PVGRF) and between groups (NTP-SL and NTP-DL). Therefore, three separate 2 x 2 (TIME x GROUP) MANOVAs were calculated at each stance phase for: HFA (deg) and KFA (deg); HERM (Nm), HAbM (Nm), KAdM (Nm); and KAS (N). All kinetic measures were normalized to body weight.

Results

Ten participants were randomly assigned to the NTP-SL group (height: 165.32 cm (157.48-172.72); weight: 59.79 kg (54.1-68.0) and the NTP-DL group (height: 165.39 cm (157.48-170.18); weight: 61.18 kg (53.64-67.7). The vertical jump (VJ), triple hop test (THT), and back squat 1-RM (BS1RM) measured lower-extremity power, agility and balance, and strength, respectively. These tests were not significantly correlated, and therefore were calculated as separate 2 x 2 (Test x Group) mixed-model ANOVAs. The descriptive statistics can be found in Table 1.

In the BS1RM, there was no significant Test x Group interaction (*F*(1,8) = .694, *p* > .05), nor was there a significant main effect for Group (*F*(1,8) = 1.134, *p* > .05). However, a significant main effect for Test was found (*F*(1,8) = 14.727, *p* < .05), indicating that when groups were combined, post-test 1RM was significantly higher. The VJ, similar to the BS1RM, saw no significant Test x Group interaction (*F*(1,8) = 4.082, *p* > .05), nor was there a significant main effect for Group (*F*(1,8) = .030, *p* > .05). There was, however, a significant main effect for Test (*F*(1,8) = 5.878, *p* < .05), indicating that when groups were combined, post-test VJ was significantly higher than the pre-test. In the THT, a significant Test x Group interaction was found (*F*(1,8) = 5.937, *p* < .05). Follow-up ANOVAs showed no significant Test x Group interaction for THT on the right (*F*(1,8) = 5.012, *p* > .05) or left (*F*(1,8) = .134, *p* > .05) legs from pre-test to post-test. There was no significant main effect for Group (*F*(2,7) = .677, *p* > .05) or Test (*F*(2,7) = 1.572, *p* > .05) during the THT.

Table 1
Descriptive Statistics for Athletic Performance Tests Pre- and Post-Test by Group

Group		N	Minimum	Maximum	Mean	Std. Deviation
NTP-SL	PREBS1RM	5	68.4	80.5	76.08	4.7140
	POSTBS1RM	5	76.5	107.4	88.78	12.7215
	PREVJ	5	17.5	21	19.6	1.3874
	POSTVJ	5	17.5	21	19.7	1.4405
	PRETHTright	5	453	511	480.2	25.1336
	POSTTHTright	5	434	541	471.7	43.4736
	PRETHTleft	5	475	522.5	492.5	19.564
	POSTTHTleft	5	458	511	491.2	21.2532
NTP-DL	PREBS1RM	5	66.7	82.1	77.52	6.6612
	POSTBS1RM	5	79.5	110.3	97.26	12.9303
	PREVJ	5	15.5	21	18.9	2.1622
	POSTVJ	5	17.5	23	20.0	2.2638
	PRETHTright	5	395.5	497	453.6	36.7753
	POSTTHTright	5	431.5	531	480.4	35.8511
	PRETHTleft	5	403	520.5	470.7	45.4101
	POSTTHTleft	5	437.5	499	475.1	22.8046

Note: PRE = Pre-test data; POST = Post-test data; BS1RM = Back squat one-repetition maximum (kg); VJ = Vertical jump height (in.); THTright = Triple-hop test distance, right leg (cm); THTleft = Triple-hop test distance, left leg (cm)

Six variables were examined from the jump landing and cut (JLC) maneuver. Since the side-cut movement was performed at a 90-degree angle in both the left and right direction, yielding five trials in each direction, kinetic and kinematic variables were examined either for the right leg (in the case of a cut to the left) or the left leg (in the case of a cut to the right).

Descriptive statistics for NTP-SL, NTP-DL, and the totals from both groups can be found in Tables 2, 3 and 4, respectively.

Table 2

Descriptive Statistics for Kinematic and Kinetic Variables in the NTP-SL Group

	Pre-Test	*Post-Test*	*Pre-Test*	*Post-Test*	*Pre-Test*	*Post-Test*
	LICHFA		LPVGRFHFA		LQSHFA	
Mean	37.8393	37.7737	39.8273	40.1398	49.3585	46.8039
Std. Deviation	4.16043	3.77533	6.40603	3.86798	8.72778	2.25905
N	5	5	5	5	5	5
	RICHFA		RPVGRFHFA		RQSHFA	
Mean	38.8616	41.8775	42.6837	41.6296	50.7173	48.8030
Std. Deviation	5.90196	4.97068	8.91248	7.25565	9.43621	9.98218
N	5	5	5	5	5	5
	LICKFA		LPVGRFKFA		LQSKFA	
Mean	14.7139	12.4913	32.2671	37.1707	55.9649	53.6662
Std. Deviation	3.11109	4.34012	5.75960	9.45330	7.84085	4.27317
N	5	5	5	5	5	5
	RICKFA		RPVGRFKFA		RQSKFA	
Mean	11.5052	12.2592	29.2912	32.6081	53.9895	52.7607
Std. Deviation	3.60241	1.35537	8.73760	9.96179	4.79306	6.54704
N	5	5	5	5	5	5
	LICKAS		LPVGRFKAS		LQSKAS	
Mean	-1.1033	-2.0628	6.7483	7.7181	7.6918	8.0878
Std. Deviation	1.19893	1.31634	2.39252	1.47619	2.41817	.69535
N	5	5	5	5	5	5
	RICKAS		RPVGRFKAS		RQSKAS	
Mean	-.6430	-1.4086	2.9787	5.0159	6.6316	7.2747
Std. Deviation	2.11817	1.20577	3.55053	3.30123	2.03056	1.58968
N	5	5	5	5	5	5
	LICKAdM		LPVGRFKAdM		LQSKAdM	
Mean	136.9441	57.8791	156.6771	322.3649	599.6049	703.9892
Std. Deviation	160.05961	134.87142	518.24192	313.46649	300.79631	187.83167
N	5	5	5	5	5	5
	RICKAdM		RPVGRFKAdM		RQSKAdM	
Mean	116.6647	37.3267	-2144.7131	-1735.1131	-886.1565	-1218.1913
Std. Deviation	136.52520	185.28096	983.93201	210.38835	491.98351	416.98351
N	5	5	5	5	5	5
	LICHAbM		LPVGRFHAbM		LQSHAbM	
Mean	365.0490	318.2415	394.1825	-98.7837	532.0257	488.9332
Std. Deviation	328.79562	518.56147	692.44814	346.05792	467.66579	398.61929
N	5	5	5	5	5	5
	RICHAbM		RPVGRFHAbM		RQSHAbM	
Mean	308.5829	93.8428	-2348.9193	-1758.7913	-685.6838	-1212.9822
Std. Deviation	445.44136	287.92491	517.88434	605.15816	435.06990	625.64687
N	5	5	5	5	5	5
	LICHERM		LPVGRFHERM		LQSHERM	
Mean	40.8909	42.4939	8.9491	-16.7952	-138.7970	-52.6118
Std. Deviation	63.12141	12.25359	112.65749	106.60524	202.64359	138.83370
N	5	5	5	5	5	5
	RICHERM		RPVGRFHERM		RQSHERM	
Mean	27.2857	52.9129	983.2171	732.2485	593.5412	660.1347
Std. Deviation	41.69444	38.56776	533.75822	125.51326	145.02132	238.41608
N	5	5	5	5	5	5

Note: L = Left; R = Right; IC = Initial contact; PVGRF = Peak vertical ground reaction force; QS = 25% of stance phase; HFA = Hip flexion angle; KFA = Knee flexion angle; KAS = Knee anterior shear force; KAdM = Knee adduction moment; HAbM = Hip abduction moment; HERM = Hip external rotation moment

Table 3

Descriptive Statistics for Kinematic and Kinetic Variables in the NTP-DL Group

	Pre-Test	*Post-Test*	*Pre-Test*	*Post-Test*	*Pre-Test*	*Post-Test*
	LICHFA		LPVGRFHFA		LQSHFA	
Mean	38.0746	37.7047	39.7786	37.5873	43.7243	39.9762
Std. Deviation	13.02549	12.31313	11.28997	8.40945	11.03008	5.97260
N	5	5	5	5	5	5
	RICHFA		RPVGRFHFA		RQSHFA	
Mean	40.9497	37.3946	43.8271	37.3213	48.5084	40.7438
Std. Deviation	8.78360	10.70556	11.99852	7.42723	11.75217	6.51618
N	5	5	5	5	5	5
	LICKFA		LPVGRFKFA		LQSKFA	
Mean	16.2149	19.5156	34.3803	36.3750	53.0588	52.7267
Std. Deviation	8.52961	8.38557	14.19264	14.10708	12.66944	16.24449
N	5	5	5	5	5	5
	RICKFA		RPVGRFKFA		RQSKFA	
Mean	14.2071	17.7807	30.5649	32.5939	49.4466	49.1007
Std. Deviation	7.79701	10.35584	22.23865	16.39739	21.65583	17.98759
N	5	5	5	5	5	5
	LICKAS		LPVGRFKAS		LQSKAS	
Mean	-1.7755	-1.3720	7.8857	9.9711	10.2254	11.6251
Std. Deviation	1.88831	2.10782	4.30057	2.65984	2.58446	1.64911
N	5	5	5	5	5	5
	RICKAS		RPVGRFKAS		RQSKAS	
Mean	-1.0076	-1.6527	5.1167	6.5948	8.1085	9.2621
Std. Deviation	1.76230	.85525	4.48628	3.69919	1.83470	4.14829
N	5	5	5	5	5	5
	LICKAdM		LPVGRFKAdM		LQSKAdM	
Mean	53.8546	108.2373	247.9056	543.6343	714.2432	1293.0041
Std. Deviation	233.43843	218.45919	704.96666	820.73144	596.52385	225.23077
N	5	5	5	5	5	5
	RICKAdM		RPVGRFKAdM		RQSKAdM	
Mean	149.8246	-6.9117	-1163.2173	-1693.1672	-562.2197	-823.2917
Std. Deviation	323.21652	286.59274	1081.36755	778.67524	1325.04455	504.25484
N	5	5	5	5	5	5
	LICHAbM		LPVGRFHAbM		LQSHAbM	
Mean	181.5090	495.1727	966.2692	23.0788	362.9506	351.6379
Std. Deviation	792.49187	1048.00081	852.29401	1283.89008	415.95411	349.46929
N	5	5	5	5	5	5
	RICHAbM		RPVGRFHAbM		RQSHAbM	
Mean	739.1521	400.5353	-1619.6045	-1957.9027	-870.6147	-1612.5587
Std. Deviation	635.02922	717.55976	1471.71055	1153.52026	738.50620	1195.69577
N	5	5	5	5	5	5
	LICHERM		LPVGRFHERM		LQSHERM	
Mean	5.8885	52.1749	-106.6171	-116.1114	-137.7483	-235.2833
Std. Deviation	44.27466	73.47766	304.21958	437.00467	411.37272	299.78021
N	5	5	5	5	5	5
	RICHERM		RPVGRFHERM		RQSHERM	
Mean	3.4644	6.5837	371.5306	842.4446	489.7540	900.6151
Std. Deviation	69.44696	41.31664	271.54285	720.86083	221.20288	657.78203
N	5	5	5	5	5	5

Note: L = Left; R = Right; IC = Initial contact; PVGRF = Peak vertical ground reaction force; QS = 25% of stance phase; HFA = Hip flexion angle; KFA = Knee flexion angle; KAS = Knee anterior shear force; KAdM = Knee adduction moment; HAbM = Hip abduction moment; HERM = Hip external rotation moment

Table 4

Descriptive Statistics for Kinematic and Kinetic Variables; Totals for NTP-SL and NTP-DL Groups

	Pre-Test	*Post-Test*	*Pre-Test*	*Post-Test*	*Pre-Test*	*Post-Test*
	LICHFA		LPVGRFHFA		LQSHFA	
Mean	37.9570	37.7392	39.8029	38.8636	46.5414	43.3900
Std. Deviation	9.11670	8.58602	8.65389	6.31584	9.83593	5.57418
N	10	10	10	10	10	10
	RICHFA		RPVGRFHFA		RQSHFA	
Mean	39.9057	39.6360	43.2554	39.4754	49.6128	44.7734
Std. Deviation	7.14018	8.21589	9.98252	7.28497	10.11501	9.01107
N	10	10	10	10	10	10
	LICKFA		LPVGRFKFA		LQSKFA	
Mean	15.4644	16.0034	33.3237	36.7728	54.5118	53.1965
Std. Deviation	6.10432	7.30274	10.27176	11.32883	10.05036	11.20903
N	10	10	10	10	10	10
	RICKFA		RPVGRFKFA		RQSKFA	
Mean	12.8562	15.0199	29.9281	32.6010	51.7181	50.9307
Std. Deviation	5.90040	7.54644	15.94319	12.79083	14.97920	12.900633
N	10	10	10	10	10	10
	LICKAS		LPVGRFKAS		LQSKAS	
Mean	-1.4394	-1.7174	7.3170	8.8446	8.9586	9.8565
Std. Deviation	1.53270	1.69626	3.33517	2.35005	2.71121	2.21345
N	10	10	10	10	10	10
	RICKAS		RPVGRFKAS		RQSKAS	
Mean	-.8253	-1.5306	4.0477	5.8054	7.3701	8.2684
Std. Deviation	1.84697	.99389	3.97715	3.40850	1.98356	3.14141
N	10	10	10	10	10	10
	LICKAdM		LPVGRFKAdM		LQSKAdM	
Mean	95.3993	83.0582	202.2914	432.9946	656.9241	998.4966
Std. Deviation	193.70939	173.20468	585.28410	597.20038	449.46034	366.87641
N	10	10	10	10	10	10
	RICKAdM		RPVGRFKAdM		RQSKAdM	
Mean	133.2446	15.2075	-1653.9652	-1714.1401	-724.1881	-1020.7415
Std. Deviation	234.56370	228.70415	1103.44145	538.18545	957.63023	482.95238
N	10	10	10	10	10	10
	LICHAbM		LPVGRFHAbM		LQSHAbM	
Mean	273.2790	406.7071	680.2258	-37.8524	447.4882	420.2855
Std. Deviation	580.11656	785.07666	791.74673	888.79728	426.66437	360.74452
N	10	10	10	10	10	10
	RICHAbM		RPVGRFHAbM		RQSHAbM	
Mean	523.8675	247.1890	-1984.2619	-1858.3470	-778.1492	-1412.7705
Std. Deviation	564.72166	540.19767	1108.86802	874.73265	579.67495	923.97950
N	10	10	10	10	10	10
	LICHERM		LPVGRFHERM		LQSHERM	
Mean	23.3897	47.3344	-48.8340	-66.4533	-138.2726	-143.9475
Std. Deviation	54.61091	49.92302	224.68593	304.41388	305.71783	240.36873
N	10	10	10	10	10	10
	RICHERM		RPVGRFHERM		RQSHERM	
Mean	15.3751	29.7483	677.3739	787.3465	541.6476	780.3749
Std. Deviation	55.44152	44.90007	513.15304	491.24938	184.63485	483.3511
N	10	10	10	10	10	10

Note: L = Left; R = Right; IC = Initial contact; PVGRF = Peak vertical ground reaction force; QS = 25% of stance phase; HFA = Hip flexion angle; KFA = Knee flexion angle; KAS = Knee anterior shear force; KAdM = Knee adduction moment; HAbM = Hip abduction moment; HERM = Hip external rotation moment

Three separate 2 x 2 (Time x Group) MANOVAs were calculated for HFA and KFA, KAS, and KAdM, HAbM, and HERM. Each variable was examined at three different periods of stance: IC, PVGRF, and QS. For HFA and KFA, no significant Test x Group interaction or main effect was found for Test or Group. Similarly, no significant Test x Group interaction or main effect was found for Test or Group for KAS. For KAdM and HAbM, no significant Test x Group interaction or main effect was found for Test or Group. There was no significant Test x Group interaction or main effect for Group for HERM during a side-cut to the right, nor was there a significant Test x Group interaction or main effect for Test or Group for HERM during a side-cut to the left. However, the main effect for Test for HERM during a side-cut to the right approached significance ($F(3,6) = .747$, $p = .050$). Follow-up univariate tests did not show significant effects for Test at any particular phase of stance (IC: $F(3,6) = .363$, $p > .05$; PVGRF: $F(3,6) = .433$, $p > .05$; QS: $F(3,6) = 2.202$, $p > .05$).

Discussion

Female soccer players experience ACL tears at a rate of up to 6 times that of their male counterparts (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Myer et al., 2006; Pantano et al., 2005; Youdas et al., 2007), resulting in significant short- and long-term co-morbidities (Alentorn-Geli et al., 2009a; Borotikar et al., 2007). At-risk biomechanics, such as an extended knee posture during landing and out-of-sagittal- plane hip and knee moments, have been positively affected by neuromuscular training programs that consist of plyometric and strength training exercises (Yoo et al., 2009). The current research aimed to elicit the contribution of strength training to the resulting alterations in biomechanical approaches to a side-cut maneuver in healthy female collegiate soccer players. Further, a comparison was made between more traditional double-leg and the purportedly more athletically-based single-leg closed-chain hip and knee exercises.

In accordance with the hypotheses of this study, both the NTP-SL and NTP-DL groups experienced a significant increase in BS 1-RM mass and VJ height. Additionally, there were no significant differences between the NTP-SL and NTP-DL groups at post-test for either measure. A concern with single-limb training is the use of less overall mass. A person who has a back squat 1-RM of 100kg on two legs cannot be expected to do the same on one leg. Similarly, performance of the VJ on two legs should result in a higher jump than a VJ performed on one leg. Jensen & Ebben (2007) report that unilateral jump heights result in approximately 58% of the bilateral equivalent. This has led to speculation that the use of lighter weights will result in a decrease in overall lower-extremity strength and power. The participants in this study did not suffer this feared decrease, with both groups instead experiencing the gains in BS 1-RM mass and VJ height that would be expected with participation in a strength training program.

The aforementioned 58% of bilateral VJ height attained by a single-limb may explain why this decrease does not occur. The person squatting 100kg would be subjecting each leg to roughly a 50kg load. Conversely, when performed one leg at a time, the same individual should be able to squat 58kg with each leg, a 16% increase in mass. Since maximal strength has a strong influence on power production (Chaouachi et al., 2009), the increase in mass carried by each limb individually could increase bilateral power to the point where it would result in increases in VJ performance above and beyond that achieved with traditional bilateral strength training. The use of EMG to measure muscle activity and temporal aspects of single-limb versus double-limb hip- and knee-dominant exercises may further illuminate these hypotheses. Additionally, future research should compare measurements of work in each limb during single- and double-limb exercises.

Participants did not experience significant gains in THT distance, regardless of the group to which they were randomly assigned. The THT, which is performed on one leg and is a measure of balance, agility, and power, was expected to improve for both groups after training, with the NTP-SL group seeing significantly greater increases in distance than the NTP-DL group. Though single-limb hops were not a part of the NTP-SL training protocol, multiple exercises were performed under loaded conditions while balancing on one leg. Such postures are thought to increase the work done by the hip rotators in order to stabilize the pelvis and maintain balance during movement. It is possible, however, that such exercises are still not specific enough to a single-limb hopping activity as to have functional carry-over.

There are other possibilities for the THT results. An examination of the means for each group (Table 1) shows a moderate decrease in THT distance for the right leg and a slight decrease for the left leg in the NTP-SL group from pre- to post-test. Conversely, the NTP-DL group experienced a substantial gain in distance in the right limb and a small gain in distance in the left limb. Small group size, a wide range in values, large standard deviations, and insufficient power likely contributed to the lack of statistical significance in THT distance comparisons. However, the distances achieved here, as well as the large standard deviations and ranges, are in agreement with previously reported results. Hamilton et al. (2008) subjected 40 participants to the THT with their right leg, yielding a mean distance of 547.2cm with a standard deviation (SD) of 97.0cm and a range of 383 – 781cm as compared to a mean of 466.9cm, SD of 32.8387cm and range of 395.5 – 511cm on the right leg at pre-test in the current study. Therefore, small group size and the concurrent lack of statistical power may be the sole reason for non-significant results.

It is interesting to note that while the NTP-DL group experienced gains in both limbs, the dominant limb (in this case, the right leg for all participants) experienced a markedly larger increase than the non-dominant limb. This was not the case for the NTP-SL group, which saw a small decrease in the distance attained by the dominant limb. It is possible that the training undertaken by the NTP-DL group caused an increase in limb dominance, whereas the NTP-SL group, by design, could not compensate the non-dominant limb by having the dominant limb perform more work. Previous literature has reported similar findings. Newton et al. (2006) examined force production during a back squat at 80% of 1-RM and the VJ under three conditions: bilateral jumping, right-limb only, and left-limb only. Participants had between one and five years of strength training at the collegiate level, which the authors report featured extensive bilateral squat, vertical jump, and other leg extensor training. Despite such training, significant contralateral imbalances in strength and power persisted. This was observed through a 6% difference in force production between limbs during the back squat and double-leg VJ and an 8% difference in force production between the dominant and non-dominant leg during the single-limb VJ. The authors hypothesized that these imbalances are perpetuated by dominance of one side of the body during skills training and competition and that specific resistance training targeting the weaker side may be required to address this issue. These findings are echoed by Kernozek et al. (2008), who report that unilateral asymmetries in kinematic and kinetic measures frequently occur between legs during double-leg landings. Whether double-limb training reinforces limb dominance and compensation movement patterns or single-limb training is able to reduce disparities between limbs is a topic for continued research.

Non-contact ACL injuries typically occur during movements involving high-risk biomechanics that result in knee valgus, varus, internal rotation, and external rotation moments, as well as anterior translation force (Alentorn-Geli et al., 2009a; Chappell et al., 2005; Chaudhari & Andriacchi, 2006; Imwalle et al., 2009; Kernozek et al., 2008; Lim et al., 2009; McLean et al., 2007; McLean & Samorezov, 2009; Myer et al., 2006; Yoo et al., 2009; Youdas et al., 2007; Yu et al., 2006). The risk of injury is magnified when these forces occur at greater degrees of hip and knee extension, a common posture for female athletes as compared to their male counterparts, resulting in less shock attenuation and higher forces experienced at the knee (Alentorn-Geli et al., 2009a; Chaudhari & Andriacchi, 2006; Lim et al., 2009; Yoo et al., 2009). Though HFA and KFA in the NTP-SL and NTP-DL groups were non-significant from pre-test to post-test at all three phases of stance, the importance of increasing these angles during at-risk movements should not be overlooked.

Current ACL neuromuscular training programs aim to lower the risk of injury by reinforcing proper postures and creating the strength and endurance necessary to maintain correct biomechanics. The NTP-SL and NTP-DL training protocols incorporated hip- and knee-dominant exercises designed to strengthen the extensor muscle groups. Increased strength during hip and knee eccentric flexion allows athletes to use sagittal plane motions to absorb the forces exerted on the body through the more elastic muscles without risk of collapse in the frontal or transverse planes, putting more strain on the less-forgiving ACL. The larger flexion angles during landing also decrease anterior shear force in the knee while placing the hamstrings at an optimal angle-of-pull to assist in resisting anterior translation of the tibia (Alentorn-Geli et al., 2009a). As such, if the athletes in the present study experienced the expected increase in lower-limb strength, there should have been a concomitant increase in hip and knee flexion angles at post-test. However, similar to the THT, it is possible that the exercises selected were not dynamic enough to have carry-over to the JLC, which is essentially a plyometric movement. Importantly, though statistically non-significant, both the NTP-SL and NTP-DL groups trended toward a consistent increase in KFA at PVGRF after training. However, this increase in KFA may be mitigated by a concurrent trend toward a decrease in HFA at PVGRF at post-test, also exhibited in both groups.

Considering there was no significant increase in HFA or KFA, it is of little surprise that there were also no significant changes in KAS in either group from pre-test to post-test. Another look at trends among means of the NTP-SL and NTP-DL groups shows that both groups experienced a similar training effect. In this case, KAS tended to decrease slightly at IC – and, in fact, be a posteriorly-directed force – in the NTP-SL group, but was higher at both PVGRF and QS phases. The same trend occurred during a side-cut to the right in the NTP-DL group, but not during a side-cut to the left, during which KAS tended to increase at all phases of stance from pre- to post-test.

KAS is bound to occur during movements involving quick changes in direction, such as side-cut maneuvers and jump-landings, but reducing the amount of shear force at the knee is still a desirable outcome. In female athletes, a predisposition toward quadriceps dominance increases the amount of this anteriorly-directed shear force (Alentorn-Geli et al., 2009a; Shields et al., 2005; Youdas et al., 2007). Despite the inclusion of hip-dominant exercises that are designed to increase hamstring strength and decrease the quadriceps-to-hamstring ratio, this intended effect was not elicited. Though KAS alone is not enough to rupture the ACL, when experienced in combination with coronal and transverse plane torques the risk of ACL rupture is elevated (Alentorn-Geli et al., 2009a; Imwalle et al., 2009; Kernozek et al., 2008; Willson et al., 2006).

In the present study, the widest variation between participants existed in KAdM, HAbM, and HERM data. In all three variables, at all phases of stance, and in each group, no significant differences were observed, nor were there any consistent trends. During the force absorption that occurs during the eccentric phase of cutting or landing from a jump, extended hip and knee postures in female athletes mean that compensatory motions must occur in order to execute the movement. Instead of collapsing in the sagittal plane, these athletes instead experience excessive out-of-plane motions, placing them at higher risk of ACL injury. Based on the current data, these compensatory movements do not appear to be universal in nature and are probably very person-specific. This is an added challenge when attempting to condition the athlete to avoid certain movement patterns and adopt others.

The dissimilarity among coronal and transverse plane kinetics in each participant does not diminish the importance of altering the moments experienced at the knee and hip. Athletes who exhibit increased hip stiffness, as characterized by an increase in hip abduction and external rotation moments, are less likely to experience a lower-extremity injury (Chaudhari & Andriacchi, 2006; Imwalle et al., 2009). Female athletes, who consistently exhibit reduced hip stiffness as compared to male athletes, stand to greatly benefit from strength programs that address hip musculature. Research has shown that women experience excessive hip external rotation when performing dynamic closed-chain movements on one limb (Zeller et al., 2003). However, it is probable that this posture results in pelvic rotation away from the stance leg as a mechanism of maintaining center of gravity. This places the hip external rotators in a shortened position, decreasing their workload and placing increased responsibility for knee control on the quadriceps. Single-limb exercises, when performed correctly, work to correct this compensatory action through gradual loading of the rotators as pelvic stabilizers.

Limitations

Small group size and insufficient statistical power may have contributed to the lack of significant differences in all variables from pre-test to post-test. Due to the nature of the strength training protocols, the access to female soccer players, and the time constraints of the spring season, only ten athletes were available to participate. In addition to decreasing the statistical power, and therefore the ability to obtain significant findings if any exist, small group sizes also threaten the external validity of the results.

Twelve training sessions that occur over a six-week period may not be enough to elicit true neuromuscular changes. As noted by Lim et al. (2009), six weeks does not correlate with the time frame needed to produce muscle hypertrophy or improved endurance. However, that should be a sufficient time frame in which to increase motor unit recruitment. Further studies should attempt to implement neuromuscular training programs over a longer period of time, allowing both neurological and morphological changes to take place. Ideally, future research should aim to incorporate several teams of female soccer players in order to gauge the true effect of the different training programs. If possible, three days a week of training, as well as a total of twelve weeks in the protocol, should be used to ensure that both neurological and morphological changes occur in the participants.

The participants recruited in this study had a minimum of one year of collegiate-level strength and conditioning experience, but it was limited to largely machine-based exercises, body-weight calisthenics, and abdominal work. Many of the hip- and knee-dominant exercises chosen for both groups were foreign to a majority of the athletes. There was an extremely large learning curve, particularly in the single-leg group, with regard to proper form during the execution of these movements. Even at the end of six weeks, it was not apparent that the participants had mastered the correct biomechanics for each exercise. This could be another reason why results were not as expected. Though a certain amount of athleticism is assumed with Division II varsity athletes, it was apparent that the focus of their previous training was centered around on-field skills training and not strength and conditioning for athletic performance or injury prevention. Therefore, six weeks may not have been sufficient time to train coordination patterns for the eccentric, amortization, and concentric phases of the chosen exercises, ensuring that there would be no significant biomechanical changes during testing modalities.

Finally, the time of year during which the testing and intervention occurred could have affected the outcomes. The participants performed their pre-tests prior to the university's spring break and at the start of an abbreviated spring schedule of games and practices. Though not as taxing as the regular season, spring season included an average of a game per week and team practices between 3-5 days a week in addition to the training protocol that was a part of this study. It is possible that fatigue became a factor in the participants by the time post-testing occurred. Furthermore, post-testing fell during the week before final exams. Many athletes reported having interrupted sleep patterns and high levels of stress, both of which could have affected the outcomes of all tests. Though it would be difficult to mitigate this issue entirely in this population, care should be taken in future investigations to reduce the chances of a fatigue-effect over the course of the training protocol, as well as scheduling pre- and post-testing for times where sleep patterns and stress levels would be roughly equal.

Future Research

The results of the current study echo findings that strength training alone is not enough to produce the desired changes in biomechanics that represent a reduced risk of ACL injury. A wide variety of strength and conditioning approaches in neuromuscular training interventions has made it difficult to compare programs from study to study. Researchers should continue to build upon the programs outlined here by increasing the length of intervention and adding in other strength training modalities, such as power exercises. It is suggested that plyometric programs are the most effective at reducing biomechanical ACL injury risk factors, but this has only been the case when a plyometric program has been performed in conjunction with a strength training protocol (Myer et al., 2006; Yoo et al., 2009). Therefore, the contribution of strength training to this effect continues to warrant further inquiry.

To the author's knowledge, no examinations of the effects of single-limb exercises have been published. Of the neuromuscular training protocols in existence that purport to reduce ACL injury risk, there is a wide variety in exercise selection and volume. In order to have two protocols that weren't inherently different, great care was taken to select both single-limb and double-limb exercises that were similar in nature. Further, no power exercises were utilized due to the author's prior knowledge of the participants' inexperience with such training methods. All athletes, regardless of group, performed two hip-dominant and two knee-dominant exercises during every training session, and all athletes performed the same upper-body and core exercises. No existing protocols met the requirements outlined above, and thus the NTP-SL and NTP-DL programs were created from scratch. In an effort to control for confounding variables, the resulting training programs did not necessarily reflect "best practices" with regard to a well-rounded strength and conditioning program. However, rather than continue to create new protocols, future research should build on the current body of literature by first expanding the time frame during which intervention occurs, and then by increasing the exercise selection, as warranted. This will enable comparisons across investigations and aid researchers in discovering the best ways in which to utilize strength training to decrease ACL injury risk.

There were no significant differences elicited between the NTP-SL and NTP-DL groups for the training intervention undertaken in this study. Due to the limitations previously discussed, the effect of single-leg training, and its place in an ACL injury prevention program, should continue to be explored. A comparison of muscle activation patterns and forces during single-leg versus double-leg hip- and knee-dominant exercises may indicate whether or not differences in these approaches exist that would result in neuromuscular changes.

Conclusions

Improved technology over the past 30 years has allowed researchers to gain extensive knowledge regarding ACL injury. In female athletes, the higher incidence rate can likely be attributed to intrinsic factors, such as hormone levels and pelvic width, as well as extrinsic factors, including increased quadriceps dominance, decreased hip stiffness, decreased hip and knee flexion angles at initial ground contact, and increased hip adduction and knee valgus during high-risk movements. These extrinsic factors appear to be modifiable and should continue to be the focus of current research.

While we continue to increase our understanding of the causes of ACL injury, there is a dearth of knowledge regarding ACL injury prevention. A handful of published studies that have examined the effects of combined plyometric and strength exercise programs have determined that it is possible to alter at-risk biomechanics through training. However, the mechanism by which this occurs is still unknown. Additionally, it is still not clear which behaviors exhibited by female athletes during at-risk movements serve to increase the risk of ACL injury and which occur as a coping mechanism to prevent ACL injury. For example, the role of the foot-ankle complex and the increased pronation that occurs in women as compared to men continues to be investigated as researchers attempt to tease out differences in those who eventually experience ACL injury versus those who do not. It is possible that the increased pronation is a form of shock attenuation, reducing the risk of injury, rather than an injurious motion in and of itself. The continued investigation of these issues will lead to improved practices regarding ACL injury prevention techniques.

The use of single-limb training in this study did not reduce gains in strength or power as measured by back squat and vertical jump over the six-week intervention period when compared to double-leg training. However, the expected improvements in hip and knee angles, forces, and moments during a side-cut maneuver did not occur. Therefore, it cannot be definitively concluded that single-limb training plays either a beneficial or a detrimental role in sport performance or ACL injury prevention programs when compared to double-limb training. Where single-limb training may be necessary, though, is in reducing inter-limb strength imbalances and challenging the athlete to reduce compensatory movement patterns. The trend of the NTP-DL group to experience such large improvements in their dominant leg during the THT lends credence to the hypothesis by Newton et al. (2006) that extensive training using double-leg support may only serve to increase deficiencies already present. Over time, such imbalances may increase the risk of injury, despite the use of these exercises to increase strength, power, and endurance and thereby reduce ACL injury risk.

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