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Effect Of An Injury Prevention Training Program On Risk Factors Associated With ACL Injury

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EFFECT OF AN INJURY PREVENTION TRAINING PROGRAM

ON RISK FACTORS ASSOCIATED WITH ACL INJURY

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Interdisciplinary Health Sciences Ph.D. Program

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Dedication

To my family who have provided me with unconditional love, support, and guidance throughout my life. You have always encouraged me to dream big and inspired me to work hard to achieve each and every goal.

EFFECT OF AN INJURY PREVENTION TRAINING PROGRAM ON RISK FACTORS ASSOCIATED WITH ACL INJURY

by

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Abstract

Increased involvement in women's sports has been met with a disproportionate incidence of anterior cruciate ligament (ACL) injuries. The underlying cause of ACL injury is likely multi-factorial, with risk factors including deficits in lower extremity kinematics, kinetics, muscle activity, strength, stability, and sensitivity. Insight into risk factors has prompted several injury prevention programs. However, program outcomes have been mixed. Therefore, the purpose of this study was to examine the effect of specialized training on risk factors theorized to increase the incidence of ACL injury.

Fifty-six (28 control, 28 intervention) apparently healthy females volunteered to participate in this study. Training was conducted three times per week for a period of six weeks. Training included agility, plyometric, balance, and strength exercises. Risk factor assessment included evaluation of simultaneous single leg drop landing 3-D motion analysis, electromyography, and ground reaction force. Data collection also included knee joint proprioception, laxity, and strength testing.

Intervention group displayed an increase ($p < 0.001$) in knee flexion and a decrease ($p = 0.02$) in knee valgus with no change in corresponding knee moments. An increase ($p < 0.001$) in maximum knee flexion angle and decrease ($p < 0.001$) in corresponding knee moment was observed. Intervention group exhibited an increase ($p < 0.001$) in amplitude and delay ($p < 0.001$) in onset time in semi-membranosus activity. There were no significant changes observed in variability of COM excursion along the x-axis, y-axis and z-axis. Vertical ground reaction force decreased ($p < 0.001$) following training. The Intervention group demonstrated greater proprioceptive sensitivity at 15˚ (p

< 0.001) and 30˚ (p = 0.001), and 45˚ (p < 0.001). A decrease in passive drawer (p < 0.001) and maximum manual drawer (p < 0.001) knee laxity was also observed

The depth of this investigation served to contribute information not previously found in ACL injury prevention program studies. The product of the current training protocol led to significant mechanical and muscular improvements in single drop landing outcomes. Future research should explore the utility of training in athletes and across a multitude of ACL injury risk factors and several high risk maneuvers.

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Chapter 1: Introduction

The collegiate sports arena has provided many female athletes the ultimate venue to showcase exceptional athletic performance through masterfully skilled ability. Women's sports have become increasingly popular with a growing number of young female athletes striving for competitive distinction and accomplishment. The respective 10- and 5-fold increase in high school and collegiate sports involvement (Hewett, Myer, & Ford, 2006) can be partially attributed to the 1000% increase in organized sports participation by adolescent females (Goldberg, Moroz, Smith, & Ganley, 2007). However, increased involvement in women's sports has been met with a disproportionate incidence of anterior cruciate ligament (ACL) injuries. The steady rise in ACL injury rates has heightened sport injury awareness and generated significant attention towards the athletic well-being of female athletes.

The National Collegiate Athletic Association (NCAA) Injury Surveillance System database (1988-2004) documented approximately 4800 ACL injuries in an epidemiology study of collegiate injuries in select sports over 16 consecutive seasons. This statistic was representative of roughly 15% of all participating collegiate sport programs (Hootman, Dick, & Agel, 2007). When ACL injuries were represented as a percentage of all possible injuries, women's basketball (4.9%), women's gymnastics (4.9%), women's lacrosse (4.3%), and women's soccer (3.7%) along with men's spring football (3.5%) were the top five sports with the highest prevalence for ACL injury. This is in stark contrast to available ACL injury statistics for men's basketball (1.4%), lacrosse (2.7%), and soccer (1.3%) (Renstrom et al., 2008). Of the selected sports analyzed across the

16 season period, the incidence of ACL injury significantly increased 1.3% per year ($p < 0.01$) (Hootman et al., 2007).

Further examination of the frequency of ACL injury as per 1000 athlete exposures indicated that women's gymnastics (0.33) and men's spring football (0.33) followed by women's soccer (0.28), and basketball (0.23) had the highest incidence of injury. This is a sizeable difference from available statistics for men's soccer (0.09) and basketball (0.07). Athlete exposure was defined as one athlete participating in one practice or game that placed the student-athlete at risk for potential injury (Hootman et al., 2007). Notably, this translates to an ACL injury rate that is three and four times higher for female athletes compared to male athletes participating in soccer and basketball, respectively (Mihata, Beutler, & Boden, 2006). The sports of soccer and basketball are often the subject of prominent ACL injury related research because of the availability of NCAA Injury Surveillance System reports and rules/parameters which make competition fundamentally the same for both women's and men's teams (Arendt, Agel, & Dick, 1999).

ACL injuries can be physically debilitating with long term effects that include knee joint degeneration and osteoarthritis (Lidén, Sernet, Rostgård-Christensen, Kartus, & Ejerhed, 2008). Surveys collected from elite level female soccer players revealed that 50% of athletes never return to organized soccer following total ACL reconstruction. An estimated 15% of athletes resumed competitive play with an equal or improved level of performance after ACL reconstruction and rehabilitation (Lohmander, Östenberg, Englund, & Roos, 2004). Athletes 14 - 18 years of age demonstrated the highest propensity for ACL injury (Renstrom et al., 2008). Injuries to the knee are responsible

for five times the number of surgeries performed on female athletes than on male athletes competing in related sports. This accounts for 76% of all surgical procedures performed on the female high school student population (Myer, Ford, & Hewett, 2005). The expense for medical treatment and rehabilitation can range from $17,000 to $25,000 per injury (Hewett, Myer, et al., 2006).

Athletic events resulting in noncontact injury to the knee are held as the primary mechanism responsible for approximately 70% of ACL injuries in female athletes (Ramesh, Von Arx, Azzopardi, & Schranz, 2005). Events are characterized by an absence of collision, irregular skill-specific mechanics, and aggressive changes in direction and speed (Renstrom et al., 2008). High-risk maneuvers include side cutting, cross cutting, and drop landings (Mihata et al., 2006).

Possible risk factors have included anthropometric differences in Q angle, pelvis width, femoral intercondylar notch shape and size, and knee joint laxity in females and males (Anderson, Dome, Gautam, Awh, & Rennirt, 2001; Lidén et al., 2008; Lohmander et al., 2004; Shelbourne, Davis, & Klootwyk, 1998; Vauhnik, Morrissey, Rutherford, Turk, Pilih, & Perme, 2009). Females are represented as having anatomical attributes that compromise knee joint stability by affecting the structural integrity and function of the lower extremity (Hertel, Dorfman, & Braham, 2004). Females commonly exhibit greater pelvis width, femoral anteversion, and knee joint valgus (Holschen, 2004). Females generally posses decreased femoral notch widths, decreased ACL volumes (Charlton, St. John, Cicotti, Harrison, & Schweitzer, 2002), and increased ligamentous laxity (Quatman, Ford, Myer, Paterno, & Hewett, 2008).

Hormonal research has focused on the effect of sex hormones on ACL injury incidence, ACL integrity, neuromuscular control and function, and the influence of contraceptives on knee joint injury and laxity (Belanger, Moore, Crisco III, Fadale, Hulstyn, & Ehrlich, 2004; Beynnon, & Shultz, 2008; Medrano, Smith, Kiran, & Carlson, 2009; Park, Stefanyshyn, Hart, Loitz-Ramage, & Ronsky, 2007; Shultz, Kirk, Johnson, Sander, & Perrin, 2004; Shultz, Gansneder, Sander, Kirk, & Perrin, 2006). Females are generally characterized as being more susceptible to ACL injuries during specific phases within the menstrual cycle (Slauterbeck, Fuzie, Smith, Clark, Xu, Starch, & Hardy, 2002; Wojtys, Huston, Lindenfeld, Hewett, & Greenfield, 1998) with notable decreases in injury incidence among females taking oral contraceptives (Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002). Elevated levels of sex hormones are thought to increase a female's vulnerability to injury by affecting the laxity of ligamentous tissues in the knee (Beynnon, Bernstein, Belisle, Brattbakk, Devanny, Risinger, & Durant, 2005; Pollard, Braun, & Hamill, 2006; Park, Stefanyshyn, Loitz-Ramage, Hart, & Ronsky, 2009; Park, Stefanyshyn, Ramage, Hart, & Ronsky, 2009; Shultz, Sander, Kirk, & Perrin, 2005).

Biomechanical investigations have included examinations of maximal hamstrings peak torque relative to maximal quadriceps peak torque at a given knee joint angular velocity (H:Q strength ratio) and lower extremity kinematics/kinetics during high risk maneuvers (Bowerman, Smith, Carlson, & King, 2006; Cote, Brunet, Gansneder, & Shultz, 2005; DiStefano, Padua, DiStefano, & Marshal, 2009; Rosene, Fogarty, & Mahaffey, 2001). Neuromuscular research has included electromyography (EMG) of knee agonist - antagonist musculature, knee proprioception, muscle recruitment

strategies, and the effects of fatigue on muscle activation patterns (Ahmad, Clark, Heilmann, Schoeb, Gardner, & Levine, 2006; Callaghan, Selfe, McHenry, & Oldham, 2008; Devan, Pescatello, Faghri, & Anderson, 2004; Markolf, O'Neill, Jackson, & McAllister, 2004; Myer et al., 2005; Rozzi, Lephart, Gear, & Fu, 1999). Female athletes are generally described as having irregular joint specific mechanics during high risk maneuvers, increased anterior knee joint laxity, diminished knee joint position sense, muscle activation patterns that favor the quadriceps, and an imbalance in hamstrings strength relative to the quadriceps strength (Rozzi et al., 1999).

Scientific interest into ACL injury risk factors has led to several high profile ACL injury prevention programs (Chappell, & Limpisivasti, 2008; Gilchrist, Mandelbaum, Melancon, Ryan, Silvers, Griffin, Watanabe, Dick, & Dvorak, 2008; Grindstaff, Hammill, Tuzson, & Hertel, 2006; Kato, Urabe, Kawamura, 2008; Louw, Grimmer, & Vaughan, 2006; Mandelbaum, Silvers, Wantanabe, Knarr, Thomas, Griffin, Kirkendall, & Garrett Jr., 2005; Myer, Ford, McLean, & Hewett, 2006; Myer, Ford, Brent, & Hewett, 2007; Newberry & Bishop, 2006; Paterno, Myer, Ford, & Hewett, 2004; Pfeiffer, Sheas, Roberts, Granstrand, & Bond, 2006; Twist, Gleeson, & Eston, 2008; Vescovi, Canavan, & Hasson, 2008). However, ACL injury prevention program outcomes have been mixed yielding little understanding of simultaneous mechanical and muscular processes following multi-component training. The gap in the knowledge base is attributed to the limited depth of research investigations surrounding prevention program outcomes (Herman et al., 2009).

The long-term goal is to contribute knowledge of the utility of a six week ACL injury prevention program synthesized from the most important training components derived

from existing prevention program studies in modifying several ACL injury risks factors theorized to increase the prevalence of ACL injury in female athletes. Research results will have a positive impact on existing training schemes currently employed in women's athletics. Other notable contributions include improvements to overall physical fitness (cardio-respiratory fitness, muscular strength, muscular endurance, flexibility) and improved mechanical performance ability during high risk sport maneuvers.

Therefore the purpose of this investigation was to comprehensively investigate the effect of a six week ACL injury prevention program across several interrelated biomechanical, neuromuscular, and performance characteristics. The central hypothesis is that a specific combination of plyometric, agility, balance, strength training skills and drills will improve knee joint deficits during high risk maneuvers thereby decreasing the risk for ACL injury. The formulation of the hypothesis was based on current understanding of athletic female attributes (Rozzi et al., 1999) and research support for the effectiveness of assorted training strategies (Chappell & Limpisivasti, 2008; Kato et al., 2008; Vescovi et al., 2008; Myer, Ford et al., 2007; Myer, Ford et al., 2006; Paterno et al., 2004)

The rationale underlying the following specific aims is that successful completion of the specialized training program will contribute to the improvement of the muscle and mechanical strategies employed during single leg drop landings. The hypotheses outlined in the proposed research were objectively tested by pursuing the following specific aims:

Specific Aim 1: Identify specialized training effects on simultaneous single leg drop landing mechanics, moments, center of mass, muscle activity, and ground reaction forces.

Hypothesis 1: Training will enhance movement and muscle recruitment patterns reducing the amount of force generated at landing.

Specific Aim 2: Identify specialized training effects on knee joint sensitivity and stability.

Hypothesis 2: Training will enhance knee joint sensitivity and increase ACL integrity at specific knee angles.

Specific Aim 3: Identify specialized training effects on knee muscle strength.

Hypothesis 3: Training will reduce hamstrings and quadriceps strength deficits

Chapter 2: Background and Significance

Investigations into the ACL injury gender disparity resulted in numerous scientific publications. Structural, hormonal, biomechanical, and neuromuscular factors have been examined as possible ACL injury risk factors (McClay Davis, & Ireland, (2003). The underlying mechanism responsible for ACL injuries is exceedingly difficult to determine with unquestionable certainty because of the interplay among risk factors. The impact of risk factors is difficult to discern because performance characteristics are highly susceptible to training effects and adaptations to the physical demands of a given sport. An overview of structural, hormonal, biomechanical, and neuromuscular ACL injury risk factors and several widely used prevention programs have been included in the following review of literature.

The structure and function of the tibiofemoral joint (knee joint) is anatomically intricate and biomechanically complex (Majewski et al., 2006). The knee is classified as a ginglymus joint because it primarily functions as a hinge moving the tibia through approximately 140° of flexion and 180° of extension. However, the knee is often characterized as a trochoginglymus joint due to the external (0 - 45°) and internal (0 - 30°) rotation that can occur when the knee is flexed beyond 30° (Floyd, 2007). The knee endures considerable stress and strain due to the amount of weight and locomotion supported at the joint. Ligamentous structures coupled with powerful knee extensors (quadriceps) and flexors (hamstrings) provide essential static and dynamic stability to the knee, respectively (Quatman et al., 2008)

The ACL is composed of multiple non-parallel fibers that join the antero-medial portion of the tibia (tibial plateau) to the postero-lateral portion of the femur. The anteromedial, posterolateral and intermediate bundles of the ACL collectively serve as

the primary restraint against anterior translation, knee hyperextension, and anterolateral rotation of the tibia relative to the femur (Frank & Jackson, 1997). The ACL also protects the knee from excessive lateral (valgus) stress by supporting medial collateral ligament function as a secondary knee stabilizer. The anatomical structures of the knee provide both mechanical stability and proprioceptive feedback during knee joint function (Cross, 1998). The ACL exhibits the capacity to minimize the stress within the knee by microscopically adjusting viscoelastic properties of the ligament according to an internal load history of past demands placed on the knee (Frank & Jackson, 1997).

Females in the pre-pubertal stage of maturity do not exhibit an increased propensity towards knee ligament injury. The onset of puberty marks a period of significant development in the anatomy and physiology of both females and males with the gender disparity in ACL injury becoming more prominent as athletes transition into adolescence. Anatomical and physiological differences following maturation are also accompanied by gender related differences in biomechanical and neuromuscular performance characteristics and strategies (Quatman et al., 2008).

2.1 RISK FACTORS

2.1.1 Anatomy

The progression into young adulthood results in a wide range of anthropometric differences between females and males. The female skeleton is generally characterized by anatomical features that are less robust than that of their male counterparts with the exception of prominent structural attributes at the level of the lower extremity. Females on average demonstrate greater pelvis widths, quadriceps angles (q-angle), femoral anteversion, and knee valgus (Holschen, 2004). Investigative research into hip, knee,

and ankle morphometry has broadened scientific understanding of the anatomical components that facilitate and affect knee joint function.

The wide separation between anterior iliac spines accounts for the greater lateral prominence observed in the hip structure of most females (Floyd, 2007). Increased pelvis width contributes to larger q-angles (Myer et al., 2005). The q-angle is calculated by measuring the superior angle created by two intersecting lines drawn from the center of the patella to the anterior-superior iliac spine of the pelvis and the tubercle of the tibia superiorly through the center of the patella (Floyd, 2007). Femoral anteversion occurs when the head and neck of the femur are positioned outward within the acetabulum relative to the frontal plane causing the lower extremity to internally rotate towards the midline of the body (Tönnis & Heinecke, 1999). Knee valgus describes the outward angulation of the distal portion of the tibiofemoral joint. Knee valgus is characterized by an inward appearance of the proximal portion of the knee joint towards the adjacent knee on the opposite appendage.

Normal alignment of the lower extremity ideally positions the load-bearing axis down the middle of the leg through the hip, knee, and ankle. Shifting of the load-bearing axis away from the medial portion of the leg is generally caused by structural variations in lower leg anatomy. Lower extremity malalignments produce mechanical consequences that have the potential to compromise the integrity of the ACL and subsequent stability of the hip, knee, and ankle. Hertel et al. (2004) found skeletal alignment issues caused by significant anterior pelvic tilt and navicular drop place females on an injury risk continuum that increases their vulnerability to ACL injury.

Females generally display significantly larger measures of anterior pelvic tilt (females: 3.5˚ ± 0.42˚, males: 1.5˚ ± 0.35˚, $p<0.0005$) and q-angles (females: 12.7˚ ± 0.62˚, males: 10.2˚ ± 0.52˚, $p=0.004$). Excessive anterior pelvic tilt is thought to shorten the hip flexors and increase internal rotation at the hip. This gender characteristic is suspected to exacerbate the dominance of the quadriceps muscle further diminishing the neuromuscular capacity of the lower extremity during high risk maneuvers. Sizeable q-angles are thought to be responsible for producing a disproportionate amount of knee valgus that is well beyond the structural limits of the ACL (Hertel et al., 2004). Valgus alignment of the knee has been shown to increase the amount of stress across the lateral compartment of the tibiofemoral joint. Irregular medial-to-lateral quadriceps recruitment patterns coupled with simultaneous lateral hamstring activity during landing tasks increase the amount of knee abduction experienced by females at low flexion angles (Myer et al., 2005).

Further examination of lower extremity malalignments identified increased anterior pelvic tilt ($R^2=0.15$, $p=0.04$) and navicular drop ($R^2=0.14$, $p=0.02$) as significant predictors of ACL injury. Athletes with inclinometer measurements of anterior pelvic tilt greater than 3.89˚ were 5.2 times as likely to incur a serious injury to the ACL. Individuals with a navicular drop index between 0.63 cm and 0.80 cm were 16 and 20 times more vulnerable to ligament injury (Hertel et al., 2004). Q-angle measurements were found to provide a poor indication of dynamic knee stability (Myer et al., 2005) and ACL injury risk (Hertel et al., 2004). Genu recurvatum ($r=0.184$, $p=0.323$), navicular drop ($r=0243$, $p=0.187$), and a composite measure of lower extremity torsion ($r=0.039$,

p=0.836) were shown to have a limited effect on anterior tibial translation (Trimble, Bishop, Buckley, & Fields, 2002).

Past literature has also asserted a pathologic relationship between femoral intercondylar notch width, ACL size, and ligament injury. Female athletes exhibiting intercondylar notch stenosis were thought to house an ACL that was less robust and resilient to the effects of movement related strain (Shelbourne et al., 1998). Compared to age matched male athletes, femoral notch (females: 4330 mm^3, males: 6047 mm^3, $p<0.001$) and ACL (females: 652 mm^3, males: 839 mm^3, $p<0.016$) volumes were significantly smaller in female athletes. Structural differences in knee joint anatomy were found to be significantly attributed to anthropometric differences in height and weight (Charlton et al., 2002).

This is in contrast to results obtained from anthropometric measures of height, weight, percent body fat, and knee joint anatomy from 100 (50 female, 50 male) high school varsity basketball players (Anderson et al., 2001). Evaluation of magnetic resonance imaging (MRI) of several intercondylar notch (total condylar width, lateral condylar width, notch width, notch width at ⅔ notch height) and ACL (width on axial views, width on sagittal views, area) dimensions established that intercondylar notch dimensions do not provide a reliable indices of ACL volume in female and male athletes. Interestingly, ACL size increased as height increased among male athletes (p=0.03), but did not show the same tendency among taller females (p=0.82). Researchers speculate that rotational and translational forces may have a greater impact on a normal sized ACL contained within a stenotic intercondylar notch because

of the relative displacement allowed by a smaller intercondylar space (Anderson et al., 2001).

2.1.2 Laxity

Articular ligamentous tissues are composed of tough strands of collagen fibers that connect one surface of bone to another. These dense fibrous bands of connective tissue are intricately arranged in a crossed pattern to help maintain proper alignment of a joint. Ligaments provide a level of restriction and tensile strength to certain degrees and directions of movement (Floyd, 2007). The amount of tibial translation permitted at the joint is thought to be influenced by gender related factors and pubertal status (Quatman et al., 2008).

Quatman et al. (2008) used the Beighton and Horan Joint Mobility Index (BHJMI) test to calculate generalized joint laxity in 418 middle and high school student athletes (275 females, 143 males). The BHJMI produces a cumulative score of fifth finger hyperextension, elbow hyperextension, thumb opposition, knee hyperextension, and relative capability to bend over and place the palms flat on the floor. A significant increase in generalized joint laxity was found as females progressed from pre-adolescence to adolescence ($p=0.042$). BHJMI scores in male athletes did not differ between the pre-pubertal group and the post-pubertal group ($p=0.582$). There was no statistical difference in female and male BHJMI scores prior to puberty ($p=0.385$). Following the transition into adolescence, females demonstrated greater cumulative joint laxity scores than their male athletic counterparts ($p<0.001$) (Quatman et al., 2008).

Ligamentous structures serve an important role in restricting perturbations that may compromise joint stability and function (Quatman et al., 2008). Researchers have

often used anterior knee joint laxity as a measure of ACL integrity (Pollard et al., 2006). Individual characteristics such as age, height, weight, and body mass index (BMI) have been investigated as potential correlates of anterior knee joint laxity (Vauhnik et al., 2009). Univariate linear regression analysis of data collected from 616 healthy female athletes participating in handball, volleyball, and basketball club teams identified a positive association between age ($R^2<0.001$, $p=0.740$) and anterior knee joint laxity. Results further indicated that height ($R^2=0.034$, $p<0.001$) and weight ($R^2<0.034$, $p=0.947$) were negatively associated with anterior knee joint laxity. Body mass index was the only variable to yield a positive association with anterior knee joint laxity ($R^2=0.004$, $p=0.110$) that was not statistically significant (Vauhnik et al., 2009).

The extent anterior tibial translation influences the prevalence of noncontact ACL injuries in high school and collegiate athletics has led to extensive research surrounding the degree in which knee joint laxity affects female and male athletes. Excessive knee joint laxity has been theorized to yield proprioception deficits that affect joint sensitivity to stress (Rozzi et al., 1999). For each bilateral difference increase of 1.33 mm in anterior/posterior knee laxity, incidence of ACL injury is expected to increase 4-fold ($p=0.002$) (Myer, Ford, Paterno, Nick, & Hewett, 2008). Diminished knee joint proprioception caused by increased laxity is suspected to result in compensatory muscle recruitment strategies needed to achieve joint stability (Rozzi et al., 1999)

Categorical comparisons of anterior knee joint laxity between female and male athletes and non-athletes have led to inconsistent research findings within the literature. Several researchers have held that knee joint laxity exists within a hierarchy among groups (Huston & Wojtys, 1996; Rozzi et al. 1999; Trimble et al., 2002). Collegiate

female athletes (6.05 ± 1.46 mm; p=0.021) have been found to exhibit significantly higher anterior knee joint laxity values than males athletes (4.80 ± 1.53 mm) at displacement load of 133 N. Huston & Wojtys (1996) found male athletes (4.56 ± 2.15 mm) to have the least amount of anterior knee joint laxity followed by female athletes (4.75 ± 1.21 mm), male non-athletes (6.32 ± 1.80 mm), and female non-athletes (7.12 ± 1.85 mm).

Medrano and Smith (2003) found passive drawer, active drawer, and manual maximum knee testing (Lachman test) results from 39 collegiate soccer athletes (19 male, 20 female) and 40 age matched non-athletes (19 male, 20 female) to partially support patterns of anterior knee laxity among groups. Results from the Lachman test identified a similar hierarchy between females and males (females: 9.72 mm, males: 8.47 mm, p=0.0056) and in the left leg of athletes and non-athletes (athletes: 8.34 mm, non-athletes: 10.34 mm, p=0.0025). Mean passive (athletes: 4.66 mm, non-athletes: 6.72 mm, p=0.0001) and active displacement (athletes: 3.94 mm, non-athletes: 5.42 mm, p=0.0001) measurements were also found to be significantly lower in athletes than in non-athletes. However, neither passive drawer testing (66 N, 89 N, and 133 N) nor active drawer testing yielded a statistically significant difference between female and male groups. The researchers concluded that physical conditioning and strength of lower extremity muscles may play a greater role in knee laxity than the gender of the individual (Medrano & Smith, 2003).

Other research comparing anterior tibial translation in 54 collegiate athletes (27 male, 27 female) and 53 non-athletes (25 male, 28 female) also identified significantly less anterior knee joint laxity in the athletic group compared to the non-athletic group at

passive displacement loads of 89 N (athletes: 3.10 mm, non-athletes: 3.65 mm, p=0.0214) and 133 N (athletes: 4.10 mm, non-athletes: 4.75 mm, p=0.0484). No significant differences were found between groups during passive drawer testing at 66 N (athletes: 2.35 mm, non-athletes: 2.75 mm, p=0.05) and manual maximum knee testing (athletes: 5.45 mm, non-athletes: 6.25 mm, p=0.08). No gender related differences were found during ACL testing (Bowerman et al., 2006).

2.1.3 Hormones

In vitro findings of estrogen and progesterone receptor sites embedded within ACL tissues has prompted numerous investigations on the influence of hormonal fluctuations across a menstrual cycle on ACL utility (Park, Stefanyshyn, Hart, Loitz-Ramage et al., 2007; Pollard et al., 2006; Beynnon et al., 2005; Shultz et al., 2006; Shultz et al., 2005; Shultz et al., 2004). Susceptibility to ACL injury during specific phases within the menstrual cycle has been an active area of research (Beynnon & Shultz, 2008). Investigators have found statistically significant associations between menstrual cycle phase and ACL injury incidence (Wojtys et al., 2002; Slauterbeck et al., 2002; Wojtys et al., 1998). Female athletes have been shown to be more susceptible to ACL injury during the ovulatory phase of the menstrual cycle with the lowest incidence of injury occurring during the follicular phase (Wojtys et al., 1998). Surges in estrogen production are theorized to increase the likelihood of non-contact ACL tears in female athletes by affecting the tensile strength of ligamentous tissue during menstrual episodes of hormonal fluctuation (Wojtys et al., 1998). The frequency of ACL injury was found to be 2.5 times lower in female athletes who regularly took oral contraceptives on a daily basis (Wojtys et al., 2002).

Slauterbeck et al. (2002) found a significantly greater predisposition to ACL injuries during the follicular phase. Salivary sex-hormone profiles taken within 72 hours of ACL rupture identified the follicular phase as the likely point in time of injury for 25 of 37 female athletes. A significant number of these injuries (n=10) occurred on days 1 and 2 of menses. One female athlete sustained an ACL injury during the ovulatory phase while the remaining 11 athletes incurred severe ACL injuries during the luteal phase of the menstrual cycle (Slauterbeck et al., 2002).

Hormones have a widespread effect on various systems and tissues throughout the body. Estrogen impacts central nervous system function, muscle development, and soft tissue strength. Progesterone has the potential to act as a central nervous system analgesic (Wojtys et al., 1998). Absolute serum hormone concentrations of estradiol, progesterone, and testosterone have been touted as reliable indicators for determining the magnitude of change in knee laxity throughout the menstrual cycle. Analysis of daily sex hormones and anterior knee joint laxity profiles taken from 22 females demonstrated that 57.6% of the variance in laxity measurements could be explained by serum hormone concentrations (Shultz et al., 2006). Shultz et al. (2005) found changes in knee laxity to coincide with significant increases in estradiol and progesterone levels.

Park et al. (2007) assessed serum estradiol and progesterone samples along with anterior knee laxity at 3 time intervals in 18 healthy females. Manual maximum knee laxity increased significantly during the ovulatory phase (14.90 ± 2.70 mm) and luteal phase (14.85 ± 2.60 mm) than in the follicular phase (13.45 ± 2.38 mm). Anterior knee laxity collected during passive drawer testing at 89 N increased during the

ovulatory phase (5.29 ± 1.74 mm) when compared to the follicular phase (4.84 ± 1.77 mm) and luteal phase (4.91 ± 1.53 mm) of the menstrual cycle (Park et al., 2007).

Subsequent research examining the effect of menstrual cycle phase on knee laxity and joint mechanics corroborated previous findings of increased knee laxity around the time of ovulation. Knee laxity was significantly higher in the ovulatory phase than in the luteal phase (follicular: 4.78 ± 1.69 mm, ovulatory: 5.20 ± 1.70 mm, luteal: 4.62 ± 1.53 mm, p=0.015) (Park, Stefanyshyn, Ramage et al., 2009). Further examination of knee laxity and knee joint stiffness across a menstrual cycle revealed similar findings from passive drawer testing at 89 N (ovulatory: 5.13 ± 1.70 mm, luteal: 4.55 ± 1.54 mm, p=0.012). Participants also demonstrated a 17% reduction in knee joint stiffness during the ovulatory phase compared to the luteal phase (ovulatory: 12.48 ± 5.46 N/mm, luteal: 15.02 ± 7.71 N/mm, p=0.042). However, results from the Lachman test indicated significantly higher knee laxity in the ovulatory phase (14.43 ± 2.60 mm) than the follicular phase (13.35 ± 2.53 mm; p=0.018) (Park, Stefanyshyn, Loitz-Ramage et al., 2009).

Pollard et al. (2006) investigated hormonal fluctuations in female participants at the onset of menses, twice during the mid-follicular phase, and twice during the mid-luteal phase while males were tested 3 times 10 - 12 days apart. Females had significantly greater knee laxity than males across all data collection periods (p=0.001). However, peaks in estrogen concentrations did not mediate change in knee laxity at any given point in time. Beynnon et al. (2005) measured serum estradiol - progesterone levels and anterior - posterior laxity at 90 N and 130 N in 17 females at 5 time points that corresponded with the early follicular (females: 9.1 mm, males: 7.0 mm) late

follicular (females: 8.9 mm, males: 6.9 mm), mid luteal (females: 8.7 mm, males: 6.9 mm), late luteal (females: 8.5 mm, males: 7.3 mm), and subsequent early follicular phase. Male participants were tested at similar intervals. Females demonstrated greater laxity than males (p=0.01).

However, Belanger et al. (2004) found no cyclic variations in laxity over time (p=0.80). Laxity measurements were taken 2 times per week for a period of 10 weeks at a passive displacement load of 134 N in 27 athletic females. Basal body temperature charts were used to identify the follicular, ovulatory, and luteal phase of the menstrual cycle. Laxity did not vary significantly with normal fluctuations in hormones across the follicular (4.6 mm), ovulatory (4.8 mm), and luteal phase (4.7 mm).

Medrano et al. (2009) examined the effect of gender and menstrual phase on daily knee joint laxity over the course of an entire menstrual cycle in 10 females and across a calendar month for 12 males. Analysis revealed no interaction effect between gender and phase (p=0.65), no main effect for gender (p=0.36), and a statistically significant main effect for phase (p<0.01). Post-hoc comparisons indicated that the mean laxity during the follicular phase (5.78 mm) was significantly lower than the ovulatory phase (6.11 mm) and the luteal phase (6.06 mm) (Medrano et al., 2009). Since male participants demonstrated a similar inclination between phases, the significance of this trend should be interpreted lightly or as a random occurrence. Due to the absence of a gender difference in knee joint laxity, it may be plausible that sex hormone concentrations have little to no effect on laxity.

2.1.4 Muscular Strength and Recruitment

Gender related differences in lower extremity strength and muscle recruitment patterns have also been explored as potential ACL injury risk factors. Females generally possess significantly less quadriceps and hamstrings strength than males (Bowerman et al., 2006). Females have also been found to demonstrate neuromuscular strategies that differ from in male athletes during high risk athletic maneuvers (Myer et al., 2005). The quadriceps and hamstrings work in concert to provide joint stability to the knee (Ahmad et al., 2006). Eccentric action of the quadriceps is responsible for deceleration of the lower extremity during landing tasks and rapid changes in direction. The hamstrings preserve knee joint integrity by opposing muscle loads produced by the quadriceps (Floyd, 2007).

The rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius collectively make up the quadriceps muscle group. The hamstrings muscle group includes the biceps femoris, semitendinosus, and semimembranosus. Muscular strength is commonly measured as the amount of torque a muscle group can generate at a given joint. The muscle’s capacity to generate force and the range through which it can effectively exert force onto the bones to which it is attached is greatly influenced by its shape, fiber arrangement, and cross-sectional diameter. The amount of force produced at the knee is directly proportional to the length of the force arm (femur) and inversely proportional to the resistance arm (tibia) (Floyd, 2007). On average, the female skeleton is smaller in stature. Shorter long-bone lengths equate to proportionally shorter limbs which reduce the amount of force achievable through relative muscular effort (Holschen, 2004).

The overall muscle-mass makeup in females is approximately 23% whereas males exhibit 17% greater muscle mass on average. The cross sectional diameter of muscle fibers in females is 60-85% less than what is typically observed in males (Holschen, 2004). The transition from childhood into adolescence can have a considerable effect on H:Q ratios among females (immature: 1.73 ± 0.32, mature: 2.06 ± 0.55) and males (immature: 1.58 ± 0.46, mature 1.48 ± 0.33). However, females experience a nominal increase in muscular strength of the quadriceps (44%) and hamstrings (27%) following the onset of puberty. This differs substantially from the gains in strength experienced by males (quadriceps, 148%; hamstrings, 179%) (Ahmad et al. 2006).

Barber-Westin, Noyes, & Galloway (2006) assessed peak knee extension/flexion torque in 1140 athletes. Among the athletes tested between 9 and 17 years of age, females were to reach maximum quadriceps strength by age 13 with no significant developments in strength noted after this age. Males reached maximum quadriceps strength by 14 years of age. Females reached maximum hamstrings strength by the age of 11 while males achieved maximum hamstrings strength by 14 years of age (Barber-Westin et al., 2006). This partially differs from age related differences in knee strength among 41 female and male basketball players. Older athletes (15 to 17 years) demonstrated more quadriceps strength than younger athletes (11 to 13 years) in both the dominant (26.6%, $p=0.002$) and non-dominant (26.0%, $p=0.004$) leg. Older athletes also had greater hamstrings strength than younger athletes in both the dominant (35.8%, $p=0.008$) and non-dominant (40.8%, $p=0.004$) leg. Quadriceps and hamstrings strength in males increased in both legs over time. Females experienced a bilateral

increase in hamstrings strength but did not did not experience an increase in quadriceps strength over time (p=0.778) (Buchanan & Vardaxis, 2003).

Regimented physical training yields considerable gains in lower extremity strength in athletes compared to non-athletes. Gender related differences in maximum peak torque can still be observed among collegiate female (quadriceps: 167.55 ± 28.75 Nm, p=0.004; hamstrings, 86.90 ± 14.09 Nm, p<0.0001) and male athletes (quadriceps: 253.14 ± 64.97 Nm, hamstrings: 131.81 ± 39.70 Nm). This is in contrast from the amount of peak torque generated by female (quadriceps: 137.22 ± 30.84 Nm, p<0.0001, hamstrings: 63.74 ± 14.67 Nm, p<0.0001) and male (quadriceps: 232.57 ± 47.99 Nm, hamstrings: 113.24 ± 28.86 Nm) non-athletes (Bowerman et al., 2006).

Male (52.01% ± 8.51, p=0019) and female athletes (52.40% ± 7.30) exhibit significantly greater H:Q ratio percentages than male (48.86% ± 6.39) and female (46.79% ± 6.00) non-athletes (Bowerman et al., 2006). Normative H:Q strength ratio ranges have been used to determine the likelihood of knee injury incidence. Categories include below normal range (60˚/s: < 60%, 300˚/s: < 80%), normal range (60˚/s: 60-69%, 300˚/s: 80-95%), and above normal range (60˚/s: > 69%, 300˚/s: > 95%) values. Females who exhibit H:Q strength ratios below normal range during isokinetic testing at 60˚/s and endurance testing at 300˚/s are susceptible to overuse knee injuries (p=0.004) (Devan et al., 2004).

The rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius are primarily responsible for knee extension. Each of the four quadriceps muscles inserts onto the patella and tibial tuberosity by way of the patellar tendon (Floyd, 2007). Concentric and eccentric contractions of the quadriceps produce a powerfully directed

force onto the anterior aspect of the tibia. Anterior cruciate ligament strain is highly correlated to the amount force produced along the quadriceps tendon (R^2=0.74, p=<0.00001) (Withrow, Huston, Wojtys, & Ashton-Miller, 2006).

Bennett, Blackburn, Boling, McGrath, Walusz, & Padua (2008) found that eccentric quadriceps strength at 60˚/s (r=0.126, p=269), 180˚/s (r=0.302, p=0.067), 300˚/s (r=0.266, p=0.095), and concentric hamstrings strength at 60˚/s (r=-0.058, p=0.390), 180˚/s (r=-0.053, p=0.398), 300˚/s (r=-0.019, p=0.464) were not significant predictors of anterior tibial shear force. Functional H_{CON}:Q_{ECC} ratios at 60˚/s (r=0.0536, p=0.430), 180˚/s (r=0.098, p=0.317), 300˚/s (r=0.127, p=0.268) were also not significant predictors of peak anterior tibial shear force. Researchers theorize that assorted muscle recruitment patterns and available eccentric quadriceps and concentric hamstrings strength at the specific point during landing when anterior tibial shear force is at its peak has a greater influence on knee injury incidence (Bennett et al., 2008).

Recruitment patterns favoring muscle activation of the quadriceps produce excessive muscular force outputs that place the ACL at risk for a potentially debilitating rupture (Ahmad et al., 2006). When knee flexion angles increase from 15 to 55˚, female athletes display greater muscle activity in the vastus medialis (216.2 ± 54.0%, p<0.05) than male athletes (140.4 ± 51.3%) while demonstrating similar percent maximum voluntary contraction values in the vastus lateralis (female athletes: 229.5 ± 108.3%, male athletes: 158.4 ± 67.0%, p=0.23). Female and male athletes also display similar activity in the biceps femoris (female: 45.3 ± 12.7%, male: 49.7 ± 7.3%, p>0.05) and semimembranosus (female: 42.3 ± 11.7%, male: 42.6 ± 24.3%, p>0.05) as knee flexion

angles increase from 15 to 55˚ (Urabe, Kobayashi, Sumida, Tanaka, Yoshida, Nishiwaki, Tsutsumi, & Ochi, 2005).

Female athletes exhibit significantly greater mean percent maximum voluntary contraction of the vastus medialis and vastus lateralis compared to the biceps femoris and semimembranosus at lower knee flexion angles. Quadriceps percent maximum voluntary contraction values were 1.5 to 5 times greater than hamstrings activity at knee flexion angles of 15 to 50˚ at ground contact during jump landings ($p<0.05$) (Urabe et al., 2005). The biceps femoris, semitendinosus, and semimembranosus are primarily responsible for posterior knee joint support. The structural positioning of the hamstrings provides greater mechanical advantage for controlling anterior-posterior tibial translation. This accounts for greater mechanical ability over the quadriceps in altering the amount of force generated at the level of the cruciate ligaments (Markolf et al., 2004).

Knee extensor moment increases significantly as angle of knee flexion increases during a single leg drop landing. As knee flexion increases beyond 0-25˚, a 75% increase in knee extensor moment occurs as the knee moves into 25-50˚ of flexion ($p=0.000$). An 85.0% increase in knee extensor moment is achieved as the knee moves across 50-75˚ of flexion ($p=0.000$). Knee flexion moments decrease 13.4% at 25-50˚ and 30.3% at 50-75˚ of knee flexion indicating a lack of co-contraction of the hamstrings to effectively counterbalance knee extensor moment (Podraza et al., 2010). Active co-contraction of the hamstrings muscle group does not increase in direct proportion with the knee extensor moments across a knee flexion range of 5 to 50˚ ($p<0.001$) (Kingma, Aalbersberg, & Van Dieen, 2004). Inadequate neuromuscular control may compromise

the integrity of the ACL by delaying the appropriate motor response needed to meet the demands placed on the knee (Kellis & Kouvelioti, 2009).

Examination of muscle activity in female and male collegiate athletes revealed no significant difference in mean activation times in the vastus medialis, vastus lateralis, semimembranosus, semitendinosus, medial gastrocnemius, and lateral gastrocnemius at ground contact during a single leg drop landing. Mean activation time of the vastus medialis was 39.20 ± 56.66 ms in females and 30.60 ± 51.98 ms in males (p=0.648). Mean activation time in the vastus lateralis was 40.51 ± 28.21 ms in females and 52.94 ± 70.59 ms in males (p=0.505). The semimembranosus displayed a mean activation time of 175.57 ± 108.56 ms in females and 182.44 ± 91.88 ms in males (p=0.843). The semitendinosus displayed a mean activation time of 187.01 ± 133.19 ms in females and 217.63 ± 108.95 ms in males (p=0.469). No significant differences were observed in mean activation time of the medial gastrocnemius (female: 241.10 ± 141.57 ms, male: 289.09 ± 177.96 ms; p=0.396), and lateral gastrocnemius (female: 193.90 ± 155.33 ms, male: 144.19 ± 98.58 ms; p=0.274) (Rozzi et al., 1999).

With the exception of the lateral hamstring muscle (female: 156.00 ± 72.59 ms, male: 84.84 ± 43.47 ms; p=0.002), no gender related differences in EMG peak amplitude were observed in the vastus medialis, vastus lateralis, semimembranosus, medial gastrocnemius, and lateral gastrocnemius. Greater muscle activity in the semitendinosus reflects a unique neuromuscular artifact in female athletes. Rozzi et al. (1999) theorized that increased activity of the lateral hamstring muscle served as a protective compensatory mechanism from potentially damaging forces at initial ground contact during landing.

Palmieri-Smith, Wojtys, and Ashton-Miller (2008) found increased vastus lateralis and semitendinosus activity in female athletes at 100 ms prior to ground contact during a single leg drop landing resulted in a significant increase in knee valgus angle ($p=0.008$). Increased lateral quadriceps and hamstrings activity during drop landings support previous research findings of gender related differences in muscle recruitment patterns. However, the delayed co-contractive behavior of medial-to-lateral quadriceps and hamstrings muscles suggest an overall inability to generate sufficient medial-to-lateral force in a timely manner that is sufficient to offset the loading and subsequent collapsing of the knee into extreme valgus (Palmieri-Smith et al., 2008).

2.1.5 Other Risk Factors

The underlying cause of ACL injury is likely multi-factorial, with no one anatomical, hormonal, biomechanical, and neuromuscular factor solely responsible (Arendt & Dick, 1995). The epidemiology of noncontact ACL injuries generally includes intrinsic and extrinsic risk factors. Intrinsic risk factors are represented by individual differences in cognitive, intrapersonal, anthropometric, physical fitness, and neuromechanical components. Extrinsic risk factors generally include external conditions such as shoe-surface interaction and the amount of traction produced by different types of cleated shoes.

Displays of aptitude for a specific sport can lead to extensive experience and ability (Murphy, Connolly, & Beynnon, 2003). An intrapersonal component is a dynamic set of characteristics representative of a number of psychological domains and processes. It is this inherent difference that drives human behavior and temperament (Schmidt & Lee, 2005). Athletes with a lower level of skill are two times more likely to

incur an injury than athletes with more experience (Peterson et al., 2000). In a computerized neurocognitive test battery administered to 80 ACL injured intercollegiate athletes and eighty matched controls, athletes who had sustained a non-contact ACL injury also performed worse on neurocognitive tests for reaction time, processing speed, visual, and verbal composite score when compared to matched controls (Swanik, Covassin, Stearne, & Schatz, 2007).

The influence of genetics results in considerable anthropometric differences in overall structural anatomy and fitness capacity. Cardio-respiratory efficiency, muscular strength, muscular endurance, flexibility, and body composition dimensions are intrinsic factors that work in concert to meet the demands of variously presented movement tasks. These individual differences lead to a divergence in human motor performance capability (Schmidt & Lee, 2005). While genetics poses limits on individual potential to improve beyond genetically determined ceilings, differences in physical fitness capacity make individual performance conducive to certain levels of ability in specific sports (Östenberg, Roos, Ekdahl, & Roos, 2000; Reilly, Bangsbro, & Franks, 2000).

Field conditions have a significant biomechanical impact on player performance and injury risk. Synthetic playing surfaces are constructed to resemble the mechanical characteristics of a natural grass playing field. Polypropylene fibers in conjunction with grounded rubber and/or sand infill are engineered to improve shoe-surface interaction and reduce the high impact associated with landing and cutting maneuvers. However, researchers have speculated that synthetic playing surfaces alter lower extremity biomechanics and foot loading patterns (Ford, Manson, Evans, Myer, Gwin, Heidt Jr., & Hewett, 2006).

Examination of 17 high school football players wearing studded molded cleats outfitted with a flexible pressure distribution measuring insole revealed different loading patterns during cutting maneuvers on turf and grass. Artificial turf was shown to significantly increase peak pressure within the central forefoot 17.5% (turf: 646.6 ± 172.6 kPa, grass: 533.3 ± 143.4 kPa, p=0.017) and toes 18.9% (turf: 429.3 ± 200.9 kPa, grass: 348.1 ± 199.0 kPa, p=0.043) compared to natural grass surface. The natural grass playing surface was shown increase the relative load within medial forefoot 9.8% (turf: 27.2 ± 5.3%, grass: 30.2 ± 6.6%, p=0.031) and lateral mid-foot 15.5% (turf: 3.4 ± 1.8%, grass: 4.1 ± 2.3%, p=0.029) compared to the turf. The type of playing surface did not result in differences in cutting performance (turf: 8.4 ± 0.5 s, grass: 8.5 ± 0.5 s, p>0.05). Researchers theorized that loading patterns were like influenced by cutting mechanics rather than playing surface cushion (Ford et al, 2006).

The shoe surface interaction of studded cleats can increase the coefficient of friction between the sole of the shoe and playing surface (Renstrom et al., 2008) Assessment of four popular soccer cleats with different stud patterns were tested under loading conditions designed to simulate athletic events that commonly place an athlete at risk for ACL injury (Grund & Senner, 2010). Translational traction is necessary for movements that involve quick starts/stops and abrupt changes in direction. The rotational traction that causes foot fixation during these movements is often considered hazardous to mechanical stability of the knee. Pneumatic testing of an artificial foot and ankle was performed with a 6-component force torque transducer secured around the ankle and 24 pressure sensors tucked in the sole of the cleat. The direction of loading was found to have a considerable impact on the amount of torque generated at the

point of contact with the ground. Results indicate that cleats with a rounded profile result in greater peak torque than cleats with an irregular wedge shape at a tibial deflection of 14˚ in the frontal plane and -10˚ in the sagittal plane (Grund & Senner, 2010).

2.2 PREVENTION PROGRAMS

Scientific interest into ACL injury risk factors has prompted several high profile ACL injury prevention programs. The combination of agility, plyometric, and balance training has been theorized to augment hip, knee, and ankle movements increasing muscle reactivity thereby improving muscular and motor performance during high risk maneuvers. However, ACL injury prevention program outcomes have been mixed yielding an incomplete understanding of simultaneous biomechanical and neuromuscular processes following multi-component training.

2.2.1 Prevent Injury and Enhance Performance (PEP) Program

The PEP program was administered to 61 NCAA Division-I women's soccer teams. The 20 minute video intervention was substituted in place of regularly scheduled warm-ups three times per week for a total of 12 weeks. Training included lower extremity stretching and strengthening of the quadriceps, hamstrings, leg adductors, and gastrocnemius. Plyometric and agility drills were incorporated into the regimen to improve forward, backward, lateral, and medial movement coordination and balance. Noncontact ACL injury rates were collected from participating athletes (852 control, 583 intervention) to quantify the value of the training protocol. Teams who employed the PEP program were 3.3 times (0.057 vs. 0.189; p=0.066) less likely to sustain a noncontact ACL injury than age and skill-matched athletes selected to serve in the

control group (Gilchrist et al., 2008). A program summary of the ACL injury intervention is provided in Table 1.

Table 1

Gilchrist et al. (2008) Prevention Program Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the effect of training in reducing ACL injury rates Participants • 61 NCAA Division I teams • 26 intervention (583 athletes) • 35 control (852 athletes) Program Duration • 12 weeks • 3 days / week	Warm-up • Jog line to line • Shuttle run • Backward running Stretching • Calf stretch • Quads stretch • Fig 4 hams stretch • Inner thigh stretch • Hip flexor stretch Strengthening • Walking lunges • Russian hamstrings • Single toe raises Plyometrics • Lateral jumps • Forward/backward hops • Single leg hops • Vertical jump headers • Scissors jumps Agility • Shuttle run • Forward/backward runs • Diagonal runs • Bounding	In Games & Practice • Intervention group sustained 7 ACL injuries compared to 18 in control group (0.199 per 1000 AE vs. 0.340, p=0.198); 41% decrease in ACL injury rate • Intervention group sustained 2 noncontact ACL injuries compared to 10 in control group (0.057 per 1000 AE vs. 0.189, p=0.066);70% decrease in ACL injury rate In Games • Intervention group sustained 7 ACL injuries compared to 12 in control group (0.814 per 1000 AE vs. 0.967, p=0.712) • Intervention group sustained 2 noncontact ACL injuries compared to 7 in control group (0.233 per 1000 AE vs. 0.564, p=0.218) In Practices • Intervention group sustained 0 ACL injuries compared to 6 in control group (0.000 per 1000 AE vs. 0.148, p=0.014) • Intervention group sustained 0 noncontact ACL injuries compared to 3 in control group (0.000 per 1000 AE vs. 0.074, p=0.083)

Inspection of injury statistics following the implementation of the 20 minute video intervention has garnished significant attention. However, the use of non-contact ACL injury rates to validate the overall success of the PEP program has contributed little to the current understanding of how the components of the intervention reduce ACL injury risk. Additional research is needed to fully comprehend the impact training has on biomechanical and neuromuscular functions. This departure from previous research

efforts may ultimately provide greater insight into prevention program strategies and outcomes.

2.2.2 Knee Ligament Injury Prevention (KLIP) Program

The KLIP program emphasized plyometric training and the use of continuous corrective feedback during jump-landing and running-deceleration drills to decrease the rate of force development and peak vertical impact force during drop landings (Pfeiffer et al., 2006). A combination of agility and plyometric drills were used to improve muscle control and joint position sense through repetitive reinforcement of proper hip, knee, and ankle joint mechanics (Newberry & Bishop, 2006). Injury statistics collected from 112 high school teams (basketball, soccer, volleyball) revealed differences in ACL injury rates between the control group (0.078 per 1000 athlete exposures) and intervention group (0.167 per 1000 athlete exposures). Specialized plyometric training exhibited a greater probability (odds ratio=2.05; 95% confidence interval=0.21 to 21.7) in reducing noncontact ACL injury incidence in female high school athletes (Pfeiffer et al., 2006). A program summary of the ACL injury intervention is provided in Table 2.

Table 2

Pfeiffer et al. (2006) Prevention Program Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the effect of specialized training in reducing noncontact ACL injuries in high school female athletes Participants • 112 female high school soccer, volleyball, basketball teams • 1439 athletes • (577 intervention, 862 control) Program Duration • 2 seasons • 2 days / week • 20 minutes	Phase 1 (Wk 1 and 2) • Straight jumps • Tuck jumps • Standing broad jumps • Bound in place Phase 2 (Wk 3 and 4) • Straight jumps • Tuck jumps • 180's • Double-leg jumps • Single-leg jumps • 45˚ lateral leaps Phase 3 (Wk 5 and 6) • Tuck jump • Single-leg lateral leaps • Single-leg forward hops • Combination jumps • 180's • 45˚ lateral leaps Phase 4 (Wk 7 end season) • Straight jumps • Single-leg forward hops • Combination jumps • 180's • Standing broad jumps • Single leg 45 lateral hops Note: • Progression from 2 to 1 foot drills • Proper technique emphasized • Participants exhibited movement proficiency before moving to next phase • Teams received personal instruction, instructional videotape, printed handouts	• Intervention group sustained 3 noncontact ACL injuries compared to 3 in control group (0.167 per 1000 AE vs. 0.078, odds ratio= 2.05, p>0.05)

As with the PEP program, the utility of the KLIP program was measured against non-contact ACL injury statistics. While the primary objective of the plyometric based intervention was to develop proper jump-landing and running-deceleration mechanics, several biomechanical measures were not included in the assessment of prevention program effectiveness. Thus it is unknown how training impacted lower extremity kinematics and kinetics of the hip, knee, and ankle during each of the movement tasks

emphasized in training. The inclusion of biomechanical testing is critically important to the understanding of how specialized training affects movement patterns and strategies.

2.2.3 Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Program

The Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program was a core strengthening, dynamic knee joint stabilization, and plyometrics routine implemented into practice six days per week for six consecutive weeks. Kinematic and kinetic analysis of landing task events identified a significant increase in initial (p=0.003) and maximum (p=0.006) knee flexion angles during the drop jump. Training also elicited a significant decrease in corresponding knee flexion moment (p=0.04). Analysis of the stop jump task revealed decreases in maximum external rotation (p=0.02) and dynamic knee valgus moments (p=0.040) following training (Chappell & Limpisivasti, 2008). A program summary of the ACL injury intervention is provided in Table 3.

Table 3

Chappell et al. (2008) Prevention Program Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the effect training on drop landing and vertical stop jump kinematics and kinetics Participants • 30 female collegiate soccer/basketball players Program Duration • 6 weeks • 6 days / week • 10-15 minutes	10 exercise routine consisting of core strengthening, dynamic joint stability training, jumping tasks, and plyometrics • Abdominal crunches • Cross crunches • Planks • Lunges • Single leg chest pass • Single leg bend pass • Single leg figure 8 • Line jumps • Lateral shuffles • Bounding	Drop jump kinematics • No change in hip kinematics • No change in pelvic kinematics • ↑in initial knee flexion (p=0.003) • ↑in max knee flexion (p=0.006) Stop jump kinematics • ↓in max hip external rotation (p=0.02) • No change in pelvic kinematics • No change in knee kinematics Drop jump kinetics • ↓ in knee flexion moment (p=0.04) Stop jump kinetics • ↓ in knee valgus movement (p=0.04)

The specific combination and inclusion of select training components should be scientifically sound and theoretically important to the success of the program. More

importantly, the inherent benefit of the training components should be empirically supported as a program outcome. One third of the Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program is dedicated to core strengthening. While core strengthening exercises have become a staple of ACL injury prevention programs, measures of postural stability during high risk maneuvers are rarely included.

2.2.4 The Sportsmetrics™ Program

The Sportsmetrics™ Program partitioned plyometrics training into three stages of motor skill development. Twenty recreationally active collegiate females implemented the 45 - 60 minute plyometrics protocol into practice three days per week for a period of six weeks (Vescovi et al., 2008). Training focused on increasing postural stability along with hip and knee flexion during jump-landing tasks. Analysis of VGRF revealed no significant change in pre-test (intervention: 2583.6 ± 505.8 N; control: 2543.1 ± 788.1 N; p=0.696) and post-test (intervention group: -222.8 ± 610.9 N; control: 54.6 ± 257.6 N; p=0.122) measurements. Maximum jump height, peak jumping velocity, and peak power values also did not improve following the completion of the plyometrics protocol (Vescovi et al., 2008). A program summary of the ACL injury intervention is provided in Table 4.

Table 4

Vescovi et al. (2008) Prevention Program Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the effect training on GRF and jump kinetics Participants • 20 female collegiate recreation basketball players • (10 intervention, 10 control) Program Duration • 6 weeks • 3 days / week • 45-60 minutes	Plyometric based exercise routine consisting of jumping tasks • Wall jumps • Tuck jumps • Broad jumps • Squat jumps • Side-to-side cone jumps • Front-to-back cone jumps • 180˚ jumps • Bound in place • Jump, jump, vertical jump • Bound for distance • Scissor jump • Hop, hop, stick • Step, jump, down, vertical • Side-to-side mattress jump • Single leg distance jump • Jump into bound • Single leg hop, hop, stick	Vertical ground reaction forces (N) • Pre Control (2543.1 ± 788.1) • Pre Intervention (2583.6 ± 508.8) • Post Control (54.6 ± 257.6) • Post Intervention (-222.8 ± 610.9) • No significant change (p=0.122) Jump Performance • No change in jump height (p=0.696) • No change in peak relative power (p=0.274) • No change in average relative power (p=0.897) • No change in peak velocity (p=0.965)

Plyometric drills generally elicit a specific pattern of muscle contraction and co-contraction. The multitude of drills found in the Sportsmetrics™program predominantly requires explosive muscle shortening of the quadriceps and lengthening of the hamstrings. The muscular effort needed to perform each of the jumping tasks promotes considerable gains in quadriceps strength relative to the hamstrings which is counterproductive for athletic females who generally exhibit overdeveloped quadriceps muscles. The number of repetitions associated with each stage of development exposes lower limb musculature to repetitive impact forces that could compromise the integrity of hip, knee, and ankle joints over time.

2.2.5 Paterno, Myer, Ford, & Hewett Training Program

Paterno et al. (2004) found exhaustive bouts of agility, plyometric, balance, and periodized resistance training improved single-limb stability when exercise duration,

volume, and intensity were progressively increased over a three week period. Corrective feedback during training was found to help athletes transition from double leg to single leg agility, plyometric, and balance drills. Analysis of anterior/posterior and medial/lateral stability revealed a main effect for training ($F_{(1,40)}$=9.4; p=0.004) with significant improvements in post-training stability. A main effect for anterior/posterior stability ($F_{(1,40)}$=11.7; p=0.001) was found with no significant difference observed between right and left lower extremities ($F_{(1,40)}$= 3.1; p=0.086). Training failed to yield a significant difference between pre- and post-training measurements for medial/lateral stability ($F_{(1,40)}$=0.2, p=0.65) with no observable differences between the right and left leg ($F_{(1,40)}$=2.5, p=0.12) (Paterno et al., 2004). A program summary of the ACL injury intervention is provided in Table 5.

Table 5

Paterno et al. (2004) Prevention Program Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the effect of exhaustive bouts of training on single-limb postural stability Participants • 41 female high school athletes Program Duration • 6 weeks • 3 days / week • 90 minutes	Stable surface (Wk 1 and 2) • Broad jump stick landing • Box drop stick landing Unstable surface (Wk 1 and 2) • Double leg balance • Double knee balance Hip/pelvis/strengthening (Wk 1 and 2) • Abdominal crunch • Superman's Stable surface (Wk 3 and 4) • Single leg stick landing • Box drop medicine ball catch Unstable surface (Wk 3 and 4) • Single leg balance • Single knee balance Hip/pelvis/strengthening (Wk 3 and 4) • BOSU abdominal crunch • BOSU superman's Stable surface (Wk 5 and 6) • Single leg over stick landing • Box drop 180˚ medicine ball Unstable surface (Wk 5 and 6) • Single leg perturbation • Hip-side balance Hip/pelvis/strengthening (Wk 5 and 6) • BOSU abdominal V-sit up • Back hyperextensions	• Analysis of anterior/posterior and medial/lateral stability revealed a main effect for training ($F_{(1,40)}=9.4$; $p=0.004$) • ↑ in anterior/posterior stability ($p=0.001$) following training • No sig difference between pre- and post-testing in medial/lateral stability ($p=0.65$)

The development of anterior/posterior and medial/lateral stability is a crucial element of ACL injury prevention program training. It is critically important during high risk maneuvers such as cutting, cross-cutting, and landing. However, biomechanical analysis of lower extremity kinematics to assess dynamic knee joint stabilization following exhaustive balance training does contribute enough to current understanding of knee joint kinesthesia. Measures of knee joint position sense provides insightful

information about the proprioceptive adaptations following double to single leg balance progressions and perturbations.

2.2.6 Kato, Urabe, & Kawamura Training Program

An ACL injury prevention program integrating basic lower extremity calisthenics, landing tasks, and balance training improved postural alignment during a quick-stop jump task after two weeks of instruction (Kato et al., 2008). Maximum lower extremity alignment angles (23.2 ± 20.1; $p<0.001$) in the coronal plane and torsion angles (13.2 ± 7.1; $p<0.019$) in the horizontal plane at two weeks were significantly lower in the intervention group than alignment (36.1 ± 23.8) and torsion (18.3 ± 10.2) angles in the control group. The intervention group displayed a continued reduction in lower extremity alignment (15.1 ± 6.5; $p=0.014$) and torsion (17.1 ± 4.6; $p=0.051$) angles following the completion of the program. This was a considerable difference from alignment (38.6 ± 25.6) and torsion (18.7 ± 10.8) angles exhibited by the control group. Torsion angles represented the angle within the horizontal plane created between the axis of the femur and axis of the ankle. However, no significant differences in knee flexion angles were observed in either the experimental or control group at pre-testing (intervention: 72.4 ± 8.7; control: 66.5 ± 6.4), two weeks (intervention: 71.4 ± 9.6; control: 65.9 ± 6.1), and post-testing (intervention: 75.7 ± 3.4, control: 68.4 ± 5.6) (Kato et al., 2008). A program summary of the ACL injury intervention is provided in Table 6.

Table 6

Kato et al. (2008) Prevention Program Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the effect short term training has on lower extremity alignment during a quick-stop jump task Participants • 20 healthy female collegiate basketball players • 10 intervention • 10 control Program Duration • 4 weeks • 3 days / week • 20 minutes	7 exercise routine consisting of basic lower extremity calisthenics, landing tasks, and balance training • Squats • Forward lunges • Jump landing • Lunge walking • Twist-ankle • BOSU single leg hold • BOSU double leg squat	• No sig differences found in max coronal plane, torsion, and knee flexion angles between groups at pretesting • ↓ in coronal plane angles in intervention group at 2 ($p<0.001$) & 4 ($p=0.014$) weeks • ↓ in torsion angles in intervention group at 2 ($p=0.019$) & 4 ($p=0.051$) weeks • No sig differences found in max knee flexion angles between groups at pre-testing, 2 weeks, and 4 weeks

The scientific consensus regarding the minimum components needed for an ACL injury prevention program include a combination of plyometrics, balance, and strength training performed more than once a week for at least six weeks (Hewett, Shultz, & Griffin, 2007). However, minimizing the number of drills to increase compliance may not be sufficient enough to evoke considerable improvements in lower extremity mechanics. The short duration of the intervention may not have allowed for adequate reinforcement of proper quick-stop jump technique thereby minimizing the effectiveness of the intervention. The lack of skill progression may have limited the mechanical development of participants.

2.2.7 Myer, Ford, McLean, & Hewett Training Program

Myer et al. (2006) found that assorted training consisting of plyometric jumping/cutting drills or dynamic stabilization exercises in conjunction with resistance training had a varied effect on drop vertical jump and single legged medial drop landing mechanics. Eighteen high school volleyball players randomly assigned to either 18

sessions of plyometric training or double to single legged drills that progressed from stable to unstable surface platforms. Both training protocols reduced hip adduction angle (p=0.015), knee abduction angle (p=0.038), and ankle eversion angle (p=0.020) during drop vertical jump and single leg stabilization tasks. Plyometric training led to increased knee flexion (p=0.031) during the drop vertical jump whereas balance training resulted in increased knee flexion (p=0.005) during the single legged medial drop landing task (Myer et al., 2006). A program summary of the ACL injury intervention is provided in Table 7.

Table 7

Myer et al. (2006) Prevention Programs Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the utility of plyometric vs. dynamic stabilization on drop vertical jump and medial drop landing tasks Participants • 18 female high school volleyball players Program Duration • 7 weeks • 18 sessions	Plyometric training group • Athletic position • Hop athletic position • Cross over athletic position • Wall jumps • Squat jumps • Squat tuck jumps • Tuck jumps • Line jumps • Broad jumps • Bounding • Forward barrier jumps • Lateral barrier jumps • Reaction barrier hops • Box drops vertical step • Lateral box drops • Power steps • Step over step ski Balance training group • Deep hold • Box butt touch • Box drop lateral hold • Forward line jump hold • Lateral line jump hold • Single leg squat hold • BOSU deep hold • BOSU drop squats • BOSU jump stick landing • BOSU drop stick landing • BOSU knee hold • BOSU crunches • BOSU pelvic bridge • BOSU supermans • BOSU swimmers • BOSU perturbations • BOSU single leg • Single le line hop • Single leg squat • Swiss ball knee hold • Swiss ball perturbations • Swiss ball hyperextensions • Reverse hyper extension • Airex lunges • Straight leg crunches Resistance training • Trapezius / Deltoids • Pectorals / Latissimus dorsi • Abdominals • Hip adductors / Abductors • Gluteals • Quadriceps / Hamstrings • Gastrocnemius	Plyometrics training - Drop vertical jump • ↓ in initial hip adduction (p=0.002) • ↓ in max hip adduction (p=0.015) • ↓ in max ankle eversion (p=0.02) • ↑ in initial knee flexion (p=0.047) • ↑ in max knee flexion (p=0.031) Balance training - Drop vertical jump • ↓ in initial hip adduction (p=0.002) • ↓in max hip adduction (p=0.015) • ↓in max ankle eversion (p=0.02) Plyometric training - Medial drop landing • ↓ in initial knee abduction (p=0.002) • ↓ in max knee abduction (p=0.038) Balance training - Medial drop landing • ↓ in initial knee abduction (p=0.002) • ↓ in max knee abduction (p=0.038) • ↑ in max knee flexion (p=0.005)

The intervention outlined above is multi-faceted in design and encompasses assorted training strategies with muscular and mechanical depth. However, evaluation of the utility of the program is not equally comprehensive in approach. Examination of program effectiveness should be measured at length across several interrelated biomechanical, neuromuscular, and performance characteristics. Assessments of an ACL injury prevention program should include biomechanical and neuromuscular measures of variables specialized training are presumed to improve. This includes lower extremity kinematics, kinetics, EMG, GRF, strength, proprioception, and stability

2.2.8 Myer, Ford, Brent, & Hewett Training Program

Knee abduction moments and VGRF during a drop vertical jump were assessed in 18 (12 high-risk, 6 low-risk) female high school basketball and soccer players after 8 weeks of regimented plyometric, balance, and strength training. High-risk athletes demonstrated a 13% decrease ($p=0.033$) in knee abduction moments from pre-test (dominant: 39.9 ± 15.8 Nm; non-dominant: 37.1 ± 9.2 Nm) to post-test (dominant: 34.6 ± 9.6 Nm; non-dominant knee: 32.4 ± 10.7 Nm). Athletes grouped in the low-risk category did not exhibit a significant reduction ($p>0.05$) in knee abduction moments from pre-test (dominant: 14.8 ± 8.8 Nm; non-dominant knee: 14.5 ± 6.4 Nm) to post-test (dominant: 17.6 ± 10.2 Nm; non-dominant: 14.7.4 ± 7.0 Nm) (Myer et al., 2007). A program summary of the ACL injury intervention is provided in Table 8.

Table 8

Myer et al. (2007) Prevention Program Strategies and Outcomes

Program Summary	Program Protocol	Program Results
Purpose • To evaluate the effect of training in post-test knee abduction moments during drop vertical jump in high-risk and low-risk athletes Participants • 29 female high school soccer basketball players • 18 intervention • (12 high risk, 6 low risk) • 11 control 4 high-risk 7 low-risk Program Duration • 8 weeks	• Plyometric (jumping and cutting) • Lower extremity stabilization exercises • Balance training • Resistance training	• No sig difference in performance measures between high-risk and low-risk groups ($p>0.05$) • Abduction moments in high-risk 0.44$\pm$.04 Nm and low-risk groups 0.44 $\pm$ 0.042 Nm • A 13% ↓peak knee abduction moments in high-risk group following training ($p=0.033$) • No sig difference in knee abduction moments in low-risk and controls following training • Training did not ↓ mean knee abduction moment values in high-risk group to levels exhibited by low-risk group

Results suggest neuromuscular training may only benefit female athletes who exhibit a predisposition to ACL injury risk (Myer et al., 2007). However, ACL injury prevention programs should also have other notable contributions to participants. Aside from improvements in mechanical performance, training should increase an athletes overall conditioning. The combination of agility, plyometric, balance, and strength training should bring about improvements in cardio-respiratory fitness, muscular strength, muscular endurance, and flexibility.

The protocols outlined above utilize similar components of agility, plyometrics, balance, and strength training to varying degrees. Training regiments were similarly designed to improve overall mechanics and performance through increased muscular strength, reactive ability, and coordination. While there is an ongoing effort to explain the inherent benefit of multi-component training in reducing the prevalence of ACL injury

among female athletes, there is still a lack of fundamental information. The overall biomechanical and neuromuscular utility of such prevention programs is unknown due to the limited depth of research investigations. Therefore, the purpose of the following research was to determine the effect of specialized plyometric, agility, balance, and strength training on mechanical and muscular deficits theorized to increase the incidence of ACL injury.

Chapter 3: Experimental Procedures

3.1 PARTICIPANTS

The research was approved by the University of Texas at El Paso Institutional Review Board (IRB). A departmental and IRB approved research flyer was used to solicit females from the university student population. Participants were also solicited through classroom visits. Female students with above-average levels of physical fitness were recruited from the general student population to ensure a level of conditioning necessary to complete the training protocol.

Student athletes were not selected for this study because of several factors that make training and testing impractical among athletes participating in select sports. Differing season schedules, team practice schedules, and team travel schedules along with substantial academic school course loads decreases the student athletes availability to attend and complete every training session in its entirety. While the proposed training is designed to be incorporated into team practice three times per week, strength training schemes and sport instruction prescribed and provided by coaching personnel adds to the difficulty of ascertaining the effect and benefit of specialized plyometric, agility, balance, and strength training in reducing ACL injury risk factors.

The purpose of the investigation, procedures, benefits, and risks associated with the study were thoroughly explained to each participant. An explanation of the participant's right to withdraw from the study was also given. All volunteers were required to provide written consent to participate in the study. Testing was conducted by the principal investigator at the Stanley E. Fulton Biomechanics and Motor Behavior

Laboratory located in the Larry K. Durham building at the University of Texas at El Paso. Data were number coded for confidentiality and used only for the strict purpose of the study.

3.2 SAMPLE SIZE DETERMINATION

A power analyses was conducted to determine the required number of participants needed to provide sufficient power to detect between group (intervention vs. control) differences. Using G*Power Version 3.1.2 software, an alpha of 0.05, a power 0.80, an effect size (Cohen's *d* =0.70) for between group differences in a kinematic variable (knee flexion) identified to be detrimental to single leg drop landing mechanics, a total of 52 participants (26 intervention, 26 control) were needed to detect an intervention effect following prevention program training (Chappell & Limpisvasti, 2008). Given the practical significance of the sample size estimate from the following power analysis computation and allowing for a conservative approximation of attrition rate, 60 participants were solicited for this study.

Fifty-six apparently healthy female students volunteered to participate in the intervention (n= 28) and control group (n= 28). Descriptive statistics for the participants at pre-testing are presented in Table 9.

Table 9

Mean ± Standard Deviation of Participant Characteristics

Participants	Age (y)	Height (cm)	Weight (kg)	BMI
Control	20.29 ± 2.46*	163.05 ± 4.05	62.41 ± 8.12	23.48 ± 3.00
Intervention	21.96 ± 2.49*	160.89 ± 5.92	63.58 ± 8.49	24.43 ± 2.78

Note: * represents statistical significance ($p<0.05$). Age was only participant characteristic to yield a significant difference between groups ($p=0.014$).

3.3 RANDOM ASSIGNMENT

Participants were randomly assigned to either the intervention group or the control group. A coin flip was used to determine participant placement.

3.4 PARTICIPANT SCREENING

Selection was based on the following inclusion criteria: 1) enrolled at the university 2) at least 18 years of age, 3) a Body Mass Index (BMI) between 18.5 - 29.5, 4) a negative knee exam, 5) no history of knee ligament injury treated by surgery, and 6) demonstration of above-average conditioning as determined by Canadian Standardized Test of Fitness standards and YMCA standards. Volunteers were screened at the biomechanics and motor behavior laboratory during a scheduled appointment set by the participant. Participants were asked to bring appropriate athletic attire (t-shirt, shorts, and shoes). Pre-screening consisted of several items and was conducted in a specific order. Participants who successfully met the criterion of each screening method were allowed to move on to subsequent assessments. Calculations of BMI were followed by bilateral knee examinations and physical fitness assessments. Participant screening required 30 minutes to complete.

3.4.1 Body Mass Index

Height (m) and weight (kg) were recorded. Height and weight measurements were performed barefoot with participants standing in anatomical position. Height was measured using a leveled Seca 220 Telescopic Measuring Rod/Column Scale. Weight was measured using a calibrated Tanita BWB-800A Class III Digital Scale. Body Mass Index ($BMI = weight/height^2$) was then calculated. Participants with a BMI outside the

approved range (18.5 - 29.5) were excluded because of the reliable indication of total body fat mass and associated underweight - overweight health risks (Waldrop, 2005).

3.4.2 Knee Examination

Due to the intense physical nature of the training protocol, a knee examination was conducted to identify pre-existing conditions that could limit performance or place the participant at increased risk for injury. Prospective candidates underwent anterior drawer, posterior drawer, varus stress, and valgus stress testing. Examinations of the right and left knee consisted of a subjective assessment of anterior, posterior, lateral, and medial translation of the tibia against the femur. Excessive translation of the tibia across the femur of the involved leg compared to the noninvolved leg was considered a positive clinical diagnostic for possible knee pathology.

Manual examination of the knee for ligamentous tears has a similar diagnostic sensitivity (80.3%) and specificity (94.2%) to magnetic resonance imaging (sensitivity: 84.3%; specificity: 91.4%). Physical examination of the knee has been shown to yield a positive predictive value of 95.3% and negative predictive value of 76.7% (Loo, Liu, Lee, & Soon, 2008). The detection of existing knee pain, knee locking, or possible tears of the anterior-posterior cruciate ligaments and/or lateral-medial collateral ligaments during screening served to lessen the likelihood of exacerbating a pre-existing injury.

The participant was placed on an examination table in a supine position with the body resting in a relaxed motionless state. Arms were comfortably placed along the body. The principal investigator assessed the right leg followed by the left leg. A knee exam was considered positive if participants demonstrated excessive knee pain and/or joint instability that could inherently compromise participant safety during agility,

plyometric, and balance training. Volunteers who exhibited a positive knee exam were dismissed from the study.

The Anterior Drawer Test was used to examine the integrity of the anterior cruciate ligament. The participant was placed in a supine position. The hips were positioned to approximately 45˚ of flexion with the knee under examination flexed to 90˚ of flexion. The foot of the lower extremity being examined was placed in a neutral position and anchored securely to the table by the examiner. The examiner's hands were firmly placed around the proximal portion of tibia with the thumbs crossing the anterior joint line. An anterior force was applied to the tibia and the knee was assessed for excessive anterior tibial translation. Anterior instability of the knee joint was determined by examining and comparing the amount of translation present in the opposite knee.

The Posterior Drawer Test was used to examine the integrity of the posterior cruciate ligament. The participant was placed in a supine position. The hips were positioned approximately to 45˚ of flexion with the knee under examination flexed to 90˚ of flexion. The foot of the lower extremity being examined was placed in a neutral position and anchored securely to the table by the examiner. The examiner's hands were firmly placed around the proximal portion of tibia with the thumbs crossing the anterior joint line. A posterior force was applied to the tibia and the knee was assessed for excessive posterior subluxation. Posterior instability of the knee joint was determined by examining and comparing the amount of translation present in the opposite knee.

The Varus Stress Test was used to examine the integrity of the lateral collateral ligament. The participant was placed in a supine position. The leg being examined was

positioned over the side of the examination table and placed in 30˚ of flexion. The examiner secured the leg above the lateral joint line holding the ankle with the opposite hand. Varus directed stress was applied to the distal portion of tibia. The knee was assessed for excessive lateral translation at the joint line opening. Lateral instability of the knee joint was determined by examining and comparing the amount of translation present in the opposite knee.

The Valgus Stress Test was used to examine the integrity of the medial collateral ligament. The participant was placed in a supine position. The leg being examined was positioned over the side of the examination table and placed in 30˚ of flexion. The examiner secured the leg above the medial joint line holding the ankle with the opposite hand. Valgus directed stress was applied to the distal portion of tibia and the fingers of the hand above the medial joint line were used to palpate increases in joint line opening. The knee was assessed for excessive medial translation at the joint line opening. Medial instability of the knee joint was determined by examining and comparing the amount of translation present in the opposite knee.

3.4.3 Physical Fitness Assessment

Balance, plyometric, and agility drills are generally incorporated into ACL injury prevention programs to improve existing proprioceptive capacity (Mandelbaum et al., 2005). Improved sensitivity to mechanical stimuli is thought to enhance the body's efficiency to sustain functional stability during knee joint motion and loading (Louw et al., 2006). Lower extremity strengthening exercises are often included in conjunction with neuromuscular training to improve H:Q strength ratio to alleviate the effect reduced hamstrings muscular strength has on motor behavior and ability (Cote et al., 2005).

Neuromuscular and biomechanical training components designed to address deficits in lower extremity mechanics, strength, and proprioception in athletes are highly dynamic in nature. Participants with above-average levels of physical fitness were recruited from the general student population to ensure a level of conditioning necessary to complete the training protocol. A three minute 12 inch step test protocol was selected from the YMCA Fitness Testing and Assessment Manual to assess cardio-respiratory fitness (Golding, 2000). A push-up and curl-up protocol were selected from The Canadian Physical Activity, Fitness & Lifestyle Appraisal: CSEP-Health & Fitness Programs Health-Related Appraisal and Counseling Strategy as cited in the 7th edition of the Exercise Testing and Prescription: A Health Related Approach to assess core strength (Nieman, 2010). Center of mass was ascertained during risk factor assessment and subsequently used to appraise the utility of the proposed prevention program training in improving core musculature strength and resulting head-torso steadiness during single leg drop landings.

Cardio-respiratory fitness was determined using the YMCA three minute 12 inch step test. The participant was fitted with a Polar RS100 Heart Monitor. A stackable step trainer with a non-slip surface was set at a height of 12 inches. A metronome was placed in front of the step platform and set to 96 bpm. The participant was instructed to step up onto the platform until both feet made contact with the center of the step at which time the participant was instructed to return both feet to the floor. Four beats of the metronome were representative of the entire time allocated to perform this action. The principal investigator monitored each step and provided feedback to help participants carry out the protocol to the beat set by the metronome. After completing

the three minute protocol, heart rate was immediately recorded. Accepted age established step-up fitness norms for females are presented in Table 10 (Golding, 2000).

Table 10

YMCA Step Test Norms for Females

Fitness Rating (bpm)	18 - 25 yr	26 - 35 yr	36 - 45 yr
Excellent *	52 - 81	58 - 80	51 - 84
Good *	85 - 93	85 - 92	89 - 96
Above Average*	96 - 102	95 - 101	100 - 104
Average	104 - 110	104 - 110	107 - 112
Below Average	113 - 120	113 - 119	115 - 120
Poor	122 - 131	122 - 129	124 - 132
Very Poor	135 - 169	134 - 171	137 - 169

Note: * Accepted cardio-respiratory fitness levels for participants

The bent knee curl-up test was used to determine muscular strength and endurance of the abdominals (Neimen, 2010). Participants were placed in a supine position with arms resting to the side of the body, hands in a pronated position, knees flexed to 90˚, and feet positioned flat on the floor. Two pieces of masking tape were used to designate the start and finish position of the curl-up and ensure uniform movement of the body during testing. The first piece of masking tape was placed by the edge of the finger tips while the second tape was set 12 cm apart from the first piece. A metronome was placed next to the participant and set to 40 bpm. The participant was instructed to perform curl-ups in a controlled manner lifting the trunk off the floor while sliding the tips of the fingers to and from the first to second piece of tape. The principal investigator carefully monitored that each curl-up was carried out to the beat set by the

metronome. Curl-ups were performed to exhaustion or until technique could not be properly maintained. Accepted age established curl-up fitness norms for females are presented in Table 11 (Nieman, 2010).

Table 11

Curl-up Norms for Females

Fitness Rating (max reps)	15 - 19 yr	20 - 29 yr	30 - 39 yr
Excellent *	25	25	25
Very Good *	22 - 24	18 - 24	19 - 24
Good *	17 - 21	14 - 17	10 - 18
Fair	12 - 16	5 - 13	6 - 9
Poor	≤ 11	≤ 4	≤ 5

Note: * Accepted upper body fitness levels for participants

The push-up test was used to determine muscular strength and endurance of the anterior deltoids, triceps, and pectoral muscles (Howley & Franks, 2007). Participants were instructed to perform the fitness assessment from a modified knee push-up position. Testing commenced from a prone position with the hands shoulder width apart, the torso in a straight line, the legs held together, and the knees in constant contact with the floor. The head and torso were kept rigid as the participant pushed the body up into a straight arm position. Participants were asked to raise and lower the body in a controlled manner to exhaustion or until technique could not be properly maintained. A tennis ball placed directly below the sternum was used to designate the end position of each decent towards the floor. Accepted age established push-up fitness norms for females are presented in Table 12 (Nieman, 2010).

Table 12

Push-up Norms for Females

Fitness Rating (max reps)	15 - 19 yr	20 - 29 yr	30 - 39 yr
Excellent *	≥ 33	≥ 30	≥ 27
Very Good *	25 - 32	21 - 29	20 - 26
Good *	18 - 24	15 - 20	13 - 19
Fair	12 - 17	10 - 14	8 - 12
Poor	≤ 11	≤ 9	≤ 7

Note: * Accepted upper body fitness levels for participants

3.5 RISK FACTOR ASSESSMENT (PRE-TEST)

The Vicon motion analysis system (Vicon, Colorado Springs, Colorado, USA) was used to capture single leg drop landing mechanics and moments. Eight high speed optical cameras were positioned around and focused on a three force plate configuration as illustrated in Figure 1.

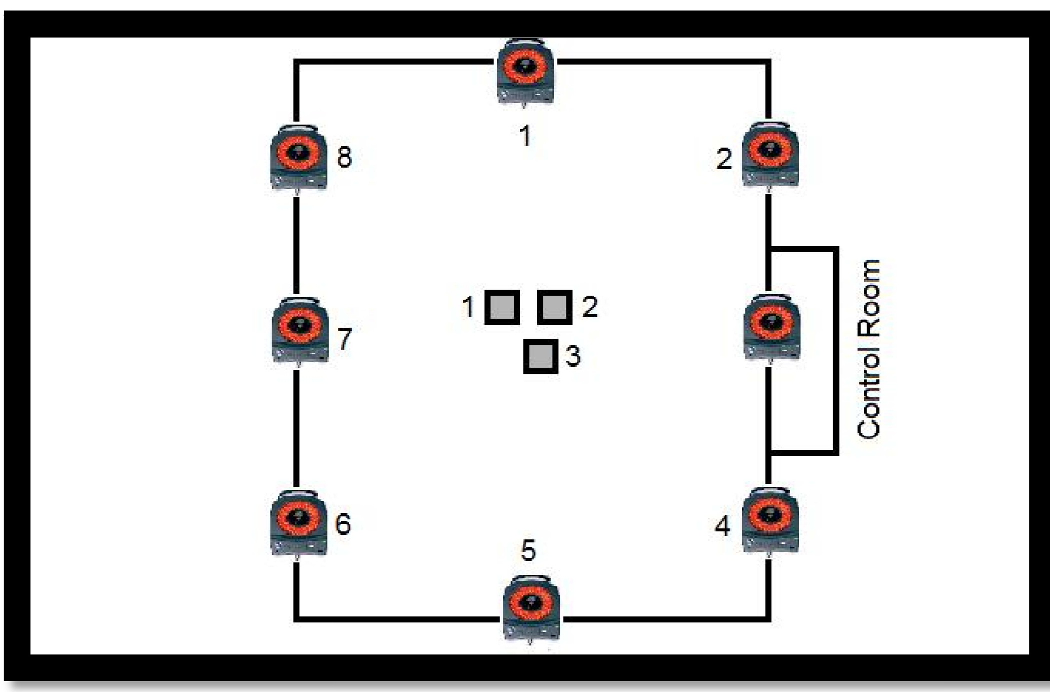


Figure 1: Vicon Motion Analysis System and Force Plate Set-up

A JVC digital video camera was set up in the control room and positioned towards the force plates on the laboratory floor. The digital video camera was used to record individual trials and provide a live feed to a television prompt in the control room.

Prior to each participant's arrival at the laboratory, all eight cameras were synced using program software. The threshold grid for each camera was inspected for reflective objects in the laboratory test field. Reflective objects were removed from camera sight or blacked out on threshold grid. Static and dynamic calibrations were performed to orient cameras to the laboratory coordinate system. Cameras were calibrated using a calibration triangle (static) and calibration wand (dynamic). The triangle was placed in the center of the camera field on the left corner of the force plate used for testing. The triangle was removed following data capture and calibration. Dynamic calibration was performed by slowly waving the 240 mm wand throughout the designated laboratory space used for testing. Following the short data collection interval, residual values for all eight cameras were assessed. If the residual for each camera was greater than 1 mm, dynamic calibration was redone.

Pre-testing was conducted a week following participant screening. Participants were asked to refrain from strenuous physical activity 72 hours prior to testing. Participants were instructed to bring appropriate athletic footwear the day of testing. Upon arriving to the laboratory, participants changed into the provided black Under Amour™ spandex shirt and shorts. Height (cm) and weight (kg) measurements were recorded again with participants standing barefoot in anatomical position. Height was measured using a leveled Seca 220 Telescopic Measuring Rod/Column Scale. Weight was measured using a calibrated Tanita BWB-800A Class III Digital Scale.

Anthropometric measurements of leg length, knee width, ankle width, shoulder offset, elbow width, wrist width, and hand thickness were determined using a retractable steel measuring tape and anthropometer (Lafayette Instrument Co., Lafayette, Indiana, USA). Leg dominance was then determined by having the participant kick a ball with their preferred leg.

A full marker set was used to capture subtle variations in human motion by providing the highest dimensionality and sub pixel accuracy of frame to frame marker paths possible. A standard Plug-in Gait marker set (Figure 1) utilizing 15 mm reflective globes were used to define joint centers and axes of rotation. Thirty-nine reflective globes were attached using 1 ¼ double-sided adhesive collars to the following anatomical landmarks illustrated in Figure 2.

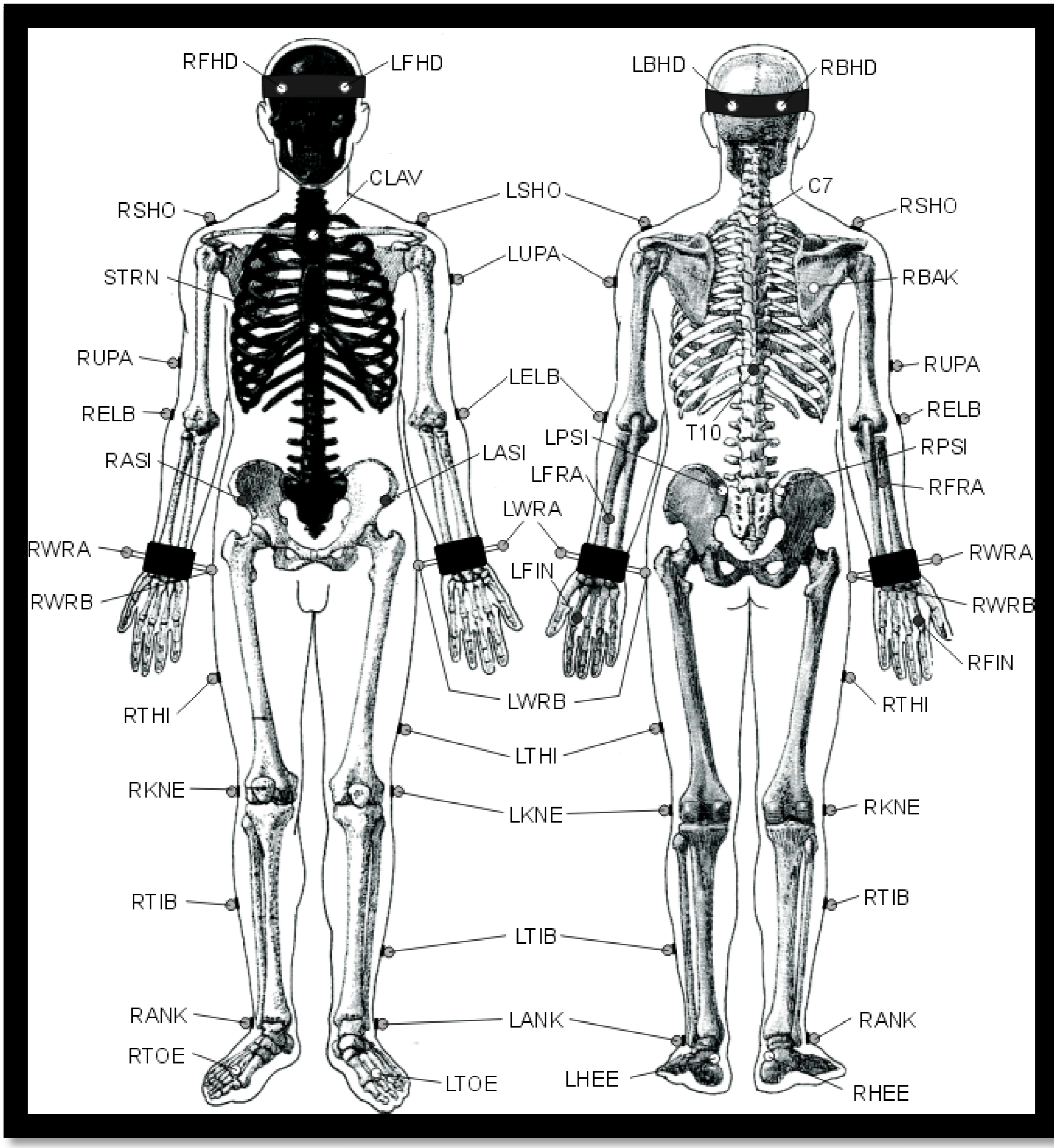


Figure 2: Marker set for the Vicon Plug-in Gait Model (Vicon, 2007)

Following marker placement, the participant was directed to the center of the lab and asked to stand in anatomical position with arms abducted to 90˚ and palms directed to the floor. A two to three second static trial was captured. Anthropometric measurements were inputted into the application to define anatomical reference points and segments.

The Delsys Electromyography (EMG) system *(*Delsys Inc, Boston, Massachusetts, USA) was used to capture simultaneous muscle activity of select quadriceps (vastus lateralis, vastus medialis), hamstrings (semitendinosus, semimembranosus), and gastrocnemius (lateral head, medial head) muscles (Figure 3).

Figure 3: Surface Electrodes Attached to Lower Extremity Muscles

The participant's spandex shorts were adjusted to provide direct exposure of the muscles selected for EMG testing. In order to avoid misplacement of the sensors due to

migration of the muscle belly during testing, the principal investigator palpated and marked individual muscle bellies as each corresponding muscle group was taken through a series of isometric contractions. The muscle area of interest was then shaved and abraded with fine grit sandpaper to remove dead skin cells in an effort to lower skin impedance and improve conductivity with EMG Sensors. The abraded area was cleaned with 70% isopropyl alcohol. Parallel-bar EMG sensors were attached with an adhesive skin interface along the muscle fiber direction of the most prominent portion of the muscle belly. Lead wires were positioned away from lower extremity reflective markers and held in place with athletic tape. A conductive adhesive dermatrode reference electrode was placed on the underside of the wrist on the same side as the test leg.

A raw EMG baseline inspection was conducted while participants were seated in a relaxed motionless state. If baseline noise exceeded 0.0001 volts, the parallel bar sensor was removed and repositioned. Visual inspections of raw EMG activity bursts during dynamic contractions were performed to evaluate the strength of the muscle signal collected from each sensor. A signal test was conducted to ascertain the amplitude associated with a maximum voluntary contraction (MVC) against a static resistance. Maximum voluntary contraction levels were used to normalize EMG readings.

Anterior resistance applied to the distal end of the tibia during seated knee extension with the hips held in an extended position with the toes slightly pointing outward was used to engage the vastus lateralis. Anterior resistance applied to the distal end of the tibia during seated knee extension close to full extension was used to

activate the vastus medialis. Posterior resistance applied to the calcaneus during seated knee flexion with the hips held in an extended position was used to engage the semitendinosus muscle. Posterior resistance applied to the calcaneus during seated knee flexion with slight internal rotation of the knee was used to engage the semimembranosus muscle. Applied resistance to the trapezius during a standing calf raise with the toes pointing forward and outward was used to engage the lateral and medial head of the gastrocnemius.

The muscle activity from both the signal test and single leg drop landing trials were processed using a root mean square algorithm. The root mean square algorithm served to rectify the EMG activity by discarding negative data points while keeping the positive data intact. The rectified data was sent through a low pass Butterworth filter with an order of four and a corner frequency set at 10Hz. Filtering the data further removes electrical noise associated with wire sway and biological artifacts. The peak amplitude achieved by each muscle during single leg drop landing trials was represented as a percentage of MVC values. Onset time was regarded as the moment when muscle activity exceeded two standard deviations of peak amplitude.

3.5.1 Motion Analysis, Ground Reaction Force, and EMG Testing Protocol

Data collection was conducted in a specific order to minimize residual effects of testing on subsequent examinations. Motion analysis, ground reaction force, and electromyography testing were conducted simultaneously. Knee proprioception, anterior knee joint laxity, and strength testing of the hamstrings and quadriceps concluded the assessment. A thorough explanation and demonstration of each protocol was provided as each participant moved from one mode of testing to the next. Data collection

required 120 minutes to complete. Participants serving in the control were asked to return to the laboratory six weeks later for post-testing. Participants serving in the intervention group were scheduled for prevention program training.

Two stackable steps with a combined measure of 60 cm [L] X 60 cm [W] X 30 cm [H]) were positioned behind a 3-D AMTI force plate. A box height of 30 cm was chosen for testing because it represents the most commonly used height in single leg drop landing testing (DiStefano et al., 2009; Kellis & Kouvelioti, 2009; Myer et al., 2006). No instructions or corrective feedback regarding landing technique were given before or during testing as to avoid altering the participant's natural performance of the task at hand. Participants performed 3 single leg drop landings with the dominant foot from the box onto the force plate (Figure 4).

Figure 4: Participant Performing Single-Leg Drop Landing

Data collection began with initiated movement off the box and ended when full recovery from the drop landing was achieved. Motion analysis data, EMG data, and force plate data were later cropped to represent a performance interval defined by 2 movement segments. The interval consisted of initial foot strike with the force plate and maximum knee flexion following contact with the ground. Initial foot strike was defined as the moment vertical (Fz) ground reaction forces exceeded 10 N (Myer et al., 2006).

The Vicon motion analysis system was used to capture and later digitize dynamic trials of single leg drop landing mechanics, moments, and center of mass. Initial and maximum angles of hip flexion-extension, abduction-adduction, and internal-external rotation were captured. Initial and maximum angles of knee flexion-extension, valgus-varus, and internal-external rotation were captured. Initial and maximum angles of ankle plantar flexion-dorsiflexion, inversion-eversion were captured. Corresponding hip, knee, and ankle moments were calculated using BodyBuilder software. Program software allowed COM to be tracked along the frontal, sagittal, and longitudinal axis. Variability of COM excursion data were used to gauge core strength through relative torso stability from initial ground to max knee flexion. Motion analysis data were collected at a sampling rate of 120 Hz.

The Delsys EMG system was used to capture muscle activity of the quadriceps (vastus lateralis, vastus medialis), hamstrings muscles (semitendinosus, semimembranosus), gastrocnemius (lateral head, medial head). EMG was used to determine muscle onset time and peak amplitude. EMG was collected at a sampling rate of 2000 Hz.

A leveled 3 dimensional AMTI force plate (AMTI Inc., Newton, MA, USA) embedded in the laboratory floor was used to capture mediolateral (Fx), anteroposterior (Fy), and vertical (Fz) ground reaction forces. Gains were set at 2000 Hz for moderate sensitivity. Channels 2 (mediolateral [Fx]), 3 (anteroposterior [Fy]), and 4 (vertical [Fz] were selected for data collection. All ground reaction forces were normalized to body weight by zeroing the force plate while the participant stood motionless on the force

plate during the static calibration trial. Ground reaction force data were collected at a sampling rate of 1200 Hz.

3.5.2 Proprioception Testing Protocol

The Biodex 3 ® Isokinetic Dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA) was used to quantify knee joint position sense at 15°, 30°, and 45°. Individual test profiles were created for each participant. An identification number along with general information such as height, weight, and leg dominance was entered into the Patient Selection screen. The Biodex chair back and seat were adjusted to fit individual leg lengths. The seatback tilt to the test chair was set to 85°.

Participants were firmly secured to the Biodex chair with stabilization straps that crossed the anterior aspect of the torso, waist, and thigh of the test leg. The lower portion of the test leg was secured to dynamometer's lever arm using a Velcro® strap and padded support placed just above the medial and lateral malleolus. The body was secured in place to prevent extraneous body movements from influencing the test leg. The joint axis created by the lateral condyle of the tibia and epicondyle of the femur were aligned with the axis of dynamometer's lever arm as illustrated in Figure 5.

Figure 5: Participant Performing Knee Joint Proprioception Testing

Range of motion limits were set to maximum flexion and extension. To set range of motion limits, participants were asked to move the test limb through a normal range of extension. The set limit button was engaged when maximum knee extension was reached. Participants were then asked to move the test limb through a normal range of

flexion. The set limit button was engaged when the maximum amount of knee flexion permitted by the dynamometer arm and chair was reached. An anatomical reference point was established to orient the dynamometer lever arm with the test limb. Full leg extension was recognized by the Biodex as 0°.

A practice trial was completed to orient participants with the proprioception testing protocol. The proprioception unilateral knee extension/flexion protocol was used to randomly assess active knee joint position sense at 15°, 30°, and 45˚ in the dominant leg. Participants were blind-folded to prevent visual orientation of the test limb to points of reference in the laboratory. The knee joint positions selected for testing were chosen to expose the range of proprioceptive capacity associated with varying degrees of knee flexion.

Testing began with the dynamometer's lever locked at 90˚ of flexion. The lever arm mechanically oriented the test limb to each target angle at an angular velocity of 30˚/s. The lever arm locked in place for 10 seconds once the target angle was reached. The test limb was released and returned to 90˚ of knee flexion. Participants were asked to actively reproduce the angle and capture the reading using a hand held trigger. Engaging the hand held trigger marked the end of the trial for that specific angle. The process was then repeated for the remaining two target angles. A total of five assessments were conducted at 15°, 30°, and 45˚ and averaged to arrive at a single active knee joint position sense score for each angle. Testing yielded a measure of absolute error (AE) associated with each active angle reproduction.

Absolute error represented the difference between the exact angle of flexion produced by the dynamometer's lever arm and the participant's estimation of knee

flexion. This magnitude of error associated with active angle reproduction corresponds with joint position sensitivity at various degrees of flexion. Participants who demonstrate joint position sense scores that deviate significantly from target angle values reflect greater AE. Increased error is thought to be indicative of less proprioceptive awareness (Callaghan et al., 2008).

3.5.3 Laxity Testing Protocol

Anterior knee joint laxity was quantified using the KT- 1000 Knee Arthrometer (MEDmetric Corporation, San Diego, CA, USA). The participant was placed on an examination table in a supine position with legs resting on an adjustable thigh support and feet positioned within the provided foot support. The thigh support was adjusted accordingly to ensure testing of the leg at 30˚ of knee flexion. Knee flexion angles between 20˚ and 35˚ place the patella within the femoral groove creating a stable foundation to effectively measure anterior translation (Kupper et al., 2007). A knee flexion angle of 30˚ is thought to represent the position where the ACL is evenly taut across the joint (Sheehan & Rebmann, 2003). The foot support was used to ensure rotational symmetry of the participant's limbs during testing. The KT-1000 knee arthrometer was placed onto the anterior aspect of the tibia of the test limb. The apparatus was secured at the level of the gastrocnemius and medial and lateral malleoli by Velcro® straps as illustrated in Figure 6.

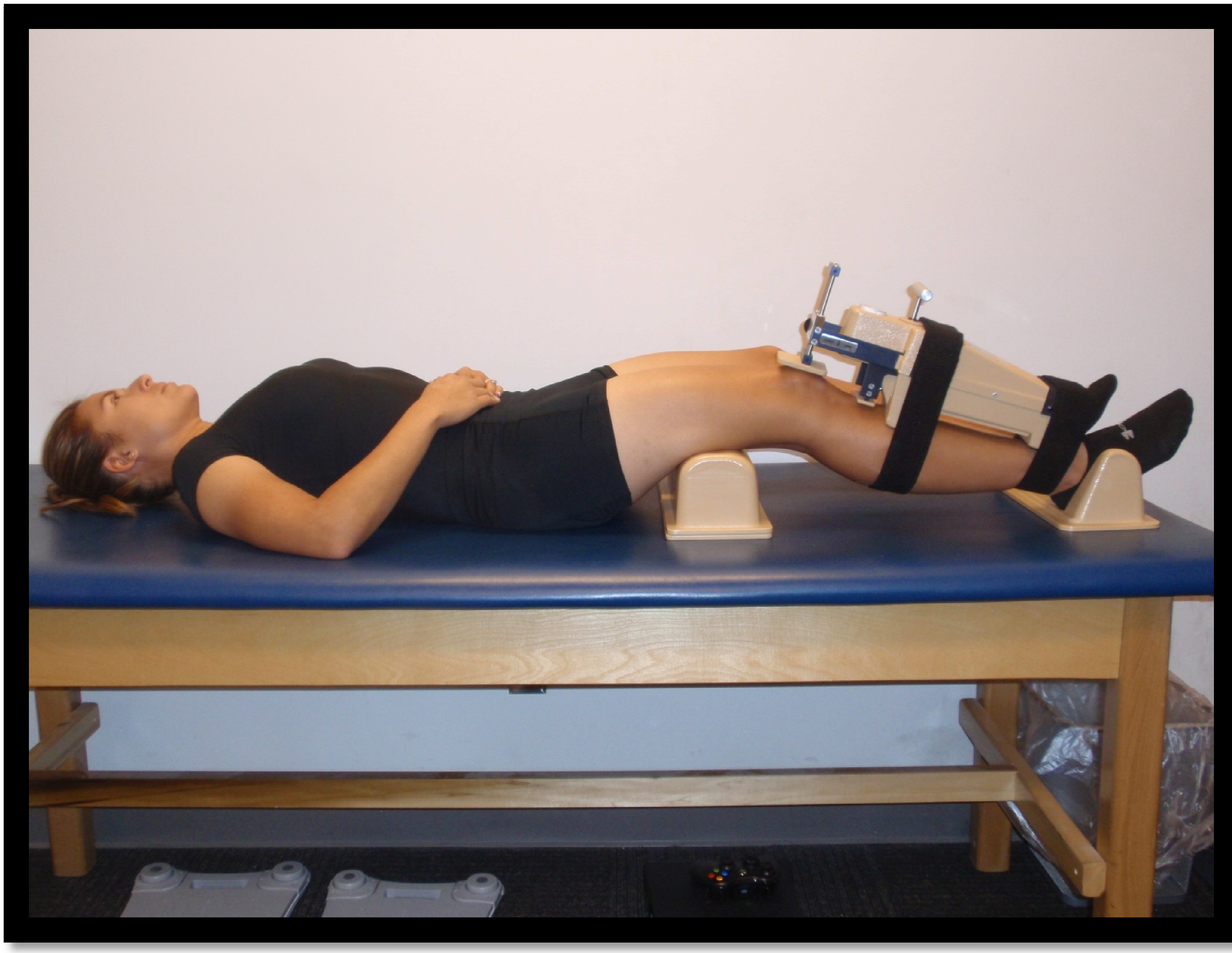


Figure 6: Participant in Supine Position During Passive Drawer Test

An anterior passive drawer test was conducted at a displacement load of 133 N (30 lb) using protocols outlined in the KT-1000 knee arthrometer user's guide (Daniel, Stone, Sachs, & Malcom, 1985). This load was chosen because it serves as a commonly reported measure for anterior tibial translation that allows for general comparisons across previous research (Shultz et al., 2004). The displacement load was applied through a force handle located 10 cm distal to the joint line of the knee. The mean of three trials was calculated and recorded as the participant's overall anterior knee laxity.

A manual maximum drawer test was also performed. A strong anterior force was applied manually to the proximal aspect of the calf while the examiner maintained a steady yet firm grip of the patella sensor pad. Maximum anterior tibial translation was recorded when the examiner was no longer able to move the leg anteriorly. If measurements for passive or manual maximum drawer testing differed by more than 0.5 mm between trials, testing was halted and redone. The KT-1000 Knee Arthrometer exhibits the highest diagnostic accuracy in instrumented evaluation of knee laxity among several widely used knee arthrometers. Diagnostic accuracy has been shown to improve with maximum manual testing (Anderson, Snyder, Federspiel, &Lipscomb, 1992; Katz & Fingeroth, 1986).

3.5.4 Muscle Strength Testing Protocol

A five minute warm-up on a cycle ergometer and a 10 minute set of lower extremity stretches were completed prior to testing. The warm-up on the cycle ergometer was performed at a self-selected pace. Lower extremity stretches consisted of three sets of five forward, backward, and lateral leg raises. Stretching concluded with walking knee holds. Participants paused during the walk across the laboratory space to grasp and hold a knee close to the chest for a few seconds after which continuing to walk a few more steps before holding the opposite knee to the chest.

The Biodex 3 ® Isokinetic Dynamometer was used to quantify maximum peak torque and time to peak torque in the hamstrings and quadriceps during isokinetic testing at angular velocities of 60°/s, 180°/s, and 300°/s. Results from isokinetic testing were also used to determine conventional H_{CON}:Q_{CON} strength ratio and functional H_{CON}:Q_{ECC} strength ratio. The process of administering the muscle strength test protocol required

identical placement of the participant on the apparatus as detailed in the proprioception protocol. Figure 7 illustrates participant placement on the Biodex.

Figure 7: Participant Performing Isokinetic Strength Test

Participants were firmly secured to the Biodex chair with stabilization straps that crossed the anterior aspect of the torso, waist, and thigh of the test leg. The lower

portion of the test leg was secured to dynamometer's lever arm using a Velcro® strap and padded support placed just above the medial and lateral malleolus. The body was secured in place to prevent extraneous body movements from influencing the test. The joint axis created by the lateral condyle of the tibia and epicondyle of the femur were aligned with the axis of dynamometer's lever arm.

Range of motion limits were set just short of maximum flexion and extension to allow for slight translation of the tibia across the femur during testing. To set range of motion limits, the participant was asked to move the test limb through a normal range of extension. The set limit button was engaged just short of maximum extension. The participant was then asked to move the test limb through a normal range of flexion. The set limit button was engaged just short of the maximum amount of knee flexion permitted by the dynamometer arm and chair. An anatomical reference point was established to orient the dynamometer arm with the test limb at 90˚ of knee flexion.

Program software was adjusted to correct for the effect of gravity taking into account both the weight of the test limb and dynamometer lever arm (Rosene et al., 2001). The quadriceps serve to extend the knee and lift the dynamometer lever arm while the hamstrings flex the knee and return the lever arm to its original position. During testing, the quadriceps contend with the additional weight of the lever arm while the hamstrings have the assistance of gravity, the weight of the limb, and the weight of the dynamometer arm during flexion of the knee. Failure to correct for the effect of gravity leads to an underestimation of quadriceps muscle strength and an overestimation of hamstrings muscle strength (Caldwell et al., 2004). The dynamometer lever arm was locked in full extension and the participant was asked to relax the test

limb allowing for the full weight of the appendage to rest on the leg support. Limb weight (N) was then gauged and inputted into the program software.

A practice trial conducted at submaximal effort was completed to orient participants with the strength testing protocol. Participants first completed one practice trial of concentric hamstrings / concentric quadriceps strength testing at submaximal effort followed by three trials at maximal effort. Participants then completed one practice trial of concentric hamstrings / eccentric quadriceps strength testing at a torque setting of 30 Nm. Participants followed the practice trial with three trials at maximum effort with the torque set at 100 Nm.

Maximum hamstrings and quadriceps strength were measured across 0˚ - 90˚ of knee flexion (90˚) and extension (0˚). A modified unilateral knee extension/flexion protocol was used to measure concentric hamstrings and concentric quadriceps strength at 60˚/sec, 180˚/sec, and 300˚/sec. Conventional H_{CON}:Q_{CON} strength ratios were derived from measures of peak concentric hamstrings torque and peak concentric quadriceps torque (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998). Testing continued with an assessment of concentric hamstrings and eccentric quadriceps strength protocol at angular velocities of 60˚/sec, 180˚/sec, and 300˚/sec. Functional H_{CON}:Q_{ECC} strength ratios for each joint angular velocity were computed by respectively dividing peak concentric hamstrings torque by peak eccentric quadriceps torque (Aagaard et al., 1998).

Strength testing of the hamstrings and quadriceps muscles was comprised of five repetitions at each angular velocity with a 60 second rest period between trials (Gleeson & Mercer, 1996). The principal investigator provided both verbal and visual cues to

immediately prompt the start and stop of each trial. Verbal encouragement throughout the trial was provided to help elicit maximal effort during testing. The testing protocol concluded with a 10 minute set of lower extremity static stretches.

3.6 ACL INJURY PREVENTION PROGRAM

The 60 minute ACL injury prevention program was comprised of highly regimented agility, plyometric, balance, and strength training components. The program was six weeks in duration and consisted of an orientation and 18 training sessions. The program was broken down into two stages of muscular and mechanical development. The difficulty and intensity of each training component increased in technical complexity as participants transitioned from one stage to the next.

Training sessions were offered Monday through Saturday at 8:30 AM, 12:30 PM, and 4:30 PM. Participants were given the opportunity to choose the days and times that were most convenient for them but asked to stagger the workouts and keep the same training schedule throughout the six week period. In the event of a missed workout, participants were allowed to make-up the training session during the remaining times that day or the following day. Participants who missed two consecutive training sessions were dismissed from the study.

Participants were required to attend a 30 minute orientation prior to beginning the program. The orientation began with a 20 minute presentation intended to provide participants insight into ACL injury risk factors, mechanisms, and prevention plan efforts. Following the presentation, participants were given a tour of the agility, plyometrics, balance, and strength training stations setup throughout the main floor of

the biomechanics laboratory. The remaining 10 minutes were allocated for questions and formulating the training schedule.

Group size varied by training time and ranged between six and eight participants. On the day of training participants were paired up and assigned to begin the circuit at a specific station. Participants were provided with a five minute warm-up which consisted of dynamic stretching. Dynamic stretching was used in place of conventional static flexibility training because of the impact static stretching has on reducing athletic performance (Bacurau et al., 2009). Training was broken into the following 15 minute segments: agility training (station one), plyometric training (station two), balance training (station three), and strength training (station four). Participants rotated from one station to next completing the training protocol with a series of static stretches.

The principal investigator demonstrated each element of the training protocol to participants. A verbal description and visual demonstration of commonly performed errors in technique associated with each mechanical task was also given. Verbal and visual feedback was specific to individual performance and given as needed throughout training. Feedback focused on correcting high risk lower extremity malalignments during drop landings. Participants were specifically instructed to remain vigilant of hip, knee, and ankle mechanics at ground contact specifically hip internal rotation, knee internal rotation, and ankle eversion. Increased hip flexion, increased knee flexion, and reduced ankle eversion has been shown to have a significant impact on peak vertical ground reaction force. Single leg drop landings with the knee flexed between 0 - 25˚ results in a VGRF of 19.3± 5.0˚ N/kg. Increasing flexion angles of 25-50˚ and 50-75˚ can significantly decrease VGRF by 11% (17.1 ±4.5 N/kg, p=0.016) and 15% (16.4 ± 3.6

N/kg, p=0.002), respectively (Podraza & White, 2010). Participants were also instructed to use the upper extremities to achieve balance and help attenuate the amount of force generated at landing.

The principal investigator shuttled from station to station providing participants a continuous stream of feedback and positive encouragement. The contribution of augmented feedback to a participant's performance has been found to positively impact the learning process when feedback is specific to individual technique. Knowledge of performance has been suggested to be as instrumental to motor learning as practice itself (Schmidt & Lee, 2005). The addition of augmented feedback during training has been shown to have a strong impact on landing mechanics, reducing ground reaction force by 13 -19% (Vescovi et al., 2008).

3.6.1 Prevention Program Training: Phase 1 (Weeks 1 - 3)

The first phase of training was emphasized on gross muscular and mechanical development. The circuit consisted of fundamental agility, plyometric, balance, and strength training skill sets. Table 13 provides a list of the skill sets used in the first stage of training. A detailed description and illustration of agility, plyometric, balance, and strengthening drills can be found in Appendix A.

Table 13

ACL Injury Prevention Program – Phase 1

Agility Training (Station 1)	Plyometrics Training (Station 2)	Balance Training (Station 3)
Ladder - forward / backward fast feet	Barrier - forward jumps	Static - double leg deep hold
Ladder - lateral fast feet	Barrier - lateral jumps	Static - double knee hold
Ladder - forward / backward hopping	Box - forward jumps	Dynamic - step up / step down
Ladder - lateral hopping	Box - lateral jumps	Dynamic - lateral step up / step down
Ladder - forward / backward fast hands	Pyramids	Stick Landing - double leg jump ups
Ladder - lateral fast hands	Bounding	Stick landing - double leg drop downs
		Perturbations - double leg
	Strength Training (Station 4)	
Core - crunches	Lower - alternating forward lunges	Hamstrings - standing leg curls
Core - leg raises	Lower- lateral leans	Hamstrings - stiff legged lift
Core - cross crunches	Lower- sumo squat	Hamstrings - single leg bridges
Core - inch sit-ups	Lower - varied heel raise	Hamstrings - lying leg curls

Multi-component training was implemented into the intervention because of the combined effectiveness mixed training has in reducing ACL injury risk (Hrysomallis et al., 2007). Stations one through four introduced multiple skills sets intended to improve upper and lower body agility, coordination, and balance during drop landings. Each station also included an element of physical conditioning. The inclusion of multiple repetitions served to enhance and reinforce motor skill development and mastery. Exhaustive bouts of agility, plyometric, balance, and periodized resistance training were avoided because of its ineffectiveness in improving medial/lateral stability (Paterno et al., 2004). Station one centered on drills that focused on patterned foot and hand movements across a 30 ft agility ladder. The agility drill skill set was primarily constructed to elicit different modes of foot adjustment during quick movements in

multiple directions. Drills that utilized the hands were intended to improve simultaneous upper and lower body coordination.

Station two included drills that evoked rapid muscle lengthening and shortening during fast paced movements. Drills served to increase the explosiveness of anterior, posterior, medial, and lateral leg musculature. The plyometric drill skill set was primarily focused on proper landing technique between jumps. Foam barrier drills provided non-threatening drills that centered on increasing hip, knee, and ankle flexion while keeping the knees in line with the toes at landing. Plyometric drills introduced increased height and speed to the skill set. Emphasis was then placed on coordinating muscular and mechanical efforts of the upper and lower body to attenuate GRF during explosive jump landing maneuvers. Participants were instructed to anticipate foot contact with the ground collapsing the ankles, knees, and hips while abducting the arms to provide balance during the descent. The addition of plyometrics to a training have led to decreased hip adduction, increased knee flexion, and decreased ankle eversion during drop vertical jumps (Myer et al., 2006).Completion of 15 training sessions incorporating a minimum of 40 plyometric jumps per session has also been shown to significantly enhance strength and maximize individual performance (Saez-Saez de Villarreal, Requena, & Newton, 2009).

Station three incorporated the BOSU balance trainer (DW Fitness, LLC, Madison NJ). The balance drill skill set was developed to improve kinesthetic awareness through increased muscular strength, reactive ability, and coordination. Drills specifically improved overall kinesthetic awareness and joint position sense by exposing participants to body positions and stimuli typically encountered during drop landings. A

series of static and dynamic joint stabilization tasks were included to develop muscle agonists and antagonists, but also engage, strengthen, and synchronize smaller stabilizing muscles that support the truck, hip, knee, and ankle. Balance training has been shown to minimize hip adduction and ankle eversion during drop vertical jumps while increasing knee flexion and decreasing knee abduction during medial drop landings (Myer et al., 2006). Multiple stick landings from an unstable to stable and stable to unstable surface were employed to stress the importance of hamstrings muscle reactivity in achieving stability at landing. Perturbations were performed to prepare participants to anticipate and adjust to multidirectional applied force.

Station four centered on strength training of the core and lower extremity musculature. The strength training skill set emphasized the muscular development of the abdominals and hamstrings. Calisthenics were used to develop the upper abdominals, obliques, and lower abdominals to improve postural stabilization during dynamic movements (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). Special consideration was taken during leg exercises to prevent the overdevelopment of the quadriceps muscle. Exercises were specific to leg adductors, leg abductors, and hamstrings musculature. Extra attention was given to hamstrings muscle development because of the semimembranosus, biceps femoris, and semitendinosus contribution to counter balancing the amount of quadriceps force exerted during explosive knee extension (Herman et al., 2009).

3.6.2 Prevention Program Training: Phase 2 (Weeks 4 - 6)

The second phase of training introduced agility, plyometric, balance, and strength training drills with a higher degree of mechanical skill and muscular intensity. The

progression and repetition of prevention program tasks were formulated to increase situational awareness and reflexive mediated muscle response during high risk maneuvers (Swanik et al., 2007). Agility drills progressed to patterned foot movements increasing in technical complexity. Agility drills involving hand movements introduced calisthenics into the sequence. Foam barrier and plyometric box drills transition to single leg jumps and drop landings at different heights. Balance drills also progressed from double to single leg static and dynamic stabilization tasks. Progressions from double to single leg balance drills from a stable to an unstable surface have been found to increase anterior/posterior postural stability (Paterno et al., 2004). The second stage of training introduced core strengthening exercises that kept the abdominal routine moving along a continuous kinetic chain of calisthenics. Lower extremity exercises included the addition of a medicine ball to include the core and further strengthen the anterior, posterior, medial and lateral muscles of the leg. The hamstrings concentration also increased in intensity by introducing super set training and incorporating resistance bands with a higher degree of tension.

Table 14 provides a list of the skill sets used in the second stage of training. A detailed description and illustration of agility, plyometric, balance, and strengthening drills can be found in Appendix B.

Table 14

ACL Injury Prevention Program – Phase 2

Agility Training (Station 1)	Plyometrics Training (Station 2)	Balance Training (Station 3)
Ladder - hop scotch drill	Barrier - forward jumps	Static - single leg deep hold
Ladder - 5 count drill	Barrier - lateral jumps	Static - single knee hold
Ladder - lateral feet drill	Box - forward jumps	Dynamic - step jump vertical / step down
Ladder - tango drill	Box- lateral jumps	Dynamic - lateral jump vertical /step down
Ladder - forward / backward push-ups	Pyramids	Stick Landing - single leg jump ups
Ladder - lateral push-ups	Bounding with rings	Stick landing - single leg drop downs
		Perturbations - single leg
Strength Training (Station 4)		
Core - planks	Lower - alternating forward lunges	Hamstrings -stiff legged lift (super set)
Core – planks alternating knee bends	Lower- lateral leans	Hamstrings - lying leg curls (super set)
Core – planks alternating roll overs	Lower- sumo squat	Hamstrings - double leg bridges w/ ball
Core - V sit-ups	Lower - varied heel raise	Hamstrings - Russian hamstrings

3.7 RISK FACTOR ASSESSMENT (POST-TEST)

Participants serving in the control group were scheduled to return to the laboratory for post-testing six weeks following initial risk factor assessment. Members of the intervention group were scheduled for post-testing 72 hours following the completion of the second phase of ACL injury prevention program training. Participants were again asked to refrain from strenuous physical activity 72 hrs prior to post-testing because of the effect delayed onset of muscle soreness has on influencing proprioceptive function (Byrne, Twist, & Eston, 2004) Post-testing was conducted using the previously outlined procedures for the motion analysis, GRF, and EMG testing protocol, proprioception testing protocol, ACL laxity testing protocol, and muscle strength testing protocol. Data

collection required 120 minutes to complete. Upon successful completion of post-testing, participants were provided with a gift card.

3.8 STATISTICAL ANALYSES

All data were analyzed using SPSS for Windows, Version 18.0 (SPSS Inc., Chicago, Illinois). The independent variables were Group (2 levels: intervention vs. control), and Time (2 levels: pre-test vs. post-test). The dependent variables were single leg drop landing kinematics, kinetics, EMG, and GRF. Additional dependant variables were knee joint proprioception, anterior knee joint laxity, and hamstrings/quadriceps strength.

For the purpose of this research, dependent variable groupings were narrowed to critical ACL injury risk factors. Single leg drop landing kinematics consisted of knee flexion-extension, valgus-varus, and internal-external rotation angles. Single leg drop landing kinetics consisted of knee flexion-extension, valgus-varus, and internal-external rotation moments. Single leg drop landing variability of center of mass measures consisted of anterior-posterior, medial-lateral, and vertical excursion. Single leg drop landing EMG consisted of onset time and peak amplitude of the medial and lateral muscles of the quadriceps, hamstrings, and gastrocnemius at initial ground contact. Single leg drop landing GRF consisted of a measure of vertical ground reaction force at initial ground contact. Proprioception consisted of knee joint position sense at 15˚, 30˚, and 45˚. Anterior knee joint laxity consisted of passive drawer test at 133 N and manual maximum drawer test of max anterior tibial translation. Strength testing measures consisted of time to peak torque, peak torque, conventional H_{CON}:Q_{CON}, and functional H_{CON}:Q_{ECC} ratios at 300˚/sec.

Separate 2 X 2 mixed between-within subjects MANOVA's were conducted to asses group differences and interactions among each dependent variable grouping. Separate 2 x 2 mixed between-within subjects ANOVA's were conducted to asses offending variables which exhibited multicolinearity within a dependent variable grouping. To probe significant interactions, the simple effects for Time and Group were calculated Alpha was set at 0.05 level of significance.

3.9 EXPECTED OUTCOMES

The subsequent hypotheses were established for the following specific aims.

Specific Aim 1: Identify specialized training effects on simultaneous single leg drop landing mechanics, moments, center of mass, muscle activity, and ground reaction forces.

It was hypothesized that simultaneous single leg drop landing mechanics, moments, center of mass, muscle activity, and ground reaction forces would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements while training in the intervention group would result in the following changes listed in Table 15.

Table 15

Expected Drop Landing Kinematic, Kinetic, EMG, and GRF Outcomes

Single Leg Kinematics	Single Leg Kinetics	Single Leg EMG	Single Leg GRF
↑ knee flexion	↓ knee flexion moment	↓ hamstrings onset time	↓ in vertical force
↓ knee valgus	↓ knee valgus moment	↑ hamstrings peak amplitude	
↓ knee internal rotation	↓ knee internal rotation moment	↑ quadriceps onset time	
		↑ quadriceps peak amplitude	
		↓ gastrocnemius onset time	
		↑ gastrocnemius peak amplitude	
Note: Training is anticipated to affect Center of Mass resulting in greater postural stability along the x, y, and z-axis			

Specific Aim 2: Identify specialized training effects on knee joint sensitivity and stability.

It was hypothesized that knee joint sensitivity and ACL integrity would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements while training in the intervention group would result in the following changes listed in Table 16.

Table 16

Expected Knee Joint Proprioception and ACL Laxity Outcomes

Active Joint Position Sense	Anterior Knee Joint Laxity
↑ active joint position sense at 15˚	↓ anterior knee joint laxity at 133 N
↑ active joint position sense at 30˚	↓ max anterior knee joint laxity
↑ active joint position sense at 45˚	

Specific Aim 3: Identify specialized training effects on knee muscle strength.

It was hypothesized that biomechanical deficits in the hamstrings and quadriceps would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements while training in the intervention group would result in the following changes listed in Table 17.

Table 17

Expected Hamstrings and Quadriceps Muscle Strength Outcomes

H_{CON}:Q_{CON} Isokinetic Testing at 300°/s	H_{CON}:Q_{ECC} Isokinetic Testing at 300°/s
↑ hamstrings time to peak torque	↑ hamstrings time to peak torque
↑ hamstrings peak torque	↑ hamstrings peak torque
↓ quadriceps time to peak torque	↓ quadriceps time to peak torque
↑ quadriceps peak torque	↑ quadriceps peak torque
↑ H_{CON}:Q_{ECC} strength ratio	↑ H_{CON}:Q_{ECC} strength ratio

Chapter 4: Results

4.1 DATA SCREENING

Data entries were examined for accuracy and missing data. None of the variables included in this research had missing data. Data screening proceeded with the inspection of frequency statistics. Measures of central tendency (mean), dispersion (standard deviation, variance, maximum values, minimum values), and distribution (skewness, kurtosis) were evaluated. Means, standard deviations, minimum, and maximum values mainly fell within the range of what is expected for measurements of this nature.

An inspection of z-scores was conducted to identify univariate outliers. Individual cases were measured against a z-score criterion of 3.29. A case with a z-score of 3.29 was deemed disconnected from other z-scores because of the distance the individual case had from remaining measures. Cases identified as univariate outliers were adjusted by positioning the score just outside the periphery of the second highest or lowest value (Tabachnick & Fidell, 2007). In the event individual cases did not exhibit a significant departure from the 3.29 cutoff but affected the normality of the distribution, cases on the highest and/or lowest end of the distribution were also adjusted to improve skewness and kurtosis.

Data were then screened for multivariate outliers using the SPSS Regression. Mahalanobis distance was the statistical method selected to identify multivariate outliers. Mahalanobis distance values were evaluated against a critical value of chi square (p=0.001). The critical value was determined by selecting the chi square with degrees of freedom that corresponded to the number of dependent variables involved in

each analysis. Outlier statistics indicated no presence of multivariate outliers in any of the dependent variable groupings.

Multicolinearity and singularity were evaluated across several statistics using SPSS Regression. Multiple R, collinearity statistics (tolerance, variance inflation factor), and collinearity diagnostics (condition index, variance proportions), and bivariate correlations were used to identify offending variables. To rectify multicolinearity within a variable grouping, similar measures were either collapsed into a composite variable or removed from analysis and analyzed separately. A detailed account of data screening steps and adjustments are included in Appendix C.

4.2 PARTICIPANT CHARACTERISTICS

Fifty-six apparently healthy female students with above average conditioning and no apparent injury to the lower extremity volunteered to participate. Selection was contingent on several inclusion criterion parameters. Examination of participant descriptives revealed no significant differences in anthropometric characteristics between groups or across pre-testing (height, weight, BMI) and post-testing (weight, BMI) intervals. However, results from a one-way between groups ANOVA found age to be significantly different between groups $F(1,54)=6.44$, $p=0.01$, $\eta_p^2 = 0.11$. Despite reaching statistical significance, the mean difference between the intervention group (21.96 ± 2.49) and control group (20.29 ± 2.46) was small. Descriptive statistics for participants are presented in Table 18.

Table 18

Participant Characteristics – Mean ± Standard Deviation

Participants	Age (y)	Height (cm)	Weight (kg) Pre-Test	Weight (kg) Post-Test	BMI Pre-Test	BMI Post-Test
Control (N=28)	20.29 ± 2.46	163.05 ± 4.05	62.41 ± 8.12	61.97 ± 7.62	23.48 ± 3.00	23.33 ± 2.89
Intervention (N=28)	21.96 ± 2.49*	160.89 ± 5.92	63.58 ± 8.49	63.14 ± 7.84	24.43 ± 2.78	24.29 ± 2.77

Note: ***** represents statistical significance between groups (p<0.05). Age was only participant characteristic to yield a significant difference between groups (p=0.01).

4.3 KNEE KINEMATICS

4.3.1 Knee Kinematics at Initial Contact

The Vicon motion analysis system utilized eight high speed optical cameras positioned around a force plate to capture single leg drop landing mechanics from a from a box height of 30 cm. Knee flexion-extension, valgus-varus, and internal-external rotation were assessed at initial contact with the ground. Initial contact with the ground was defined as the moment the initiated movement off the box resulted in a foot strike against the force plate. Single leg drop landing knee kinematics for participants are presented in Table 19.

Table 19

Knee Kinematics at Initial Contact

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**Flexion Extension (deg)**	**Valgus Varus (deg)**	**Internal External (deg)**	**Flexion Extension (deg)**	**Valgus Varus (deg)**	**Internal External (deg)**
Control	21.99 ± 7.58	-1.75 ± 4.88	8.32 ± 7.28	21.52 ± 7.19	-1.95 ± 4.31	8.43 ± 6.86
Intervention	21.83 ± 7.20	-0.54 ± 5.94	6.71 ± 7.77	33.54 ± 6.58	2.40 ± 6.78	9.33 ± 6.85

A 2 x 2 mixed between-within subjects MANOVA was performed on single leg drop landing kinematics. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were knee flexion-extension angles, knee valgus-varus angles, and knee internal-external rotation angles. The direction of the knee movement was characterized by positive and negative values. Positive values were associated with knee flexion, varus, and external rotation. Negative values were associated with knee extension, valgus, and internal rotation.

Given the Wilks' criterion, results from the MANOVA indicated a significant interaction between Group x Time, Wilks' Λ = 0.476, $F(3, 52) = 19.049$, $p < 0.001$, $\eta_p^2 = 0.524$. There was a significant main effect for Time, Wilks' Λ = 0.524, F(3, 52) = 15.754, $p < 0.001$, $\eta_p^2 = 0.476$ and Group, Wilks' Λ = 0.781, $F(3, 52) = 4.867$, $p = 0.005$, $\eta_p^2 = 0.219$. In an effort to better understand the results from the MANOVA, an examination of the univariate findings surrounding each of the kinematic variables was conducted. Results from the analyses are presented in Table 20.

Table 20

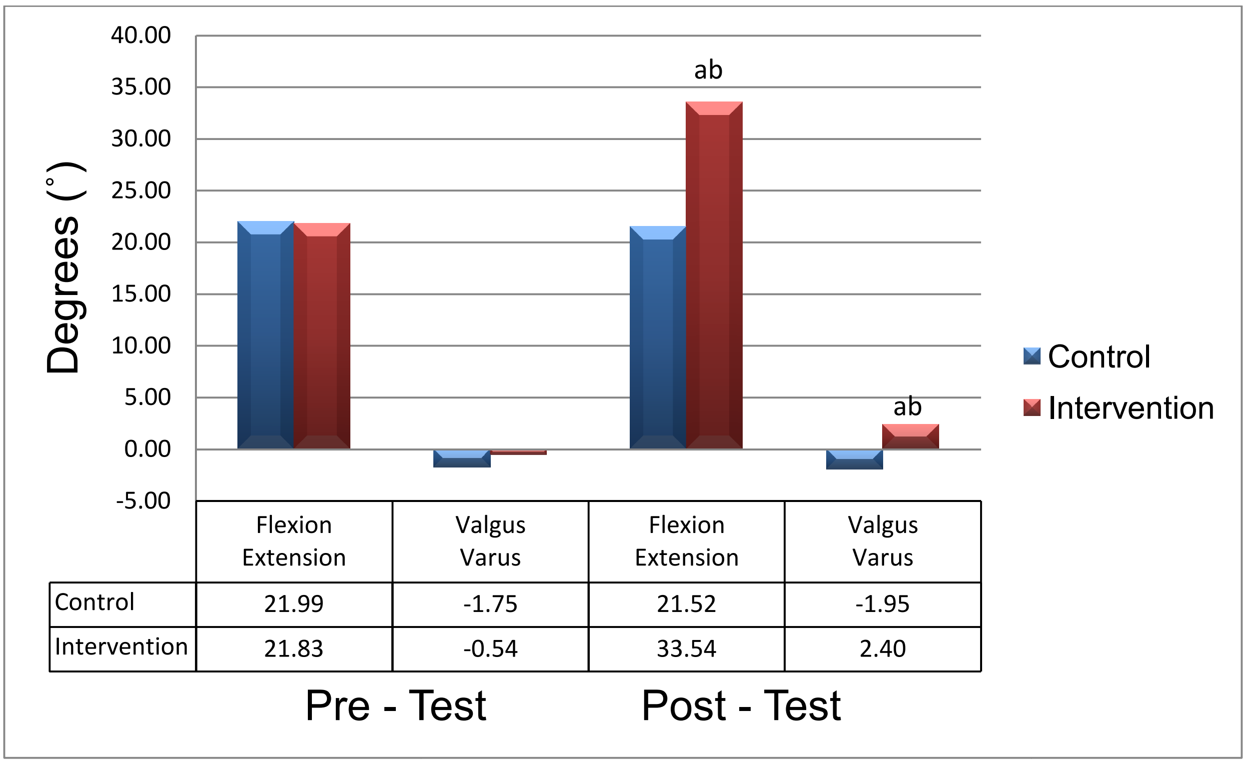
Results of Univariate ANOVA's for Knee Kinematics at Initial Contact

Group Main Effect			
Variable	***df***	***F***	**Significance**
X Knee (deg)	1, 54	12.00	$p = 0.001$
Y Knee (deg)	1, 54	4.24	$p = 0.04$
Z Knee (deg)	1, 54	0.04	$p = 0.84$
Time Main Effect			
Variable	***df***	***F***	**Significance**
X Knee (deg)	1, 54	44.25	$p < 0.001$
Y Knee (deg)	1, 54	4.87	$p = 0.03$
Z Knee (deg)	1, 54	3.53	$p = 0.07$
Group x Time Interaction			
Variable	***df***	***F***	**Significance**
X Knee (deg)	1, 54	51.93	$p < 0.001$
Y Knee (deg)	1, 54	6.43	$p = 0.01$
Z Knee (deg)	1, 54	3.00	$p = 0.09$

To probe the significant interactions for knee flexion and knee valgus, the simple effects for Time were calculated separately for each treatment group. Among control participants these analyses revealed no significant changes in knee flexion, $F(1, 27) = 0.19$, $p = 0.67$, $\eta_p^2 = 0.01$, or knee valgus $F(1, 27) = 0.39$, $p = 0.54$, $\eta_p^2 = 0.01$. In contrast, the intervention group demonstrated a significant increase, $F(1, 27) = 81.82$, $p < 0.001$, $\eta_p^2 = 0.75$, in knee flexion from pre-test to post-test and a significant decrease, $F(1, 27) = 6.03$, $p = 0.02$, $\eta_p^2 = 0.18$, in knee valgus from pre-test to post-test.

Examination of the simple effects for Group at each Time point revealed no significant Group differences in knee flexion, $F(1, 27) = 0.01$, $p = 0.94$, $\eta_p^2 < 0.001$, or

knee valgus $F(1, 27) = 0.52$, $p = 0.48$, $\eta_p^2 = 0.02$, at pre-test. However, significant Group differences were found in post-test measurements of knee flexion, $F(1, 27) = 47.51$ $p < 0.001$, $\eta_p^2 = 0.64$, and knee valgus $F(1, 27) = 8.08$, $p = 0.01$, $\eta_p^2 = 0.23$. As Figure 8 illustrates, the intervention group demonstrated significantly greater knee flexion than the control group at landing. The intervention group also demonstrated a significant lower extremity adjustment towards knee varus at landing while the control group continued to display an inclination towards knee valgus at contact with the ground.



	Flexion Extension	Valgus Varus	Flexion Extension	Valgus Varus
Control	21.99	-1.75	21.52	-1.95
Intervention	21.83	-0.54	33.54	2.40

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 8: Single Leg Drop Landing Knee Kinematics

4.3.2 Knee Kinematics at Maximum Flexion

A mixed between-within subjects ANOVA was performed on sagittal plane kinematics. The independent variables were Group (2 levels: intervention vs. control)

and Time (2 levels: pre-test vs. post-test). The dependent variable was maximum knee flexion angle. Single leg drop landing kinematics for maximum knee flexion are presented in Table 21.

Table 21

Knee Kinematics at Maximum Flexion

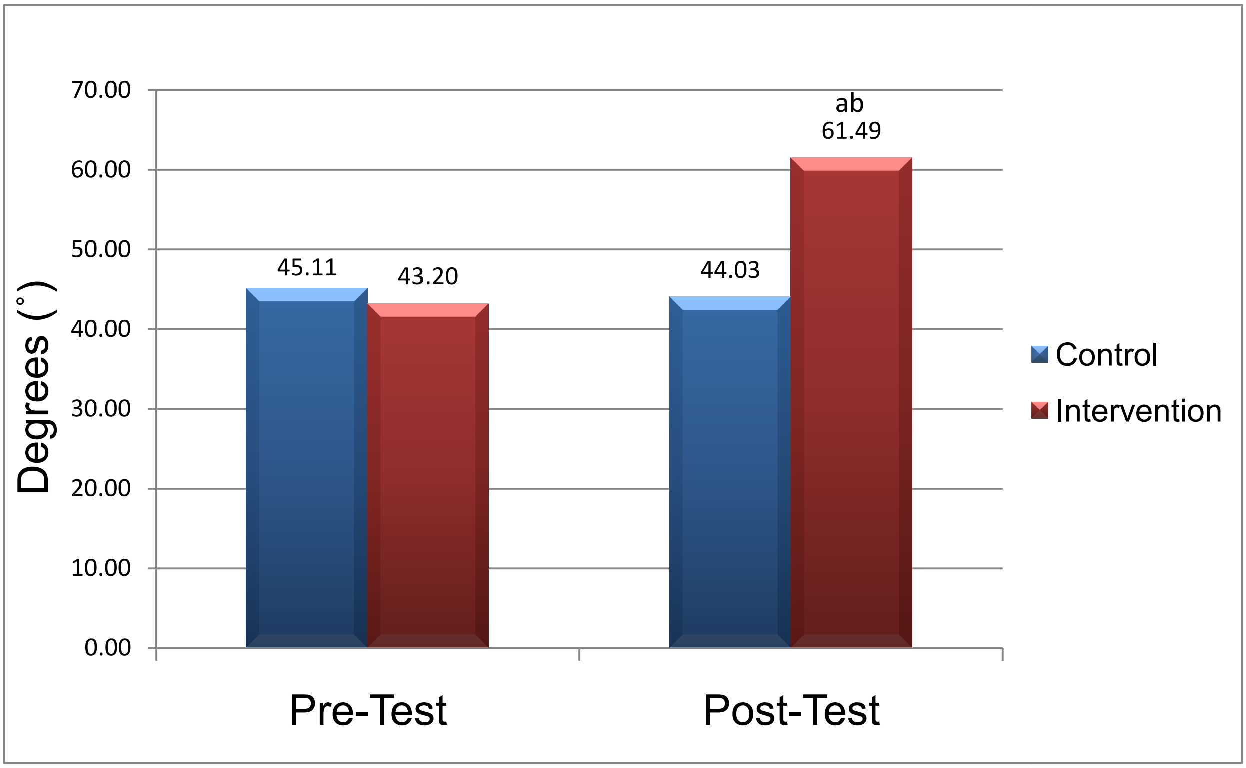
	Pre-Test (Mean ± SD)	Post-Test (Mean ± SD)
Participants	**Maximum Flexion (deg)**	**Maximum Flexion (deg)**
Control	45.11 ± 9.68	44.03 ± 11.52
Intervention	43.20 ± 10.97	61.49 ± 13.52

Given the Wilks' criterion, results indicated a significant interaction between Group x Time, Wilks' $\Lambda = 0.509$, $F(1, 54) = 51.99$, $p < 0.001$, $\eta_p^2 = 0.491$. There was a significant main effect for Time, Wilks' $\Lambda = 0.568$, $F(1, 54) = 41.02$, $p < 0.001$, $\eta_p^2 = 0.432$. The main effect comparing Groups was also found to be significant, $F(1, 54) = 7.90$, $p = 0.01$, $\eta_p^2 = 0.13$.

To probe the significant interaction for maximum knee flexion angle, the simple effects for Time were calculated separately for each treatment group. Among control participants these analyses revealed no significant changes in maximum knee flexion angle, $F(1, 27) = 0.56$, $p = 0.46$, $\eta_p^2 = 0.02$. In contrast, the intervention group demonstrated a significant increase, $F(1, 27) = 65.13$, $p < 0.001$, $\eta_p^2 = 0.71$, in maximum knee flexion angle from pre-test to post-test.

Examination of the simple effects for Group at each Time point revealed no significant Group differences for maximum knee flexion angle, $F(1, 27) = 0.66$, $p = 0.43$, $\eta_p^2 = 0.02$, at pre-test. However, a significant Group difference was found in post-test

measurements of maximum knee flexion angle, $F(1, 27) = 46.60$ $p < 0.001$, $\eta_p^2 = 0.63$. As Figure 9 illustrates, the intervention group demonstrated significantly greater maximum knee flexion than the control group following contact with the ground.



[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 9: Single Leg Drop Landing Knee Kinematics at Maximum Knee Flexion

4.4 KNEE MOMENTS

4.4.1 Knee Moments at Initial Contact

During motion analyses of the single leg drop landing, participants were outfitted with a standard Plug-in Gait marker set. The full marker set consisted of 39 reflective globes. The reflective globes (15 mm) were attached to specific anatomical landmarks and used to define joint centers and axes of rotation. The use of high speed optical cameras allowed subtle variations in human motion to be captured and digitized.

Program software then permitted knee joint kinetics to be calculated frame by frame along each marker path. Single leg drop landing knee moments for participants are presented in Table 22.

Table 22

Knee Moments at Initial Contact

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**Flexion Extension (Nm)**	**Valgus Varus (Nm)**	**Internal External (Nm)**	**Flexion Extension (Nm)**	**Valgus Varus (Nm)**	**Internal External (Nm)**
Control	766.95 ± 878.36	87.81 ± 614.38	36.75 ± 110.56	763.86 ± 867.92	112.45 ± 629.88	41.76 ± 90.83
Intervention	870.91 ± 723.70	72.49 ± 516.67	30.80 ± 84.27	744.17 ± 427.13	53.46 ± 473.09	17.55 ± 84.86

A 2 x 2 Mixed Between-Within subjects MANOVA was performed on single leg drop landing kinetics around the x-axis and y-axis. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were knee flexion-extension moments and knee valgus-varus moments. The direction of the knee moments were characterized by positive and negative values. Positive values were associated with knee flexion and varus. Negative values were associated with knee extension and valgus.

Given the Wilks' criterion, results from the MANOVA indicated no significant interaction between Group x Time, Wilks' $\Lambda = 0.995$, $F(2, 53) = 0.123$, $p = 0.884$, $\eta_p^2 = 0.005$. There was no significant main effect for Time, Wilks' $\Lambda = 0.996$, $F(2, 53) = 0.112$, $p = 0.894$, $\eta_p^2 = 0.004$ and Group, Wilks' $\Lambda = 0.997$, $F(2, 53) = 0.089$, $p = 0.915$, $\eta_p^2 = 0.003$.

Due to the multicolinearity within the knee moment variable grouping (XMoment Knee, YMoment Knee, and ZMoment Knee) ZMoment Knee was removed from the

analysis and a separate mixed between-within subjects ANOVA was performed. The independent variable was Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variable was knee internal-external rotation moment. The direction of the knee moment was characterized by positive and negative values. Positive values were associated with external rotation. Negative values were associated with knee internal rotation.

Given the Wilks' criterion, results indicated no significant interaction between Group x Time, Wilks' Λ = 0.992, $F(1, 54) = 0.428$, $p < 0.516$, $\eta_p^2 = 0.008$. There was no significant main effect for Time, Wilks' Λ = 0.998, $F(1, 54) = 0.087$, $p < 0.769$, $\eta_p^2 = 0.002$. The main effect comparing Groups was not found to be significant $F(1, 54) = 0.534$, $p = .468$, $\eta_p^2 = 0.010$.

4.4.2 Knee Moments at Maximum Flexion

A mixed between-within subjects ANOVA was performed on sagittal plane knee moment at maximum flexion. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variable was maximum knee flexion moment. Single leg drop landing kinetics for maximum knee flexion moment are presented in Table 23.

Table 23

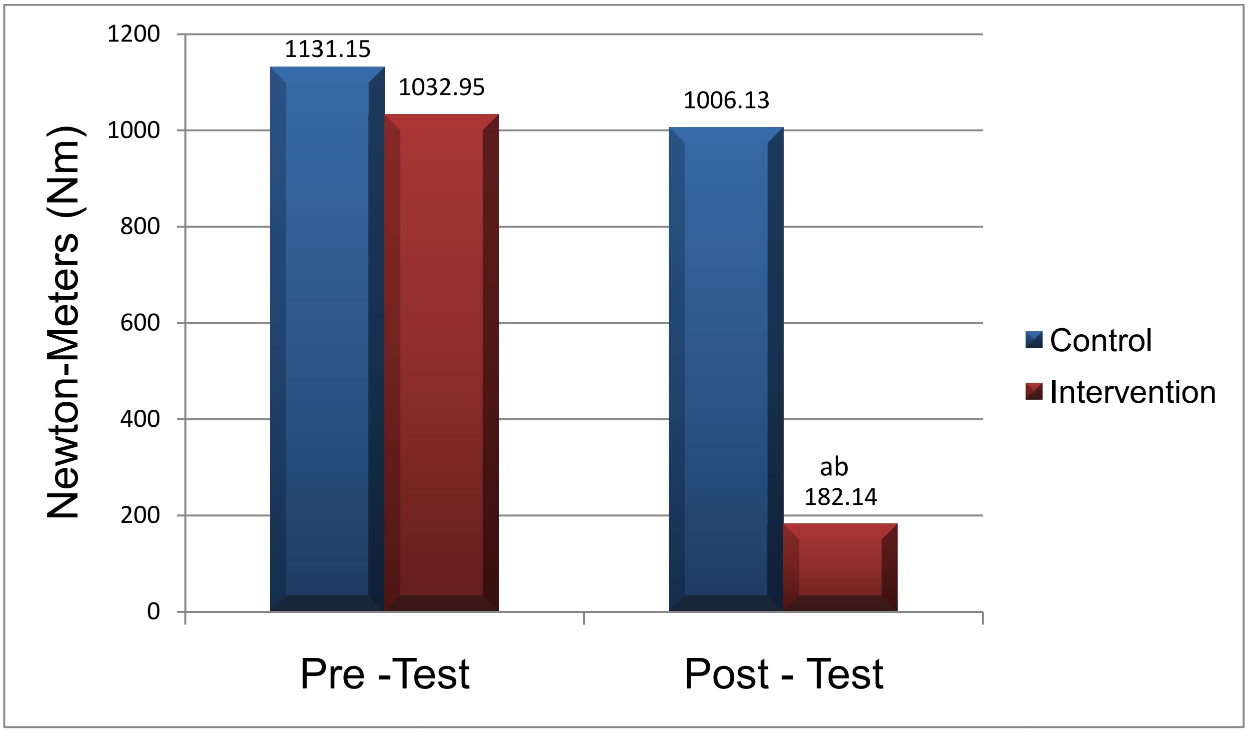
Knee Moments at Maximum Flexion

	Pre-Test (Mean ± SD)	**Post-Test (Mean ± SD)**
Participants	**Maximum Flexion (Nm)**	**Maximum Flexion (Nm)**
Control	1131.15 ± 585.62	1006.13 ± 605.11
Intervention	1032.95 ± 630.08	182.14 ± 448.20

Given the Wilks' criterion, results indicated a significant interaction between Group x Time, Wilks' Λ = 0.760, $F(1, 54) = 17.04$, $p < 0.001$, $\eta_p^2 = 0.240$. There was a significant main effect for Time, Wilks' Λ = 0.637, $F(1, 54) = 30.81$, $p < 0.001$, $\eta_p^2 = 0.363$. The main effect comparing Groups was also found to be significant, $F(1, 54) = 13.62$, $p = 0.001$, $\eta_p^2 = 0.201$.

To probe the significant interaction for maximum knee flexion moment, the simple effects for Time were calculated separately for each treatment group. Among control participants these analyses revealed no significant changes in maximum knee flexion moment, $F(1, 27) = 0.80$, $p = 0.34$, $\eta_p^2 = 0.03$. In contrast, the intervention group demonstrated a significant decrease, $F(1, 27) = 63.63$, $p < 0.001$, $\eta_p^2 = 0.70$, in maximum knee flexion moment from pre-test to post-test.

Examination of the simple effects for Group at each Time point revealed no significant Group differences in maximum knee flexion moment, $F(1, 27) = 0.39$, p = 0.54, $\eta_p^2 = 0.01$ at pre-test. However, a significant Group difference was found in post-test measurements of maximum knee flexion moment, $F(1, 27) = 62.93$ $p < 0.001$, $\eta_p^2 = 0.70$. As Figure 10 illustrates, the intervention group demonstrated significantly less maximum knee flexion moment than the control group following contact with the ground.



[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 10: Single Leg Drop Landing Knee Moment at Maximum Flexion

4.5 EMG OF LOWER EXTREMITY MUSCULATURE

Select quadriceps (vastus lateralis, vastus medialis), hamstrings (semitendinosus, semimembranosus), and gastrocnemius (lateral head, medial head) muscle activity were captured using wireless myomonitor transmission and datalogging. The Delsys EMG system was used to collect measures of peak amplitude and onset time during drop landing trials. Peak amplitude was calculated as a percentage of the maximum voluntary contraction (MVC) value obtained during signal testing. Onset time was recorded as the moment the muscle response exceeded a threshold equivalent to two standard deviations of the peak amplitude achieved during that individual trial. EMG for the quadriceps, hamstrings, and gastrocnemius are presented in Table 24.

Table 24

EMG of Lower Extremity Musculature

		Pre-Test (Mean ± SD)		Post-Test (Mean ± SD)	
Muscle	**Participants**	**Amplitude (% of MVC)**	**Onset Time (ms)**	**Amplitude (% of MVC)**	**Onset Time (ms)**
Vastus Medialis	Control	58.67 ± 16.48	87.19 ± 25.21	57.40 ± 21.45	123.16 ± 37.63
	Intervention	63.59 ± 16.94	90.27 ± 29.98	61.46 ± 16.13	165.24 ± 48.92
Vastus Lateralis	Control	45.43 ± 22.20	88.75 ± 11.57	58.21 ± 18.97	82.88 ± 11.65
	Intervention	49.40 ± 21.01	91.00 ± 11.54	65.66 ± 15.37	89.15 ± 12.80
Semi-Membranosus	Control	34.74 ± 19.04	109.24 ± 12.35	34.70 ± 16.59	109.23 ± 14.05
	Intervention	31.82 ± 14.18	104.12 ± 10.83	49.81 ± 18.77	124.41 ± 15.44
Semi-Tendonosus	Control	52.22 ± 21.82	84.74 ± 5.95	49.22 ± 22.52	83.15 ± 5.50
	Intervention	50.94 ± 16.99	83.22 ± 5.09	51.91 ± 19.50	86.19 ± 6.97
Gastrocnemius – Medial Head	Control	48.81 ± 19.54	142.34 ± 33.76	52.44 ± 15.16	127.41 ± 26.70
	Intervention	47.49 ± 18.16	131.55 ± 37.14	54.32 ± 15.63	125.57 ± 24.97
Gastrocnemius – Lateral Head	Control	50.19 ± 22.08	121.23 ± 23.97	52.89 ± 20.39	115.84 ± 20.12
	Intervention	51.36 ± 21.19	110.82 ± 15.84	57.02 ± 22.48	117.96 ± 22.94

A 2 x 2 mixed between-within subjects MANOVA was performed on single leg drop landing EMG of the lower extremity muscles. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were peak amplitude and onset time of select muscles in the quadriceps, hamstrings, and gastrocnemius. Onset times for the vastus lateralis, semi-membranosus, and semi-tendonosus were not included in the analysis because of the multicollinearity exhibited among variables entered into the analysis.

Given the Wilks' criterion, results from the MANOVA indicated a significant interaction between Group x Time, Wilks' Λ = 0.603, $F(9, 46) = 3.361$, $p = 0.003$, η_p^2 =

0.397. There was a significant main effect for Time, Wilks' Λ = 0.303, $F(9, 46) = 11.783$, $p < 0.001$, $\eta_p^2 = 0.697$ but not for Group, Wilks' Λ = 0.715, $F(9, 46) = 2.036$, $p = 0.056$, $\eta_p^2 = 0.285$. In an effort to better understand the results from the MANOVA, an examination of the univariate findings surrounding each of the lower extremity EMG variables was conducted. Results from the analyses are presented in Table 25.

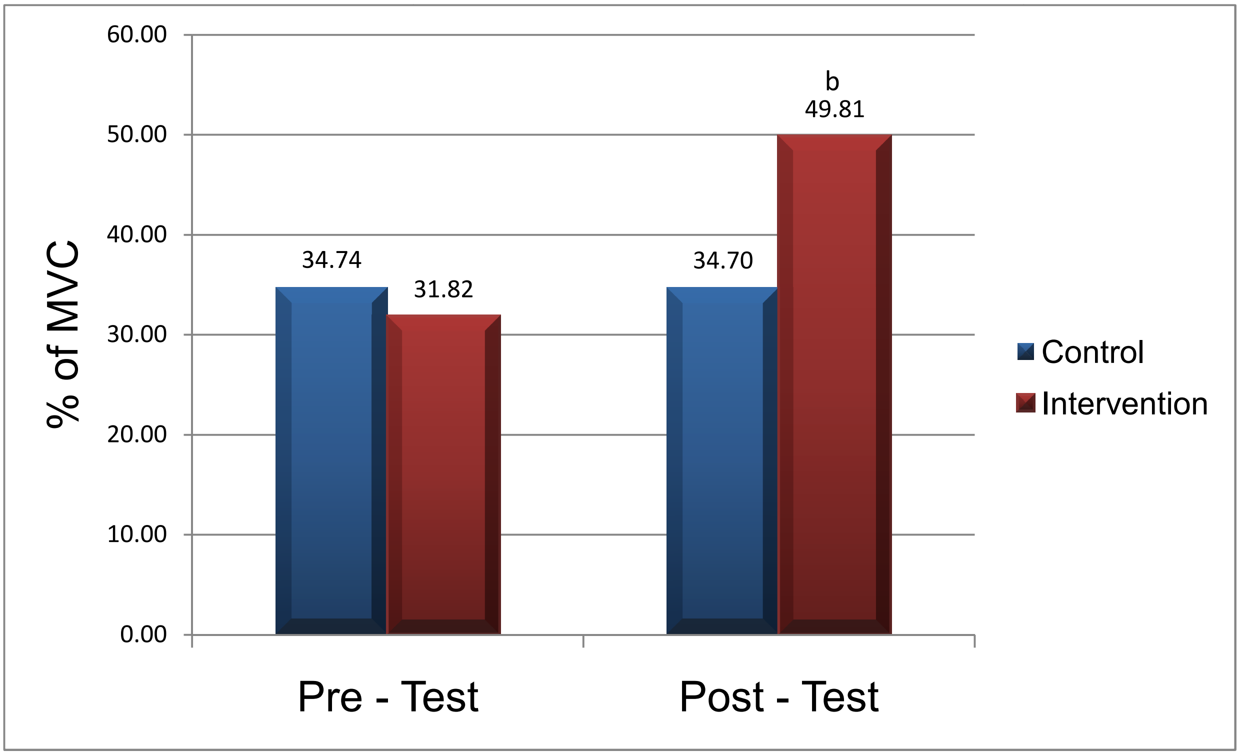
Table 25

Results of Univariate ANOVA's for EMG of Lower Extremity Musculature

Group Main Effect						
	df		***F***		**significance**	
Variable	**Amplitude**	**Onset Time**	**Amplitude**	**Onset Time**	**Amplitude**	**Onset Time**
Vastus Medialis	1, 54		1.38	11.96	$p = 0.25$	$p = 0.001$
Vastus Lateralis	1, 54		2.05		$p = 0.16$	
Semi-Membranosus	1,54		2.35		$p = 0.13$	
Semi-Tendonosus	1,54		0.02		$p = 0.88$	
Gastrocnemius – MH	1,54		0.01	0.92	$p = 0.94$	$p = 0.34$
Gastrocnemius – LH	1,54		0.33	0.91	$p = 0.57$	$p = 0.35$
Time Main Effect						
	df		***F***		**Significance**	
Variable	**Amplitude**	**Onset Time**	**Amplitude**	**Onset Time**	**Amplitude**	**Onset Time**
Vastus Medialis	1, 54		0.35	58.28	$p = 0.56$	$p < 0.001$
Vastus Lateralis	1, 54		18.45		$p < 0.001$	
Semi-Membranosus	1,54		14.69		$p < 0.001$	
Semi-Tendonosus	1,54		0.12		$p = 0.73$	

Gastrocnemius – MH	1,54		3.88	4.31	p = 0.05	p = 0.04
Gastrocnemius – LH	1,54		1.44	0.07	p = 0.24	p = 0.80
Group x Time Interaction						
	df		***F***		**Significance**	
Variable	**Amplitude**	**Onset Time**	**Amplitude**	**Onset Time**	**Amplitude**	**Onset Time**
Vastus Medialis	1, 54		0.02	7.20	p = 0.88	p = 0.10
Vastus Lateralis	1, 54		0.27		p = 0.609	
Semi-Membranosus	1,54		14.84		p < 0.001	
Semi-Tendonosus	1,54		0.47		p = 0.50	
Gastrocnemius – MH	1,54		0.36	0.79	p = 0.55	p = 0.38
Gastrocnemius – LH	1,54		0.18	3.33	p = 0.67	p = 0.07

To probe the significant interaction for semi-membranosus amplitude, the simple effects for Time were calculated separately for each treatment group. Among control participants these analyses revealed no significant changes in semi-membranosus amplitude, $F(1, 27) < 0.001$, $p = 0.99$, $\eta_p^2 < 0.001$. In contrast, the intervention group demonstrated a significant increase, $F(1, 27) = 28.11$, $p < 0.001$, $\eta_p^2 = 0.51$, in semi-membranosus amplitude from pre-test to post-test. As Figure 11 illustrates, the intervention group demonstrated significantly greater semi-membranosus amplitude at contact with the ground while control group demonstrated no significant change in semi-membranosus amplitude at post-test.



[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 11: Single Leg Drop Landing EMG – Semi-Membranosus Amplitude

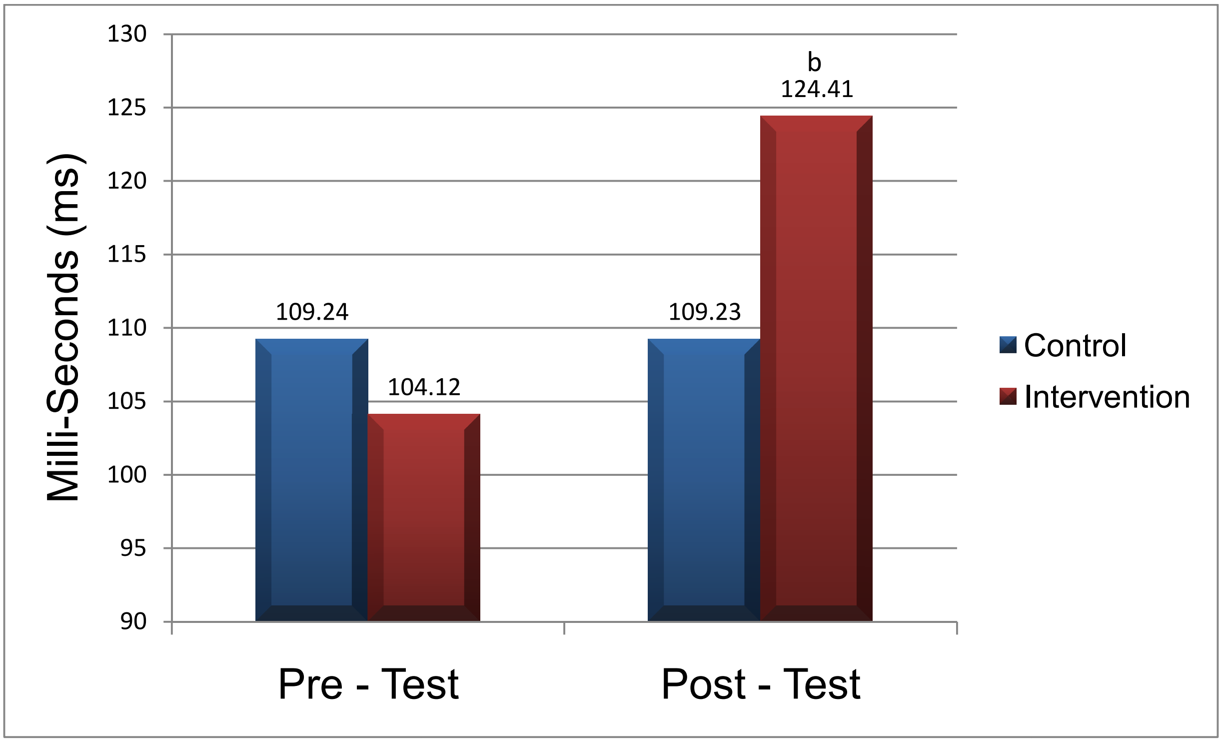
Due to the multicolinearity within the lower extremity EMG variable grouping (quadriceps, hamstrings, and gastrocnemius amplitude - onset times), vastus lateralis, semi-membranosus, and semi-tendonosus onset times were removed from analysis and separate mixed between-within subjects ANOVA's were performed on each variable. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were onset times for the vastus lateralis, semi-membranosus, and semi-tendonosus.

Given the Wilks' criterion, results for vastus lateralis onset time indicated no significant interaction between Group x Time, Wilks' Λ = 0.980, $F(1, 54) = 1.088$, p = 0.302, $\eta_p^2 = 0.020$. There was no significant main effect for Time, Wilks' Λ = 0.931, F(1,

54) = 4.007, p = 0.069, η_p^2 = 0.058. The main effect comparing Groups was not found to be significant F(1, 54) = 2.84, p = 0.098, η_p^2 = 0.050.

Results for semi-membranosus onset time indicated a significant interaction between Group x Time, Wilks' Λ = 0.727, F(1, 54) = 20.28, p < 0.001, η_p^2 = 0.273. There was a significant main effect for Time, Wilks' Λ = 0.725, F(1, 54) = 20.468, p < 0.001, η_p^2 = 0.275. However, the main effect comparing Groups was not found to be significant, F(1, 54) = 3.31, p = 0.074, η_p^2 = 0.058.

To probe the significant interaction for semi-membranosus onset time, the simple effects for Time were calculated separately for each treatment group. Among control participants these analyses revealed no significant changes in semi-membranosus onset time, F(1, 27) < 0.001, p = 0.99, η_p^2 < 0.001. In contrast, the intervention group demonstrated a significant increase, F(1, 27) = 34.41, p < 0.001, η_p^2 = 0.56, in semi-membranosus onset time from pre-test to post-test. As Figure 12 illustrates, the intervention group demonstrated significantly greater semi-membranosus onset time at contact with the ground while control group demonstrated no significant change in semi-membranosus onset time at post-test.



[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 12: Single Leg Drop Landing EMG – Semi-Membranosus Onset Times

Results for semi-tendonosus onset time indicated a significant interaction between Group x Time, Wilks' Λ = 0.923, $F(1, 54) = 4.533$, $p = 0.038$, $\eta_p^2 = 0.077$. There was no significant main effect for Time, Wilks' Λ = 0.992, $F(1, 54) = 0.417$, $p = 0.521$, $\eta_p^2 = 0.008$. The main effect comparing Groups was not found to be significant $F(1, 54) = 0.42$, $p = 0.52$, $\eta_p^2 = 0.01$.

4.6 CENTER OF MASS

The ACL injury prevention program training protocol incorporated calisthenics that focused on the development of core musculature. Increased core musculature strength was surmised to improve active stabilization of the participant during single leg drop landing testing. The Vicon motion analysis system was employed to track

variability of COM excursion along the frontal, sagittal, and longitudinal axis. Measurements for variability of COM excursion are presented in Table 27.

Table 26

Center of Mass

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**Medial Lateral (SD)**	**Anterior Posterior (SD)**	**Vertical (SD)**	**Medial Lateral (SD)**	**Anterior Posterior (SD)**	**Vertical (SD)**
Control	4.21 ± 2.04	14.41 ± 5.50	14.83 ± 8.51	4.26 ± 2.83	14.36 ± 6.67	12.96 ± 8.08
Intervention	4.68 ± 2.63	16.46 ± 6.48	14.71 ± 7.08	4.51 ± 2.14	15.89 ± 6.47	16.39 ± 6.51

A 2 x 2 mixed between-within subjects MANOVA was performed on variability of COM excursion during a single leg drop landing. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were measures of the variability associated with medial-lateral excursion along the x-axis, anterior-posterior excursion along the y-axis, and vertical excursion along the z-axis. Variability of COM excursion was characterized as the body's relative position from initial contact with the ground to maximum knee flexion.

Given the Wilks' criterion, results from the MANOVA indicated a significant interaction between Group x Time, Wilks' Λ = 0.800, $F(3, 52) = 4.323$, $p = 0.009$, $\eta_p^2 = 0.200$. There was no significant main effect for Time, Wilks' Λ = 0.982, F(3, 52) = 0.325, $p = 0.807$, $\eta_p^2 = 0.018$ or Group, Wilks' Λ = 0.974, $F(3, 52) = 0.463$, $p = 0.709$, $\eta_p^2 = 0.026$.

4.7 VERTICAL GROUND REACTION FORCE

Ground reaction forces are equal in magnitude and opposite in direction to the amount of force the body exerts at contact with the ground. Foot strikes generate mediolateral (Fx), anteroposterior (Fy), and vertical (Fz) ground reaction forces. A three dimensional AMTI force plate was used to assess vertical (Fz) ground reaction force. Ground reaction force was normalized to body weight. Vertical ground reaction force values for participants are presented in Table 27.

Table 27

Vertical Ground Reaction Force

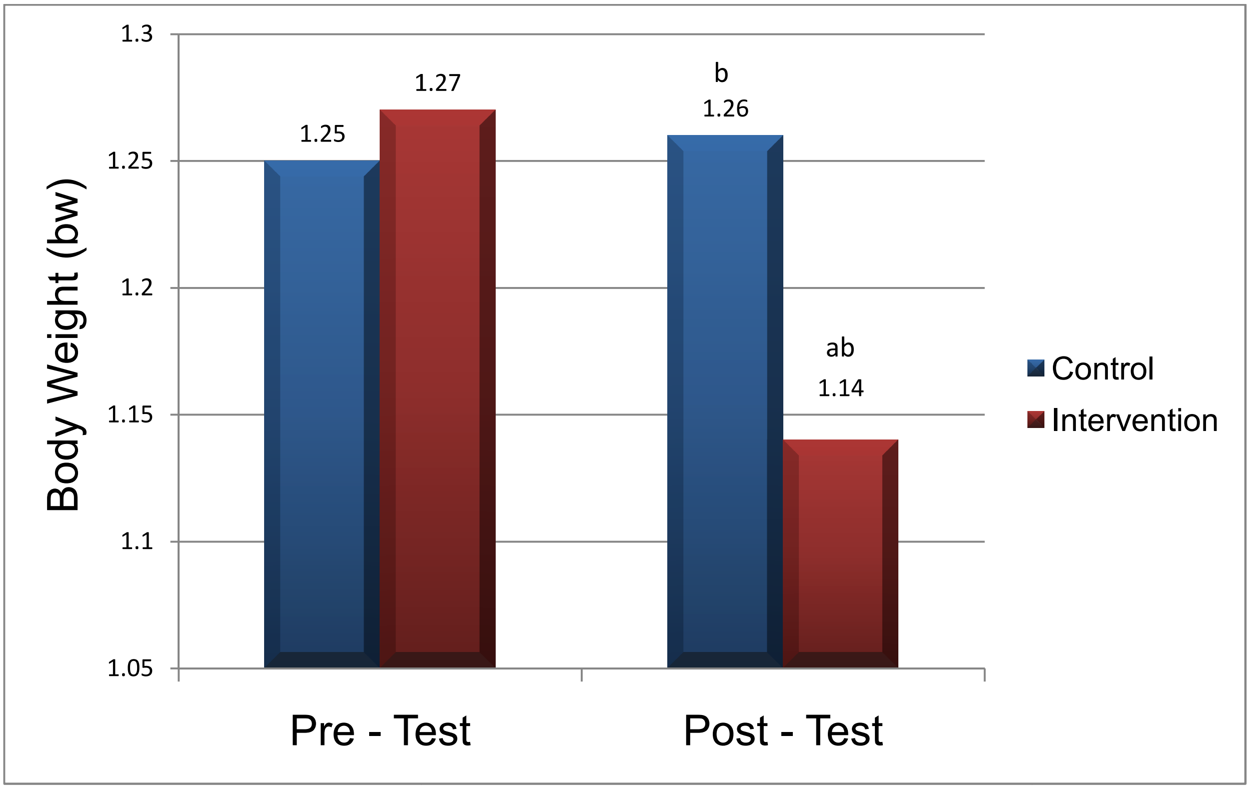
	Pre-Test (Mean ± SD)	**Post-Test (Mean ± SD)**
Participants	**VGRF (bw)**	**VGRF (bw)**
Control	1.25 ± 0.07	1.27 ± 0.07
Intervention	1.26 ± 0.06	1.14 ± 0.06

A mixed between-within subjects ANOVA was performed on ground reaction force. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test and post-test). The dependent variable was vertical ground reaction force. Given the Wilks' criterion, results indicated a significant interaction between Group x Time, Wilks' $\Lambda = 0.401$, $F(1, 54) = 80.674$, $p < 0.001$, $\eta_p^2 = 0.599$. There was a significant main effect for Time, Wilks' $\Lambda = 0.555$, $F(1, 54) = 43.343$, $p < 0.001$, $\eta_p^2 = 0.445$. The main effect comparing Groups was also found to be significant, $F(1, 54) = 15.063$, $p < 0.001$, $\eta_p^2 = 0.218$.

To probe the significant interaction for vertical ground reaction force, the simple effects for Time were calculated separately for each treatment group. Among control

participants these analyses revealed a significant increase in vertical ground reaction force, $F(1, 27) = 4.84$, $p = 0.04$, $\eta_p^2 = 0.15$. In contrast, the intervention group demonstrated a significant decrease, $F(1, 27) = 86.17$, $p < 0.001$, $\eta_p^2 = 0.76$, in vertical ground reaction force from pre-test to post-test.

Examination of the simple effects for Group at each Time point revealed no significant Group difference in vertical ground reaction force, $F(1, 27) = 0.26$, $p = 0.61$, $\eta_p^2 = 0.01$, at pre-test. However, a significant Group difference was found in post-test measurements in vertical ground reaction force, $F(1, 27) = 84.59$ $p < 0.001$, $\eta_p^2 = 0.76$. As Figure 13 illustrates, the intervention group demonstrated significantly less vertical ground reaction force than the control group at contact with the ground. The control group exhibited a significant increase in vertical ground reaction force at post-test.



[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 13: Single Leg Drop Landing Vertical Reaction Ground Reaction Force

4.8 KNEE JOINT PROPRIOCEPTION

Knee joint proprioception is the spatial sensitivity arising from stimuli within the body to changes in knee orientation. The Biodex 3 ® Isokinetic Dynamometer was used to quantify the absolute error associated with active angle reproduction at 15°, 30°, and 45°. Absolute error represented the difference between the mechanical orientation of the test limb to an exact angle of flexion and the participant's estimation of the perceived angle. Measures of knee joint position sense at 15°, 30°, and 45° are presented in Table 28.

Table 28

Knee Joint Proprioception

	Pre-Test (Mean ± SD)			**Post-Test (Mean ± SD)**		
Participants	**15° (abs)**	**30° (abs)**	**45° (abs)**	**15° (abs)**	**30° (abs)**	**45° (abs)**
Control	6.15 ± 2.88	5.41 ± 1.85	5.14 ± 2.78	5.42 ± 2.25	5.31 ± 2.28	5.35 ± 2.19
Intervention	5.62 ± 2.02	5.47 ± 2.00	5.10 ± 2.28	3.40 ± 1.34	3.60 ± 1.59	3.49 ± 1.78

A 2 x 2 mixed between-within subjects MANOVA was performed on knee joint proprioception. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were active knee joint position sense at 15˚, 30˚, and 45˚. Given the Wilks' criterion, results from the MANOVA indicated a significant interaction between Group x Time, Wilks' $\Lambda = 0.823$, $F(3, 52) = 3.722$, $p = 0.017$, $\eta_p^2 = 0.177$. There was a significant main effect for Time, Wilks' $\Lambda = 0.688$, $F(3, 52) = 7.871$, $p < 0.001$, $\eta_p^2 = 0.312$ and Group, Wilks' $\Lambda = 0.834$, $F(3, 52) = 3.443$, $p = 0.023$, $\eta_p^2 = 0.166$. In an effort to better understand the results from the MANOVA, an examination of the univariate findings surrounding each of knee joint proprioception variables was conducted. Results from the analyses are presented in Table 29.

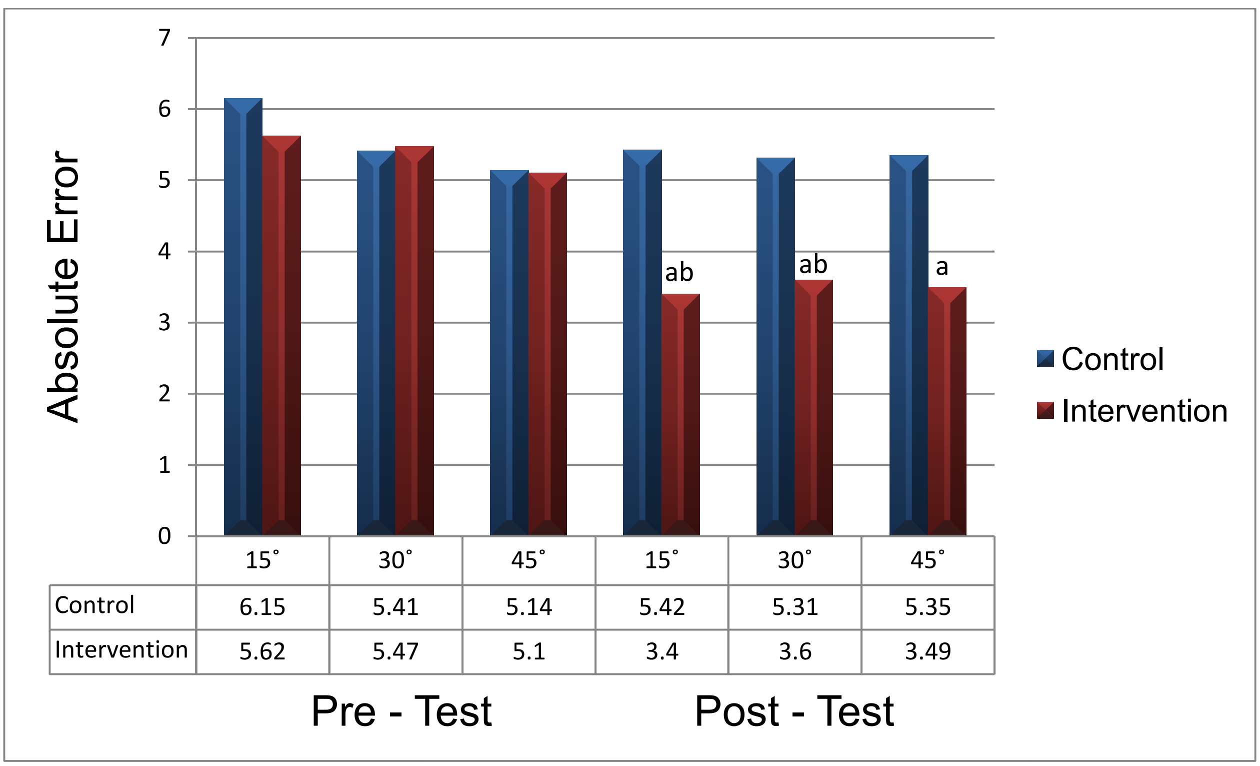
Table 29

Results of Univariate ANOVA's for Knee Joint Proprioception

Group Main Effect			
Variable	***df***	***F***	**significance**
Prop 15 (abs error)	1, 54	7.37	p = 0.01
Prop 30 (abs error)	1, 54	4.49	p = 0.04
Prop 45 (abs error)	1, 54	4.66	p = 0.04
Time Main Effect			
Variable	***df***	***F***	**significance**
Prop 15 (abs error)	1, 54	17.84	p < 0.001
Prop 30 (abs error)	1, 54	8.18	p = 0.01
Prop 45 (abs error)	1, 54	2.71	p = 0.11
Group x Time Interaction			
Variable	***df***	***F***	**significance**
Prop 15 (abs error)	1, 54	4.52	p = 0.04
Prop 30 (abs error)	1, 54	6.64	p = 0.01
Prop 45 (abs error)	1, 54	4.53	p = 0.04

To probe the significant interactions for active knee joint position sense at 15˚ and 30˚, the simple effects for Time were calculated separately for each treatment group. Among control participants these analyses revealed no significant changes in active knee joint position sense at 15˚, (F(1, 27) = 1.86, p = 0.18, η_p^2 = 0.07, or 30˚, F(1, 27) = 0.05, p = 0.83, η_p^2 = 0.002. In contrast, the intervention group demonstrated a significant increase, F(1, 27) = 24.64, p < 0.001, η_p^2 = 0.48, in active knee joint position sense at 15˚ and a significant increase, F(1, 27) = 13.05, p = 0.001, η_p^2 = 0.33, in active knee joint position sense at 30˚ from pre-test to post-test.

Examination of the simple effects for Group at each Time point revealed no significant Group differences active knee joint position sense at 15˚, $F(1, 27) = 0.63$, p = 0.44, $\eta_p^2 = 0.02$, 30˚ $F(1, 27) = 0.02$, $p = 0.90$, $\eta_p^2 = 0.001$, or 45˚ $F(1, 27) = 0.01$, $p = 0.94$, $\eta_p^2 < 0.001$ at pre-test. However, significant Group differences were found in post-test measurements of active knee joint position sense at 15˚, $F(1, 27) = 13.58$, $p < 0.001$, $\eta_p^2 = 0.34$, 30˚ $F(1, 27) = 9.58$, $p = 0.01$, $\eta_p^2 = 0.26$, and 45˚ $F(1, 27) = 13.03$, $p < 0.001$, $\eta_p^2 = 0.33$. As Figure 14 illustrates, the intervention group demonstrated significantly greater active knee joint position sense at 15˚ and 30˚. The intervention group demonstrated significantly greater knee joint proprioception than the control group at 15˚ and 30˚, and 45˚.



	15˚	30˚	45˚	15˚	30˚	45˚
Control	6.15	5.41	5.14	5.42	5.31	5.35
Intervention	5.62	5.47	5.1	3.4	3.6	3.49

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 14: Knee Joint Proprioception at 15˚, 30˚, and 45˚ of Knee Flexion

4.9 ANTERIOR KNEE JOINT LAXITY

Knee joint laxity is the amount of anterior tibial translation permitted by the ligamentous tissues within the knee joint. Anterior knee laxity is generally used as an indirect measure of the tensile strength of the anterior cruciate ligament. Anterior knee joint laxity was quantified using the KT- 1000 Knee Arthrometer. An anterior passive drawer test and manual maximum drawer test were performed. The anterior passive drawer test was conducted at a displacement load of 133 N (30 lb). The manual maximum drawer test was conducted to ascertain the maximum anterior tibial translation permitted at the knee joint. Both measures of anterior knee joint laxity are presented in Table 30.

Table 30

Anterior Knee Joint Laxity

	Pre-Test (Mean ± SD)		Post-Test (Mean ± SD)	
Participants	**PD 133N (mm)**	**MMD (mm)**	**PD 133N (mm)**	**MMD (mm)**
Control	6.10 ± 1.75	12.21 ± 1.78	6.38 ± 1.83	12.48 ± 1.89
Intervention	5.96 ± 1.75	12.34 ± 2.40	4.77 ± 1.43	10.57 ± 1.89

A 2 x 2 mixed between-within subjects MANOVA was performed on anterior knee joint laxity measures. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were passive drawer and maximum manual drawer measures of anterior knee joint laxity. Given the Wilks' criterion, results from the MANOVA indicated a significant interaction between Group x Time, Wilks' Λ = 0.608, $F(2, 53) = 17.057$, $p < 0.001$, $\eta_p^2 = 0.392$. There was a significant main effect for Time, Wilks' Λ = 0.773, $F(2, 53) = 7.760$, p = 0.001, $\eta_p^2 = 0.227$ but not for Group, Wilks' Λ = 0.918, $F(2, 53) = 2.368$, $p = 0.103$, η_p^2 =

0.082. In an effort to better understand the results from the MANOVA, an examination of the univariate findings surrounding each of the anterior laxity variables was conducted. Results from the analyses are presented in Table 31

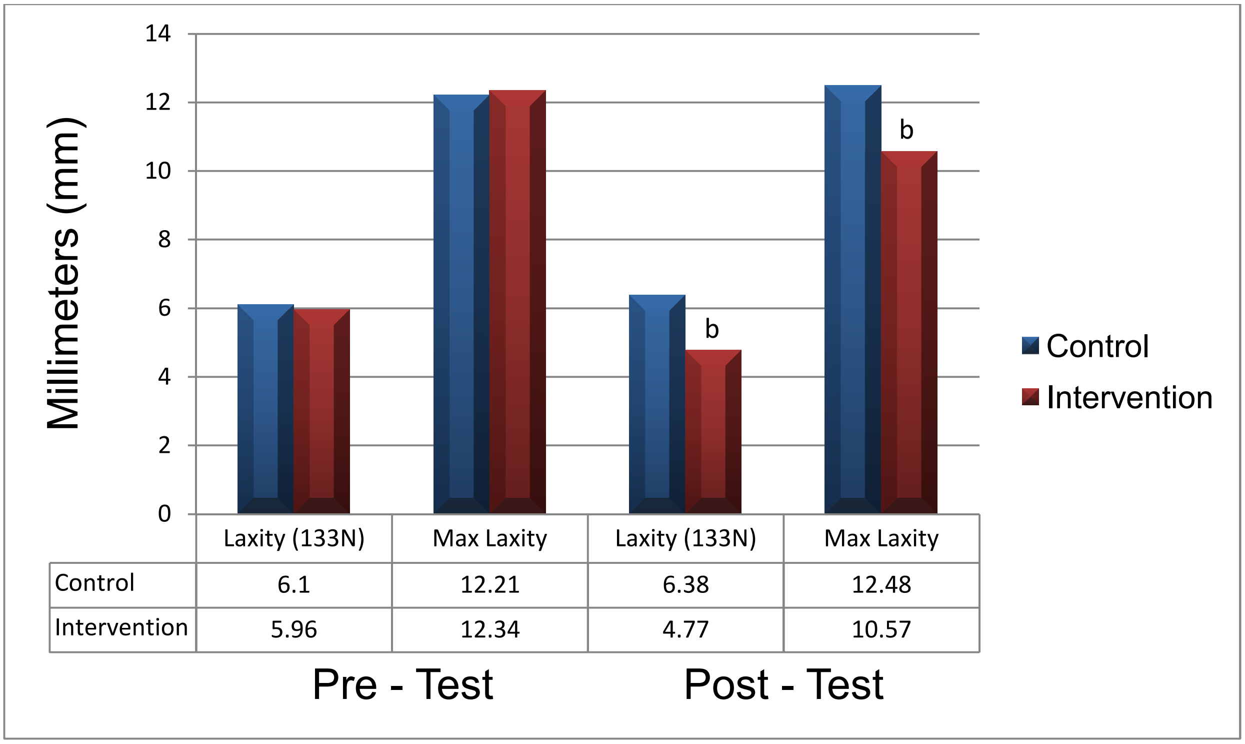
Table 31

Results of Univariate ANOVA's for Anterior Knee Joint Laxity

Group Main Effect			
Variable	***df***	***F***	**significance**
PD 133N (mm)	1, 54	4.28	$p = 0.04$
Lachman (mm)	1, 54	3.47	$p = 0.07$
Time Main Effect			
Variable	***df***	***F***	**significance**
PD 133N (mm)	1, 54	7.27	$p = 0.01$
Lachman (mm)	1, 54	9.69	$p = 0.003$
Group x Time Interaction			
Variable	***df***	***F***	**significance**
PD 133N (mm)	1, 54	19.46	$p < 0.001$
Lachman (mm)	1, 54	17.85	$p < 0.001$

To probe the significant interactions for passive drawer and maximum manual drawer measures of anterior knee joint laxity, the simple effects for Time were calculated separately for each treatment group. Among control participants these analyses revealed no significant changes in anterior knee joint laxity for either passive drawer, $F(1, 27) = 2.43$, $p = 0.13$, $\eta_p^2 = 0.08$, or maximum manual drawer, $F(1, 27) = 0.68$, $p = 0.41$, $\eta_p^2 = 0.02$, measures of anterior knee joint laxity. In contrast, the intervention group demonstrated a significant decrease, $F(1, 27) = 18.11$, $p < 0.001$, $\eta_p^2 = 0.40$, in passive drawer and a significant decrease, $F(1, 27) = 24.81$, $p < 0.001$,

$\eta_p^{\ 2}$ = 0.48, in maximum manual drawer measures of anterior knee joint laxity from pre-test to post-test. As Figure 15 illustrates, the intervention group demonstrated significantly less passive and maximum laxity at post-test.



[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Figure 15: Anterior Knee Joint Laxity – PD (133N) and Max

4.10 HAMSTRINGS:QUADRICEPS STRENGTH AND TIME TO PEAK TORQUE

4.10.1 $H_{CON}Q_{CON}$ STRENGTH AND TIME TO PEAK TORQUE

The Biodex 3 ® Isokinetic Dynamometer was also used to quantify peak concentric hamstrings torque and peak concentric quadriceps torque. Testing was conducted at an angular velocity of 300°/s. Results from isokinetic testing were used to determine conventional H_{CON}:Q_{CON} strength ratio. Time to peak torque was also measured for the hamstrings and quadriceps. Results from isokinetic testing of the knee are presented in Table 32.

Table 32

H_{CON}:Q_{CON} Strength and Time to Peak Torque

	Pre-Test (Mean ± SD)			**Post-Test (Mean ± SD)**		
Participants	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**
Control	83.21 ± 24.35	136.43 ± 28.70	0.69 ± 0.14	81.79 ± 14.92	123.21 ± 31.51	0.67 ± 0.13
Intervention	90.71 ± 24.93	146.07 ± 39.57	0.71 ± 0.15	76.07 ± 13.43	117.50 ± 23.19	0.78 ± 0.13

A 2 x 2 mixed between-within subjects MANOVA was performed on measures of lower extremity strength. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were time to peak torque of the quadriceps and hamstrings. Given the Wilks' criterion, results from the MANOVA indicated no significant interaction between Group x Time, Wilks' Λ = 0.904, F(2, 53) = 2.825, p = 0.068, η_p^2 = 0.096. There was a significant main effect for Time, Wilks' Λ = 0.728, F(2, 53) = 9.20, p < 0.001, η_p^2 = 0.272 but not for Group, Wilks' Λ = 0.998, F(2, 53) = 0.043, p = 0.958, η_p^2 = 0.002.

Due to the multicolinearity within the strength variable grouping (time to peak torque of the Hamstrings-Quadriceps, and conventional H_{CON}:Q_{CON} strength ratio), H_{CON}:Q_{CON} strength ratio was removed from analysis and a separate mixed between-within subjects ANOVA was performed. The independent variable was Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variable was H_{CON}:Q_{CON} strength ratio.

Given the Wilks' criterion, results indicated a significant interaction between Group x Time, Wilks' Λ = 0.902, F(1, 54) = 5.883, p = 0.019, η_p^2 = 0.098, but no significant main effect for Time, Wilks' Λ = 0.959, F(1, 54) = 2.283, p = 0.137, η_p^2 =

0.041. The main effect comparing Groups was not found to be significant $F(1, 54) = 3.89$, $p = 0.05$, $\eta_p^2 = 0.067$.

4.10.2 $H_{CON}Q_{ECC}$ STRENGTH AND TIME TO PEAK TORQUE

The Biodex 3 ® Isokinetic Dynamometer was used to quantify peak concentric hamstrings torque and peak eccentric quadriceps torque. Testing was conducted at an angular velocity of 300°/s. Results from isokinetic testing were used to determine functional $H_{CON}:Q_{ECC}$ strength ratio. Time to peak torque was also measured for the hamstrings and quadriceps. Results from isokinetic testing of the knee are presented in Table 33.

Table 33

$H_{CON}:Q_{ECC}$ Strength and Time to Peak Torque

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**
Control	201.79 ± 61.04	196.07 ± 29.86	0.97 ± 0.12	202.15 ± 49.02	220.36 ± 38.34	1.01 ± 0.11
Intervention	216.43 ± 63.38	204.64 ± 39.57	0.98 ± 0.12	175.00 ± 57.45	204.29 ± 30.60	0.99 ± 0.09

A 2 x 2 mixed between-within subjects MANOVA was performed on measures of anterior and posterior lower extremity strength. The independent variables were Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variables were time to peak torque of the quadriceps and hamstrings. Given the Wilks' criterion, results from the MANOVA indicated a significant interaction between Group x Time, Wilks' $\Lambda = 0.820$, $F(2, 53) = 5.830$, $p = 0.005$, $\eta_p^2 = 0.180$. There was no significant main effect for Time, Wilks' $\Lambda = 0.902$, $F(2, 53) = 2.891$, $p = 0.064$, $\eta_p^2 = 0.098$ and Group, Wilks' $\Lambda = 0.987$, $F(2, 53) = 0.345$, $p = 0.710$, $\eta_p^2 = 0.013$.

Due to the multicolinearity within the strength variable grouping (time to peak torque Hamstrings - Quadriceps, and functional H:Q strength), $H_{CON}:Q_{ECC}$ strength ratio was removed from the analysis and a separate mixed between-within subjects ANOVA was performed. The independent variable was Group (2 levels: intervention vs. control) and Time (2 levels: pre-test vs. post-test). The dependent variable was $H_{CON}:Q_{ECC}$ strength ratio. Given the Wilks' criterion, results indicated no significant interaction between Group x Time, Wilks' Λ = 0.989, $F(1, 54) = 0.578$, $p = 0.450$, $\eta_p^2 = 0.011$. There was no significant main effect for Time, Wilks' Λ = 0.967, $F(1, 54) = 1.819$, $p = 0.183$, $\eta_p^2 = 0.033$. The main effect comparing Groups was not found to be significant $F(1, 54) = 0.21$, $p = 0.885$, $\eta_p^2 < 0.001$.

Chapter 5: Discussion

The purpose of this study was to evaluate the effect six weeks of specialized training had on knee joint deficits theorized to increase the risk of ACL injury. Risk factor assessment included the examination of simultaneous single leg drop landing knee kinematics, knee moments, EMG, and vertical ground reaction force. Pre-test and post-test measurements also included assessments of knee joint proprioception, knee joint laxity, and lower extremity strength. These specific variables were chosen because they represented ACL injury risk factors that exhibited the potential to be modified through training. The following sections provide a brief summary of expected outcomes, research results, and interpretations of research findings. The discussion was broken down into the following variable groupings: single leg drop landing knee kinematics, knee moments, EMG, COM, VGRF, knee joint proprioception, knee joint laxity, and lower extremity strength.

5.1 KNEE KINEMATICS

It was hypothesized that single leg drop landing mechanics would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training would yield a significant increase in knee flexion, decrease in knee valgus, and decrease in knee internal rotation at initial contact with the ground. The following table provides the expected knee kinematics along with research findings.

Table 34

Knee Kinematics at Initial Contact

	Pre-Test (Mean ± SD)			**Post-Test (Mean ± SD)**		
Participants	**Flexion Extension (deg)**	**Valgus Varus (deg)**	**Internal External (deg)**	**Flexion Extension (deg)**	**Valgus Varus (deg)**	**Internal External (deg)**
Control	21.99 ± 7.58	-1.75 ± 4.88	8.32 ± 7.28	21.52 ± 7.19	-1.95 ± 4.31	8.43 ± 6.86
Intervention	21.83 ± 7.20	-0.54 ± 5.94	6.71 ± 7.77	33.54 ± 6.58 [ab]	2.40 ± 6.78 [ab]	9.33 ± 6.85

Expected Knee Kinematics at Initial Contact (Control)

- ↔ knee flexion at initial contact
- ↔ knee valgus at initial contact
- ↔ knee internal rotation at initial contact

Expected Knee Kinematics at Initial Contact (Intervention)

- ↑ knee flexion at initial contact
- ↓ knee valgus at initial contact
- ↓ knee internal rotation at initial contact

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings partially supported the hypotheses. The intervention participants demonstrated a significant increase ($p < 0.001$) in knee flexion angle and a significant decrease ($p = 0.02$) in knee valgus angle. Single leg drop landing kinematics of the knee following specialized training corresponded to findings from previous ACL injury prevention program research (Chappell & Limpisivasti, 2008; Kato et al., 2008; Myer et al., 2006). Collegiate female athletes were found to exhibit a significant increase ($p = 0.003$) in initial knee flexion from pre-test (29.9 deg ± 9.00) to post-test (35.1 deg ± 7.4) after completing The Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program (Chappell & Limpisivasti, 2008).

Results also compared to findings surrounding the effects of plyometrics on lower extremity biomechanics during a drop vertical jump. Myer et al. (2006) found a significant increase ($p = 0.047$) in knee flexion from pre-test (29.8 deg ± 6.6) to post-test (35.6 deg ± 7.5). Study findings indicated a 53.64% increase in knee flexion among

intervention participants. Results surpassed the 17.39% (Chappell & Limpisivasti, 2008) and 19.46% (Myer et al., 2006) gains in the knee flexion observed in previous research.

Intervention participants exhibited a significant reduction in knee valgus angle following training. This was in contrast to the non-significant change ($p = 0.09$) found in post-test measures of knee valgus in athletes who participated in The Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program. The amount of knee valgus present in collegiate athletes was 6.1 deg ± 6.2 at pre-test and 8.1 deg ± 7.9 following six weeks of neuromuscular training (Chappell & Limpisivasti, 2008). The magnitude of change in knee valgus from pre-test to post-test was 2.94˚ with intervention participants demonstrating directional shift towards knee varus at landing. This represented the greatest percent change (344.44%) among knee kinematic variables.

Though results for internal-external rotation did not achieve statistical significance in either study, research findings do not compare with the internal-external rotation observed in vertical stop jump kinematics in collegiate soccer and basketball players (Chappell & Limpisivasti, 2008). Intervention participants in the current study demonstrated knee external rotation during testing of single leg drop landing mechanics. Athletes who completed The Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program demonstrated an increase in pre-test (30.60 deg ± 19.80) to post-test (37.60 deg ± 18.50) measures of knee internal rotation (Chappell & Limpisivasti, 2008). The intervention participants exhibited a 34.05% increase in external rotation while previous research results indicate a 22.88% increase in internal rotation at landing (Chappell & Limpisivasti, 2008).

Study findings indicate that intervention participants on average exhibited less knee valgus during landing at pre-test and significantly less knee valgus at post-test. Anatomically, as knee flexion increases greater internal-external rotation of the tibia is permitted at the knee. The combination of knee flexion and knee external rotation prevented an inward collapse of the knee as indicated by study findings.

During rapid deceleration tasks and aggressive changes in direction, unconventional mechanics at initial contact with the ground compromise knee joint integrity by placing the body in an upright position with the femur externally rotated and the knee collapsed inward (Grindstaff et al., 2006). The mechanical strategies employed during drop landings are critical to the magnitude of impact loads and ensuing deformational forces that affect the internal structures that comprise the knee joint. The combination of reduced energy absorption at landing and excessive knee loading increases the ACL's vulnerability to spontaneous rupture (DiStefano et al., 2009). Normal alignment of the lower extremity ideally positions the load-bearing axis down the middle of the leg through the hip, knee, and ankle. Lower extremity mechanics that yield greater valgus alignment at ground contact increases the amount of stress across the lateral compartment of the knee (Myer et al., 2005).

Intervention participants were instructed to increase hip, knee, and ankle flexion while keeping the knees in line with the toes at landing. Participants were taught to preserve this neutral position throughout the landing task by avoiding excessive external rotation of the femur and internal rotation of the tibia. Minimizing exposure to high risk positions was reinforced by continuously providing visual demonstrations and verbal descriptions of proper drop landing mechanics.

Corrective feedback was provided with the intent to increase participant awareness of the cumulative effects hip, knee, and ankle mechanics have on overall joint knee stability. The resulting drop landing technique culminated in greater hip flexion, knee flexion, and plantar flexion with decreased external rotation of the femur and internal rotation of the tibia. Improved technical adeptness led to greater moment to moment adjustments of upper and lower extremities.

It was also anticipated that maximum knee flexion kinematics would not significantly change in control participants whereas training would elicit a significant increase in maximum knee flexion angle in intervention participants. It was also hypothesized that measurements of maximum knee flexion would not differ between groups at pre-test. The following table provides the expected knee kinematics at maximum knee flexion along with research findings.

Table 35

Knee Kinematics at Maximum Flexion

	Pre-Test (Mean ± SD)	**Post-Test (Mean ± SD)**
Participants	**Maximum Flexion (deg)**	**Maximum Flexion (deg)**
Control	45.11 ± 9.68	44.03 ± 11.52
Intervention	43.20 ± 10.97	61.49 ± 13.52 [ab]
Expected Knee Kinematics at Maximum Flexion • ↔ Maximum knee flexion		**Expected Knee Kinematics at Maximum Flexion** • ↑ Maximum knee flexion

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings supported the hypotheses. The intervention participants demonstrated a significant increase ($p < 0.001$) in maximum knee flexion angle. The significant increase in maximum knee flexion observed in the current study

corresponded with mechanical adjustments seen in collegiate and high school athletes following neuromuscular training (Chappell & Limpisivasti, 2008; Myer et al., 2006). NCAA Division I soccer and basketball athletes exhibited a significant increase (p = 0. 006) in maximum knee flexion from 81.3 deg ± 10.5 at pre-test to 86.9 deg ± 10.3 at post-test (Chappell & Limpisivasti, 2008). High school volleyball athletes participating in a neuromuscular training protocol centered on plyometrics also exhibited a significant increase (p = 0.031) in maximum knee flexion following training (pre-test: 93.4 deg ± 54.2; post-test: 101.6 deg ± 50.5) (Myer et al., 2006).

Kato et al., (2008) also assessed maximum knee flexion during the ground contact phase of a quick-drop step before a basketball jump shot. However, training did not yield a significant increase in maximum knee flexion among healthy female collegiate basketball players. Kato et al., (2008) found that four weeks of lower extremity calisthenics, balance training, and landing tasks led to a minimal increase in maximum knee flexion from pre-test (72.4 deg ± 8.7) to post-test (75.7 deg ± 3.4).

The substantial difference between measures of maximum knee flexion in the current study and previous ACL injury prevention program research can be attributed to the testing protocol employed. Chappell and Limpisivasti (2008), Kato et al., (2008), and Myer et al., (2006) had participants immediately follow drop landing with a measure of jump performance. Participants moved into a position of greater knee flexion following contact with the force plate to prepare for the ensuing vertical jump. Therefore, measures of maximum knee flexion did not drastically change from pre-test to post-test. In the current study there was greater room for improvement because participants were not inclined to maximize knee flexion at initial contact with the ground for the purpose of

following one movement task with another. Examination of percent change revealed a 42.34% increase in maximum knee flexion from pre-test to post-test. As expected the percent change was substantially greater than the 6.89% increase (Chappell & Limpisivasti, 2008) and 4.56% increase (Myer et al., 2006) observed in previous research.

The plyometric drill skill set used in the intervention introduced consecutive barrier and box jumps at varying heights. Emphasis was placed on the muscular and mechanical efforts needed to maintain upper and lower body coordination and balance during landing tasks. The importance of knee flexion following contact with the ground was stressed to increase participant awareness of the impact knee flexion has on preserving technique and attenuating ground reaction force. A series of repetitions coupled with augmented feedback was used to help define, refine, and reinforce jump landing technique. It has been theorized that an action of a specific movement task can be modified through internal/external feedback and practice until skilled motor performance becomes automatic (Louw et al., 2006).

Reduced knee flexion during high risk maneuvers contributes to a significant increase in vertical ground reaction force (Louw et al., 2006). Intervention participants were instructed to anticipate foot strike then gradually collapse the ankle, knee, and hips to dissipate the mechanical stress along each lower extremity segment as the foot made contact with the ground. The significant increase in maximum knee flexion allowed participants to soften the landing. Eliminating the abruptness of initial contact with the ground through continued knee flexion allowed the body to decelerate to a complete stop in a controlled manner reducing ensuing knee moments.

5.2 SINGLE LEG DROP LANDING KNEE MOMENTS

It was hypothesized that single leg drop landing knee moments would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training would yield a significant decrease in knee flexion moment, knee valgus moment, and knee internal rotation moment at initial contact with the ground. The following table provides the expected knee moments along with research findings.

Table 36

Single Leg Drop Landing Knee Moments at Initial Contact

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**Flexion Extension (Nm)**	**Valgus Varus (Nm)**	**Internal External (Nm)**	**Flexion Extension (Nm)**	**Valgus Varus (Nm)**	**Internal External (Nm)**
Control	766.95 ± 878.36	87.81 ± 614.38	36.75 ± 110.56	763.86 ± 867.92	112.45 ± 629.88	41.76 ± 90.83
Intervention	870.91 ± 723.70	72.49 ± 516.67	30.80 ± 84.27	744.17 ± 427.13	53.46 ± 473.09	17.55 ± 84.86
Expected Knee Moments at Initial Contact (Control) • ↔ knee flexion moment at initial contact • ↔ knee valgus moment at initial contact • ↔ knee internal rotation moment at initial contact				**Expected Knee Moments at Initial Contact (Intervention)** • ↓ knee flexion moment at initial contact • ↓ knee valgus moment at initial contact • ↓ knee internal rotation moment at initial contact		

[a] Significant Group main effect $p < 0.05$
[b] Significant Time main effect $p < 0.05$

Research findings did not support the hypotheses. The intervention participants did not demonstrate a significant decrease in knee flexion moment, knee valgus moment, and knee internal rotation moment. Single leg drop landing knee moments following specialized training compared to findings from previous ACL injury prevention program research which found no significant change in knee moments (Chappell & Limpisivasti, 2008). Chappell and Limpisivasti (2008) also found no significant change

(p = 0.28) in measures of knee valgus moment among athletes who completed The Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program. Collegiate soccer and basketball players exhibited a minimal change in knee valgus moment from pre-test (0.695 bw ± 0.37) to post-test (0.663 bw ± 0.26).

While findings were not significant, knee flexion moment decreased 14.56%, knee valgus moment decreased 26.25%, and knee external rotation moment decreased 43.02%. It is possible that the height of the platform used for testing contributed to the lack of significance observed in knee moments. The platform height of 30 cm leaves the participant a small window of a few milliseconds to make any significant lower extremity adjustments prior to contact with the ground. The drop landing height of 30 cm makes it difficult to maximize single leg drop landing technique to effectively dissipate the amount of rotary force needed to quickly extend the lower extremity to meet the ground.

It was hypothesized that knee kinetics at maximum flexion would not significantly change in control participants whereas training would elicit a significant decrease in maximum knee flexion moment among intervention participants. It was also surmised that measurements of maximum knee flexion moment would not differ between groups at pre-test. The following table provides the expected knee moments at maximum knee flexion along with research findings.

Table 37

Single Leg Drop Landing Knee Moments at Maximum Flexion

	Pre-Test (Mean ± SD)	**Post-Test (Mean ± SD)**
Participants	**Maximum Flexion (Nm)**	**Maximum Flexion (Nm)**
Control	1131.15 ± 585.62	1006.13 ± 605.11
Intervention	1032.95 ± 630.08	182.14 ± 448.20 [ab]
Expected Knee Moment at Maximum Flexion (Control) • ↔ Knee moment at maximum flexion	**Expected Knee Moment at Maximum Flexion (Intervention)** • ↓ Knee moment at maximum flexion	

[a] Significant Group main effect $p < 0.05$
[b] Significant Time main effect $p < 0.05$

Research findings supported the hypotheses. The intervention participants demonstrated a significant decrease ($p < 0.001$) in maximum knee flexion moment. Single leg drop landing moments of the knee at maximum flexion following training correspond to findings from previous ACL injury prevention program research which resulted in a decrease in knee moment (Chappell & Limpisivasti, 2008). Collegiate athletes participating in The Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program also demonstrated a significant reduction ($p = 0.04$) in maximum knee flexion moment. Similar to the knee moment outcomes observed in the current research, maximum knee flexion moment was the only knee kinetic variable to be significantly affected by training. Chappell and Limpisivasti (2008) found collegiate female athletes to exhibit a significant pre-test (0.739 bw ± 0.37) to post-test (0.583 bw ± 0.30) reduction in maximum knee flexion moment during drop jump testing .

The intervention participants exhibited an 82.37% reduction in maximum knee flexion moment which far exceeds the 21.11% decrease observed in past research (Chappell & Limpisivasti, 2008). Employing greater knee flexion following contact with

the ground allows lower extremity segments to decelerate over an extended period of time dissipating the amount of knee moment experienced at maximum flexion. Chappell & Limpisivasti, (2008) included a measure of jump performance with drop landing knee kinematics and kinetics. Athletes did not attempt to reduce the rate of deceleration following contact with the ground as an effort to maximize jump performance. The rapid approach towards maximum knee flexion left little time prior to the forceful extension upward to fully dissipate maximum knee flexion moment.

5.3 SINGLE LEG DROP LANDING EMG OF LOWER EXTREMITY

It was hypothesized that single leg drop landing muscle activity would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training would yield a significant increase in quadriceps, hamstrings, and gastrocnemius amplitude. Training was also expected to significantly quicken muscle activation times in the hamstrings and gastrocnemius while prompting a significant delay in the onset times of the medial and lateral muscles of the quadriceps. The following table provides the expected quadriceps, hamstrings, and gastrocnemius EMG along with research findings.

Table 38

Single Leg Drop Landing EMG of Lower Extremity

		Pre-Test (Mean ± SD)		Post-Test (Mean ± SD)	
Muscle	**Participants**	**Amplitude (%)**	**Onset Time (ms)**	**Amplitude (%)**	**Onset Time (ms)**
Vastus Medialis	Control	58.67 ± 16.48	87.19 ± 25.21	57.40 ± 21.45	123.16 ± 37.63
	Intervention	63.59 ± 16.94	90.27 ± 29.98	61.46 ± 16.13	165.24 ± 48.92
Vastus Lateralis	Control	45.43 ± 22.20	88.75 ± 11.57	58.21 ± 18.97	82.88 ± 11.65
	Intervention	49.40 ± 21.01	91.00 ± 11.54	65.66 ± 15.37	89.15 ± 12.80
Semi-Membranosus	Control	34.74 ± 19.04	109.24 ± 12.35	34.70 ± 16.59	109.23 ± 14.05
	Intervention	31.82 ± 14.18	104.12 ± 10.83	49.81 ± 18.77 [b]	124.41 ± 15.44 [b]
Semi-Tendonosus	Control	52.22 ± 21.82	84.74 ± 5.95	49.22 ± 22.52	83.15 ± 5.50
	Intervention	50.94 ± 16.99	83.22 ± 5.09	51.91 ± 19.50	86.19 ± 6.97
Gastrocnemius – Medial Head	Control	48.81 ± 19.54	142.34 ± 33.76	52.44 ± 15.16	127.41 ± 26.70
	Intervention	47.49 ± 18.16	131.55 ± 37.14	54.32 ± 15.63	125.57 ± 24.97
Gastrocnemius – Lateral Head	Control	50.19 ± 22.08	121.23 ± 23.97	52.89 ± 20.39	115.84 ± 20.12
	Intervention	51.36 ± 21.19	110.82 ± 15.84	57.02 ± 22.48	117.96 ± 22.94

Expected Lower Extremity EMG (Control)	**Expected Lower Extremity EMG (Intervention)**
• ↔ Hamstrings onset time • ↔ Hamstrings peak amplitude • ↔ Quadriceps onset time • ↔ Quadriceps peak amplitude • ↔ Gastrocnemius onset time • ↔ Gastrocnemius peak amplitude	• ↓ Hamstrings onset time • ↑ Hamstrings peak amplitude • ↑ Quadriceps onset time • ↑ Quadriceps peak amplitude • ↓ Gastrocnemius onset time • ↑ Gastrocnemius peak amplitude

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings partially supported the hypotheses. The intervention participants demonstrated a significant increase ($p < 0.001$) in semi-membranosus amplitude. Contrary to the anticipated results, intervention participants exhibited a significant delay ($p < 0.001$) in semi-membranosus onset time. Electromyography of lower extremity muscles during single drop landing was comparatively similar to findings

from previous ACL injury risk factor research (Rozzi et al., 1999; Myer et al., 2005). Electromyography findings revealed an activation pattern within lower extremity musculature with medial muscle recruitment occurring more rapidly than lateral muscle recruitment. Rozzi et al. (1999) found a similar pattern in onset times for the quadriceps (medial: 39.20 ms ± 56.66; lateral: 40.51 ms ± 28.21) and hamstrings (medial: 175.57 ms ± 108.56; lateral: 187.01 ms ± 133.19). Myer et al., (2005) also observed a similar medial (0.507 rms ± 0.181) to lateral (0.689 rms ± 0.235) muscle recruitment pattern in the quadriceps.

However, electromyography findings surrounding muscle onset times in the gastrocnemius were not similar to neuromuscular characteristics observed in female soccer and basketball players. Rozzi et al. (1999) found the muscle recruitment pattern to differ between the medial head (241.10 ms ± 141.57) and lateral head (193.90 ms ± 155.33) of the gastrocnemius.

Examination of muscle activation patterns revealed that the semi-membranosus was the only muscle to exhibit a significant change in onset time. While results did not achieve statistical significance, the vastus medialis exhibited an 83.05% delay in onset time and the medial head of the gastrocnemius exhibited a 4.55% quicker onset time. These were the only muscles to reflect the anticipated outcomes for muscle activation patterns.

Study findings also indicated that semi-membranosus amplitude was the only muscle to exhibit a significant increase (56.54%) in percent MVC. While pre-test to post measures of amplitude for the remaining muscles did not achieve statistical significance, four of the five muscles evaluated demonstrated increase in percent MVC.

Vastus lateralis amplitude increased 32.92%. Semi-tendonosus amplitude increased 1.90%. While muscle amplitude of the medial and lateral head of the gastrocnemius increased 14.38% and 11.02%, respectively.

Unconventional neuromuscular control compromises the integrity of the ACL by delaying the appropriate motor response needed to meet the demands placed on the knee (Kellis & Kouvelioti, 2009). Medial-to-lateral quadriceps recruitment coupled with increased lateral hamstring activity during landing tasks exacerbates the amount of knee valgus experienced by female athletes at lower flexion angles (Myer et al., 2005). Delayed co-contractive behavior of the hamstrings worsens the posterior muscles ability to generate force in a timely manner to offset muscle loading in the quadriceps (Palmieri-Smith et al., 2008).

Special considerations were taken during training to prevent the overdevelopment of the quadriceps muscle. The strength training skill set of the intervention included a hamstrings concentration. Strengthening of posterior thigh musculature was focused on improving the hamstrings ability to counter balance the activity of the quadriceps during movement tasks. The balance drill skill set was also promoted muscle agonist and antagonist development, but also engaged, strengthened, and synchronized smaller stabilizing muscles that support the truck, hip, knee, and ankle. Intervention participants worked on improving proper landing technique from unstable to stable, stable to unstable, onto and off box platforms, and over barriers in order to improve muscle reactive ability and coordination.

Neuromuscular control refers to the muscular response to proprioceptive stimuli arising from joint motion and loading (Riemann & Lephart, 2002). Prevention program

training was constructed to improve the time needed to propagate agonist and antagonist muscle response. Contraction and immediate co-contraction of anterior to posterior and medial to lateral musculature of the lower extremity alleviates the mechanical loads imposed on the ACL during highly dynamic maneuvers. It is possible that agonist-antagonist patterning during rapid movement does not allow enough stimulus-to-response processing to produce significant changes in motor behavior to offset agonist EMG activity (Schmidt & Lee, 2005). The lack of the significant increase in muscle amplitude may be attributed to the short duration of the intervention program. The first weeks of training elicits neural adaptations. Participants undergo a period where the brain learns how to facilitate more force given the amount of contractile tissue (Baechle & Earle, 2008).

However, research findings demonstrate changes in muscle activity of the quadriceps, hamstrings, and gasctocnemius. The semi-membranosus (124.41 ms ± 15.44) and semi-tendonosus (86.19 ms ± 6.97) were actively engaged to oppose incoming force generated by the vastus medialis (165.24 ms ± 48.92) and vastus lateralis (89.15 ms ± 12.80). Measures of semi-membranosus (49.81% ± 18.77) and semi-tendonosus (51.91 % ± 19.50) amplitude illustrate the muscles capacity to offset the force produced by the vastus medialis (57.40 % ± 21.45) and vastus lateralis (65.66 %± 15.37).

This proportionate balance in quadriceps and hamstrings capacity lessens the compressive force exerted on the knee by providing essential support to allow the lower extremity to land in a flexed position. Increased strength of the quadriceps, hamstrings, gastrocnemius protect the knee joint by providing greater resistance to anterior tibial

translation. Greater muscular capability and timely activation of the hamstrings alleviates the amount force the quadriceps direct onto the anterior aspect of the tibia. Greater muscular capability and timely activation of medial to lateral musculature alleviates the amount shear force directed onto knee joint.

5.4 SINGLE LEG DROP LANDING VARIABILITY OF COM EXCURSION

It was hypothesized that variability of COM excursion along the x-axis (medial-lateral), y-axis (anterior-posterior), and z-axis (superior-inferior) would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training in the intervention group would yield greater dynamic stability at initial contact with the ground. The following table provides the expected variability of COM excursion along with research findings.

Table 39

Single Leg Drop Landing Variability of COM Excursion

	Pre-Test (Mean ± SD)			**Post-Test (Mean ± SD)**		
Participants	**Medial Lateral (SD)**	**Anterior Posterior (SD)**	**Vertical (SD)**	**Medial Lateral (SD)**	**Anterior Posterior (SD)**	**Vertical (SD)**
Control	4.21 ± 2.04	14.41 ± 5.50	14.83 ± 8.51	4.26 ± 2.83	14.36 ± 6.67	12.96 ± 8.08
Intervention	4.68 ± 2.63	16.46 ± 6.48	14.71 ± 7.08	4.51 ± 2.14	15.89 ± 6.47	16.39 ± 6.51

Expected COM (Control)	**Expected COM (Intervention)**
• ↔ in variability of excursion along X-axis • ↔ in variability of excursion along Y-axis • ↔in variability of excursion along Z-axis	• ↓ in variability of excursion along X-axis • ↓ in variability of excursion along Y-axis • ↓ in variability of excursion along Z-axis

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings did not support the hypotheses. The intervention participants did not demonstrate a significant decrease in the variability of medial-lateral excursion along the x-axis, anterior-posterior excursion along the y-axis, and superior-inferior excursion along the z-axis. Results were similar to related research findings from previous ACL injury prevention program research which found no change in postural balance (Paterno et al., 2004). Anterior-posterior and medial-lateral stability during single leg perturbations was evaluated in female high school basketball, soccer, and volleyball players. Athletes underwent six weeks of neuromuscular training which included high volume - low intensity bouts of plyometric, balance, and periodized resistance training. Medial-lateral stability did not significantly change ($p = 0.65$) from pre-test (right: 2.0 ± 0.9; left: 2.1 ± 0.7) to post-test (right: 1.9 ± 0.6; left: 2.1 ± 0.8). However, athletes exhibited a significant improvement ($p = 0.001$) in pre-test (right: 3.6 ± 1.6; left: 3.9 ± 2.3) to post-test (right: 2.7 ± 1.0; left: 3.0 ± 1.2) measures of anterior-posterior stability (Paterno et al., 2004).

Center of mass refers to the geometric location where the body's mass is evenly balanced in all directions .Variability of COM excursion refers to the body's deviation along the x-axis, y-axis, and z-axis. Measurements of variability of COM excursion as it relates to this study reflects the amount of medial-lateral, anterior-posterior, superior-inferior excursion from the moment of foot strike to the moment of maximum knee flexion. Results give a relative indication of postural control within that movement time frame.

The strength training skill set of the intervention program was also partitioned to include core strengthening of the rectus abdominis, obliques (internal-external), and

quadratus lumborum. Efforts were made to maximize core strength to improve active postural stabilization. Abdominal muscles affect frontal, sagittal, and traverse plane movements. Frontal plane movements include lateral flexion to ipsilateral side and lateral pelvic rotation to contralateral side. Sagittal plane movements include lumbar flexion, posterior pelvic rotation, lumbar extension, and anterior pelvic rotation. Transverse plane movements include lumbar rotation to contralateral side and lumbar rotation to ipsilateral side. Collectively the abdominal muscles work in concert to stabilize the lumbar spine and pelvis (Floyd, 2007).

Core strength is integral to the production, the transfer, and the control of force generated throughout the body (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). Core strength preserves dynamic control of the body during sudden perturbations. Deficits in neuromuscular control can result in uncontrolled displacement of the trunk which can affect lower extremity mechanics thereby increasing the amount of strain imposed on internal structures within the knee joint (Hewett, et al., 2005). Abdominal musculature creates a stable platform for hamstrings function by controlling lumbar spine and pelvis movement (Devlin, 2000). Lower extremity musculature then in turn carries the important task of supporting and stabilizing the body's center of mass while reducing drop landing velocity in a controlled manner (Wikstrom, Tillman, Schenker, & Borsa, 2008).

While findings were not significant, decreases were observed in anterior-posterior (3.46%) and medial-lateral (3.63%) variability of COM excursion which is indicative of improved postural stabilization. Superior-inferior variability of COM excursion exhibited an 11.42% increase. Fewer oscillations in the anterior-posterior and

medial-lateral direction suggest greater postural equilibrium at landing. The increase in superior-inferior variability of COM excursion implies greater movement along the longitudinal axis. The resulting increase in the distance traveled from ground contact to the moment maximum knee flexion was achieved reflects the increased superior-inferior variability of COM excursion.

Results did not achieve statistical significance because a single leg drop landing from a height of 30 cm may not have presented a significant motor challenge to evoke greater variability of COM excursion along the x-axis, y-axis, and z-axis. The decreases observed in anterior-posterior and medial-lateral variability of COM excursion could be the result of active core stabilization and manipulation of the torso and extremities to provide balance during the descent. This assumption is further supported by results collected for control participants who demonstrated no improvements in measurements in variability of COM excursion.

5.5 SINGLE LEG DROP LANDING VGRF

It was hypothesized that single leg drop VGRF would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training in the intervention group would yield a significant decrease VGRF at initial contact with the ground. The following table provides the expected VGRF along with research findings.

Table 40

Single Leg Drop Landing VGRF

	Pre-Test (Mean ± SD)	Post-Test (Mean ± SD)
Participants	**VGRF (bw)**	**VGRF (bw)**
Control	1.25 ± 0.07	1.27 ± 0.07
Intervention	1.26 ± 0.06	1.14 ± 0.06 [ab]
Expected Drop Landing VGRF (Control) • ↔ In vertical force	**Expected Drop Landing VGRF (Intervention)** • ↓ In vertical force	

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings supported the hypotheses. The intervention group demonstrated a significant decrease ($p < 0.001$) in vertical ground reaction force. Vertical ground reaction force results differed from findings from previous ACL injury prevention program research which found no significant change in ground reaction force (Chappell & Limpisivasti, 2008; Vescovi et al., 2008). Chappell and Limpisivasti (2008) found no significant decrease ($p = 0.06$) in vertical ground reaction force following the completion of The Kerlan-Jobe Orthopaedic Clinic Modified Neuromuscular Training Program. Athletes demonstrated a peak vertical ground reaction force of 2.12 bw ± 0.65 at pre-test and a 2.30 bw ± 0.52 at post-test. The Sportsmetrics™ Program, a six week plyometrics training protocol partitioned into three stages of motor skill development also did not elicit a significant decrease in pre-test to post-test measures of vertical ground reaction force in twenty recreationally active collegiate females. Intervention participants exhibited 2583.6 ± 505.8 N of vertical ground reaction force at pre-test with a minimal reduction of -222.8 ± 610.9 N following training (Vescovi et al., 2008).

Intervention participants displayed 9.52% decrease in vertical ground reaction force compared to the 8.49% increase (Chappell and Limpisivasti, 2008) and 8.62%

decrease (Vescovi et al., 2008) observed in past research. The extent vertical ground reaction force differs between ACL injury prevention program studies can be attributed to the task performed at initial contact with the ground, the exact moment ground reaction force was assessed, and the height at which participants were landing on the force plate. Chappell and Limpisivasti (2008) assessed drop jumps and stop jumps which inclined participants to approach and land much more aggressively to push off for the jumping task that follows. Past research included measures of peak vertical ground reaction force which does not always coincide with the exact moment of impact with the ground. The height of the landing was not disclosed in the study. The current study defined initial foot strike as the moment vertical (Fz) ground reaction force exceeded 10 N (Myer et al., 2006).

Female athletes considered to be at risk for serious ligamentous injuries generally display a myriad of ACL injury risk factors (Myer et al., 2007). The impact of ACL injury risk factors adversely influences mechanical and muscular processes which may compromise performance during high risk maneuvers. The biomechanical and neuromuscular strategies employed during drop landings are critical to the ensuing force generated at landing. Force is characterized by its magnitude, direction, and point of application. Landing upright as opposed with greater knee flexion contributes to increased vertical ground reaction force that can exceed 2 to 4.5 times the bodyweight at ground contact (Louw et al., 2006).

Intervention participants were instructed to remain vigilant of hip, knee, and ankle mechanics at ground contact specifically avoiding excessive external rotation of the femur and internal rotation of the tibia. Greater kinesthetic awareness coupled with

improved landing technique allowed participants to make fluid hip, knee, and ankle adjustments. Plantar flexion at initial foot strike rapidly gave way to dorsiflexion, knee flexion, and hip flexion which softened and slowed the body's decent reducing the amount of force imparted to the ground. Ensuing knee flexion further reduced muscle loading and helped attenuate vertical ground reaction force over a longer period of time.

5.6 KNEE PROPRIOCEPTION

It was hypothesized that knee joint proprioception at 15˚, 30˚, and 45˚ would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training in the intervention group would yield increased knee joint sensitivity to 15˚, 30˚, and 45˚ of knee flexion during active knee joint position sense testing. The following table provides the expected knee joint proprioception along with research findings.

Table 41

Knee Proprioception

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**15° (abs)**	**30° (abs)**	**45° (abs)**	**15° (abs)**	**30° (abs)**	**45° (abs)**
Control	6.15 ± 2.88	5.41 ± 1.85	5.14 ± 2.78	5.42 ± 2.25	5.31 ± 2.28	5.35 ± 2.19
Intervention	5.62 ± 2.02	5.47 ± 2.00	5.10 ± 2.28	3.40 ± 1.34 [ab]	3.60 ± 1.59 [ab]	3.49 ± 1.78 [a]

Expected Knee Proprioception (Control)	**Expected Knee Proprioception (Intervention)**
• ↔ Active joint position sense at 15˚ • ↔ Active joint position sense at 30˚ • ↔ Active joint position sense at 45˚	• ↑ Active joint position sense at 15˚ • ↑ Active joint position sense at 30˚ • ↑ Active joint position sense at 45˚

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings supported the hypotheses. The intervention participants demonstrated significantly greater knee joint position sense at 15˚($p < 0.001$) and 30˚ (p

= 0.001) and 45˚ ($p < 0.001$). Results were similar to related research findings from previous ACL injury risk factor research which found no change in postural balance (Rozzi et al., 1999). Rozzi et al., (1999) assessed knee joint kinesthesia using an instrumented device that passively moved the knee joint into flexion or extension at 0.5°/sec. The angular threshold at which the participant was able to detect passive motion into flexion or extension was recorded. Collegiate athletes participating in basketball and soccer were found to have decreased proprioceptive sensitivity for movement into extension. This compares to control and intervention participants who demonstrated greater proprioceptive deficits closer to full extension.

Intervention participants exhibited a decrease in the absolute error associated with active angle reproduction at 15˚ (39.50%), 30˚ (34.19%), and at 45˚ (31.57%). The decrease in absolute error represented greater joint position sensitivity at each knee flexion angle. The control group also exhibited a decrease in the absolute error associated with active angle reproduction at 15˚ (11.87%), and 30˚ (1.85%). Post-test measurements of knee joint position sense testing at 45˚ revealed a 4.09% increase in absolute error which is indicative of less proprioceptive awareness (Callaghan et al., 2008). A practice effect may account for the improvements observed in control participants and to a similar degree in intervention participants.

The knee joint functions within an extremely complex and interactive neuromusculoskeletal system (Frank & Jackson, 1997). Increased somatosensory sensitivity heightens overall awareness to changes in motor coordination (Buchanan & Horak, 2003). Prevention program training was devised to elicit a wide range of proprioceptive stimulation through an array of functional motor challenges. Visual and

verbal feedback was provided to improve motor performance through conscious kinesthetic awareness (Liebenson, 2006). The inclusion of multiple repetitions of movement tasks served to reinforce motor skill development and mastery. This increased capacity to internalize proprioceptive feedback reduces mechanical deficits known to exist between 10° to 30° of knee flexion (Delfico & Garrett, 1998).

5.7 KNEE LAXITY

It was hypothesized that anterior knee joint laxity would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training in the intervention group would yield a significant decrease in measurements of passive displacement and maximum manual displacement. The following table provides the expected anterior knee joint laxity along with research findings.

Table 42

Knee Laxity

	Pre-Test (Mean ± SD)		**Post-Test (Mean ± SD)**	
Participants	**PD 133N (mm)**	**MMD (mm)**	**PD 133N (mm)**	**MMD (mm)**
Control	6.10 ± 1.75	12.21 ± 1.78	6.38 ± 1.83	12.48 ± 1.89
Intervention	5.96 ± 1.75	12.34 ± 2.40	4.77 ± 1.43 [b]	10.57 ± 1.89 [b]

Expected Knee Joint Laxity (Control)	**Expected Knee Joint Laxity (Intervention)**
• ↔ Anterior knee joint laxity at 133 N • ↔ Max anterior knee joint laxity	• ↓ Anterior knee joint laxity at 133 N • ↓ Max anterior knee joint laxity

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings supported the hypotheses. The intervention participants demonstrated a significant decrease in passive drawer ($p < 0.001$) and maximum

manual drawer ($p < 0.001$) measures of anterior knee joint laxity. Anterior knee joint laxity results partially corresponded to findings from previous research examining ACL injury risk factors in female athletes (Medrano & Smith, 2003; Rozzi et al. 1999; Huston & Wojtys, 1996). Rozzi et al. (1999) found athletic females participating in soccer and basketball at the collegiate level to exhibit 6.05 mm ± 1.46 of anterior knee joint laxity when measurements where collected at a displacement load of 133 N. Medrano and Smith (2003) also found a similar measure of mean passive displacement among collegiate female soccer players. The combined right and left knee measurement of passive displacement collected at 133 N was 5.67 mm ± 1.43. Interestingly, post-test measurements of passive displacement compare to findings investigating neuromuscular performance characteristics in elite female athletes. Huston & Wojtys (1996) found female athletes to exhibit 4.75 mm ± 1.21 of anterior tibial translation during passive drawer testing.

Passive anterior knee joint laxity results did not compare with lower values of passive displacement from research comparing factors influencing ACL injury in male and female athletes and non-athletes. Bowerman et al. (2006) assessed anterior knee joint laxity in collegiate female athletes and age matched female non-athletes. Female athletes were solicited from a variety of sports which included soccer, softball, volleyball, basketball, track, and tennis. Results revealed an anterior knee laxity measure of 4.20 mm ± 1.49 for female athletes and 4.70 mm ± 1.60 for female non-athletes (Bowerman et al., 2006).

Maximum anterior knee joint laxity results did not correspond with findings from previous research examining maximum manual displacement in female athletes which

found substantially smaller laxity values (Bowerman et al., 2006; Medrano & Smith, 2003). Female athletes (6.00 mm ± 2.05) and non-athletes (6.10 mm ± 2.30) were found to exhibit less maximum anterior knee joint laxity (Bowerman et al., 2006). Medrano and Smith (2003) found a similar trend in the combined right and left leg measures of maximum laxity in athletes (8.84 mm ± 1.64) and in non-athletes (10.6 mm ± 2.05).

Study findings indicate a 19.97% and 14.34% decrease in passive drawer and maximum manual drawer measures of anterior knee joint laxity, respectively. Intervention participants demonstrated comparable measures of knee joint laxity to collegiate female athletes (Medrano & Smith, 2003; Rozzi et al. 1999; Huston & Wojtys, 1996). Participant selection in the current study was dependent on the demonstration of above-average conditioning. Increased physical conditioning and lower extremity strength has been considered to influence the degree of knee joint laxity in athletes and non-athletes (Medrano & Smith, 2003). While the conditioning of recreationally active participants does not mirror the conditioning of collegiate athletes, it considerably narrows the general female student population to a select few who may demonstrate similar attributes.

The magnitude of passive anterior knee joint laxity observed in intervention participants did not compare to results reported in previous research (Bowerman et al., 2006). Bowerman et al., (2006) assessed knee joint laxity in athletes participating in a variety of sports which included soccer, softball, volleyball, basketball, track, and tennis. Sport specific training yields sports specific attributes that are characteristic to the sport, position, and level of play. The physical conditioning in athletes participating in sports that require regular explosive movements may lead to a level of muscularity that

provides greater knee joint stability. Such athletes may deflate measures of passive drawer displacement within the group.

The extent of maximum anterior knee joint laxity observed in intervention participants did not compare to past research results (Bowerman et al., 2006). The difference in maximum anterior knee joint laxity can be attributed to the displacement load applied during the maximum manual drawer testing. The amount of anterior tibial translation observed during testing is highly dependent on the examiner's ability to displace the tibia until the leg is no longer able to move anteriorly. This requires considerable strength and consistency on the part of the examiner.

The ACL exhibits the capability to diminish stress within the knee by microscopically adjusting viscoelastic properties of the ligament according to an internal load history of past demands placed on the knee (Frank & Jackson, 1997). Prevention program tasks exposed participants to a multitude of knee positions and stresses gradually increasing the function of supporting knee joint musculature and tensile strength of the ligament (Stone & Karatzaferi, 2008). Improved viscoelastic recovery from compromising stresses strengthens the function of ligamentous tissue as the primary restraint against anterior translation, knee hyperextension, and anterolateral rotation of the tibia relative to the femur. The ACL's resistance to deformation also yields greater protection from excessive lateral (valgus) stress by supporting medial collateral ligament function as a secondary knee stabilizer (Floyd, 2007). Since the viscoelastic response does not return the ACL to resting length immediately, musculature supporting knee function becomes a crucial component to joint stability.

Landing and cutting tasks represent a closed kinetic chain of intricate hip, knee, and ankle movements. Injury to the ACL results when the load applied to it exceeds the capacity the ligament can support (Hrysomallis et al., 2007). Excessive knee joint laxity has been theorized to diminish proprioceptive function and increase the vulnerability of the knee to injury (Rozzi et al., 1999). Mechanical adjustments to drop landing technique alleviate a portion of the stress and strain acting on the ligament. Ligamentous structures coupled with powerful knee extensors (quadriceps) and flexors (hamstrings) work together to facilitate knee joint stability during dynamic movements (Quatman et al., 2008).

5.8 STRENGTH

5.8.1 CONVENTIONAL STRENGTH RATIO

It was hypothesized that $H_{CON}:Q_{CON}$ strength ratio and time to peak torque in the hamstrings and quadriceps would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training in the intervention group would yield increased strength ratio, decreased time to peak torque in the hamstrings, and increased time to peak torque in the quadriceps. The following table provides the expected lower extremity strength and time to peak torque of the hamstrings and quadriceps along with research findings.

Table 43

$H_{CON}:Q_{CON}$ Strength

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**
Control	83.21 ± 24.35	136.43 ± 28.70	0.69 ± 0.14	81.79 ± 14.92	123.21 ± 31.51	0.67 ± 0.13
Intervention	90.71 ± 24.93	146.07 ± 39.57	0.71 ± 0.15	76.07 ± 13.43	117.50 ± 23.19	0.78 ± 0.13

Hypothesized $H_{CON}:Q_{CON}$ Strength (Control)

- ↔ Hamstrings time to peak torque
- ↔ Hamstrings peak torque
- ↔ Quadriceps time to peak torque
- ↔ Quadriceps peak torque
- ↔ $H_{CON}:Q_{CON}$ strength ratio

Hypothesized $H_{CON}:Q_{CON}$ Strength (Intervention)

- ↓ Hamstrings time to peak torque
- ↑ Hamstrings peak torque
- ↑ Quadriceps time to peak torque
- ↑ Quadriceps peak torque
- ↑ $H_{CON}:Q_{CON}$ strength ratio

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings did not support the hypotheses. The intervention participants did not demonstrate a significant increase in $H_{CON}:Q_{CON}$ strength ratio and a significant change in time to peak torque in the quadriceps and hamstrings. Though not significant, the intervention participants exhibited a 16.14% decrease in quadriceps time to peak torque. The time to peak torque in the hamstrings decreased 19.56%. The control group demonstrated a 1.71% decrease in quadriceps time to peak torque and a 9.69% decrease in hamstrings time to peak torque. The decrease in time to peak torque may be attributed to the increase in motor unit recruitment. This adaptation to agility and plyometrics training includes the recruitment of larger motor units which have higher neural thresholds that are sensitive to explosive movement (Haff, Whitley, & Potteiger, 2001). Isokinetic strength testing at 300°/s actively engage these larger motor units more rapidly and efficiently thus decreasing the time to peak torque.

Conventional $H_{CON}:Q_{CON}$ strength ratio results were comparatively similar to findings from previous research examining ACL injury risk factors in female athletes (Devan et

al., 2004). The H_{CON}:Q_{CON} strength ratios observed in intervention participants compare to the conventional strength in NCAA Division I athletes participating in women's field hockey, soccer, and basketball. Devan et al., (2004) found bilateral isokinetic testing at 300°/s to yield a H_{CON}:Q_{CON} strength ratio of 73.6% ± 14.0 and 74.7% ± 16.1 for the right and left leg, respectively.

The larger H_{CON}:Q_{CON} strength ratio observed in collegiate athletes can be attributed to the type training and the time actively involved in the training. Collegiate athletics generally encompass sports specific training that is highly regimented and designed to optimize individual performance and strength. Athletes are generally engaged in a structured strength training program throughout the pre-season, the in-season, and post-season.

The training protocol employed in the current study was broken down into two stages of muscular development that increased in intensity as participants transitioned from one stage to the next. Drills served to increase anterior, posterior, medial, and lateral leg muscle strength through agility drills, plyometric drills, balance drills, and calisthenics. The strength training component of the program included an additional concentration centered on increasing the strength of the semi-membranosus, biceps femoris, and semi-tendonosus.

Following the completion of training, intervention participants demonstrated a 9.86% increase in H_{CON}:Q_{CON} strength ratio. The intensity, volume, and frequency of the training protocol may not have optimally induced the neuromuscular adaptations (motor unit recruitment, rate coding, and synchronization) needed to achieve significant gains in strength. It is not uncommon to observe a 25% to 100% improvement in strength

within three to six months of beginning a resistance training regiment (Wilmore & Costill, 1999).

Female athletes generally exhibit disproportionately greater strength in the quadriceps compared to the hamstrings (Rosene et al., 2001). Overdeveloped quadriceps affect the integrity of the ACL by generating powerfully unconstrained muscle loads during rapid changes in direction and landing tasks. As knee flexion decreases (<30˚), the anterior tibial shear force produced by the quadriceps compromise ACL integrity and overall knee joint stability (DeMorat, Weinhold, Blackburn, Chudik, & Garret, 2004). This significant imbalance in lower extremity strength renders the hamstrings ineffective in protecting the ACL against excessive anterior tibial translation (Liebenson, 2006).

Knapik, Bauman, Jones, Harris, & Vaughn (1991) found that female athletes who exhibit a H:Q strength ratio below 75% were 1.6 times more likely to incur a serious lower extremity injury. Conventional strength ratios generally fall between 50 – 80% (Harter, Ostering, & Standifer, 1990). As a strength ratio approaches 100%, hamstrings exhibit a greater functional capacity to maintain knee joint stability (Harter et al., 1990). The anatomical positioning of the hamstrings presents a mechanical advantage for attenuating the amount of strain generated at the level of the cruciate ligaments by controlling the amount of anterior-posterior tibial translation permitted at the knee (Markolf et al., 2004).

Study findings indicate that intervention participants experienced a 9.86% increase in $H_{CON}:Q_{CON}$ strength ratio. The $H_{CON}:Q_{CON}$ strength ratio of 78% implies greater knee joint stability (Harter et al., 1990) and suggests a decrease in the probability for

lower extremity injury (Knapik et al., 1991). Findings also demonstrate that the hamstrings generate sufficient force to actively counteract opposing torque produced by the quadriceps in a timely manner.

5.8.2 FUNCTIONAL STRENGTH RATIO

It was hypothesized that H_{CON}:Q_{ECC} strength ratio and time to peak torque in the hamstrings and quadriceps would not differ between the intervention group and control group at pre-testing. It was hypothesized that post-test measurements in the control group would remain relatively consistent to pre-test measurements. It was theorized that prevention program training in the intervention group would yield increased strength ratio, decreased time to peak torque in the hamstrings, and increased time to peak torque in the quadriceps. The following table provides the expected lower extremity strength and time to peak torque of the hamstrings and quadriceps along with research findings.

Table 44

H_{CON}:Q_{ECC} Strength

	Pre-Test (Mean ± SD)			Post-Test (Mean ± SD)		
Participants	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**	**Q TTPT (ms)**	**H TTPT (ms)**	**H:Q Ratio**
Control	201.79 ± 61.04	196.07 ± 29.86	0.97 ± 0.12	202.15 ± 49.02	220.36 ± 38.34	1.01 ± 0.11
Intervention	216.43 ± 63.38	204.64 ± 39.57	0.98 ± 0.12	175.00 ± 57.45	204.29 ± 30.60	0.99 ± 0.09

Hypothesized H_{CON}:Q_{ECC} Strength (Control)	**Hypothesized H_{CON}:Q_{ECC} Strength (Intervention)**
• ↔ Hamstrings time to peak torque • ↔ Hamstrings peak torque • ↔ Quadriceps time to peak torque • ↔ Quadriceps peak torque • ↔ H_{CON}:Q_{CON} strength ratio	• ↓ Hamstrings time to peak torque • ↑ Hamstrings peak torque • ↑ Quadriceps time to peak torque • ↑ Quadriceps peak torque • ↑ H_{CON}:Q_{CON} strength ratio

[a] Significant Group simple effect $p < 0.05$
[b] Significant Time simple effect $p < 0.05$

Research findings did not support the hypotheses. The intervention participants did not demonstrate a significant increase in H_{CON}:Q_{ECC} strength ratio and a significant change in time to peak torque in the quadriceps and hamstrings. Study findings indicate that time to peak torque in the quadriceps decreased 19.14% while time to peak torque in the hamstrings decreased 0.17%. This is contrast to control participants who exhibited a 0.18% and 12.39% increase in time to peak torque in the quadriceps and hamstrings, respectively.

H_{CON}:Q_{ECC} strength ratio results differed from findings from previous research examining functional strength. Functional strength ratios were examined in 26 female recreational athletes. Isokinetic testing was conducted at a velocity of 300°/s. Bennett et al., (2008) found that recreational athletes produced a functional H_{CON}:Q_{ECC} strength ratio of 3.292 ± 1.509.

Intervention participants demonstrated a 1.02% increase in H_{CON}:Q_{ECC} strength ratio. The substantial difference between measures of functional strength in the current study and previous lower ACL injury risk factor research can be attributed to the testing protocol parameters employed. Participants in the current study performed H_{CON}:Q_{ECC} isokinetic testing with maximum hamstrings and quadriceps strength measured across 0˚ - 90˚ of knee flexion (90˚) and extension (0˚) with the torque setting fixed at 100 Nm. Bennett et al., (2008) performed functional H_{CON}:Q_{ECC} strength testing with maximum hamstrings and quadriceps strength measured across 20˚ - 90˚ of knee flexion (90˚) and extension (20˚) which would inflate H:Q measures because participants would have greater leverage during knee extension. While it is unknown what specific adjustments

were made during isokinetic testing of H_{CON}:Q_{ECC} strength in the previous research, a lower torque setting would allow for greater peak torque values.

The combination of a powerful quadriceps contraction coupled with an insufficient hamstrings co-contraction when the knee is rapidly moving generates substantial knee flexion-extension and knee internal-external rotation loading (Shimokochi & Shultz, 2008). Rapid concentric and eccentric contractions of the quadriceps muscle deliver a powerfully directed force onto the anterior aspect of the tibia because the four quadriceps muscles collectively insert onto the patella and tibial tuberosity by way of the patellar tendon (Floyd, 2007). The amount force produced along the quadriceps tendon highly correlates (R^2=0.74, p=<0.00001) with the amount strain produced along the anterior cruciate ligament (Withrow et al., 2006). The musculoskeletal response to forces critically affects structures within the knee (Swanik et al., 2007).

Past research has shown that a force-velocity relationship exists during isokinetic testing (Kong and Burns, 2010; Hole et al., 2000; Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998). As velocity increases, the lower extremity rapidly moves towards maximum extension ideally positioning knee flexors closer to the optimal length to generate the amount of torque needed to achieve dynamic knee joint stabilization (Aagaard et al., 1998). As a result, functional strength ratios approach and/or exceed 100% as velocity increases. Therefore, knee joint stability is sustained throughout the movement task because knee flexors effectively dissipate the amount of force generated by opposing musculature (Liebenson, 2006).

The plyometric drill skill set was constructed to improve muscle contraction and co-contraction response of anterior-posterior and medial-lateral musculature.

Plyometrics produce a rapid eccentric muscle action followed by a rapid concentric muscle action. This type of muscle loading engages the stretch reflex to actively recruit larger more powerful motor units (Howley & Franks, 2007). This may account for the 19.14% and 0.17% decrease in the time to peak torque in the quadriceps and hamstrings, respectively. As the quadriceps assumes the role of the antagonist muscle group during H_{CON}:Q_{ECC} isokinetic testing, larger motor units which have a higher neural threshold are stimulated by the rapid velocity of the test protocol. As the quadriceps rapidly engages the hamstrings, the amount of peak torque produced by the hamstrings is minimized by the opposing eccentric muscle contraction.

5.9 PROGRAM STRENGTHS

The major strength of the training program was the ability to facilitate improvements across multiple ACL injury risk factors. The ACL injury prevention program resulted in significant improvements in knee kinematics at initial contact with the ground and at maximum knee flexion. Drop landing mechanics led to a better attenuation of the knee moment experienced at maximum flexion. Intervention participants demonstrated a significant increase in semi-membranosus amplitude. Intervention participants exhibited significantly greater knee joint position sense at 15˚, 30˚ and 45˚. Anterior knee joint laxity also significantly decreased following training. Mechanical and muscular adjustments to drop landing technique resulted in a significant decrease in vertical ground reaction force.

The protocol employed in this study can also serve as a useful training supplement in both collegiate and high school athletics. The program is educationally geared to minimize high risk motor behaviors through verbal descriptions and visual

demonstrations of commonly performed errors associated with mechanical tasks generally observed in a sports setting. Multiple repetitions of movement tasks along with corrective feedback serve to improve and reinforce motor skill development and mastery. Training also includes multiple skill sets that incorporate upper and lower body conditioning. Agility, plyometric, balance, and strength training components are designed to yield muscular and mechanical benefits that are essential to improving components of sports related fitness.

The protocol can also be easily implemented into existing training sessions. The ACL injury prevention program can serve as a training supplement which can be incorporated before, during, or after practice. The training protocol requires few pieces of equipment that are commonly available in most sports equipment outlets. Training is designed to accommodate single or multiple participants. The use of agility ladders, box platforms, BOSU balance trainers, resistance bands, and medicine balls can be maximized during practice sessions by conducting training in a circuit. The equipment needed to carry out training can easily be modified or substituted with economical alternatives. Pieces of equipment which carry a larger expense such as the BOSU balance trainers can be substituted with inflatable balance discs, aeromat balance blocks, balance pods, or wobble boards.

The protocol can also be safely implemented into existing training sessions. Training can be integrated during the pre-season, season, and post-season. Skill sets are taught in progression thereby maximizing the educational component of the program while minimizing the risk of injury to the athlete. The conditioning elements incorporated in the prevention program are gradually increased in intensity reducing the

risk of overtraining. Participants must progress from calisthenics before incorporating resistance bands and medicine balls into the routine. Exhaustive bouts of agility, plyometric, balance, and periodized resistance training were avoided because of its ineffectiveness in reducing ACL injury risk factors and potential to compromising mechanical ability (Paterno et al., 2004).

The training protocol can also be modified onsite to address the individual needs of the participant(s). High risk positions are minimized through appropriate visual demonstrations and verbal descriptions of proper technique. The inclusion of augmented feedback during training also significantly impacts the learning process. Feedback specific to individual technique has been suggested to be as instrumental to motor development as practice itself (Schmidt & Lee, 2005). The intensity of training can also be adjusted to meet the individual needs of athletes with various levels of conditioning. Increasing or decreasing the sets and repetitions within the circuit offers the added room to optimize muscular development at an appropriate pace and intensity.

Prevention program training also evoked a positive reaction from intervention participants. The entire group of intervention participants completed the 18 training sessions never missing their scheduled practice time. Participants developed a constructive rapport with fellow group members. Participants were eager to continue training and requested additional practice sessions following the completion of the program. A majority of participants also expressed interest in a third phase of training which would introduce agility, plyometric, balance, and strength training drills with a higher degree of mechanical skill and muscular intensity.

5.10 PROGRAM LIMITATIONS

The time needed to conduct and complete training requires a significant commitment on the part of the coaching staff and athlete. Training must be conducted three times per week for a period of six consecutive weeks. Training requires approximately 45 to 60 minutes to complete with the length of training sessions being contingent on the level of muscular and mechanical ability of participants. This is a significant portion of time allocated to ACL injury prevention program training which has the potential to detract from sports specific training. Prevention program training also partitions the amount of time dedicated to team strategy and scrimmaging. The training protocol also requires that equipment to be set up and put away six times per week.

The contributions of coaching personnel and staff have to be matched by the athlete’s commitment to the training and receptiveness to constructive critiques of mechanical performance. This requires coaching personnel and staff to be mindful of proper movement technique and ACL injury risk factors that affect performance. Coaching personnel and staff must be able to provide verbal descriptions and visual demonstrations of each skill presented in the training protocol. This is crucial to instilling the appropriate motor behavior and making participants cognizant of the commonly performed errors associated with each mechanical task. The feedback provided during training also becomes critically important to modifying motor behavior. This requires onsite considerations of individual performance as athletes’ progress from one skill set to the next.

Program limitations also include the cost of equipment. The equipment needed to carry out training may result in a considerable investment depending on the size of the

training cohort. This investment may seem unreasonable for a six week training program. Box platforms and the BOSU balance trainers represent a substantial expense. The expense of equipment is further compounded by the cost of replacing resistance bands which lose their elasticity with extended use. Given the size and weight of box platforms, BOSU balance trainers, and medicine balls may also require the purchase of a utility cart to move equipment from one location to another. The storage of equipment may lead to an additional cost if existing storage space and facilities are limited.

5.11 STUDY STRENGTHS

This study contributed several unique artifacts not previously found in past ACL injury prevention program studies. Pre-test and post-test assessments included an in depth look across several interrelated ACL injury risk factors not examined collectively in previous research (Chappell, & Limpisivasti, 2008; Gilchrist et al., 2008; Kato et al., 2008; Myer et al., 2007; Myer et al., 2006; Paterno et al., 2004; Pfeiffer et al., 2006; Vescovi et al., 2008). Past prevention program studies have generally focused on lower extremity kinematics, moments, and resulting ground reaction forces. The product of the research was greater scientific insight into the biomechanical and neuromuscular effects of specialized training on high risk movement strategies, moments, muscle recruitment patterns, dynamic postural stabilization, ground reaction forces, muscular strength, knee joint proprioception, and knee joint laxity. The inclusion of muscle recruitment strategies, dynamic postural stabilization, muscular strength, knee joint proprioception, and knee joint laxity were unique scientific contributions made to existing prevention program research.

An important strength in the design of the study was the inclusion of a control group. The value of adopting an experimental design allowed results of the investigation to be validated through rigorous scientific control. Evaluation of participant characteristics indicated that there were no significant differences between control participants and intervention participants. Pre-test assessment of modifiable ACL injury risk factors also demonstrated that the control group and intervention group did not significantly differ in any measurement at baseline. Post-test measurements illustrated that participation in prevention program training led to significant improvements in several modifiable ACL injury risk factors. Group differences also indicated training and learning effects which correspond with changes in physical functional capacity and improved skill acquisition and mastery.

The training protocol employed in this study was synthesized the most effective training elements derived from existing ACL injury prevention programs. The definitive objective was to construct a training program that would have a positive impact on existing training schemes currently employed in women's athletics. The inclusion of agility, plyometric, balance, and strength training elements were incorporated to maximize prevention program effectiveness. The prevention program consisted of six consecutive weeks of training (Chappell & Limpisivasti, 2008; Paterno et al., 2004) with a minimum of 18 practice sessions (Myer et al., 2007; Myer et al., 2006) because of the time frame needed to elicit significant changes in knee kinematics and moments. A combination of training components were implemented into the protocol to improve program effectiveness (Chappell & Limpisivasti, 2008; Kato et al., 2008; Myer et al., 2007; Myer et al., 2006; Paterno et al., 2004). Training tasks were also taught in

progression to improve muscle and motor development (Kato et al., 2008; Paterno et al., 2004).

5.12 STUDY LIMITATIONS

Though this study has provided crucial insight into the impact of specialized training on modifiable ACL injury risk factors, this research is not without its limitations. Sample selection was centered on the recruitment of apparently healthy females from the general student population. Inclusion criteria reduced participant selection to physically active females with above-average levels of conditioning from the general student population. However, it is unknown through the scope of this research how specialized training would impact high school and collegiate athletes with sports specific conditioning and skill sets.

Renstrom et al. (2008) found that female athletes participating in basketball followed by gymnastics, lacrosse, and soccer had the highest prevalence for ACL injury in women’s athletics. The mechanism for 70% of ACL injuries (Ramesh et al., 2005) are characterized by an absence of collision, irregular skill-specific mechanics, and aggressive changes in direction and speed (Renstrom et al., 2008). Sports specific conditioning and skill sets exhibited by female athletes poise groups of athletes participating in specific sports to greater risk of ACL injury. The influence of extraneous variables such as the quality of existing technical and tactical instruction, the type of conditioning employed, and the ensuing adaptations to the demands placed on an athlete while participating in a particular sport and position are factors which may affect the utility of prevention program training.

It is also unknown how the prevention program would affect motor development during other high-risk maneuvers. Medial drop landings, cutting, and cross-cutting each encompass aggressive changes in direction and speed and present unique challenges to overall skill-specific mechanics (Renstrom et al., 2008; Mihata et al., 2006). Each mechanical task requires distinctive biomechanical and neuromuscular processes to complete the movement. Prevention program training may have a varied effect on high risk maneuvers leading to improvements in one task and/or decrements in skill acquisition and performance in the remaining movement tasks.

An additional limitation included the failure to track long term progress and collect ACL injury statistics. It is unknown whether the benefits from the prevention program are contingent on continued training. It is possible the intensity, volume, and frequency of the six week training protocol may not have optimally induced the muscular and mechanical response needed to preserve skilled motor performance. Therefore, follow-up testing is needed to determine whether decrements in performance occur. Long term observations would help establish the rate these diminishments in performance materialize. Tracking injury statistics among control and intervention group participants would also have allowed an additional method to gauge the effectiveness of prevention program training. The combination of injury statistics and comprehensive ACL risk factor assessments would have provided greater generalizability of program efficacy.

5.13 CONCLUSION

The ACL Injury Prevention Program improved 27 of the 35 variables examined. Specialized agility, plyometrics, balance, and strength training was found to significantly impact lower extremity kinematics, kinetics, EMG, VGRF, laxity, and proprioception.

Though not significant, improvements in postural stability and lower extremity strength were also observed. Completion of training led to the development of sound drop landing mechanics and muscle recruitment strategies that led to greater knee joint stability. Research findings suggest that training has the potential to reduce the risk of ACL injury risk factors. While this research contributed information not previously found in ACL injury prevention program studies, future research should examine the utility of training in female athletes and several high risk maneuvers.

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Glossary

Anterior Cruciate Ligament

Tough connective tissue composed of multiple non-parallel fibers that attach the tibia to the femur

Anterior Tibial Translation

The anterior migration of the tibia across the femur

Concentric Contraction

Shortening of the muscle that causes motion at the joint it crosses

Conventional H_{CON}:Q_{CON} Strength Ratio

Maximal concentric hamstrings peak torque divided by maximal concentric quadriceps peak torque

Eccentric Contraction

Elongation of the muscle that attempts to control of motion at the joint it crosses

Functional H_{CON}:Q_{ECC} Strength Ratio

Maximal concentric hamstrings peak torque divided by maximal eccentric quadriceps peak torque

Hamstring to Quadriceps (H:Q) strength ratio

Maximal hamstrings peak torque divided by maximal quadriceps peak torque.

Joint Position Sense

Ability to perceive the position and orientation of a body segment around a particular joint

Kinematics

Description of motion without consideration to force

Kinetics

Study of forces associated with motion

Knee Joint Laxity

Amount of knee joint translation permitted within the constraints of its ligaments

Knee Valgus

The outward deviation of the distal end of the lower extremity often is characterized by a "knocked knee" appearance

Knee Varus

The inward deviation of the distal end of the lower extremity often is characterized by a "bow legged" appearance

Muscle Agonist

Muscle or muscle group primarily responsible for joint movement during contraction

Muscle Antagonist

Muscle or muscle group that primarily opposes the contraction of another muscle

Peak Torque

Maximum force output generated at a particular axis of rotation. Peak torque is often used as measure of muscular strength capability

Plyometrics

Type of exercise training designed to produce fast, powerful movements through repeated and rapid contractions of muscles

Proprioception

Perception of movement and orientation of the body from stimuli provided by internal receptors located within the body

Q-Angle

Angle created by two intersecting lines drawn from the center of the patella to the anterior-superior iliac spine of the pelvis and the tubercle of the tibia back through the center of the patella

Torque

The rotary effect of force acting about an axis of rotation often referred to as moment or moment of force

Appendix A

PREVENTION PROGRAM TRAINING: PHASE 1 (WEEKS 1 - 3)

Table 45

PREVENTION PROGRAM TRAINING: CIRCUIT 1

Agility Training (Station 1)	Plyometrics Training (Station 2)	Balance Training (Station 3)
Ladder - forward / backward fast feet 3 Sets	Barrier - forward jumps 3 Sets, 10 Reps	Static - double leg deep hold 3 Sets, 1 Minute
Ladder - lateral fast feet 3 Sets	Barrier - lateral jumps 3 Sets, 10 Reps	Static - double knee hold 3 Sets, 1 Minute
Ladder - forward / backward hopping 3 Sets	Box - forward jumps 3 Sets, 10 Reps	Dynamic - step up / step down 3 Sets, 10 Reps
Ladder - lateral hopping 3 Sets	Box - lateral jumps 3 Sets, 10 Reps	Dynamic - lateral step up / step down 3 Sets, 10 Reps
Ladder - forward / backward fast hands 3 Sets	Pyramids 3 Sets	Stick Landing - double leg jump ups 3 Sets, 10 Reps
Ladder - lateral fast hands 3 Sets,	Bounding 3 Sets, 10 Reps	Stick landing - double leg drop downs 3 Sets, 10 Reps
		Perturbations - double leg 3 Sets, 1 Minute
Strength Training (Station 4)		
Core – crunches 3 Sets, 10 Reps	Lower - alternating forward lunges 3 Sets, 10 Reps	Hamstrings - standing leg curls 3 Sets, 10 Reps
Core - leg raises 3 Sets, 10 Reps	Lower- lateral leans 3 Sets, 10 Reps	Hamstrings - stiff legged lift 3 Sets, 10 Reps
Core - cross crunches 3 Sets, 10 Reps	Lower- sumo squat 3 Sets, 10 Reps	Hamstrings - single leg bridges 3 Sets, 10 Reps
Core - inch sit-ups 3 Sets, 10 Reps	Lower - varied heel raise 3 Sets, 10 Reps	Hamstrings - lying leg curls 3 Sets, 10 Reps

Table 46

AGILITY TRAINING (PHASE 1)

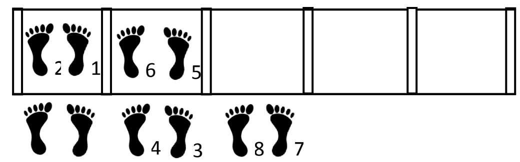
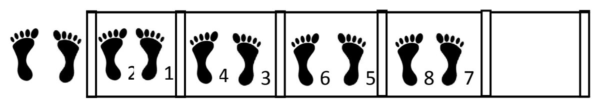
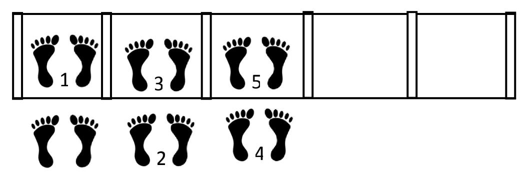
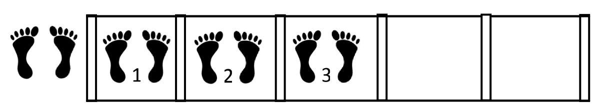
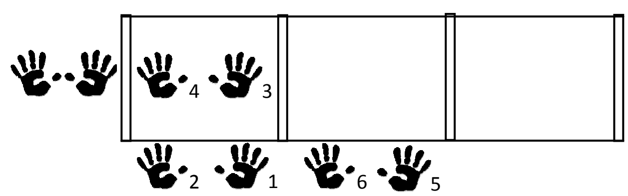
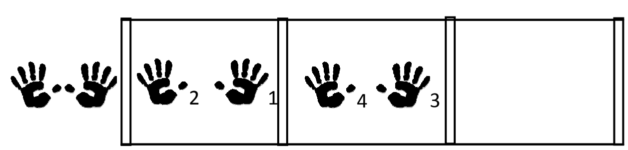
Agility Training (Station 1)	
Exercise	Visual
Ladder - forward / backward fast feet • Start perpendicular to ladder • Step forward into ladder with right foot followed by left • Step back out of ladder with right foot followed by left • Exercise is completed after leading with both right and left sides through the length of the ladder	
Ladder - lateral fast feet • Start perpendicular to the ladder • Step over the ladder rungs always leading with the same foot keeping them parallel • Both feet must meet inside rungs prior to next move • Exercise is completed after leading with both right and left sides through the length of the ladder	
Ladder - forward / backward hopping • Start with both feet together • Hop both feet forward into the ladder. • Then hop both feet backward out of the ladder • Exercise is completed after leading with both right and left sides through the length of the ladder	
Ladder - lateral hopping • Start with both feet together • The exercise will be to hop with both feet together through the ladder. • Exercise is completed after leading with both right and left sides through the length of the ladder	
Ladder - forward / backward fast hands • Start perpendicular to ladder • Cross over and under ladder sides always leading with same hand • Hands must meet prior to next move • Exercise is completed after leading with both right and left sides through the length of the ladder	
Ladder - lateral fast hands • Start perpendicular to ladder • Cross over the ladder rungs always leading with the same hand keeping them parallel • Hands must meet prior to next move • Exercise is completed after leading with both right and left sides through the length of the ladder	

Table 47

PLYOMETRICS TRAINING (PHASE 1)

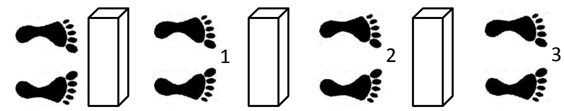
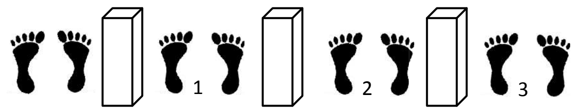
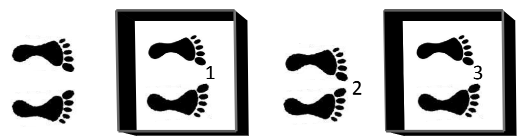
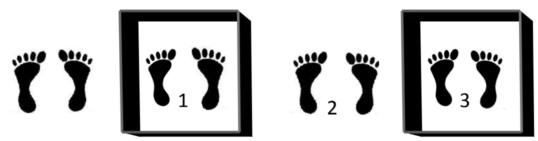
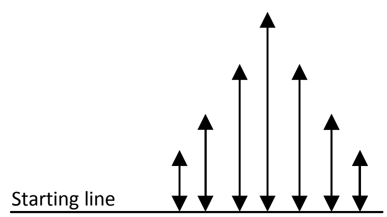
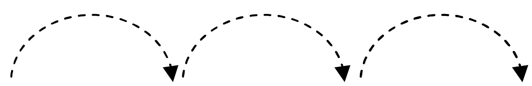
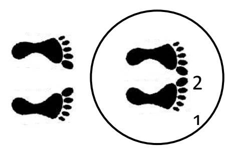
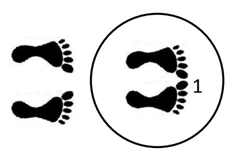
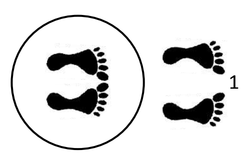
Plyometrics Training (Station 2)	
Barrier - forward jumps • Start with feet together • Jump forward with both feet over the barrier • Continue pattern until completion	
Barrier - lateral jumps • Start with feet together • Jump laterally right with both feet over the barrier • Jump laterally left with both feet over the barrier • Continue pattern until completion	
Box - forward jumps • Start with feet shoulder width apart • Jump forward onto the box with both feet • Jump forward off of the box with both feet • Continue pattern until completion	
Box - lateral jumps • Start with feet shoulder width apart • Jump laterally right onto the box with both feet • Jump laterally right off the box with both feet • Jump laterally left onto the box with both feet	
Pyramids • Starting location is similar in all pyramids • Furthest distance of the pyramid is the halfway point at 20 yards • Distances increase and decrease in increments of five yards • Perform one pyramid in a forward run, another as a backpedal, and one as a lateral slide facing the same direction	
Bounding • Start in a jogging motion • Push off each foot to increase time in the air while driving arms forward	

Table 48

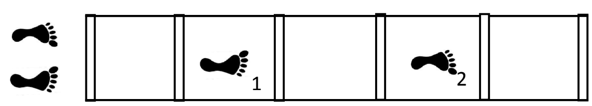
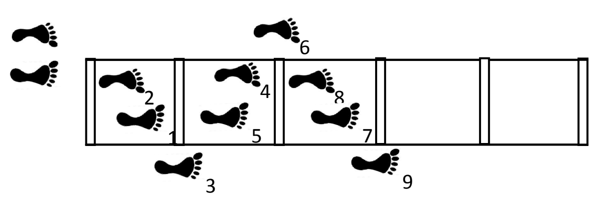
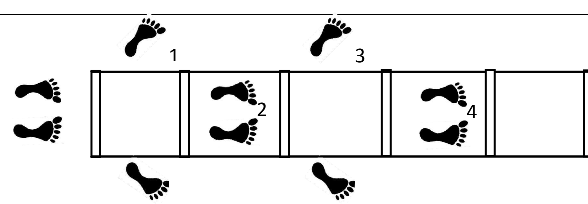
BALANCE TRAINING (PHASE 1)

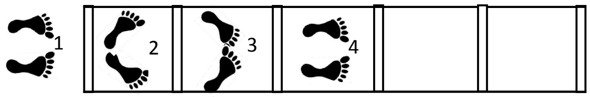
Balance Training (Station 3)	
Static - double leg deep hold • Start on BOSU with feet shoulder width apart • Drop into a deep squat and hold position on BOSU	
Static - double knee hold • Kneel onto the BOSU with both knees • Lift feet off the ground • Maintain balance and focus on keeping posture upright	
Dynamic - step up / step down • Start with feet together behind BOSU • Step onto BOSU with the right foot, left foot follows • Step back off BOSU with the right foot, left foot follows • Continue pattern until completion	
Dynamic - lateral step up / step down • Step laterally onto BOSU with right foot, left foot follows • Step laterally off BOSU with the right foot • Step laterally off BOSU with the left foot • Upon completion the participant will continue exercise in opposite direction	
Stick Landing - double leg jump ups • Start with feet behind the BOSU • Jump onto the BOSU with both feet • Once balance is maintained, step down • Continue pattern until completion	
Stick landing - double leg drop downs • Start with feet on the BOSU • Jump off the BOSU with both feet attempting to get maximal vertical height • Landing should be balanced and controlled • Continue pattern until completion	

Perturbations - double leg • BOSU is placed upside down with the flat side up • Stand on flat side of the BOSU with both feet • Perturbations will be experienced from 360 degrees	

Table 49

STRENGTH TRAINING (PHASE 1)

Strength Training (Station 4)	
Core – crunches • Start in a supine position with finger tips on head • Feet flat of floor • Lift upper body off the ground engaging abdominals • Slowly lower your upper body off the ground • Repeat movement in a controlled manner	
Core - leg raises • Start in a supine position with legs extended • Position hands below lower back for support • Lift straight legs until a 45 degree angle is formed • Slowly lower legs to just above the ground • Repeat movement in a controlled manner	
Core - cross crunches • Start in a supine position with hands behind your ears • Extend one leg out and flex the other • Lift upper body and touch elbow to opposite knee • Extended opposite leg and rotate torso to touch elbow to opposite knee • Repeat movement in a controlled manner	
Core - inch sit-ups • Start in a supine position with hands behind your ears • Lift legs to create a 90 degree angle at the knees • Lift upper body off ground and touch elbows to knees • Lower body so elbows stay within an inch of knees and return elbows to knees • Repeat elbow-knee tap keeping knees at 90 degrees	
Lower - alternating forward lunges • Start feet together • Perform alternating lunges through the ladder while passing over 2-3 rungs on each step	
Lower- lateral leans • Start with feet together to the left of the ladder • Leading with right foot step into ladder one foot at a time with a slightly staggered stance • Right foot then steps out of ladder with all of weight distributed on that foot • Left foot then steps forward into ladder followed by right • Foot pattern continues until end of ladder is reached	
Lower- sumo squat • Start feet shoulder width apart • Jump forward and out of the ladder with toes outward • Perform a sumo squat dropping body into a deep squat • Jump both feet forward and into the ladder • Pattern continues until end of ladder is reached	

Lower - varied heel raise • Start feet shoulder width apart and perform 3 heal raises with toes forward • Jump forward toes outward and perform 3 heal raises • Jump forward toes inward and perform 3 heal raises • Continue pattern until end of ladder is reached	
Hamstrings - standing leg curls • Start feet shoulder width apart with forearms on a wall • Flex the leg by raise heel off the ground against resistance band • In a controlled motion return foot to ground	
Hamstrings - stiff legged lift • In a standing position place resistance band under both feet and hold ends of band • From a 45 degree bend at the hip slowly stand erect • In a controlled motion return to 45 degree bend	
Hamstrings - single leg bridges • In a supine position place one foot on the ground keeping a bend at the knee • Extent the opposite leg and lift so knees are touching • Slowly raise hips to maximum height while keeping foot on ground and using hands for additional support • Slightly lower hips and raise again before ground contact	
Hamstrings - lying leg curls • In a pronated position place resistance band over ankles • Raise feet off the ground flexing the legs • In a controlled motion return feet to ground	

Appendix B

PREVENTION PROGRAM TRAINING: PHASE 2 (WEEKS 4 - 6)

Table 50

PREVENTION PROGRAM TRAINING: CIRCUIT 2

Agility Training (Station 1)	Plyometrics Training (Station 2)	Balance Training (Station 3)
Ladder - hop scotch drill 3 Sets	Barrier - forward jumps 3 Sets, 10 Reps	Static - single leg deep hold 3 Sets, 1 Minute
Ladder - 5 count drill 3 Sets	Barrier - lateral jumps 3 Sets, 10 Reps	Static - single knee hold 3 Sets, 1 Minute
Ladder - lateral feet drill 3 Sets	Box - forward jumps 3 Sets, 10 Reps	Dynamic - step jump vertical / step down 3 Sets, 10 Reps
Ladder - tango drill 3 Sets	Box- lateral jumps 3 Sets, 10 Reps	Dynamic - lateral jump vertical /step down 3 Sets, 10 Reps
Ladder - forward / backward push-ups 3 Sets	Pyramids 3 Sets	Stick Landing - single leg jump ups 3 Sets, 10 Reps
Ladder - lateral push-ups 3 Sets	Bounding with rings 3 Sets, 10 Reps	Stick landing - single leg drop downs 3 Sets, 10 Reps
		Perturbations - single leg 3 Sets, 1 Minute
	Strength Training (Station 4)	
Core – planks 3 Sets, 1 Minute	Lower - alternating forward lunges 3 Sets, 10 Reps	Hamstrings -stiff legged lift 3 Sets, 10 Reps
Core – planks alternating knee bends 3 Sets, 10 Reps	Lower- lateral leans 3 Sets, 10 Reps	Hamstrings - lying leg curls 3 Sets, 10 Reps
Core – planks alternating roll overs 3 Sets, 10 Reps	Lower- sumo squat 3 Sets, 10 Reps	Hamstrings - double leg bridges w/ ball 3 Sets, 10 Reps
Core - V sit-ups 3 Sets, 10 Reps	Lower - varied heel raise 3 Sets, 10 Reps	Hamstrings - Russian hamstrings 3 Sets, 10 Reps

Table 51

AGILITY TRAINING (PHASE 2)

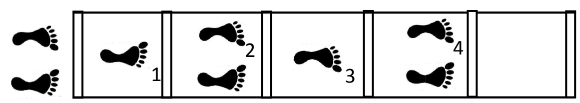
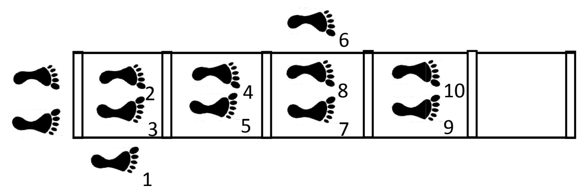
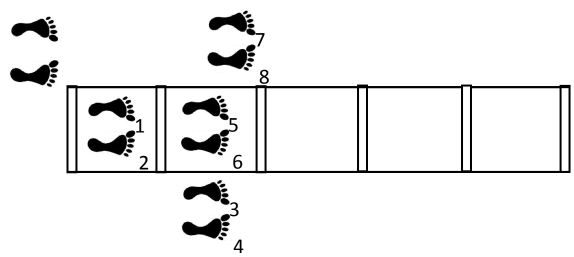
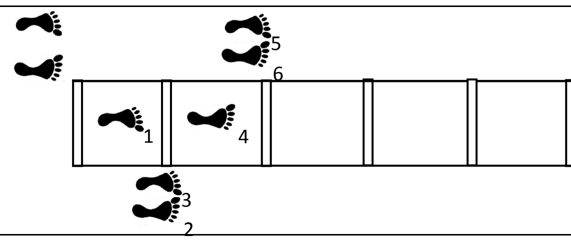
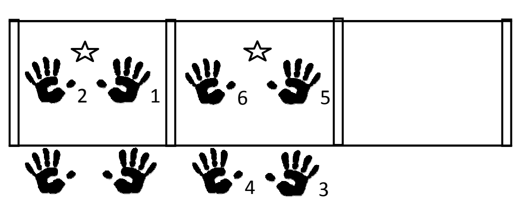
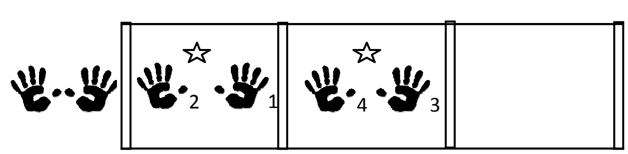
Agility Training (Station 1)	
Exercise	Visual
Ladder – hop scotch drill • Start with feet together • Jump forward with both feet and land only on one foot • Jump forward and land with both feet • Jump forward with both feet and land on opposite foot • Repeat pattern for length of ladder	
Ladder – 5 count drill • Start feet together • Step with the right foot to the side of the ladder • Then step left foot forward and follow with right foot • Step the left foot forward followed by the right again • Step the left foot to the side of the ladder • Then step the right foot forward and follow with left foot • Step the right foot forward followed by the right again. • Repeat pattern for length of ladder	
Ladder – lateral feet drill • Position feet at a diagonal to ladder • Cross left foot into the ladder followed by your right • Cross left foot out of the ladder followed by your right • Step laterally with left foot into ladder followed by the right foot • Step laterally with left foot out of ladder followed by the right foot • Continue pattern for length of ladder	
Ladder – tango drill • Position feet at a diagonal to ladder • Cross left foot into the ladder • Step right foot out of the ladder followed by your left • Cross your right foot into the ladder • Step left foot out of the ladder followed by your right • Continue pattern for length of ladder	
Ladder - forward / backward push-ups • Start perpendicular to ladder • Cross over and under ladder sides always leading with same hand • Hands must meet prior to next move and perform a pushup between rungs • Exercise is completed after leading with both right and left sides through the length of the ladder	
Ladder - lateral pushups • Start perpendicular to ladder • Cross over the ladder rungs always leading with the same hand keeping them parallel • Hands must meet and perform a push-up • Exercise completed after leading with both right and left sides through the length of the ladder	

Table 52

PLYOMETRICS TRAINING (PHASE 2)

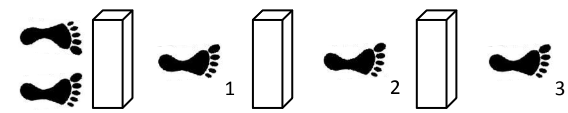
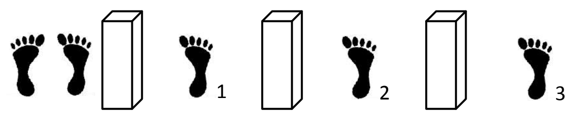
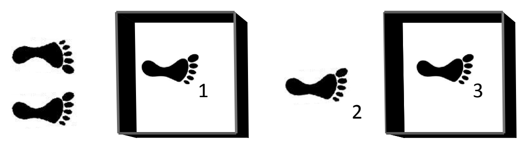
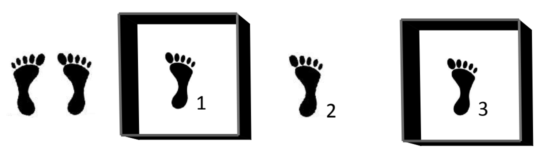
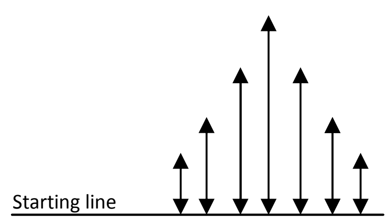
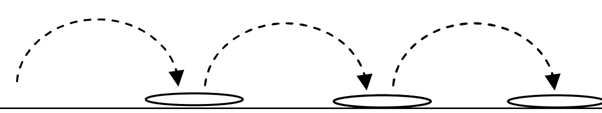
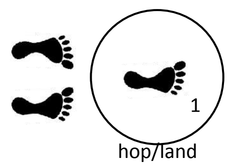
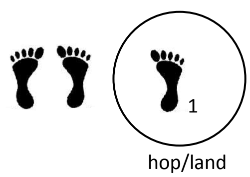
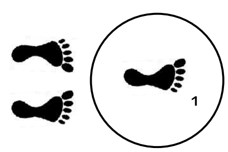
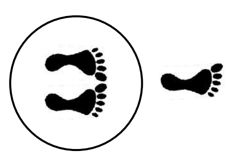
Plyometrics Training (Station 2)	
Barrier - forward jumps • Start with feet together • Jump forward over the barrier and land on one foot • Continue pattern until completion	
Barrier - lateral jumps • Start with feet together • Jump laterally over the barrier landing on one foot • Continue pattern until completion	
Box - forward jumps • Start with feet shoulder width apart • Jump forward onto the box with both feet • Jump forward off of the box with both feet • Continue pattern until completion	
Box - lateral jumps • Start with feet shoulder width apart • Jump laterally right onto the box with both feet • Jump laterally right off the box with both feet • Jump laterally left onto the box with both feet	
Pyramids • Starting location is similar in all pyramids • Furthest distance of the pyramid is the halfway point at 20 yards • Distances increase and decrease in increments of five yards • Perform one pyramid running forward and backpedaling in the same cycle and one as a lateral crossover, or carioca, facing the same direction	
Bounding with rings • Start in a jogging motion • Push off each foot to increase time in the air while driving arms forward • Each stride lands in the preset rings	

Table 53

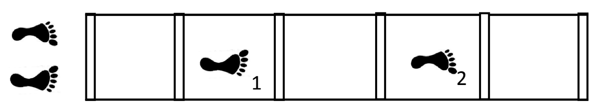
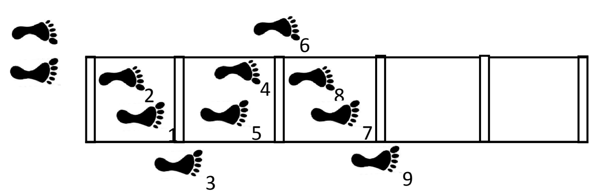
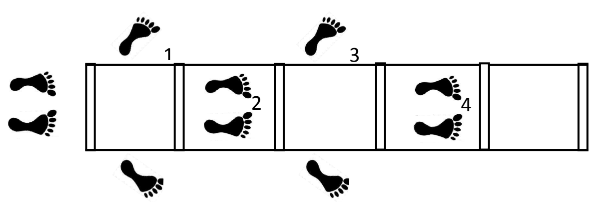
BALANCE TRAINING (PHASE 2)

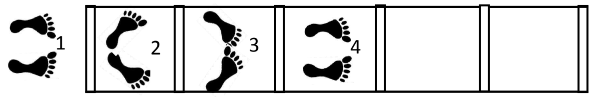
Balance Training (Station 3)	
Static - single leg deep hold • Start on BOSU on one foot • Drop into a deep squat and hold position on BOSU • Repeat with opposite foot	
Static - single knee hold • Kneel onto the BOSU on one knee • Lift feet off the ground • Maintain balance and focus on keeping posture upright • Repeat with opposite foot	
Dynamic - step jump vertical / step down • Start with feet together behind the BOSU • Step onto BOSU with the right foot and use the left leg to propel upward • Land on the BOSU with the right foot • Once balance is maintained step off BOSU • Repeat pattern on opposite foot	
Dynamic - lateral jump vertical /step down • Start with feet together parallel to the BOSU • Step laterally onto the BOSU with the right foot and use the left leg to propel in a vertical hop • Land on the BOSU with the left leg • Once balanced is maintained step down • Repeat pattern on opposite foot	
Stick Landing - single leg jump ups • Start with feet behind the BOSU • Jump onto the BOSU with single leg • Once balance is maintained, step down • Continue until completion and with opposite leg	
Stick landing - single leg drop downs • Start with feet on the BOSU • Jump off the BOSU with both feet attempting to get maximal vertical height • Landing should be balanced and controlled on one foot • Continue until completion and with opposite foot	

Perturbations - single leg • BOSU is placed upside down with the flat side up • Stand on flat side of the BOSU with one foot • Perturbations will be experienced from 360 degrees	

Table 54

STRENGTH TRAINING (PHASE 2)

Strength Training (Station 4)	
Core – planks • Start in a push-up position with your forearms and hands on the ground • Be sure your elbows are directly under your shoulders • Hold this position engaging the core muscles	
Core - planks alternating knee bends • Start in a plank position • While holding this position with your torso, slightly flex one knee while the other stays extended. • Alternate the knee extensions repeatedly while maintaining the plank	
Core - planks alternating roll overs • Start in a plank • Rotate hips right while holding upper body upright • Rotate hips left while holding upper body upright • Continue rotating back and forth while maintaining the plank position	
Core - V sit-ups • Start in a supine position with legs and feet extended • Keep arms extended close to ears while lifting the legs and torso off the ground creating a 'V' with the body • Slowly lower the torso and legs to the ground • Continue pattern until completion	
Lower - alternating forward lunges • Start feet together • Perform alternating lunges through the ladder while passing over 2-3 rungs on each step • Extend medicine ball outward with each lunge	
Lower- lateral leans • Start with feet together to the left of the ladder • Leading with right foot step into ladder one foot at a time with a slightly staggered stance • Right foot then steps out of ladder with all of weight distributed on that foot and leans with the medicine ball • Left foot then steps forward into ladder followed by right • Foot pattern continues until end of ladder is reached	
Lower- sumo squat • Start feet shoulder width apart • Jump forward and out of the ladder with toes outward • Perform a sumo squat dropping body into a deep squat lowering the medicine ball to the ground each squat • Jump both feet forward and into the ladder • Pattern continues until end of ladder is reached	

Lower - varied heel raise • Start feet shoulder width apart and perform 3 heel raises with toes forward • Jump forward toes outward and perform 3 heel raises • Jump forward toes inward and perform 3 heel raises • Extend medicine ball outward for duration of heel raises • Continue pattern until end of ladder is reached	
Hamstrings - stiff legged lift • In a standing position place resistance band under both feet and hold ends of band • From a 45 degree bend at the hip slowly stand erect • In a controlled motion return to 45 degree bend Start feet shoulder width apart with forearms on a wall	
Hamstrings - lying leg curls • In a pronated position place resistance band over ankles • Raise feet off the ground flexing the legs • In a controlled motion return feet to ground	
Hamstrings – single leg bridges w/ ball • In a supine position place one foot on the medicine ball keeping a bend at the knee • Extent the opposite leg and lift so knees are touching • Slowly raise hips to maximum height while keeping foot on ground and using hands for additional support • Slightly lower hips and raise again before ground contact	
Hamstrings - Russian hamstrings • Start in a kneeling position • With a rigid torso and hip extension lower upper body slowly to the ground • Extend arms to land the body slowly • Push up and engage hamstrings to pull body back to kneeling position keeping extension in the hip	

Appendix C

DATA SCREENING

Data entries were examined for accuracy and missing data. The data set did not have missing data. Measures of central tendency (mean), dispersion (standard deviation, variance, maximum values, minimum values), and distribution (skewness, kurtosis) were evaluated. Means, standard deviations, minimum, and maximum values mainly fell well within the range of what is expected for measurements of this nature.

An inspection of z-scores was conducted to identify univariate outliers. Individual cases were measured against a z-score criterion of 3.29. Cases identified as univariate outliers were adjusted by positioning the score just outside the periphery of the second highest or lowest value (Tabachnick & Fidell, 2007). In the event individual cases did not exhibit a significant departure from the 3.29 cutoff but affected the normality of the distribution, cases on the highest and/or lowest end of the distribution were also adjusted to improve skewness and kurtosis. The following table lists univariate outliers, adjustments, z-scores, and the impact on skewness and kurtosis.

Table 55

UNIVARIATE OUTLIERS

Participant Characteristics						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
101	Age	35.00 → 28.00	4.50 → 2.65	1.965 → 0.894	6.177 → -0.014	-1.20 → 2.65
148	Height	182.00 → 172.90	3.38 → 2.13	0.580 → 0.017	1.593 → -0.389	-2.13 → 2.13
Knee Joint Kinematics						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
137	ZKnee_Deg_PreI	-57.33 → -10.99	-5.71 → -2.47	-3.471 → -0.474	18.830 → -0.005	-2.47 → 1.89
104	XKnee_Deg_PostI	111.85 → 42.89	5.78 → 1.69	3.411 → -0.274	19.825 → -0.925	-2.19 → 1.69
104	XKnee_Deg_PostM	119.27 → 84.69	3.75 → 2.09	0.613 → -0.054	2.810 → -0.373	-2.18 → 2.09
Knee Joint Moments						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
162	YMKnee_Nm_PreI	-1977.24 → -1060.10	-3.36 → -2.03	0.843 → -0.404	1.060 → -0.549	-2.03 → 1.77
162	YMKnee_NM_PostI	-2481.22 → -1144.50	-3.98 → -2.22	-1.084 → -0.219	3.323 → -0.391	-2.22 → 2.07
162	ZMKnee_Nm_PostM	-585.25 → -160.22	-5.15 → -2.16	-2.321 → 0.182	12.040 → 0.068	-2.16 → 2.30
Vertical Ground Reaction Force						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
137	ZGRF_bw_Post	1.57 → 1.40	3.69 → 2.21	0.882 → 0.212	1.917 → -0.727	-1.57 → 2.21
Center of Mass						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
131 102	YCOM_deg_Pre	51.55→ 27.24 36.35→ 26.24	4.47 → 1.95 2.55 → 1.79	1.875 → 0.259	6.420 →- 0.744	-2.45 → 1.95
132 156	ZCOM_deg_Post	47.94 → 32.72 44.88 → 31.72	3.64 → 2.41 3.30 → 2.28	1.425 → 0.382	3.632 → -0.319	-1.82→ 2.41
EMG of Lower Extremity Musculature						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
115 107	VMed_Amp_Pre	9.16 → 27.42 17.87 → 28.42	-2.86 → -2.01 -2.38 → -1.95	1.111 → 0.139	3.371 → -0.736	-2.01 → 1.87

118 132	VMed_Onset_Pre	234.58 → 149. 38 204.22 → 148.38	3.46 → 2.21 2.71 → 2.17	1.973 → 1.379	3.010 → 0.279	-.900 → 2.21
162	VLat_Onset_Pre	325.59 → 115.77	6.61 → 2.25	5.216 → 0.332	36.131 → -0.248	-1.81 → 2.25
162	SMem_Onset_Pre	175.92 → 129.21	3.92 → 1.91	1.573 → 0.128	3.616 → -0.832	-1.71 → 1.91
126	STen_Onset_Pre	166.27 → 98.64	6.44 → 2.64	5.145 → 0.284	32.019 → 0.616	-1.43 → 2.64
162 154	GMed_Onset_Pre	328.71 → 205.92 314.56 → 204.92	3.62 → 1.94 3.35 → 1.91	1.851 → 0.264	4.664 → -0.432	-2.03 → 1.94
154 105	VLat_Onset_Post	151.32 → 113.28 141.99 → 112.28	3.76 → 2.18 3.21 → 2.10	1.893 → 0.800	4.154 → -0.457	-1.34 → 2.18
105	STen_Onset_Post	179.40 → 100.96	6.43 → 2.54	5.101 → 1.024	31.683 → 0.297	-1.55 → 2.54
105 170	GLat_Onset_Post	251.76 → 160.69 233.92 → 159.69	4.23 → 2.09 3.65 → 2.04	2.329 → 0.525	7.483 → -0.159	-1.86 → 2.09
Knee Joint Proprioception						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
157	Prop_15 _Post	24.75 → 10.50	6.01 → 2.90	4.125 → 0.930	23.590→ 0.626	-1.51 → 2.90
157	Prop_30_Post	12.00 → 10.00	3.29 → 2.72	1.165 → 0.973	1.313 → 0.240	-1.50 → 2.72
Knee Joint Laxity						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
102	Laxity_30_Pre	14.00 → 10.50	4.06 → 2.58	1.328 → 0.514	3.482 → -0.446	-1.46 → 2.58
Functional Strength and Time to Peak Torque						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z-Range
140	QEC_Accel_Pre	480 → 370	3.78 → 2.19	1.632 →0.560	3.313 → -0.456	-1.46 → 2.19
112 107	HEC_Accel_Pre	980 →280 680 → 270	5.89 → 2.92 3.55 → 2.49	4.770 → 0.892	24.748 → 1.142	-2.20 → 2.92
155 124	EC_HQRatio_Pre	1.53 → 1.21 1.50 → 1.20	3.44 →1.96 3.25 → 1.88	1.111 → -0.623	4.020 → 1.210	-2.91→ 1.96
159 140	QEC_Accel_Post	520 → 330 460 →320	4.21 → 2.59 3.44 → 2.40	2.170 → 0.445	7.109 → 0.704	-2.17 → 2.59
146	EC_HQRatio_Post	2.32 → 1.22	6.48 → 2.26	4.976 → -0.311	32.826 → 0.917	-2.67 → 2.26
Conventional Strength and Time to Peak Torque						
Case #	Variable	Adjustment	Z Score	Skewness	Kurtosis	Z Score

180	HCC_Accel_Pre	290 → 240	3.92 → 2.85	1.412 → 0.861	3.287 → 0.554	-1.48 → 2.85
157	QCC_Accel_Post	420 → 120	7.02 → 2.86	6.504 → 0.768	46.045 → 0.160	-1.32 → 2.86
162	HCC_Accel_Post	370 → 190	5.75 → 2.74	3.541 → 0.453	19.352 → -0.298	-1.83 → 2.74

Data were then screened for multivariate outliers using SPSS Regression. Mahalanobis distance was selected to identify multivariate outliers. Mahalanobis distance values were evaluated against a critical value of chi square (p=0.001). Outlier statistics indicated no presence of multivariate outliers in any of the dependent variable groupings.

The plausibility of multicolinearity and singularity were evaluated across several statistics using SPSS Regression. Multiple R, collinearity statistics (tolerance, variance inflation factor), and collinearity diagnostics (condition index, variance proportions), and bivariate correlations were used to identify offending variables. To rectify multicolinearity within a variable grouping , similar measures were either collapsed into a composite variable or removed from analysis and analyzed separately. The following table lists multivariate outliers, multicollinearity statistics, and the variable (s) removed from analysis in order to arrive at acceptable collinearity statistics.

Table 56

MULTIVARIATE OUTLIERS & MULTICOLLINEARITY

Knee Joint Moments Variable Grouping								
Test	**Multivariate Outliers**		**Multicollinearity**					
	x^2	Mahalanobis Distance	R	Significance	Condition Index	Variance Proportions	Collinearity	
							Tolerance	VIF
Pre	16.27	0.21 – 10.80	0.29	F(3,52) = 1.60, p =0.20	3.77	Dimension 4 (3)	0.83	2.56
Post	16.27	0.20 – 8.08	0.28	F(3,52) = 1.49, p =0.23	3.60	Dimension 4 (2)	0.87	2.05
Removed: ZMKnee								
EMG of Lower Extremity Musculature								
Test	**Multivariate Outliers**		**Multicollinearity**					
	x^2	Mahalanobis Distance	R	Significance	Condition Index	Variance Proportions	Collinearity	
							Tolerance	VIF
Pre	32.91	3.64 – 20.93	0.52	F(12,43) = 1.31, p =0.25	85.01 (4)	Acceptable	0.80	2.59
Post	32.91	4.50 – 24.18	0.55	F(12,43) = 1.55, p =0.14	82.667 (4)	Acceptable	0.75	2.86
Removed: Vastus Lateralis Onset Time, Semi-Membranosus Onset Time, and Semi-Tendonosus Onset Time								
Functional Strength and Time to Peak Torque								
Test	**Multivariate Outliers**		**Multicollinearity**					
	x^2	Mahalanobis Distance	R	Significance	Condition Index	Variance Proportions	Collinearity	
							Tolerance	VIF
Pre	16.27	0.06 – 20.31	0.22	F(3,52) = 0.87, p =0.46	30.24	Dimension 4 (2)	0.93	1.11
Post	16.27	0.04 – 13.43	0.13	F(3,52) = 0.29, p =0.83	30.59	Acceptable	0.98	1.10
Removed: H:Q Ratio								
Conventional Strength and Time to Peak Torque								
Test	**Multivariate Outliers**		**Multicollinearity**					
	x^2	Mahalanobis Distance	R	Significance	Condition Index	Variance Proportions	Collinearity	
							Tolerance	VIF
Pre	16.27	0.03 – 12.21	0.25	F(3,52) = 1.17, p =0.33	16.04	Dimension 3 (2)	0.99	1.33
Post	16.27	0.01 – 10.38	0.20	F(3,52) = 0.69, p =0.57		Dimension 3 (2)	0.95	1.25
Removed: H:Q Ratio								

Vitae

Daniel Medrano was born in El Paso, Texas, on August 21, 1976. He is son of Salvador Hernandez and Maria Elena Hernandez. He attended Coronado High School in El Paso, Texas. Upon graduation, he enrolled at the University of Texas at El Paso where he earned a B.S. (December 1999) in Kinesiology, a M.S. (May 2002) in Kinesiology with an emphasis in Biomechanics, and a Ph.D. in Interdisciplinary Health Science (August 2011). Throughout his college career, he maintained professional memberships to a number of organizations relevant to his area of study and actively contributed his time and services to the community.

The Golden Key National Honor Society recognized him for his academic achievements while working on his M.S. As a Ph.D. student, he was recognized by both The National Scholars Honor Society and The Honor Society of PHI KAPPA PHI for his academic accomplishments and service to the community. He was awarded the Hussmann & Golding Endowed Gift for Student Excellence and was a two time recipient of the Cotton Memorial Scholarship.