The Effectiveness of Neuromuscular Training on a Modifiable Anterior Cruciate Ligament Injury Risk Factor

A thesis presented to

the faculty of

the College of Health Sciences and Professions of Ohio University

In partial fulfillment

of the requirements for the degree

Master of Science

Conrad M. Gabler

June 2012

This thesis titled

The Effectiveness of Neuromuscular Training on a Modifiable Anterior Cruciate Ligament Risk Injury Factor

by

CONRAD M. GABLER

has been approved for

the School of Applied Health Sciences and Wellness

and the College of Health Sciences and Professions by

Brian G. Ragan

Assistant Professor of Applied Health Sciences and Wellness

Randy Leite

Dean, College of Health Sciences and Professions

ABSTRACT

GABLER, CONRAD M., M.S., June 2012, Athletic Training

The Effectiveness of Neuromuscular Training on a Modifiable Anterior Cruciate Ligament Injury Risk Factor

Director of Thesis: Brian G. Ragan

Problem: Females sustain 4-6 times more anterior cruciate ligament (ACL) injuries than males due to their greater number of risk factors. Neuromuscular training (NMT) programs have shown to reduce the rate of ACL injuries among females by modifying risk factors. However, a major problem with this research is it lacks adequate control groups, making it difficult to determine whether these positive outcomes are due to specific NMT programs or an increase in exercise workload. Methods: Female college underclassmen (N = 35; age = 18-20 years) were recruited and assigned to either an NMT group or resistance training (RT) group by covariate adaptive randomization. Baseline and posttraining testing was done to assess for risk factor modification. Conclusions: There were no significant differences between the NMT group and RT group in the modification of the ACL risk factor. This suggests that RT has the same effectiveness as NMT on reducing ACL injuries.

Approved: ____

Brian G. Ragan

Assistant Professor of Applied Health Sciences and Wellness

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Anterior cruciate ligament (ACL) tears are disabling injuries that place significant burdens on athletes. It has been estimated that 1 in every 3,000 people in the United States suffer an ACL rupture each year (Miyaska, Daniel, & Stone, 1991). Depending on the type of graft used, the average cost for ACL reconstruction is estimated to be approximately $17,000 per patient, and full recovery commonly takes around 6 months to achieve (Andrews, Harrelson, & Wilk, 2004; Paxton, Kymes, & Brophy, 2010). ACL reconstruction has also been found to lead to the presence of osteoarthritis (OA) in patients, years after surgery (Kessler et al., 2008; Lohmander, Ostenberg, Englund, & Roos, 2004; Porat, Roos, & Roos, 2004). OA has been found to be largely attributable to the excessive tibial rotation that develops after ACL reconstruction (Stergiou, Ristanis, Moraiti, & Georgoulis, 2007). These injuries not only present financial problems, but also lead to personal problems for athletes. First, the time commitment and high amount of work ethic required with rehabilitation can be both physically and emotionally exhausting. Second, athletes who sustain a torn ACL miss the rest of their sport's season, and if they are multiple sport athletes, they often miss an entire year of athletic participation. Third, for those athletes who are potential college prospects, it can impact their scholarship funding opportunities and ultimately hurt their chances of being recruited. This not only places a high amount of stress on the individual, but also, if they are identified as an "athlete," it can lead to a prolonged state of depression (Freedman, Glasgow, Glasgow, & Bernstein, 1998).

Roughly 80% of ACL injuries are linked to a noncontact mechanism, with more than 70% of them occurring while landing from a jump (Boden, Dean, Feagin, & Garrett, 2000; Noyes, Mooar, Matthews, & Butler, 1983). Upon landing from a jump, the lower body may fall into what Ireland (1996) refers to as the “position-of-no-return” (PNR) or valgus collapse. This position involves several kinematics that place a high amount of stress on the ACL, which can ultimately lead to a complete rupture. In sports that involve jumping or cutting activities, females have been found to sustain 4-6 times more ACL injuries than males who participate in the same sports (Arendt & Dick, 1995). This is attributable to the higher number of ACL injury risk factors that females possess compared to males. Although some of the risk factors such as Q-angle and intercondylar notch width cannot be modified because they are biologically permanent in nature, there are risk factors that can be modified through training to help reduce the risk of noncontact ACL injury. Upon maturation, males exhibit a neuromuscular spurt, with increased power, strength, and coordination, whereas females do not (Beunen & Malina, 1988; Malina, Bouchard, & Bar-Or, 2004). This neuromuscular spurt allows the body to compensate for the increases in height and weight demonstrated during puberty. The most common neuromuscular imbalances demonstrated by females are known as quadriceps dominance, ligament dominance, and leg dominance (Myer, Ford, & Hewett, 2004). Coincidentally, all of these dominances can be linked to the landing kinematics of the knee when placed in the PNR.

Quadriceps dominance is characterized by the extended knee posture that is displayed in the PNR when landing from a jump (Chappell, Yu, Kirkendall, & Garrett, 2002; Huston, Vibert, Ashton-Miller, & Wojtys, 2001; Shultz et al., 2001). When landing on an extended knee, the tibia is translated anteriorly to the femur, causing the ACL to become taut. In order to prevent the ACL from rupturing, the hamstrings must activate to flex the knee and translate the tibia posteriorly. In response to anterior tibial translation, females are found to utilize a different muscle recruitment pattern than males by contracting their quadriceps before their hamstrings, whereas males follow the opposite pattern (Huston & Wojtys, 1996). By contracting the quadriceps first, the hamstrings are overpowered, which allows for further anterior tibial translation to occur during landing.

Ligament dominance is evidenced by the increased knee valgus that is displayed in the PNR when landing and cutting (Besier, Lloyd, Cochrane, & Ackland, 2001; Ford, Myer, & Hewett, 2003; Hewett, Stroupe, Nance, & Noyes, 1996; Myer, Ford, & Hewett, 2002). Myer et al. (2004) suggested that female athletes allow the ground reaction force to control the direction of motion of their lower extremity joints rather than controlling it intrinsically. During these maneuvers, females rely more on their knee ligaments rather than lower extremity musculature to absorb ground reaction forces (Hewett, Paterno, & Myer, 2002). This tendency places a high amount of stress on the ACL, which in turn, increases the probability of it rupturing.

The third neuromuscular imbalance that females tend to demonstrate is known as leg dominance. Leg dominance is an imbalance between muscle strength and joint kinematics in contralateral lower extremities (Myer et al., 2004). These side-to-side differences place both the dominant and nondominant legs at risk for injury. By relying more on the dominant leg to absorb the ground reaction forces, greater stress is put on the knee of the dominant leg compared to the nondominant leg. Likewise, the nondominant leg is at an equally high risk of injury as the dominant leg because it is not as capable of absorbing these forces, making it more prone to a valgus collapse.

Due to the high rate of noncontact ACL injuries seen in female athletes, neuromuscular training (NMT) programs have been developed in an attempt to prevent or reduce the risk of injury (Caraffa, Cerulli, Projetti, Aisa, & Rizzo, 1996; Gilchrist et al., 2008; Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Mandelbaum et al., 2005; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005). These programs are administered either as an off-season regimen or as an inseason warm-up routine, and they incorporate a combination of plyometric, proprioceptive, and strength training exercises, with particular focus being placed on correct technique. By modifying neuromuscular imbalances, NMT programs have been able to significantly reduce the rate of noncontact ACL injury (Caraffa et al., 1996; Gilchrist et al., 2008; Hewett et al., 1999; Mandelbaum et al., 2005; Olsen et al., 2005). However, it is unclear whether NMT programs cause these positive outcomes or if they are from a greater exercise workload. A major concern with published research studies is that they lack adequate control groups. For example, most describe in detail the type and frequency of exercise performed by the intervention group, but they fail to clarify the workload of the control group. With unknown potential differences between the intervention and control groups, it is difficult to determine whether the modified risk factors and reduced ACL injuries result from NMT or a general training effect. Therefore, the purpose of this study was to determine the effect that NMT has on a modifiable ACL injury risk factor by comparing an NMT program (Sportsmetrics™) that has reported positive outcomes to a controlled resistance training (RT) program of equal exercise workload.

Specific Aims

1. To evaluate an NMT program's effect on modifying at-risk frontal plane landing kinematics compared to an RT program of equal exercise workload.
2. To evaluate an NMT program's effects on improving maximal vertical jump height compared to an RT program of equal exercise workload.

Hypotheses

1. Over the 6-week training period, the participants of the NMT group will demonstrate a greater increase in their knee separation distance during a landing task, compared to a smaller increase demonstrated in the participants of the control group, who will be completing an RT program of equal volume, frequency, and mode.
2. Over the 6-week training period, the participants of the NMT group will demonstrate a greater increase in their ankle separation distance during a landing task, compared to a smaller increase demonstrated in the participants of the control group, who will be completing an RT training program of equal volume, frequency, and mode.
3. Over the 6-week training period, the NMT group will demonstrate a greater increase in their maximal vertical jump height compared to the control group.

Dependent Variables

1. The knee separation distance of each participant was measured at the prelanding, landing, and take-off instances during the drop-jump test to assess for modifications in landing kinematics.
2. The ankle separation distance of each participant was measured at the prelanding, landing, and take-off instances during the drop-jump test to assess for modifications in landing kinematics.
3. The maximal vertical jump height of each participant was measured before and after training to assess for modifications in muscular power.

Independent Variables

1. The participants underwent a treatment of either NMT or RT.
    a. The participants assigned to the intervention group performed a 6-week NMT program.
    b. The participants assigned to the control group performed a 6-week RT program.
2. The participants were pretested and posttested before and after training.
    a. The participants underwent pretesting measurements before their 6-week training program began.
    b. The participants underwent posttesting measurements after their 6-week training program was completed.

CHAPTER 2: REVIEW OF LITERATURE

Introduction

This chapter begins with a discussion of the consequences that athletes encounter after sustaining an ACL injury. It will then provide an overview of the pathology of ACL injuries, beginning with the anatomical location and function, followed by a discussion of the mechanisms involved in these injuries. This will lead to a discussion of the epidemic of ACL injuries that are seen in female athletes. It will then continue with an overview of the risk factors associated with noncontact ACL injuries, and provide information on why females are at a greater risk of sustaining a noncontact ACL injury compared to their male counterparts. The final section of this chapter will be devoted to ACL injury prevention. It will primarily focus on the history of neuromuscular training (NMT) programs development, their efficacy in reducing the risk of noncontact ACL injuries in female athletes, the issues with previously published investigations, and what needs to be done to improve the quality of this research.

Anterior Cruciate Ligament Injuries

Consequences of ACL Injury

ACL injuries can have many consequences for athletes, especially following a complete rupture. It has been estimated that 1 in every 3,000 people in the United States suffer an ACL rupture each year (Miyaska et al., 1991). Furthermore, the average cost for ACL reconstruction is estimated to be approximately $17,000 per patient, and full recovery commonly takes approximately six months to achieve (Andrews et al., 2004; Paxton et al., 2010). ACL reconstructed knee patients have also been found to have an increased likelihood of developing OA (Kessler et al., 2008; Lohmander et al., 2004; Porat et al., 2004). In a retrospective cohort study by Kessler et al. (2008), patients with isolated ACL rupture who underwent ACL reconstruction had a higher incidence of OA 11 years after surgery. The development of OA in the ACL reconstructed knee is said to be attributable to excessive tibial rotation that has been documented in ACL reconstructed patients (Stergiou et al., 2007). These injuries present not only financial physical problems for athletes, but also personal problems as well. Athletes who sustain a ruptured ACL are forced to lose a majority of their sports season participation. This is particularly devastating to high school athletes who are potential college prospects, because it may impact their scholarship funding opportunities. The rehabilitation process for ACL injuries requires both a significant amount of time commitment and a high degree of effort from athletes in order to achieve a complete recovery. According to Freedman et al. (1998), ACL injuries may also affect the mental health and academic performance of athletes, particularly those whose identity is largely defined by being an athlete. Once their sports participation is taken away from them, they are no longer able to define themselves and begin to lose their identity. This often leads to a stage of depression, where athletes become apathetic and lose interest in everyday matters.

Anatomical Position and Function

The ACL is one of the static stabilizers of the tibiofemoral (knee) joint. It originates on the posteromedial surface of the lateral femoral condyle and diagonally attaches to the medial intercondylar eminence of the tibia. The ACL is comprised of two segments: an anteromedial bundle and a posterolateral bundle (Starkey & Ryan, 2002).

When the knee is fully extended, the posteromedial bundle is tight, and when the knee is fully flexed, the bundles juxtapose their positions, causing the ACL to wind upon itself and the anteromedial bundle to become taut. Its primary functions are to prevent the femur from translating posteriorly on the tibia when weight bearing, and to limit anterior translation of the tibia on the femur when nonweight bearing. The secondary functions of the ACL are to prevent excessive internal rotation of the tibia and to act as a restraint against valgus and varus stresses at the knee joint (Prentice, 2009).

Mechanism of Injury

ACL injuries result from either a contact or noncontact mechanism. Contact injuries involve an external force that alters the position of the knee joint and places stress on the ACL. Noncontact injuries most commonly occur during activities that involve rapid deceleration of the lower extremity, such as landing from a jump or planting prior to cutting (Ireland, Guadette, & Crook, 1997). It has been found that roughly 80% of ACL injuries are the result of a noncontact mechanism, and more than 70% of them occur while landing from a jump (Boden et al., 2000). Upon landing, the lower body falls into what Ireland et al. (1996) refers to as the "position-of-no-return" (PNR) or valgus collapse. This position involves forward trunk flexion, hip adduction, internal rotation of the hip, 20-30° knee flexion, knee valgus, external rotation of the tibia, and forefoot pronation (see Figure 1). Together, the landing kinematics involved with the PNR places a high amount of stress on the ACL and can ultimately lead to a complete rupture.

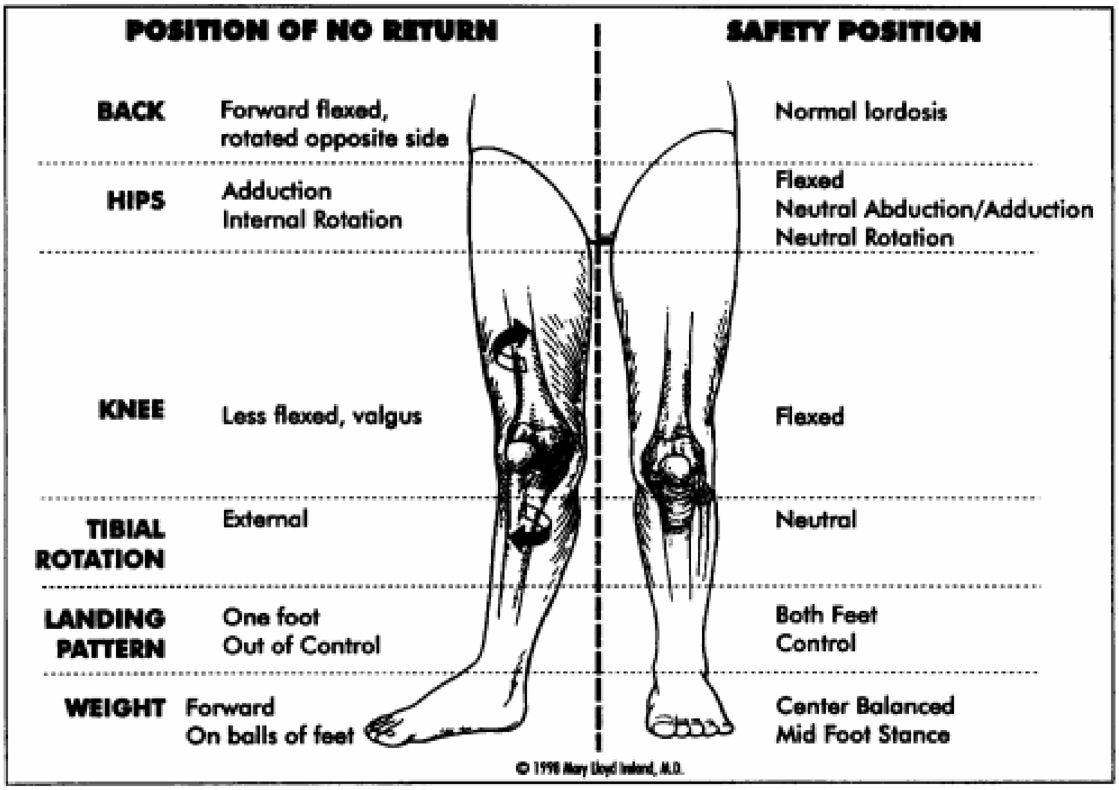

Figure 1. The PNR mechanism for noncontact ACL injury and the safety position. Adapted from “Anterior Cruciate Ligament Injury in Female Athletes: Epidemiology,” by M. L. Ireland, 1999, *Journal of Athletic Training, 34*, p. 152. Copyright 1998 by M. L. Ireland. Reprinted with permission.

Epidemic in Female Athletes

In 1972, the Title IX Educational Assistance Act was passed to ensure equal rights for both male and female athletes enrolled at federally funded institutions. Since that time, female participation in athletics has increased 10-fold at the high school and 5-fold at the collegiate level (National Collegiate Athletic Association, 2002; National Federation of State High School Associations, 2002). With this increased participation in athletics, more injuries have been seen in females; the rate of injury is now far greater than what is seen in males. ACL injuries have been found to occur at a 4 to 6-fold greater rate in female athletes compared with male athletes playing the same landing and cutting sports (Arendt & Dick, 1995; Malone, Hardaker, Garrett, Feagin, & Bassett, 1993). This has led to an estimated 38,000 ACL injuries in girls' and womens' athletics in the United States annually (Toth & Cordasco, 2001).

Prior to puberty, girls and boys are shown to have an equal number of ACL sprains (Andrish, 2001; Buehler-Yund, 1999). It is the period following their growth spurt, and into maturity, that females begin to demonstrate a higher rate of ACL injury compared to males (Tursz & Crost, 1986). A study conducted by Hewett et al. (2004) found that prepubescent boys and girls demonstrated no differences in knee valgus upon landing from a jump. However, girls in the late pubertal stage displayed significantly greater knee valgus than the boys in that stage. These differences are thought to be attributable to the fact that as females grow and mature, they begin to possess a greater number of ACL risk factors compared to males.

Noncontact Anterior Cruciate Ligament Injury Risk Factors

There are multiple factors that contribute to increasing the risk of sustaining a noncontact ACL injury. These risk factors are commonly separated into two main categories: extrinsic and intrinsic. The extrinsic category is comprised of solely environmental risk factors; the intrinsic category, of nonmodifiable and modifiable physical risk factors. The nonmodifiable risk factors include anatomical and physiological influences that are biologically permanent. Conversely, the modifiable risk factors consist of neuromuscular imbalances that can be modified through training.

Extrinsic

Environmental Risk Factors

Environmental risk factors are defined as external factors that increase the risk of sustaining a noncontact ACL injury. This category of risk factors includes meteorological conditions, surface type, and the type of footwear. Table 1 lists and defines the environmental factors associated with noncontact ACL injuries.

Table 1

Extrinsic Environmental Risk Factors for Noncontact ACL Injuries

Risk factor	Definition
Meteorological Conditions	Climates that are dry and high in temperature
Surfacing	The increased traction that certain surfaces provide
Footwear	The increased traction that certain footwear provides

Meteorological conditions. In a prospective study that evaluated the effects of meteorological conditions on the incidence of noncontact ACL injuries in Australian football, Orchard et al. (1999) reported that noncontact ACL injuries were more prevalent in conditions of low rainfall and high evaporation. These meteorological conditions cause the ground to become hard and dry, which increases the shoe-surface traction. Increased shoe-surface traction causes the foot to be fixed on the ground for a longer period of time, making it more likely for overrotation at the knee to occur. Another study found that in outdoor grass stadiums, cold weather was associated with a lower risk of significant ACL injuries when compared with hot weather (Orchard & Powell, 2003). This is because cold weather reduces the shoe-surface traction more on outdoor grass compared to hot weather.

Surfacing. Studies regarding the surface type in relation to noncontact ACL injuries remain controversial and inconclusive. There has been evidence of artificial turf contributing to more ACL injuries, and there has been evidence of natural grass contributing to more ACL injuries (Meyers & Barnhill, 2004; Scranton, Whitesel, & Powell, 1997). However, a retrospective analysis of ACL injuries in Norwegian team handball found an increased risk of ACL injury on artificial floors, compared to natural wood floors (Olsen, Myklebust, Engebrestsen, Holme, & Bahr, 2003). Friction tests have revealed a higher coefficient of friction on artificial floors, concluding that the shoe-surface traction would be increased. The natural consensus is that the greater amount of friction between the shoe and the surface, the higher the risk of sustaining a noncontact ACL injury.

Footwear. The concept behind cleats is to grip the ground during dynamic movement and prevent slippage. This, in turn, allows athletes to make sharper cuts and keep their footing more effectively. Although increasing shoe-surface traction is associated with better performance, it also places the athlete at a higher risk of sustaining a noncontact ACL injury. In football, cleat design has not only been found to be an important factor in torsional resistance, but also has been found to influence ACL injury rates. This suggests that shorter cleat length reduces the risk of noncontact ACL injury (Lambson, Barnhill, & Higgins, 1996).

Intrinsic

Nonmodifiable Intrinsic Risk Factors

There are particular nonmodifiable risk factors that have been correlated with an increased risk of noncontact ACL injury. These risk factors are both anatomical and physiological, and they include increased quadriceps femoris angle (Q angle), decreased intercondylar notch width, increased general joint laxity, excessive foot pronation, and hormonal fluctuations. The mechanical alignment and construction of the lower extremity largely influences the stability of the knee joint. Likewise, the hormonal fluctuations demonstrated in the menstrual cycle influence the tensile strength of the ACL itself. Table 2 lists and defines the nonmodifiable risk factors associated with noncontact ACL injuries.

Table 2

Nonmodifiable Intrinsic Risk Factors for Noncontact ACL Injuries

Risk factor	Definition
Increased Q Angle/Pelvis Width	The angle of the quadriceps femoris. The wider the pelvis, the greater the Q angle.
Narrow Intercondylar Notch Width	The femoral notch is where the ACL in housed within. The smaller the notch, the smaller the ACL.
Increased General Joint Laxity	The increased ability to manipulate an individual's joints.
Excessive Foot Pronation	The tendency to bear weight on the inside of the foot.
Menstruation	The fluctuation of hormones throughout the menstrual cycle.

Increased Q angle. Large Q angles have been associated with an increased risk of noncontact ACL injury in athletes (Heiderscheit, Hamill, & Caldwell, 2000; Mizuno et al., 2001; Shambaugh, Klein, & Herbert, 1991). The Q angle is determined by measuring the angle produced by two intersecting lines. One line is drawn from the center of the patella to the tibial tuberosity, and a second line is drawn from center of the patella to the anterior superior iliac spine (Shambaugh et al., 1991). The normal Q angle is 10° for males and 15° for females (Prentice, 2009). Shambaugh et al. (1991) investigated the relationship between lower extremity alignment and knee injury in recreational basketball players. Various structural components were measurements taken on 45 athletes to reveal that the mean Q angles of the athletes who sustained knee injuries were significantly larger than the mean Q angles of the uninjured athletes (14° vs. 10°).

The magnitude of the Q angle has also been found to predict the position of the knee upon landing from a jump (Buchanan, 2003). In 2003, Buchanan (2003) assessed whether Q angle could predict the valgus-varus knee position on landing. It was found that the static Q angle predicted 32.4% to 46% of the variance in valgus-varus knee position. As discussed previously, knee valgus is one of the landing kinematics involved in the PNR, and it is a common mechanism for noncontact ACL injury.

Due to females having a wider pelvis width, their Q angle tends to be greater than that of males (Horton & Hail, 1989; Livingston, 1998; Moul, 1998). In the same study, Buchanan et al. (2003) compared the valgus-varus knee positions on landing between male and female basketball players. They found that among the peripubescent and postpubescent groups, females had mostly valgus knee positions, whereas males had mainly had varus knee positions. This implies that the greater Q angle in females predisposes them to a valgus knee position upon landing from a jump.

Narrow intercondylar notch width. A large amount of evidence supports the association between narrow intercondylar notch (ICN) width and increased ACL injury risk (Charlton, St John, Ciccotti, Harrison, & Schwietzer, 2002; Harner, Paulos, Greenwald, Rosenberg, & Cooley, 1994; LaPrade & Burnett, 1994; Lund-Hassen et al., 1994; Shelbourne & Kerr, 1998; Souryal & Freeman, 1993; Souryal, Moore, & Evans, 1988; Uhorchak et al., 2003). This is largely due to that fact that a small ICN is associated with a small ACL (small house = small person) (Charlton et al., 2002; Shelbourne & Kerr, 1998; Shelbourne & Kerr, 2001; Uhorchak et al., 2003). It is generally accepted that an ACL of smaller volume will fail at a lower load than an ACL of larger volume.

In 1988, Souryal et al. (1988) devised a method to measure and compare ICN widths on plain radiographs. This method defined the notch width index (NWI) as the ratio of the width of the ICN to the width of the distal femur at the level of the popliteal groove on a tunnel view radiograph. They discovered that the NWI in patients with bilateral ACL injuries was less in patients with unilateral ACL injuries and patients with uninjured knees. Athletes with an NWI less than 17 mm are said to be at higher risk of ACL injury (Lund-Hassen et al., 1994).

In a prospective study of 902 high school athletes, Souryal and Freeman (1993) concluded that athletes with a smaller NWI are at a significantly greater risk of sustaining a noncontact ACL injury. LaPrade and Burnett (1994) conducted a similar prospective study on a cohort of 213 collegiate athletes, and concurred that those athletes with narrow ICN widths are at an increased risk for noncontact ACL injuries. With this evidence, it can be assumed that a decreased ICN width not only increases the risk of ACL injury in general, but more specifically, it increases the risk of sustaining a noncontact ACL injury.

The width of an individual's ICN and ACL size has been found to be directly associated with their height (Anderson, Dome, Gautam, Awh, & Rennirt, 2001; Charlton et al., 2002). The smaller the individual, the smaller the width of their ICN and size of their ACL (and vice versa). Both the width and the shape of the ICN have a significant association with ACL injury risk. Measurement of the ICN width or NWI is two-dimensional, but the actual ICN and ACL are three-dimensional. Fu and Stone (1994) categorized the ICN into three different shapes: a wide reverse U or C-shape, and intermediate H-shape, and a stenotic A-shape. They concluded that individuals with an A-shaped ICN and low notch-to-femur ratio are at the highest risk for ACL ruptures. The ACL is more vulnerable within an A-shaped ICN because when the knee is in full extension, the ACL impinges on the anterior ICN. If the knee were to go into hyperextension and anterior tibial translation occurred, the ACL would be severed by the anterior ICN (similar to a guillotine) (Anderson, Lipscomb, Liudahl, & Addlestone, 1987; Ireland, 1994).

However, the correlation between ICN width and ACL injury remains inconclusive and controversial. The primary reason for this is the high variability of measurement techniques used in published studies, making it difficult to allow for a definitive conclusion. Arendt et al. (1995) conducted a literature review that summarized the existing data on ICN width and its relationship to ACL injury. Of the studies that were reviewed, CT scan, radiographic and direct caliper techniques were used to measure the ICN width (Anderson et al., 1987; Good, Odensten, & Gillquist, 1991; Souryal et al., 1988). More recently, MRI is now being used to indirectly measure ICN width (Anderson et al., 2001). In order for a definitive statement to be made concerning the correlation between ICN width and ACL injury, a standardized measurement tool must be universally accepted.

Females tend to have smaller intercondylar notches than males mainly because they are generally smaller in body size. Consequentially, their ACL has been found to be smaller in length, cross-sectional area, volume, and mass when normalized by height and weight (Anderson et al., 2001; Chandrashekar, Slauterbeck, & Hashemi, 2005; Charlton et al., 2002). Chandrashekar et al. (2006) discovered that when compared to a male ACL, the female ACL has a lower mechanical quality (8.3% lower strain, 14.3% lower stress at failure, and 22.49% lower modulus of elasticity), meaning that it requires less force for a rupture to occur. These findings ultimately place females at greater risk of sustaining a noncontact ACL injury, especially if they are smaller in stature (Lund-Hassen et al., 1994; Uhorchak et al., 2003). Uhorchak et al. (2003) reported that when comparing women, those with a narrow intercondylar width (<13mm) had a 16.8 times greater risk ratio than those with a larger notch width.

Increased general joint laxity. Another anatomical risk factor that has been associated with ACL injury is increased general joint laxity (hypermobility) (Ireland et al., 1997; Loudon, Jenkins, & Loudon, 1996; Soderman, Alfredson, Pietila, & Werner, 2001; Uhorchak et al., 2003; Woodford-Rogers, Cyphert, & Denegar, 1994). Soderman et al. (2001) conducted a prospective study investigating leg injury risk factors. They followed 146 female soccer players for one season, and found that generalized joint laxity significantly increased their risk for knee injury. Likewise, in a prospective 4-year study on 859 US military cadets, Urochak et al. (2003) discovered that the women cadets with knee laxity values that exceeded 1 SD above the mean had a 2.7 times greater relative risk of ACL injury than did women with lower knee laxity values.

More specifically, increased anterior laxity at the knee makes the knee more vulnerable to ACL injury. Genu recurvatum (knee hyperextension) is a general indicator of increased anterior laxity in the knee (Ireland et al., 1997). There has been evidence showing that genu recurvatum and increased anterior knee laxity have a high correlation with ACL injuries (Loudon et al., 1996; Woodford-Rogers et al., 1994). Boden et al. (2000) reported that ACL-injured patients demonstrated significantly more genu recurvatum at 10° and 90° of hip flexion. The reasoning behind this evidence is that hyperextension of the knee causes the ACL to be impinged within the ICN, resulting in increased tensile strain (Ireland et al., 1997).

Joint laxity not only affects sagittal motion of the knee (genu recurvatum) but coronal motion (valgus) as well. By the knee being in a static valgus position, it places stress on the ACL and can increase its risk of being injured (Boden et al., 2000; Markolf et al., 1995). Increased generalized joint laxity is commonly a genetically inherited trait. However, ligamentous laxity may have as much to do with conditioning as it does with genetics. Improving individuals' neuromuscular properties may improve their dynamic stability and decrease the amount of hypermobility in their joints.

In general, females have greater generalized joint laxity than their male counterparts (Boden et al., 2000; Uhorchak et al., 2003). More specifically, females have been found to demonstrate greater knee joint laxity (anterior tibial translation) and hyperextension (genu recurvatum) than males (Rozzi, Lephart, Gear, & Fu, 1999; Soderman et al., 2001). Rozzi et al. (1999) discovered that the excessive knee joint laxity in women contributes to diminished joint proprioception, rendering the knee less sensitive to potentially damaging forces and possibly increasing the risk for noncontact ACL injury. In fact, a study conducted on females found those with knee laxity values greater than 1 SD had a 2.7 times greater risk of ACL injury than those without laxity (Uhorchak et al., 2003).

Excessive foot pronation. Joint laxity at the knee is not the only area linked to ACL injuries. Research strongly suggests that laxity at the foot also contributes to the incidence of ACL injury (Allen & Glasoe, 2000; Bonci, 1999; Loudon et al., 1996; Trimble, Bishop, Buckley, Fields, & Rozea, 2002; Woodford-Rogers et al., 1994). A large majority of these studies use what is known as the navicular drop test to measure the amount of subtalar pronation in their participants (Loudon et al., 1996; Trimble et al., 2002; Woodford-Rogers et al., 1994). This test is performed by taking the navicular height in a seated, subtalar neutral position and again in a standing, full weight-bearing position. The difference in height of the navicular from sitting to standing, recorded as navicular drop, indicates the degree of navicular drop (Starkey & Ryan, 2002). It is been reported that individuals with ACL injury demonstrated a 8.4 mm navicular drop, while individuals without ACL injury only dropped 5.9 mm (Loudon et al., 1996; Woodford-Rogers et al., 1994).

Woodford-Rogers et al. (1994) conducted a case-control study, using 14 ACL-injured football players and 8 ACL-injured female basketball players and gymnasts. They matched them with 22 athletes (without history of ACL) by sport, gender, team, position, and level of competition. They found that the athletes with ACL injuries had greater degrees of navicular drop (subtalar pronation), suggesting that hyperpronation is associated with ACL injury.

Likewise, Allen and Glasoe (2000) compared the navicular drop in 18 individuals previously diagnosed with a torn ACL to an uninjured control group (matched by age, sex, and limb). Their results revealed that the ACL-injured group had a greater mean navicular drop than the control group. They concluded that excessive subtalar pronation may contribute to ACL injury.

One of the main reasons that excessive subtalar pronation is linked to ACL injury is because it has been shown to increase anterior translation of the tibia. Trimble et al. (2002) reported that navicular drop was a significant predictor of anterior tibial translation. Therefore, by allowing the tibia to be translated into a more anterior position, the tensile strain on the ACL increases, placing the ACL at greater risk of rupturing.

Menstruation. The fluctuation of sex hormone levels during the menstrual cycle in females has also been shown to be a risk factor for ACL injury (Beynnon et al., 2006; Deie, Sakamaki, Sumen, Urabe, & Ikuta, 2002; Heitz, 1999; Liu, al-Shaikh, & Panossian, 1996; Shultz, Sander, Kirk, & Perrin, 2005; Slautebeck, Fuzie, & Smith, 2002; Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002; Yu, Liu, Hatch, Panossian, & Finerman, 1999; Yu, Panossian, Hatch, Liu, & Finerman, 2001). Sex hormones have been considered a risk factor for noncontact ACL injury ever since the receptors for these hormones were discovered in human ACL tissue (Liu et al., 1996). There is no consensus as to which phase of the menstrual cycle that the ACL is the most prone to injury due to the conflicting results among studies. The main reason for this controversy is that certain studies failed to measure actual hormone concentrations to confirm the phase of the menstrual cycle, or they limit testing to a single test day rather than a period of time to represent a phase (Beynnon, Bernstein, & Belisle, 2005; Karageanes, Blackburn, & Vangelos, 2000; Van Lunen, Roberts, Branch, & Dowling, 2003). Figure 2 provides a diagram of the female menstrual cycle and the phases that occur within the cycle. It has been agreed upon that estrogen and relaxin significantly affect the tensile properties of ligaments (Liu et al., 1996). Yu et al. (1999, 2001) also evaluated the effects of both estradiol and progesterone on cell proliferation and collagen synthesis in human ACL fibroblast cell cultures. These in vitro studies revealed a decrease in both fibroblast proliferation and type I procollagen synthesis with increased levels of estradiol. However, there was an inhibitory effect displayed with increased levels of progesterone. Controlled levels of estradiol and increased levels of progesterone actually displayed an increase in fibroblast proliferation and type I procollagen synthesis.

Several studies have reported that knee laxity increases occur during the periovulatory and early luteal phases of the menstrual cycle. Shultz et al. (2005) reported that sex hormones explain approximately 68% of the change in knee laxity within each female across their menstrual cycle. As far as the relationship between the phase of the menstrual cycle and the incidence of noncontact ACL injury, the results of studies fail to provide a clear answer.

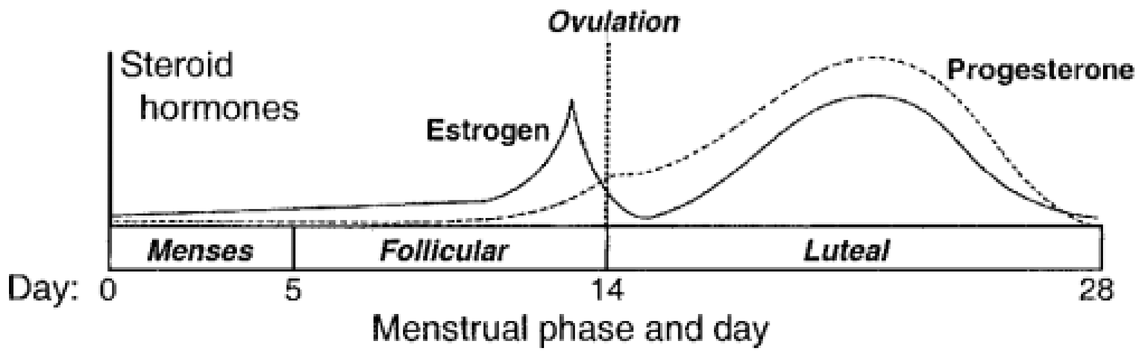

Figure 2. Changes in concentrations of estrogen and progesterone during the menstrual cycle. Adapted from “The Menstrual Cycle, Sex Hormones, and Anterior Cruciate Ligament Injury,” by J. R. Slauterbeck, S. F. Fuzie, M. P. Smith, R. J. Clark, K. T. Xu, D. W. Starch, D .M. Hardy, *Journal of Athletic Training, 37*, p. 277. Copyright 2002 by Journal of Athletic Training. Reprinted with permission.

There are only a few studies that have measured actual hormone levels to confirm cycle phase and the time of injury. Wojtys et al. (2002) measured urine hormone levels in 69 women at the time of injury and identified more injuries around the ovulatory phase (with high estrogen levels) and before the rise of progesterone. Similarly, Slauterbeck et al. (2002) used questionnaires and saliva samples within 72 hours of injury and identified a higher frequency of ACL injury in the days immediately before and after the onset of menses. In a more recent study, Beynnon et al. (2006) examined the likelihood of sustaining an ACL injury by cycle phase in a case control study of 91 alpine skiers (46 injured, 45 uninjured). The menstrual cycle was divided into preovulatory and postovulatory phases based on progesterone levels obtained at the time of injury. They reported that 74% of the injured participants were in the preovulatory phase, whereas only 56% of the uninjured subjects were in that phase.

Estrogen affects not only anatomical properties, but also, both directly and indirectly, the neuromuscular system. Sarwar et al. (1996) discovered that quadriceps strength increases and muscle relaxation slows significantly during the time of ovulation within the menstrual cycle. This finding indicates that estrogen has measureable effects on neuromuscular function and strength.

Using this information, it is safe to conclude that females are at the highest risk of sustaining a noncontact ACL prior to ovulation during the menstrual cycle. This is due to the increased concentration of estrogen that is displayed prior to ovulation (Slautebeck et al., 2002). Collectively, increased estrogen levels have been shown to decrease the tensile strength and increase the laxity of the ACL, and to decrease the neuromuscular function and strength of the lower extremity (Beynnon et al., 2006; Liu et al., 1996; Sarwar et al., 1996; Shultz et al., 2005; Slautebeck et al., 2002; Wojtys et al., 2002).

Modifiable Intrinsic Risk Factors

Upon maturation, males demonstrate a neuromuscular spurt, whereas females show little changes throughout puberty (Beunen & Malina, 1988; Malina et al., 2004). The neuromuscular spurt is defined as increased power, strength, and coordination as demonstrated by maturing adolescent males (Beunen & Malina, 1988; Malina et al., 2004). Adolescent females, however, fail to demonstrate similar neuromuscular increases upon maturation. For example, vertical jump height (whole-body power) increases steadily in males during puberty, but not in females. Martin et al. (2004) reported that no gender differences in peak leg power are noted before age 14, but by age 16, females begin to plateau while males continue to improve. These neuromuscular adaptations are necessary to accommodate for the rapid growth that occurs throughout puberty. Skeletal growth leads to increases in height for both male and females. Increases in height leads to longer levers and potentially a greater amount of torque created at the knee joint. Likewise, weight gains also increase in both males and females during maturation. In males, fat mass remains relatively stable, with gains in skeletal muscle and muscle mass primarily being responsible for the observed increase in mass (Beunen & Malina, 1988; Malina et al., 2004). Conversely, females experience less dramatic gains in skeletal muscle and muscle mass, but demonstrate a continuous increase in fat mass during puberty (Beunen & Malina, 1988; Malina et al., 2004).

These increases in height and weight elevate the center of mass and makes neuromuscular control of body position more difficult, which may translate into larger joint forces at the knee (Hewett et al., 2004). If the appropriate adaptations do not occur, neuromuscular imbalances can present themselves, which increases the risk of sustaining a noncontact ACL injury. The neuromuscular imbalances commonly observed in females are quadriceps dominance, ligament dominance, and leg dominance (Myer et al., 2004). Coincidentally, all of these neuromuscular imbalances are linked to the landing kinematics of the knee when in the PNR. However, unlike the anatomical and physiological risk factors mentioned previously in this chapter, these neuromuscular imbalances can be modified through training. Table 3 lists and defines the modifiable risk factors associated with noncontact ACL injuries.

Table 3

Modifiable Intrinsic Risk Factors for Noncontact ACL Injury

Risk factor	Definition
Quadriceps Dominance	Decreased hamstring-to-quadriceps strength ratio. Preactivation of the quadriceps relative to hamstrings.
Ligament Dominance	Knee ligaments are used to absorb ground reaction forces rather than the lower extremity musculature.
Leg Dominance	Side-to-side differences in lower extremity strength and kinematics

Quadriceps Dominance

Quadriceps dominance is an imbalance between the quadriceps and hamstring strength and activation patterns (Myer et al., 2004). Baratta et al. (1988) found an increased risk of ligamentous damage in athletes with hamstring-to-quadriceps (HQ) strength imbalances and reduced HQ muscle cocontraction patterns. Females tend to utilize their quadriceps muscles more than their hamstring muscles when performing lower extremity sport movements (Hewett et al., 1996). This overreliance on the quadriceps muscles can lead to a large imbalance in strength between the quadriceps and hamstring muscles. Knapik et al. (1991) reported that female athletes who have a HQ peak torque ratio of less than 75% are at a higher risk of sustaining a knee injury. It has been hypothesized that HQ strength ratios lower than 60% predispose an athlete to serious knee injury (Dunnam, Hunter, & Williams, 1988).

During landing and cutting activities, several studies have reported that females also demonstrate a quadriceps-dominant activation pattern when compared to males (Colby et al., 2000; DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004; Huston & Wojtys, 1996; MacWilliams, Wilson, DesJardins, Romero, & Chao, 1999; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; More et al., 1993; Torzilli, Deng, & Warren, 1994; White, Lee, Cutuk, Hargens, & Pedowitz, 2003; Zazulak et al., 2005). Hewett et al. (1996) reported that peak flexor moments at the knee were 3-fold higher in males than in females when landing from a jump. A quadriceps-dominant activation pattern produces significant anterior tibial translation at the knee, and ultimately places more stress on the ACL (DeMorat et al., 2004; Wascher, Markolf, Shapiro, & Finerman, 1993). A study by DeMorat et al. (2004) discovered that an isolated quadriceps force is capable of rupturing a cadaveric ACL. The hamstrings function to pull the tibia posteriorly, so by contracting the quadriceps first, the hamstrings are overpowered, which allows for further anterior tibial translation to occur during landing and cutting. Huston and Wojtys (1996) discovered that in response to anterior tibial translation, females contract their quadriceps before their hamstrings, whereas males follow the opposite pattern to counteract the anterior displacement.

Premature activation of the quadriceps is characterized by the extended knee posture that is displayed in the PNR when landing from a jump (Chappell et al., 2002; Huston et al., 2001; Shultz et al., 2001). As anticipated, females have been shown to perform both cutting and landing activities with significantly lower knee flexion angles than males (Huston et al., 2001; Malinzak et al., 2001). When landing on an extended knee, the tibia is translated anteriorly to the femur, causing the ACL to become taut. The longer duration that this movement occurs without significant cocontraction of the hamstrings to stabilize the joint, the more prone the ACL is to injury. Several studies have concluded that ACL strain increases at knee flexion angles 45° or less and decreases at knee flexion angles 60° or greater (Arms et al., 1984; Besier et al., 2001; Beynnon, Howe, Pope, Johnson, & Fleming, 1992; Beynnon et al., 1995). When comparing female athletes who subsequently sustained ACL injury and uninjured athletes, Hewett et al. (2005) reported that the knee flexion angle upon landing was 10° less in the ACL-injured athletes than uninjured athletes. McNair et al. (1990) reported that ACL injury occurred between 0° to 20° of knee flexion. Using video analyses, two studies have agreed that ACL injury occurs between 0° to 30° of knee flexion (Boden et al., 2000; Olsen, Myklebust, Engebretsen, & Bahr, 2004). At these low knee-flexion angles, the quadriceps muscles antagonistically contract against the hamstrings to pull the tibia anteriorly, while at greater knee-flexion angles, the quadriceps have been shown to synergistically contract with the hamstrings to pull the tibia posteriorly, reducing strain on the ACL (Boden et al., 2000).

Imbalances in activation patterns occur not only anterior to posterior, but also medial to lateral. Rozzi et al. (1999) reported that females demonstrate a four times greater activation of their lateral hamstrings compared to male athletes during a jump landing. Females have also been found to possess a decreased ratio in medial to lateral quadriceps activation (Myer, Ford, & Hewett, 2005). Unbalanced medial to lateral quadriceps recruitment, combined with increased lateral hamstring activation, compresses the lateral joint, distracts the medial joint, and increases anterior shear force (Ford et al., 2003; Markolf et al., 1995; Rozzi et al., 1999; Sell, Ferris, & Abt, 2004). These movements ultimately place the knee into valgus, which directly loads the ACL. This imbalanced medial to lateral recruitment has been thought to be related to decreased control of coronal plane forces at the knee (Kim, Rosen, Brander, & Buchanan, 1995; Markolf et al., 1995; Rozzi et al., 1999). Cocontraction of the quadriceps and hamstring muscles is required to provide compression and stabilization of the knee joint, and prevent significant anterior tibial translation from occurring during activity (Fleming et al., 2003; Solomonow, Baratta, & Zhou, 1987). Markolf et al. (1978) demonstrated that muscular contraction can decrease valgus laxity of the knee up to 3-fold.

Ligament Dominance

Ligament dominance is defined as when an athlete utilizes passive knee stabilizers (knee ligaments) rather than dynamic knee stabilizers (lower extremity musculature) to absorb ground reaction forces during sports maneuvers (Hewett et al., 2002). It is thought that female athletes allow the ground reaction force to control the direction of motion of their lower extremity joints rather than controlling it intrinsically (Myer et al., 2004). This tendency is visibly evident by increased medial knee motion (knee valgus) during sports activities such as landing, cutting, or decelerating, which can result in high ground reaction forces (Besier et al., 2001; Ford et al., 2003; Hewett et al., 1996; Myer et al., 2002). Although this motion is the most evident at the knee, internal moments at the hip and ankle influence the moments occurring at knee (Winter, 1990). As introduced by Ireland et al. (1996), the PNR, demonstrated by a valgus collapse, involves hip adduction, hip internal rotation, tibial external rotation, and forefoot pronation. This absence of muscular activation at the lower extremity places females near the PNR which increases their risk of sustaining ACL injuries (Ireland, 2002).

Leg Dominance

The third neuromuscular imbalance that females tend to demonstrate more than males is leg dominance. Myer et al. (2004) describes leg dominance as an imbalance between muscle strength and joint kinematics in contralateral lower extremities. Side-to-side imbalances in muscular strength, flexibility, and coordination have been shown to contribute to an increased injury risk (Baumhauer, Alosa, Renstrom, Trevino, & Beynnon, 1995; Hewett et al., 2005; Knapik et al., 1991). Females have been shown to generate lower hamstring torques and greater knee-valgus angles contralaterally in their nondominant leg when compared to males upon landing (Ford et al., 2003; Hewett et al., 1996). These side-to-side differences put not only the nondominant leg at risk for injury, but the dominant leg as well. By relying more on the dominant leg to absorb the ground reaction forces, greater stress is placed on the dominant leg's knee compared to the nondominant leg. Likewise, the nondominant leg is equally at a high risk of injury because, compared to the dominant leg, it does not have the neuromuscular capability to absorb these forces, making it more prone to a valgus collapse.

Anterior Cruciate Ligament Injury Prevention

Due to the high rate of noncontact ACL injuries seen in female athletes, training programs have been developed in an attempt to prevent or reduce the risk of injury (Caraffa et al., 1996; Gilchrist et al., 2008; Heidt, Sweeterman, Carlonas, Traub, & Tekulve, 2000; Hewett et al., 1999; Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen et al., 2005; Pfeiffer, Shea, Roberts, Grandstrand, & Bond, 2006; Soderman, Werner, Pietila, Engstrom, & Alfredson, 2000; Wedderkopp, Kaltoft, Holm, & Froberg, 2003). Because the anatomical and hormonal risk factors associated with females are biologically permanent, these programs focus on modifying the neuromuscular risk factors associated with noncontact ACL injuries. By successfully modifying neuromuscular risk factors, NMT programs have been able to significantly reduce the rate of noncontact ACL injury (Caraffa et al., 1996; Gilchrist et al., 2008; Hewett et al., 1999; Mandelbaum et al., 2005; Olsen et al., 2005). Noyes and colleagues (Noyes, Baber-Westin, Fleckenstein, Walsh, & West, 2005) assessed for significant modifications in the frontal plane landing kinematics that are associated with the PNR following an NMT program introduced by Hewett et al. (1996; 1999). Knee separation distances of participants were measured when performing a drop-jump test before and after training. The rationale behind this is that decreased knee separation distance negatively correlates with the hip adduction and knee valgus movements that are seen in the PNR. Noyes et al. (2005) reported significant increases in knee separation distance in female athletes following the completion of NMT compared to baseline measurements. As a result of positive outcomes such as these, NMT programs have been adopted by a number of high school, collegiate, and Olympic female sport teams around the nation in attempt to prevent ACL injuries.

Efficacy of Neuromuscular Training Programs

The NMT programs that have been studied over the past 15 years have demonstrated both significant and nonsignificant outcomes in reducing noncontact ACL injuries. Based on these outcomes, the efficacy of NMT programs is difficult to determine. Table 4 provides a concise description of the published NMT studies and their resulting outcomes. By grouping these studies based on methods, comparisons can be made across the outcomes, making the efficacy of NMT programs more apparent. Despite the mixed results, the larger studies (more participants) tend to demonstrate more positive outcomes. For example, Gilchrist et al. (2008) included nearly 1,500 participants and found that the ACL injury rate in the control group was triple that of the intervention group. Conversely, Soderman et al. (2000) included 140 participants and found that 80% of all ACL injuries occurred in the intervention group. There are also similarities in training among the studies that have shown nonsignificant outcomes. These studies incorporated exercises that involved very little RT and proprioceptive training involving an unstable platform, while studies showing significant outcomes used exercises that incorporated a combination of plyometric training, RT, and proprioceptive training. For example, Pfeiffer et al. (2006) required their participants to perform a 20-minute warm-up during the inseason that consisted of jumping and agility exercises, but was unable to produce significant outcomes. Conversely, Mandelbaum et al. (2005) required their

Table 4
Published ACL Prevention Studies Involving Neuromuscular Training Programs

Author	Sport/s	Sex (G)	Size (N)	Study duration	Training program duration	Exercise/s (I)	Outcome
Caraffa et al. (1996) (NR)	SC	M (I/C)	I (300) C (300)	3 seasons	20 min per day; 30 days (preseason)	Proprioceptive and flexibility training	(I=0.15) ACL injuries per team/season vs. (C=1.15)
Hewett et al. (1999) (R)	BB VB SC	F (I/C) M (C)	I (366) C/F (463) C/M (434)	1 year	60-90 min/day; 3 days/week; 6 weeks (offseason)	Plyometric, resistance, and flexibility training	(I=0) noncontact ACL injuries vs. (C/F=5)
Heidt et al. (2000) (NR)	SC	F (I/C)	I (42) C (258)	1 year	20 sessions; 7 weeks (preseason)	Cardiovascular conditioning, plyometric, resistance, and flexibility training	Not statistically significant; (I= 2.4%) injury rate in vs. (C=3.1%)
Soderman et al. (2000) (R)	SC	F (I/C)	I (62) C (78)	7 months	Warm-up 10-15 min for 30 days; 3x/week after 30 days (in-season)	Balance board training	4/5 of ACL injuries occurred in intervention
Myklebust et al. (2003) (NR)	TH	F (I/C)	I (1705) C (942)	3 seasons	Warm-up 15 min; 3x/week; 5-7 weeks (preseason); Once a week (inseason)	Running, jumping, and wobble board exercises	In elite team division, risk of injury was reduced among those who completed program (odds ratio, 0.06) compared with control

R: randomized, NR: nonrandomized, BB: basketball, VB: volleyball, SC: soccer, TH: team handball, G: grouping; M: males, F: females; N: number of participants; I: intervention group; C: control group

Table 4 *(Continued)*

Author	Sport/s	Sex (G)	Size (N)	Study duration	Training program duration	Exercise/s (I)	Outcome
Wedderkopp et al. (2003) (R)	TH	F (I/C)	I (77) C (86)	9 months	Warm-up 10-15 min ankle disc training (inseason)	Functional strength and ankle-disc training	Unspecified knee injuries were not significantly less in intervention
Pfeiffer et al. (2004) (NR)	BB VB SC	F (I/C)	I (577) C (862)	2 seasons	Warm-up 20 min; 2x/week (inseason)	Jumping and agility exercises	(I=3) noncontact ACL injuries in group vs. (C=3) in control group = no direct effect
Mandelbaum et al. (2005) (NR)	SC	F (I/C)	I (1885) C (3818)	2 years	Warm-up 20 min (inseason)	Flexibility, resistance, plyometric, and agility training	(I=0.09) ACL incidence rate vs. (C=0.49)
Olsen et al. (2005) (R)	TH	F (I/C) M (I/C)	I (958) C (879)	8 months	Warm-up 15-20 min/day for 15 sessions; 1x/week after 15 sessions (inseason)	Running, jumping, and proprioceptive training	(I=25) unspecified knee injuries vs. (C=44)
Gilchrist et al. (2008) (R)	SC	F (I/C)	I (583) C (852)	1 season	Warm-up 3x/week; 12 weeks (inseason)	Flexibility, resistance, plyometric, and agility training	Noncontact ACL injury rate was 3.3 times less in intervention

R: randomized, NR: nonrandomized, BB: basketball, VB: volleyball, SC: soccer, TH: team handball, G: grouping; M: males, F: females; N: number of participants; I: intervention group; C: control group participants to perform a warm-up of the same duration during the inseason that incorporated a combination of plyometric, resistance, flexibility, and agility training, and produced significant outcomes.

Issues with Anterior Cruciate Ligament Prevention Programs

It is unclear as to whether NMT programs cause these positive outcomes or whether the outcomes result from greater exercise workloads. A major problem with published investigations is that they lack adequate control groups. For example, most describe in detail the type and frequency of exercise performed by the intervention group, but they fail to clarify the workload of the control group (see Figure 3). These investigations either did not create a program for the control group to perform, or they created a program, but failed specify the exercise workload (Caraffa et al., 1996; Gilchrist et al., 2008; Hewett et al., 1999; Mandelbaum et al., 2005; Olsen et al., 2005). With unknown potential differences between the intervention and control groups, it is difficult to determine whether the modified risk factors and reduced ACL injuries result from NMT or a general training effect.

Developing an Adequate Control Group

To develop an adequate control group that is comparable to the intervention group, the exercise workload must be balanced between the groups. In the present study, the effect of the NMT program introduced by Hewett et al. (1999) is being compared to that of a RT program. To assure that the RT program was comparable to the NMT program in exercise workload, it was developed with an equal volume, frequency, and mode of exercise.

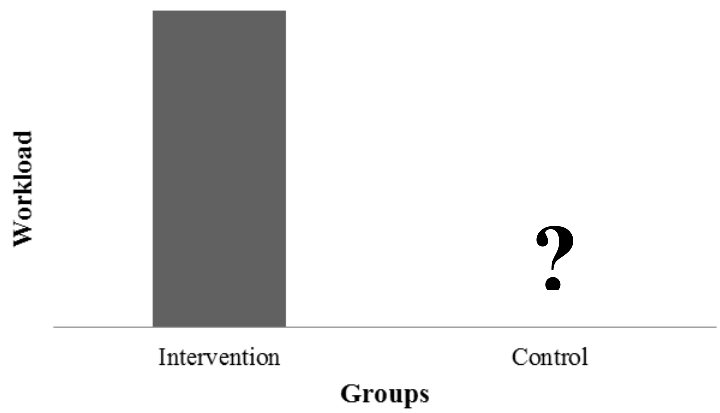

Figure 3. Group workload comparison in published NMT studies. In previous studies, the exercise workload of the control is unspecified.

Hewett et al.'s (1999) NMT program training program consisted primarily of lower body plyometric exercise that was progressed throughout the span of 6 weeks. The NMT program was divided into three, 2-week phases, comprised of 3 sessions a week (on nonconsecutive days). Each phase was comprised of 7-8 plyometric exercises performed per session, with one set of each exercise being performed. Each set of plyometric exercise lasted either 20-30 seconds or 5-10 repetitions, with the higher volume occurring in the later phases. In comparison, the RT program consisted primarily of lower body resistance exercise that was progressed throughout the same 6-week timespan. The control group also attended 3 sessions a week throughout the 6 weeks. To compare volume, the control group performed 8 resistance exercises, with each exercise consisting of 8 repetitions. In an attempt to produce the maximal neuromuscular outcomes, the resistance exercises were performed in compound sets. A compound set involved sequentially performing two different exercises for the same muscle group, purposely making it more demanding and time efficient for the individual.

The exercise progressions of the RT program incorporated the overload principle of preventing neuromuscular adaptations and allowing continuous improvements by increasing exercise intensity. At the same time, the progressions were done properly to avoid overtraining and possible injuries. The amount of load increase for the control group in this study was calculated by following the progression guidelines recommended by the National Strength and Conditioning Association (NSCA) (Baechle, Earle, & Wathen, 2008).

To develop an adequate control group, the participants in the intervention and control groups must be comparable. In this study, covariate adaptive randomization was used to achieve a covariate balance. Covariate adaptive randomization involves assigning a new participant to either the intervention or control group based on specific covariates and assignments of previous participants. These covariates included body mass index and previous participation in athletics. Body mass index (BMI) was chosen because higher BMI rates have been shown to increase the risk of ACL injury (Uhorchak et al., 2003). The amount of participation in high school athletics was chosen because it may affect the degree of neuromuscular control that an individual possesses (Viitasalo, Salo, & Lahtinen, 1998).

Specific Aims

1. To evaluate an NMT program ‘s effect on modifying at-risk frontal plane landing kinematics compared to a RT program of equal exercise workload.
2. To evaluate an NMT program’s effect on improving maximal vertical jump height compared to a RT program of equal exercise workload.

Hypotheses

1. Over the 6-week training period, the participants of the NMT group will demonstrate a greater increase in their knee separation distance during a landing task, compared to a smaller increase demonstrated in the participants of the control group, who will complete a RT program of equal volume, frequency, and mode.
2. Over the 6-week training period, the participants of the NMT group will demonstrate a greater increase in their ankle separation distance during a landing task, compared to a smaller increase demonstrated in the participants of the control group, who will complete a RT program of equal volume, frequency, and mode.
3. Over the 6-week training period, the NMT group will demonstrate a greater increase in their maximal vertical jump height compared to the control group.

CHAPTER 3: METHODOLOGY

Design and Setting

This study was a single-blinded randomized clinical trial (Identifier: NCT01433718) conducted at Ohio University. All of the testing and training sessions were performed at the School of Applied Health Sciences and Wellness. This clinical trial was registered on clinicaltrials.gov. Figure 4 illustrates a flow chart of the study's methods.

Participants

Recruitment

Participants were female college underclassmen (N = 42, ages 18-20) recruited from Ohio University. Recruiting flyers were posted in all dormitories and in several facilities on campus (see Appendix A). All of the participants volunteered to participate in the study and their informed written consent was obtained prior to testing (see Appendix B).

Inclusion/Exclusion Criteria

To be included in this study, participants must have previously participated in high school athletics. All participants must have been healthy and without musculoskeletal injury at the time of training to be included in the study. They must have had a body mass index (BMI) that was normal to overweight (18.5 – 29.9 kg/m^2), and their blood pressure must have been below hypertension (140/90 mmHg) (Cortez-Cooper et al., 2005; Wolk, Berger, Lennon, Brilakis, & Somers, 2003). Any participants who underwent a surgical intervention within the past year (not including facial or dental) or were currently pregnant were excluded from the study. Individuals involved in Ohio University intercollegiate athletics were not allowed to participate. Participants with a history of ACL injury or previous ACL prevention training were automatically excluded from the study. A signed informed consent was received prior to participation in this study.

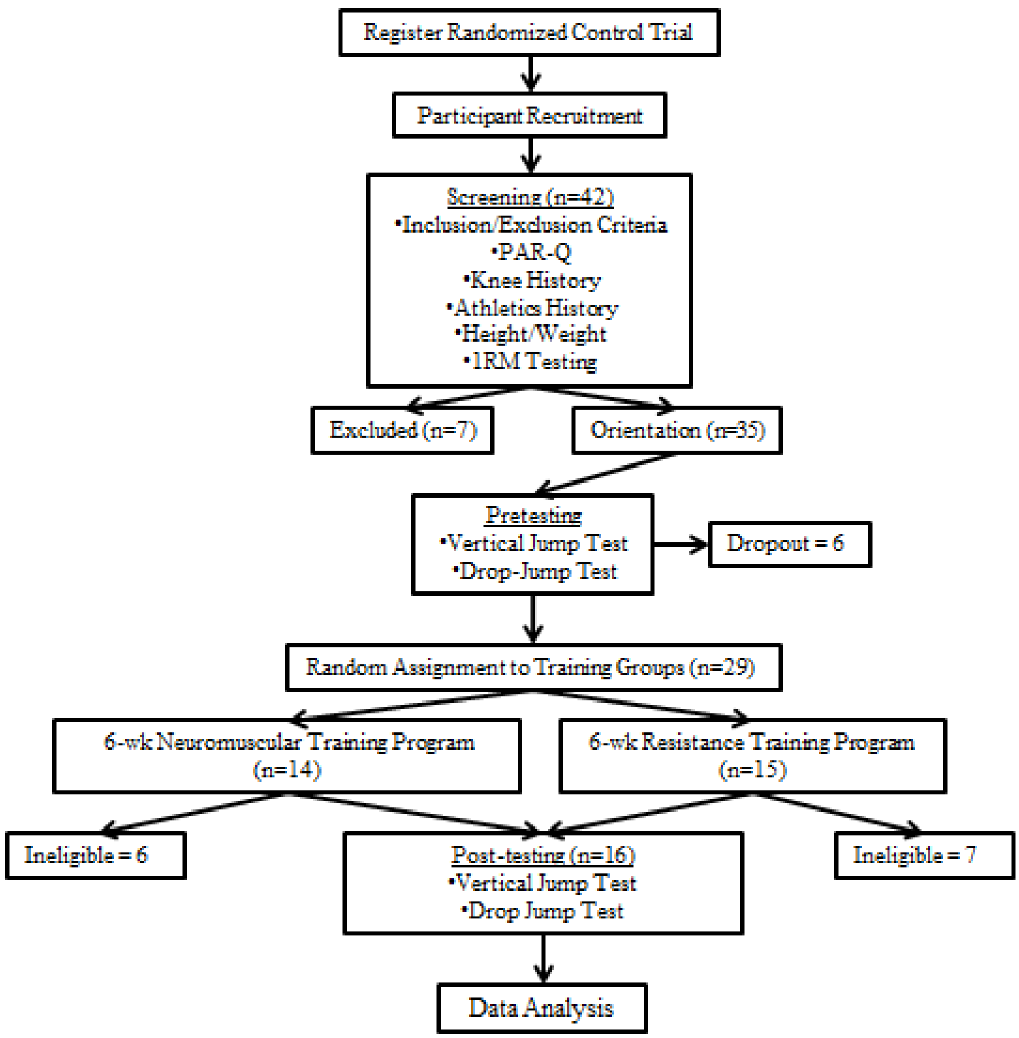

Figure 4. CONSORT study flowchart.

Sample Size and Power Analysis

A power analysis was conducted taking into consideration the repeated measures design of the data. The effect size was based on previous finding from Noyes et al. (2005). The power analysis indicated that a total sample of N = 24 was needed based on an effect size of 0.3 (small), alpha level at 0.05, to achieve a power of 0.8. This sample size was applied to all variables. Because of the repeated design and the strong possibility of attrition, an additional 11 participants (N = 35) were enrolled to ensure that the study was adequately powered.

Measures

Height and Weight

The height of the participants was measured using a stadiometer (Detecto, Webb City, MO) and was recorded in inches to the nearest 0.25 inch and later converted to centimeters. The weight of the participants was measured to the nearest 0.5 pounds using a scale (Detecto, Webb City, MO) and was recorded in kilograms. Height and weight measurements were used to calculate the participants' BMI as height relative to weight (kg/m^2).

Blood Pressure

Blood pressure of the participants was measured by a licensed athletic trainer with the use of an appropriate-sized blood pressure cuff, sphygmomanometer, and stethoscope. Measurements were taken in a seated position following the completion of the questionnaires. Blood pressure was recorded as millimeters of mercury (mmHg).

Vertical Jump Test

To assess for improvements in power, the vertical jump test was performed before and after training. The maximal vertical jump height of the participants was measured using a Vertec (Vertec, Columbus, OH). Each participant's standing reach was recorded prior to performing the vertical jump test. The participants performed three trials, with the highest jump height being recorded. Participants began the test by standing directly underneath the Vertec markers and jumping vertically, while reaching with their hand to swipe the highest marker possible. Arm swing was allowed for the jump, but an approach-step was not. The participants' standing arm reach was subtracted from their maximal vertical jump height to obtain their true vertical jump height. The maximal vertical jump height was measured to the nearest 0.5 inch and later converted to centimeters for recording purposes.

Drop-Jump Test

With a prospective study on ACL injury incidence being beyond the scope of this project due to time, frontal plane landing kinematics associated with the PNR were evaluated before and after training in each group to assess for significant risk modification. To assess for improvements in frontal plane landing kinematics, the knee and ankle separation distances when performing a drop-jump test were compared before and after the training program by using a video analysis (Noyes et al., 2005). Decreased knee separation distance correlates with the knee valgus and hip adduction landing kinematics that are seen in the PNR. A video camera equipped with a memory stick was used to visually record each participant's frontal view during their drop-jump trial. The video camera was fixed to a tripod that is 81.28 cm (32 in) in height and placed approximately 365.76 cm (12 ft) away from the box, which was 30.48 cm (12 in) in height and 50.8 cm (20 in) in width. A calibrating placard was placed next to the front edge of the box for analyzing purposes. Figure 5 portrays the set-up of the drop-jump test.

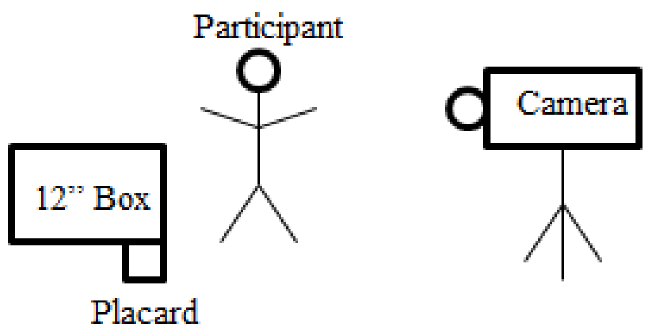

Figure 5. Set-up of the drop-jump test

Prior to beginning the training program, all participants underwent the drop-jump test to obtain a baseline measurement. Participants were instructed to wear fitted, dark shorts and low-cut gym shoes. White ping pong balls were adhered bilaterally to the greater trochanter and lateral malleolus, and white tape was adhered to the center of each patella. These were used as reflective markers for the video analysis. An investigator demonstrated the drop-jump sequence for each participant, and they were each allowed one practice trial before completing three consecutive trials. This practice trial provided the participants with a better understanding of the test and prevented a learning curve. Participants began the test by standing on a box, dropping off, landing straight in front of the box on both feet, and immediately performing a maximum vertical jump.

Knee and ankle separation distance of each participant's drop-jump test was analyzed using the Sportsmetrics^{TM} Software for Analysis of Jumping Mechanics (Cincinnati SportsMedicine & Orthopaedic Center (Cincinnati, OH) on a PC with a Windows Emulator. Following the completion of the three trials, the examiner objectively chose the trial in which the participant displayed the highest jump to best represent the participant's jumping ability for video analysis. By advancing the video frame by frame, the following instances of the drop-jump were captured as still photographs: (a) prelanding, where the participant's toes first touch the ground after the jump off of the box; (b) land, where the participant is at their deepest point during the land; and (c) take-off, where the initial upward movement of the body begins as the participant prepares for the maximum vertical jump. Knee and ankle separation distance was recorded in absolute and normalized values. Absolute knee and ankle separation distance was measured in centimeters between the knees and ankles. With hip width remaining static throughout the drop-jump, normalized knee and ankle separation distance was calculated as the percentage of separation between the knees and ankles relative to the participant's hip width. These measurements were recorded at each participant's prelanding, landing, and take-off instances during their drop-jump test. Figure 6 provides a visual example of the absolute and normalized values that are recorded during the drop-jump test analysis.

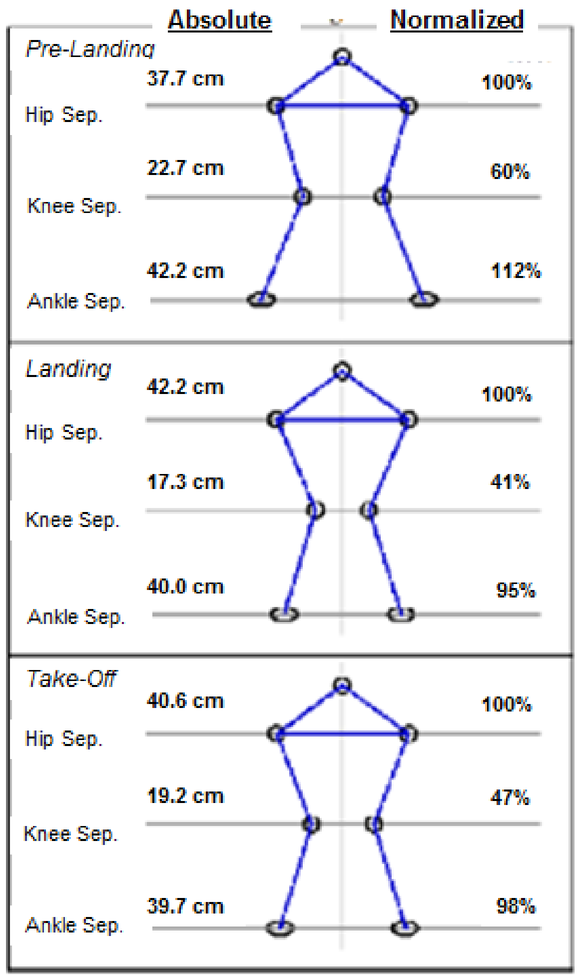

Figure 6. Visual example of absolute and normalized separation values.

Procedures

Eligibility Screening

Recruitment flyers directed interested females to contact the study personnel. Interested females were scheduled for an informed consent visit at which time they were given an approved informed consent form to read and sign. During this session, after giving consent to participate, interested individuals were asked to complete an inclusionary/exclusionary criteria questionnaire to verify their eligibility (see Appendix

C). If eligible to participate, participants were asked to then complete questionnaires regarding their physical health and athletic history. Additionally, height and weight were measured to confirm that they are within the desired BMI (18.5-29.9 kg/m^2), and their blood pressure was measured to verify that they were not hypertensive (< 140/90 mmHg).

Criteria Questionnaire

The participants were required to complete a criteria questionnaire that consisted of the inclusion and exclusion criteria questions. This was used to help determine their eligibility.

Physical Activity Readiness Questionnaire (PAR-Q)

The participants were required to complete a physical activity readiness questionnaire (PAR-Q) (Thomas, Reading, & Shepard, 1992). This insured that the participants were healthy enough to engage in physical activity. The PAR-Q consists of "YES or NO" questionnaires regarding heart conditions, chest pain, and bone or joint problems. If the participants answered "YES" to any one of the questions, they were automatically excluded from the study (see Appendix D).

Knee History Questionnaire

The participants were required to complete a knee history form to assure that none of the participants had knee conditions. This form consisted of questions regarding surgeries, current/ongoing injuries, current knee pain, patellar instability, or swelling. It also assured that a participant was never diagnosed with an ACL injury or previously participated in in an ACL prevention program (see Appendix E).

Athletics History Questionnaire

The participants completed an athletics history form regarding their participation in high school athletics. This form requires the individual to list the high school sport/s that they participated in, and the number of years/seasons they were involved in each sport. This helped to assure equal athletics exposure between the groups (see Appendix F).

One-Repetition-Maximum Testing

Prior to training and before group assignment, each participant performed a one-repetition-maximum (1RM) lift for each resistance exercise and assistance strength exercise to determine the amount of weight that they should be lifting (see Appendix G).

Orientation Meeting

After 1RM testing was concluded, a brief orientation meeting was held to prepare the participants to the study. The participants were given a sign-up sheet for the pretest and informed of when they would be notified which group they were assigned to along with the starting date of training.

Pretesting

Prior to training, all participants performed both the vertical jump and drop-jump tests (see Appendix H). These pretests served as baseline measurements for the participants. Pretesting was performed within 1 week prior to the beginning of training.

Blinding

A blinded investigator was responsible for performing the analysis of each participant's drop-jump test. This individual had no knowledge of group assignment.

Random Assignment to Training Groups

Covariate adaptive randomization was used for this study because it can achieve covariate balance (Kang, Ragan, & Park, 2008). It was the preferred randomization approach for this study because the participants were enrolled on a continuous basis over the startup period. Covariate adaptive randomization involves assigning a new participant to an intervention group or control based on the specific covariates and previous assignments of participants. This approach increases power and validity of the findings. The covariates that were considered in this study include BMI and previous participation in high school athletics (Uhorchak et al., 2003; Viitasalo et al., 1998). These specific covariates were used because they have all been shown to correlate with modifiable ACL risk factors. Covariate adaptive randomization helped to ensure that these variables were similar between the groups. After the pretesting was completed, the participants were randomly assigned to intervention and control groups.

Training Programs

Fourteen of the participants who were assigned to the intervention group performed an NMT program that has demonstrated positive outcomes, while the 15 participants who were assigned to the control group performed an RT program of equal volume, frequency, and mode of exercise (see Appendix I). The focus of the intervention group was to build muscular power and enhance proprioception by engaging in lower body plyometric activity. The focus of the control group was to build lower body muscular strength by performing resistance exercises at the appropriate sets and repetitions developed by the National Strength and Conditioning Association (NSCA)

(Baechle et al., 2008). Each program consisted of 3 sessions a week (on nonconsecutive days), with each session lasting approximately 60 minutes, for the duration of 6 weeks. The session times occurred at multiple times of the day. Figure 7 represents how the minutes were intended to be spent for both groups, controlling for total time. Participants were asked to sign in and out for each training session. This allowed the researchers to track attendance and compare training time between groups (see Appendix J).

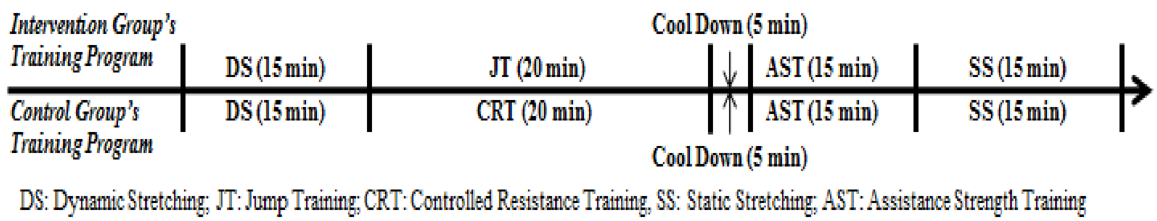

Figure 7. 60-minute training session itinerary for both groups.

Intervention Group's Training Program

Sportsmetrics™, an NMT program developed by the Cincinnati SportsMedicine Research and Education Foundation, was completed by the intervention group. This program consisted of a dynamic warm-up, jump training, static stretching, and strength training. The jump program was comprised of three separate phases. Phase I (technique) included the initial 2 weeks where proper jump-landing technique is drilled. Phase II (fundamental) concentrated on building a base of strength, power, and agility. Lastly, Phase III (performance) focused on improving the height and quality of each jump. A certified Sportsmetrics™ instructor led and supervised the intervention group. The instructor demonstrated proper technique and provided constant verbal and visual feedback regarding all exercises. When performing the jumps, participants were encouraged to maintain neutral alignment from their heads to their heels, land with increased hip and knee flexion, land with their toes and knees pointing forward, and land initially on their forefoot and then rocking back to their heels. Each participant was encouraged to perform as many jumps as possible within the time period while using proper technique. Throughout each phase, either the duration or difficulty of the jumps was progressed to limit neuromuscular adaptation.

A 15-minute dynamic stretching session was performed at the beginning of each training session prior to jump training. Immediately following RT, a 5-minute cool-down was given and participants then transitioned to assistance strength training. A 15-minute static stretching session was completed after the assistance strength training. The participants lifted 70% of their 1RM for each assistance strength exercise. The amount of resistance was increased by 5-10% every two weeks to progressively overload the participants (Baechle et al., 2008). A 1-minute rest period was allotted between each jump and assistance strength exercise. Training logs were given to each participant in the intervention group for them to check off the exercises as they completed them (see Appendix K).

Control Group's Training Program

The control group completed an RT program of equal exercise volume, frequency, and mode to the intervention group's NMT program. This program was created using the guidelines developed by the NSCA. The participants performed 8 repetitions of each exercise with the amount of resistance being based on 80% of their 1RM. To make the programs more comparable in time, the control group performed compound set (back-to-back) exercises in their RT program.

A 15-minute dynamic stretching session was performed at the beginning of each training session prior to resistance training. Immediately following RT, a 5-minute cool-down was given and the participants then transitioned to assistance strength training. A 15-minute static stretching session was completed after the assistance strength training. Participants lifted 70% of their 1RM for each assistance strength exercise. The amount of resistance in both the compound set exercises and assistance strength exercises was increased by 5-10% to progressively overload the participants (Baechle et al., 2008). A 1-minute rest period was allotted between each compound set and assistance strength exercise. Training logs were given to each participant in the control group for them to check off the exercises as they completed them (see Appendix L).

Posttesting

After the completion of the 6-week training period, all participants repeated the vertical jump test and drop-jump test for comparison to baseline values. These tests were performed within 1 week following the completion of training (see Appendix M). Based on the guidelines established by Hewett et al. (1999), all participants must have attended 12 of 18 training sessions to be included in the posttest.

Data Analyses

The independent variables of this study were treatment (intervention vs. control) and time (pre and post). The dependent variables of this study were knee separation distance, ankle separation distance, and max vertical jump height. SPSS 18.0 software was used for data analyses. The comparability of the intervention and control groups at baseline was examined using *t*-tests. Descriptive statistics for outcome variables were expressed as mean ± standard deviation and range. All data was checked to determine if the variables were distributed normally. Repeated measures ANOVAs were used to analyze the primary and secondary outcome measures. If participant dropout occurred during the study, analyses were performed using the intent-to-treat analysis: all randomized participants who had at least one efficacy measurement during the training period.

CHAPTER 4: RESULTS

Group Demographics

The independent t-tests revealed that there were no significant differences in age, height, BMI, or the amount of participation in high school athletics between the NMT and RT groups ($p > .05$). Table 5 summarizes the demographics of the NMT and RT groups.

Table 5

Demographic Comparison between the NMT group and RT group

Demographic	NMT group (n = 14)	RT group (n = 15)
Age	18.7 ± 0.6 years	18.9 ± 0.8 years
Height	164.3 ± 8.4 cm	167.9 ± 2.2 cm
Weight*	58.1 ± 6.8 kg	64.8 ± 9.6 kg
Body mass index	21.6 ± 1.4 kg/m^2	23.1 ± 5.6 kg/m^2
High school participation	8 ± 2.9 seasons	7.6 ± 2.0 seasons

* Statistically significant difference between groups.

Group Training Effects

Completion and Attendance

At the beginning of the training, 29 female participants (NMT = 15; RT = 14) attended the training sessions. After the 6-week training period was completed, only 17 participants (NMT: 8; RT: 9) attended at least 12 of the 18 training sessions, making them eligible for posttesting. The attrition was mostly due to either injury/illness, lack of availability, or personal issues. There was one participant who completed 13 sessions, but acquired mononucleosis at the end of training, and was not able to perform the posttest. Therefore, 16 participants (NMT: 8; RT: 8) underwent posttesting.

Training Sessions & Participant Training Time

The one-way ANOVA tests revealed that there were no significant differences in either the average number of training sessions attended (F = 0.15; df = 15; p =.47) or average participant training time between the NMT and RT groups (F = 3.0; df = 15; p =.06). Figures 8 and 9 provide a graphical representation of the comparison of average sessions attended and average participant training time between the NMT group and RT group.

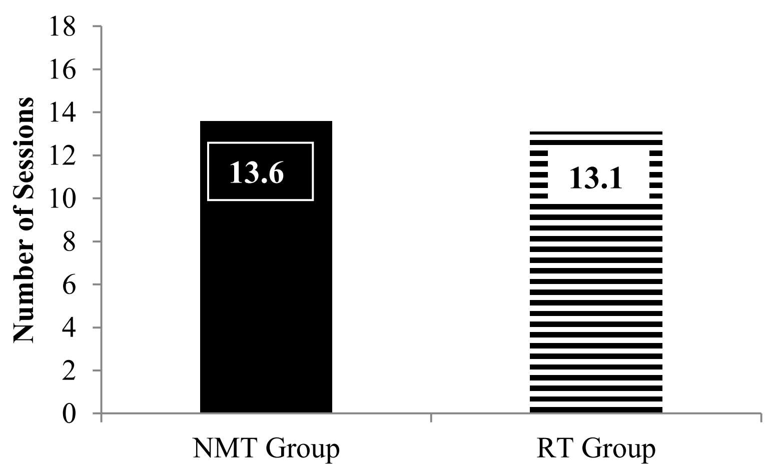

Figure 8. The average number of training sessions attended between the NMT group and RT group.

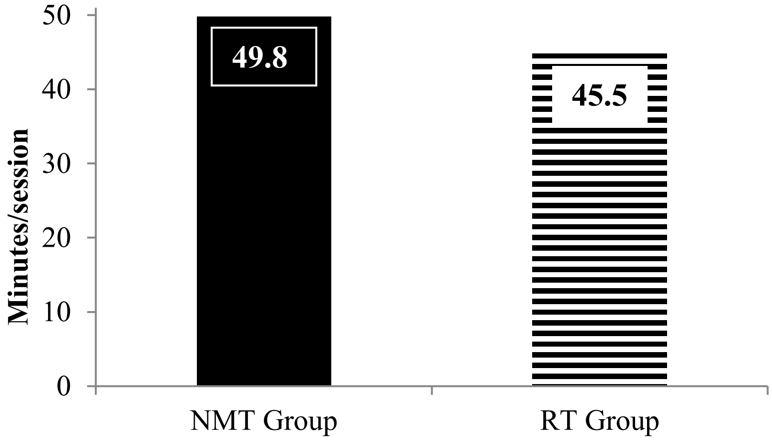

Figure 9. The average participant training time per session between the NMT group and RT group.

Knee and Ankle Separation

The repeated measures ANOVA revealed that there were no statistically significant differences after training in absolute and normalized knee and ankle separation distances for all phases of the jump-land sequence ($p > .05$). Table 6 provides the repeated measures ANOVA statistics for the knee separation results. Table 7 provides the repeated measures ANOVA statistics for the ankle separation results.

The repeated measures ANOVA revealed a statistically significant ($p < .05$) main effect in the NMT and RT group with a decrease in absolute and normalized knee separation on prelanding. There was also a statistically significant main effect in the NMT group and RT group with a decrease in absolute ankle separation on landing ($p < .05$). Table 8 provides a breakdown for the descriptive statistics of the knee and ankle separation results.

Table 6

Repeated Measures ANOVA of Absolute and Normalized Knee Separation

Effect		df	MS	F	P
Time	Prelanding (A)	1	22.526	8.628	.007*
	Prelanding (N)	1	.012	7.394	.011*
	Landing (A)	1	29.291	3.914	.058
	Landing (N)	1	.017	3.827	.61
	Take-Off (A)	1	5.840	.914	.348
	Take-Off (N)	1	.002	.482	.493
Time x Group	Prelanding (A)	1	1.605	.615	.44
	Prelanding (N)	1	.00008	.05	.823
	Landing (A)	1	3.036	.406	.53
	Landing (N)	1	.002	.432	.516
	Take-Off (A)	1	4.956	.776	.386
	Take-Off (N)	1	.002	.423	.521
Error (Time)	Prelanding (A)	27	2.611		
	Prelanding (N)	27	.002		
	Landing (A)	27	7.483		
	Landing (N)	27	.004		
	Take-Off (A)	27	6.391		
	Take-Off (N)	27	.004		

A = Absolute separation; N = Normalized separation; * Statistically Significant ($p < .05$).

Table 7

Repeated Measures ANOVA of Absolute and Normalized Ankle Separation

Effect		df	MS	F	P
Time	Prelanding (A)	1	.774	.145	.707
	Prelanding (N)	1	.001	.273	.606
	Landing (A)	1	11.313	5.826	.023*
	Landing (N)	1	.007	4.009	.055
	Take-Off (A)	1	1.415	.706	.408
	Take-Off (N)	1	.001	.603	.444
Time x Group	Prelanding (A)	1	.158	.030	.865
	Prelanding (N)	1	.003	1.135	.296
	Landing (A)	1	.416	.214	.647
	Landing (N)	1	.00003	.014	.906
	Take-Off (A)	1	.399	.199	.659
	Take-Off (N)	1	.001	.709	.407
Error (Time)	Prelanding (A)	27	5.347		
	Prelanding (N)	27	.003		
	Landing (A)	27	1.942		
	Landing (N)	27	.002		
	Take-Off (A)	27	2.004		
	Take-Off (N)	27	.001		

A = Absolute separation; N = Normalized separation; * Statistically Significant ($p < .05$).

Table 8

Descriptive Statistics for Knee and Ankle Separation between the NMT and RT Groups

	Preland				Land				Take-off			
	Knee		Ankle		Knee		Ankle		Knee		Ankle	
NMT Group	A (cm)	N (%)	A (cm)	N (%)	A (cm)	N (%)	A (cm)	N (%)	A (cm)	N (%)	A (cm)	N (%)
Pretest	25.4	61	33.8	83	20.8	50	31.0	75	20.3	48	30.2	71
Posttest	23.8	59	33.7	84	18.9	45	29.9*	72	19.1	46	30.0	71
Change	-1.6*	-2*	-0.1	1	-1.9	-5	-1.1	-3	-1.2	-2	-0.2	0
RT Group	A	N	A	N	A	N	A	N	A	N	A	N
Pretest	22.2	54	32.7	79	17.8	41	29.9	70	16.9	39	29.8	69
Posttest	21.2	51	32.4	77	16.8	39	29.2*	68	16.9	39	29.3	68
Change	-1.0*	-3*	-0.3	-2	-1.0	-2	-0.7	-2	0.0	0	-0.5	-1

A = Absolute separation distance (cm); N = Normalized separation distance (%); * Statistically significant main effect ($p < .05$).

Maximal Vertical Jump Height

The repeated measures ANOVA revealed that there was no statistically significant difference ($p > .05$) in maximal vertical jump height between groups before and after training. Table 9 provides the repeated measures ANOVA statistics for maximal vertical jump height results. Figure 10 provides a graphical representation of the maximal vertical jump heights of the NMT and RT groups.

Table 9

Repeated Measures ANOVA for Maximal Vertical Jump Height

Effect	df	MS	F	P
Time	1	3.918	.532	.472
Time x Group	1	.358	.049	.827
Error (Time)	27	7.365		

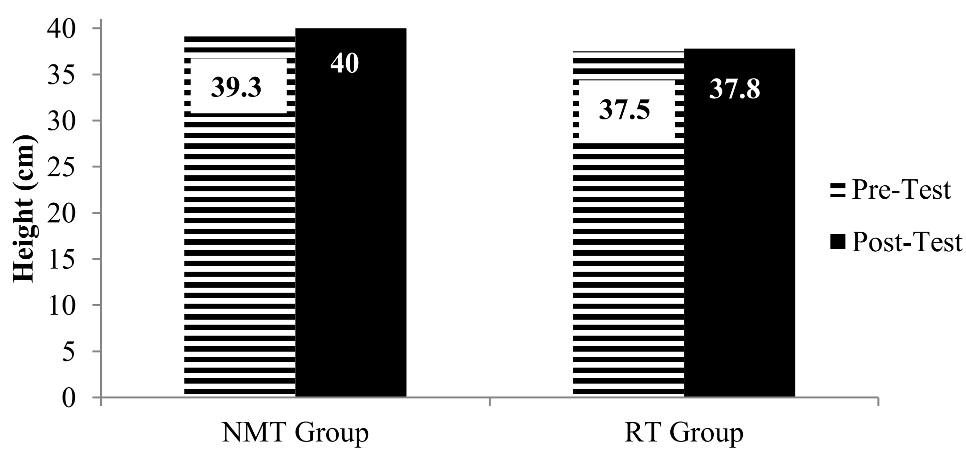

Figure 10. Average maximal vertical jump height comparison between the NMT group and RT group from pretest to posttest.

CHAPTER 5: DISCUSSION

Introduction

This chapter provides an interpretation of the results from our study. It will begin by discussing the equivalent kinematic outcomes that were displayed between the groups and how it relates to previous research studies. This will be followed by a discussion of the unchanged maximal vertical jump height that was revealed from the results. This chapter will continue by discussing the rationale behind the intent-to-treat analysis. This will be followed by a discussion of the limitations that were encountered during our study. Lastly, a conclusion will be provided to discuss the clinical relevance and application of our study, and recommend future areas of research that should be investigated.

Equivalent Group Outcomes

The purpose of this study was to determine the effectiveness that NMT has on a modifiable ACL injury risk factor by comparing a NMT program (Sportsmetrics^{TM}) that has reported positive outcomes of a controlled resistance training (RT) program of equal exercise workload. Our findings were unable to support the hypotheses that over the 6-week training period, the NMT group would demonstrate a significantly greater increase in knee and ankle separation distance during the landing task compared to the RT group. After training, there were no statistically significant modifications between the two groups in either knee or ankle separation distance ($p > .05$). Although our study was unable to support the hypotheses, these findings imply that NMT and RT are equally effective at modifying frontal plane landing kinematics in females. The primary purpose of this study was evaluate the effect that a NMT program has on modifying at-risk landing kinematics compared to a RT program of equal exercise workload. Our methods were similar to that of the study done by Noyes et al. (2005) in that they evaluated the effectiveness that the same NMT program (Sportsmetrics™) had on modifying the same at-risk landing kinematics (knee and ankle separation). They reported significant increases in both knee and ankle separation distance in females at all three instances of the drop-jump ($p < .001$) (Noyes et al., 2005). Our study did not reproduce these results in the NMT group. A possible explanation for this may be the differences in population, sample size, and training time between our study and the study by Noyes et al. (2005). In their study, 62 high school female athletes completed the 6-week NMT program and underwent the drop-jump test analysis (Noyes et al., 2005). The participants in our study were female college students who were current nonathletes, and only 8 of the participants in the NMT group completed the program and underwent the drop-jump test analysis. With our participants being current nonathletes, they may not have been exposed to as much exercise outside of the study as opposed to if they were current athletes. Their study also reported the training sessions to last approximately 60 minutes (Noyes et al., 2005), while the average training session time of the participants in our NMT group was 49.8 minutes. If our study consisted of a larger sample size and a longer training session duration, we may have seen significant increases in knee and ankle separation distance of our participants. However, unlike that of Noyes et al. (2005), we included a balanced control group to compare to our NMT group. By including an RT group of equal exercise workload, our study provided a better approach to revealing the true effectiveness of the NMT program.

It is important to note that the study by Noyes et al. (2005) separately analyzed 39 of the 62 (63%) female athletes whose normalized knee separation distance was <60% of hip separation before training. Individuals who land with a normalized knee separation distance of <60% of hip separation are considered to be at higher risk of noncontact ACL injury (Noyes et al., 2005). Only 23 of the 39 (59%) females in their study improved and landed with a knee separation distance >60% of hip separation after training (Noyes et al., 2005). They suggested that those individuals who are more at risk and land with a normalized knee separation <60% of hip separation, may require further training to elicit improvements in knee separation distance (Noyes et al., 2005). Before training, the mean normalized knee separation distance of both the NMT group and RT group in our study was <60% of hip separation. Because of this, the participants in our study may have needed a training duration longer than 6 weeks to demonstrate modifications in landing kinematics.

The drop-jump test was used in both our study and the study done by Noyes et al. (2005) to evaluate modifications in frontal plane landing mechanics from pretest to posttest. They introduced this screening test as a tool that would provide a general indicator of an athlete's lower limb axial alignment in the frontal plane during a straight forward drop-jump and vertical take-off task. Separation distances at the hip, knee, and ankle are recorded during the drop-jump test to assess for this lower limb alignment. Since the width of the hips does not change, they are used as the reference point of the knees and ankles. The desired result would be if the participant performed the entire drop-jump test with the same degree of knee and ankle separation as the hip. When analyzing the drop-jump test, particular attention is placed on knee separation distance relative to hip separation distance because provides the closest relation to knee valgus. The theory is that decreased knee separation that is displayed during the drop-jump test relates to increased knee valgus (Noyes et al., 2005). This pattern suggests that an individual may possess a modifiable neuromuscular risk factor for noncontact ACL injury known as ligament dominance (Hewett et al., 2002; Myer et al., 2004). Ligament dominance is visually evident by a sign of knee valgus in an individual during jumping or cutting activities (Besier et al., 2001; Ford et al., 2003; Hewett et al., 1996; Myer et al., 2002). Ligament dominance was the primary modifiable risk factor evaluated in this study. However, the drop-jump test has yet to undergo validity and reliability testing to determine whether it can be used as risk indicator for noncontact ACL injury. Although the drop-jump test does allow for measurements to be made easier from a screening standpoint, a multicamera system with 3-D analysis is the gold standard for evaluating kinematics. A sophisticated system such as this takes both frontal and sagittal views, and the measurements are recorded in angular degrees. This not only allows for a better assessment of knee valgus, but also evaluates quadriceps dominance by assessing knee flexion (Chappell et al., 2002; Huston et al., 2001; Shultz et al., 2001). Decreased knee flexion can result in the same unwanted force to the ACL as knee valgus due to its correlation with increased anterior tibial translation (Boden et al., 2000).

A number of ACL prevention studies that were aimed at modifying the incidence of noncontact ACL injuries in females reported significant injury reduction in the females who performed an NMT program (Caraffa et al., 1996; Gilchrist et al., 2008; Hewett et al., 1999; Mandelbaum et al., 2005; Olsen et al., 2005). When evaluating the same NMT program as our study (Sportsmetrics^{TM}), a study done by Hewett et al. (1999) reported a significant decrease in the incidence of noncontact ACL injuries in female athletes who perform the NMT program, compared to those females who did not. In that report, 0 of 366 trained female athletes sustained a noncontact ACL injury, while 5 of 463 untrained female athletes sustained a noncontact ACL injury. The aim of our study was different in that we focused on ACL risk factor modification rather than injury incidence modification. Unlike their study, our study was unable to report positive outcomes in our NMT group. A possible explanation for this finding could be due to our different participant population, low sample size, attendance rate, and training time compared to the study done by Hewett et al.'s (1999). Their study enrolled 355 high school female athletes to complete a NMT program. Our study recruited female college underclassmen who were current nonathletes, and only 15 of them were enrolled to complete the same program in our NMT group. Again, since our participants were current nonathletes, they may not have been exposed to as much exercise outside of the study compared to the current athletes in their study. Their study also required the participants to complete at least 4 out of the 6 weeks (12 of 18 sessions) of the NMT program to be included in the study (Hewett et al., 1999). Of their participants, 68% (248 of 366) fulfilled this criterion, compared to only 53% (8 of 15) of the participants in our NMT group. Of the

53% who fulfilled this criterion, the average number of sessions attended (13.6 sessions) by our NMT group was near the bare minimum of 12 sessions. Hewett et al. (1999) also reported their training sessions lasted approximately 60-90 minutes. As mentioned previously, the training sessions of the participants in our NMT group lasted an average of 49.8 minutes. The fact that our sample size, attendance rate and training time were much smaller than that of Hewett et al. (1999), may explain the difference in outcomes.

Like previous ACL prevention studies, the study by Hewett et al. (1999) did not included a balanced control group. Our study did provided a controlled RT group that was of equal exercise workload to that of the NMT group. By including an adequate control group, it provides a more justifiable comparison of effectiveness between the groups and revealed the true uniqueness of the NMT program. We did not report statistically significant risk factor modifications when comparing the NMT group and controlled RT group. These findings suggest that an NMT program that has reported positive outcomes is equally effective at reducing the rate of noncontact ACL injuries as a RT program of equal volume, frequency, and mode of exercise.

There was a statistically significant main effect for time in absolute and normalized knee separation distance on prelanding ($p < .05$). However, these differences were actually decreases in knee separation distance, meaning that they were landing in greater knee valgus after training than beforehand. There is no explanation for these results. Our training protocol replicated studies that reported significant positive outcomes in their female participants after performing the same NMT program used in our study (Hewett et al., 1999; Noyes et al., 2005).

Unchanged Maximal Vertical Jump Height

Our findings were also unable to support the hypothesis that over the 6-week training period, the NMT group would demonstrate a significantly greater increase in maximal vertical jump height compared to the RT group. In fact, our results revealed no significant differences between the groups in the modification of maximal vertical jump height, and there was no main effect for time in maximal vertical jump in either group. This finding is contrary to what has been demonstrated in previous studies concerning the effect of NMT on maximal vertical jump height (Allerheilegen & Roger, 1995; Hewett et al., 1996; Potach, Katsavelis, Karst, Stergiou, & Latin, 2009). The NMT program (Sportsmetrics™) that was evaluated in our study was first introduced by Hewett et al. (1996; 1999) as an ACL prevention program. This program primarily focuses on lower body plyometric training by incorporating numerous jumping exercises that are progressed in intensity and volume over a 6-week training period. When performed correctly, plyometric training has been shown to be a reliable method for improving muscular power (Hewett et al., 1996; Potach et al., 2009). In Hewett et al.'s (1996) first study that introduced the NMT program (Sportsmetrics™), he evaluated the neuromuscular effect that the program had on the maximal vertical jump height of female athletes. The female participants in his study demonstrated a significant average increase (9.2%) in maximal vertical jump height over a 6-week training period (P =.016). A more recent study done by Potach et al. (2009) reported a significant increase in maximal vertical jump in their participants after performing a different plyometric training program during a shorter 4-week timeframe.

By implementing the same NMT program (Sportsmetrics^{TM}) that was used by Hewett et al. (1996) for the NMT group in our study, we were unable to produce the same maximal vertical jump increases during the 6-week training period. Again, a possible explanation for this finding could be due to our shorter training session time. The training sessions of the 11 female participants in Hewett et al.'s (1996) study were reported to have lasted approximately 120 minutes. Meanwhile, the average training session time of the 8 participants in our NMT group (49.8 minutes) was less than half of that time. Therefore, a longer training session duration may have produced significant increases in maximal vertical jump height in our NMT group.

The RT group in our study demonstrated an equal modification in maximal vertical jump height compared to the NMT group after the same 6-week training period. Similar to the NMT group, the RT group was also unable to demonstrate a main effect in the modification maximal vertical jump height over 6 weeks. The RT group being unable to demonstrate a significant increase in maximal vertical jump height was expected, whereas the NMT group's parallel finding was not. The RT group in our study performed a RT program that was of equal exercise volume, frequency, and mode as the NMT program, and over the same 6-week period. The reason why we did not expect the RT group to demonstrate an improvement in maximal vertical jump height but expected the NMT group to do so, was because the NMT program was designed to increase power, while the RT program was designed to increase strength. The RT program was designed using NSCA guidelines, and included structural exercises that were intended to increase lower body and core strength (Baechle et al., 2008). Prior to training, each participant performed a 1RM test for each exercise to determine the amount weight that they should be lifting when they began the RT program. At the start of the second and fourth week of the RT program, each participant's weight was increased by 5-10% for each exercise. This was done to progressively overload the participants' muscles and produce improvements in strength (Baechle et al., 2008). Every participant in the RT program was able to fluidly progress the amount of weight that they were lifting throughout the 6-week training period. This suggests that the participants in the RT group were able to improve their lower body and core strength. Although we were unable to support the hypothesis of a NMT program being more effective at increasing maximal vertical jump height than a RT program, we are unable to stand by these results due to the opposing findings of previous research. We still believe that the plyometric training implemented in the NMT program is more effective at improving maximal vertical jump height compared to the strength training implemented in the RT program.

Intent-to-Treat Analysis

The intent-to-treat analysis is the preferred approach when analyzing data from a randomized clinical trial such as our study. In almost all clinical trial studies, the circumstance of attrition is encountered. Only analyzing the results of the participants who completed the trial and performed posttesting can lead to a potential biases, increase the chance of false-positive results, and negate the randomization of the groups. The rationale of the intent-to-treat approach is to diminish the effect of attrition by including those participants who began the treatment, but did not finish the trial and perform posttesting. Of those participants who drop out, the pretesting measurements carry over to become their posttesting measurements as well.

Although the intent-to-treat analysis is a valid method for countering the effects of attrition in clinical trials, it also can introduce a bias. By carrying over the pretest measurements to the posttest measurements, it assumes that the treatment is ineffective because the measurements are identical. In clinical trials that encounter a high rate of attrition such as ours, the measurements of the participants who drop out can mask the true effectiveness of the treatment. The degree of attrition can become so large that the intent-to-treat analysis is unable to detect the effect of the treatment. Clinical trials that encounter a significantly higher rate of attrition compared to completion may therefore be susceptible to illusive results.

Limitations

Previous ACL prevention studies evaluated the effectiveness that a NMT program had modifying the incidence of noncontact ACL injuries (Caraffa et al., 1996; Gilchrist et al., 2008;; Mandelbaum et al., 2005; Olsen et al., 2005; Chappell et al., 2002; Hewett et al., 1999). Due to the participant population and small timeframe of this study, our focus was on ACL risk factor modification rather than injury incidence modification. To avoid a prolonged parental consent process, our study recruited female college underclassmen who were 18-20 years of age. Our study's methods were similar to the study by, although they reported significant positive outcomes in their NMT group. One explanation for this difference may be attributed to the higher number of female participants that were able to successfully complete the NMT program compared to our study (62 females vs. 8 females).

Another explanation for the lack of positive outcomes this may be due to the different population of our participants compared to previous ACL prevention studies (Caraffa et al., 1996; Gilchrist et al., 2008; Mandelbaum et al., 2005; Olsen et al., 2005; Hewett et al., 1999). Of the ACL prevention programs that reported significant reductions in noncontact ACL injuries, the participants who completed an NMT program were all current high school athletes (Caraffa et al., 1996; Gilchrist et al., 2008; Mandelbaum et al., 2005; Olsen et al., 2005; Hewett et al., 1999). In particular, the study by Hewett et al. (1999) involved females who were currently involved in a high school sport complete the same NMT program as the NMT group in our study, and they were able to reported positive outcomes. In attempt to increase the availability of our participants, we only enrolled participants who were currently not involved in an intercollegiate sport. By including current athletes, the participants in Hewett et al.'s (1999) study may have been exposed to more exercise outside of the study as opposed to the participants in our study. This higher exercise workload may be the reason for the positive outcomes that were demonstrated in the previous ACL prevention studies (Caraffa et al., 1996; Gilchrist et al., 2008; Mandelbaum et al., 2005; Olsen et al., 2005; Hewett et al., 1999).

The high attrition rate in our randomized clinical trial was a major limitation of this study. The effect size of 0.3 (small) was based on previous findings from Noyes et al. (2005). The power analysis indicated that a total sample of N = 24 was needed to achieve a power of 0.8 ($\alpha = .05$). Because of the repeated design and the strong possibility of attrition, an additional 11 female participants (N = 35) were enrolled to ensure that the study was adequately powered. However, of the 35 participants that were enrolled, 29 of them attended at least one training session, and only 17 of them attended at least 12 of the total 18 sessions to be eligible for posttesting. One of the 17 participants was diagnosed with mononucleosis prior to posttesting, therefore only 16 participants were officially posttested.

To evaluate the unique effectiveness of the NMT program, we had to create a controlled RT program of equal exercise volume, frequency, and mode. Controlling for exercise frequency and mode were the least difficult when designing the RT program. The exercise frequency of the RT program design was identical to that of the NMT program, because each program had three sessions per week throughout the six-week training period. The exercise mode between the two groups was similar because the NMT program primarily focused on lower body plyometric training, while the RT program focused on lower body resistance training.

Controlling for exercise volume was a more complex assignment. Exercise volume relates to the total amount of work that is performed in a training session. However, RT volume and plyometric volume have different definitions. RT volume is defined as the total amount of weight that is lifted in a training session (Baechle et al., 2008; Fleck & Kraemer, 2003). It is best expressed by multiplying the total number of sets by the number of repetitions per set, and then multiplying that by the weight lifted per repetition (load-volume) (Baechle et al., 2008). Plyometric volume is typically expressed as the number of repetitions and sets performed during a given training session (Allerheilegen & Roger, 1995; Baechle & Earle, 2008; Chu, 2008). Plyometric repetitions can be expressed as the number of foot contacts or time per set (Allerheilegen & Roger, 1995; Chu, 2008; Hewett et al., 1999). The NMT program that was evaluated in our study primarily used plyometric repetitions that lasted 20-30 seconds per set. To make the RT program's volume comparable to the NMT program, we had to make the RT repetitions comparable to the plyometric repetitions of time per set. By conducting pilot tests, we found that performing a compound set of two 8-repetition RT exercises was similar to a 20-30 second plyometric exercise set in the NMT program. The NMT program was progressed every two weeks by increasing the time of their plyometric repetitions. To accommodate for this, we progressed the exercises in the RT program by increasing the amount of weight of each exercise by 5-10% every two weeks (Baechle et al., 2008). The rationale behind this was that by adding weight instead of repetitions to the RT exercises, it would require more time to complete a compound set, but continue to emphasize muscular strength instead of muscular endurance.

Our statistical representation of exercise volume was expressed as average participant training time. An equal average participant training time between the NMT group and RT group would reveal that the RT program was comparable in exercise volume to the NMT program. We were able to report no significant differences between the NMT group and RT group in average participant training time ($p > .05$). When developing the framework for the two training programs, we intended the training sessions to last around 60 minutes for each group. The average participant training time of the NMT group was 49.8 minutes/session, and the average participant training time of the RT group was 45.5 minutes/session. However, the NMT program in our study was the same NMT program introduced by Hewett et al. (1999) as an ACL prevention program. In that study they reported their training sessions lasting approximately 60-90 minutes, while the training session time in both our NMT group and RT group lasted approximately 45-50 minutes. A possible explanation for this difference is that although participants in both groups performed all of the exercises correctly, they tended to move through the exercises very efficiently, and frequently elected not to use their rest periods.

Conclusion

The results from our study revealed that an NMT program designed to reduce the incidence of noncontact ACL injury is equally effective at modifying at-risk frontal plane landing kinematics associated with noncontact ACL injuries when compared to an RT program of equal exercise workload. With the information gathered from this study and from previous ACL prevention research, we conclude that a training program that incorporates both lower body plyometric training and lower body RT exercises can effectively modify at-risk landing kinematics associated with noncontact ACL injuries, and in turn, reduce the incidence of noncontact ACL injuries in female athletes. We recommend that young female athletes who currently participate or are planning to participate in sports that involve jumping or cutting activities, undergo an offseason training program that incorporates the principle of both the NMT and RT program from our study. Coaches and strength and conditioning specialists are also encouraged to adopt these concepts into their offseason regimen as an approach to injury prevention.

Although our study was able to provide conclusive information regarding an NMT program, there remain unanswered questions concerning NMT for ACL prevention that requires future research. We created a balanced RT control group that adequately compared to an NMT program that has been shown not only to reduce the risk of noncontact ACL injury in female athletes, but also to improve at-risk frontal plane landing kinematics for these injuries. However, our study only evaluated the effectiveness of the NMT program on modifying frontal plane landing kinematics. Further research is need to evaluate the effectiveness of an NMT program on modifying the incidence of noncontact ACL injury in females compared to a control RT group of balanced exercise workload. Our study also focused only on at-risk frontal plane landing kinematics associated with noncontact ACL injury. Future investigations should also evaluate the effectiveness that NMT programs have on modifying at-risk sagittal plane landing kinematics associated with noncontact ACL injury compared to a controlled RT group of balanced exercise workload. Lastly, the effectiveness of a training program that incorporates verbal augmentation in an attempt to correct the at-risk landing kinematics associated with noncontact ACL injury should be compared to that of an NMT program and RT program. This could help determine whether there should be particular emphasis placed on a type of training when designing a comprehensive ACL prevention program, or if NMT, RT, and verbal augmentation training should be evenly integrated.

REFERENCES

Allen, M. K., & Glasoe, W. M. (2000). Metrecom measurement of navicular drop in subjects with anterior cruciate ligament injury. *Journal of Athletic Training, 35*, 403-406.

Allerheilegen, B., & Roger, R. (1995). Plyometrics program design. *Journal of Strength and Conditioning, 17*(4), 26-31.

Anderson, A. F., Dome, D. C., Gautam, S., Awh, M. H., & Rennirt, G. W. (2001). Correlation of anthropometric measurements, strength, anterior cruciate ligament size and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. *American Journal of Sports Medicine, 29*, 58-66.

Anderson, A. F., Lipscomb, A. B., Liudahl, K. J., & Addlestone, R. B. (1987). Analysis of the intercondylar notch by computed tomography. *American Journal of Sports Medicine, 15*, 547-552.

Andrews, J. R., Harrelson, G. L., & Wilk, K. E. (2004). *Physical rehabilitation of the injured athlete* (3rd ed.). Philadelphia, PA: Elsevier Inc.

Andrish, J. T. (2001). Anterior cruciate ligament injuries in the skeletally immature patient. *American Journal of Orthopedics, 30*, 103-110.

Arendt, E., & Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *American Journal of Sports Medicine, 23*, 694-701.

Arms, S. W., Pope, M. H., Johnson, R. J., Fischer, R. A., Arvidsson, I., & Eriksson, E. (1984). The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. *American Journal of Sports Medicine, 12*(1), 8-18.

Baechle, T. R., & Earle, R. W. (2008). Plyometric training. In T. R. Baechle, & R. W. Earle (Eds.), *Essentials of strength training and conditioning/National Strength and Conditioning Association* (3rd ed., pp. 413-456). Champaign, IL: Human Kinetics.

Baechle, T. R., Earle, R. W., & Wathen, D. (2008). Resistance training. In T. R. Baechle, & R. W. Earle (Eds.), *Essentials of strength training and conditioning/National Strength and Conditioning Association* (3rd ed., pp. 381-412). Chicago, IL: Human Kinetics.

Baratta, R., Solomonow, M., & Zhou, B. H. (1988). Muscular coactivation: The role of the antagonist musculature in maintaining knee stability. *American Journal of Sports Medicine, 16*, 113-122.

Baumhauer, J. F., Alosa, D. M., Renstrom, A. R., Trevino, S., & Beynnon, B. (1995). A prospective study of ankle injury risk factors. *American Journal of Sports Medicine, 23*, 564-570.

Besier, T. F., Lloyd, D. G., Cochrane, J. L., & Ackland, T. R. (2001). External loading of the knee joint during running and cutting maneuvers. *Medicine and Science in Sports and Exercise*, 33, 1168-1175.

Beunen, G., & Malina, R. M. (1988). Growth and physical performance relative to the timing of the adolescent spurt. *Exercise and Sport Sciences Reviews, 16*, 503-540.

Beynnon, B., Howe, J. G., Pope, M. H., Johnson, R. J., & Fleming, B. C. (1992). The measurement of anterior cruciate ligament strain in vivo. *International Orthopaedics, 16*, 1-12.

Beynnon, B. D., Bernstein, I., & Belisle, A. (2005). The effect of estadiol and progesterone on knee and ankle laxity. *American Journal of Sports Medicine, 33*, 1298-1304.

Beynnon, B. D., Fleming, B. C., Johnson, R. J., Nichols, C. E., Renstrom, P. A., & Pope, M. H. (1995). Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *American Journal of Sports Medicine, 23*, 24-34.

Beynnon, B. D., Johnson, R. J., Braun, S., Sargent, M., Bernstein, I. M., Skelly, J. M., & Vacek, P. M. (2006). The relationship between mentrual cycle phase and anterior cruciate ligament injury: A case-control study of recreational alpine skiers. *American Journal of Sports Medicine, 34*, 757-764.

Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573-578.

Bonci, C. M. (1999). Assessment and evaluation of predisposing factors to anterior cruciate ligament injury. *Journal of Athletic Training, 34*, 155-164.

Buchanan, P. A. (2003). *Developmental perspectives on basketball players' strength, knee position in landing, and ACL injury gender differences* (Unpublished doctoral dissertation). Indiana University, Bloomington, IN.

Buehler-Yund, C. (1999*). A longitudinal study of injury rates and risk factors in 5 to 12 year old soccer players* (Unpublished doctoral dissertation). University of Cincinnati, Cincinnati, OH.

Caraffa, A., Cerulli, G., Projetti, M., Aisa, G., & Rizzo, A. (1996). Prevention of anterior cruciate ligament injuries in soccer: A prospective controlled study of proprioceptive training. *Knee Surgery, Sports Traumatology, Arthroscopy, 4*, 19-21.

Chandrashekar, N., Mansouri, H., Slauterbeck, J., & Hashemi, J. (2006). Sex-based differences in the tensile properties of the human anterior cruciate ligament. *Journal of Biomechanics, 39*, 2943-2950.

Chandrashekar, N., Slauterbeck, J., & Hashemi, J. (2005). Sex-based differences in the anthropometric characteristics of the anterior cruciate ligament and its relation to intercondylar notch geometry. *American Journal of Sports Medicine, 33*(10), 1492-1498.

Chappell, J. D., Yu, B., Kirkendall, D. T., & Garrett, W. E. (2002). A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *American Journal of Sports Medicine, 30*, 261-267.

Charlton, W. P., St John, T. A., Ciccotti, M. G., Harrison, N., & Schwietzer, M. (2002). Differences in femoral notch anatomy between men and women: A magnetic resonance imaging study. *American Journal of Sports Medicine, 30*, 329-333.

Chu, D. (2008). *Jumping into plyometrics* (2nd ed.). Champaign, IL: Human Kinetics.

Colby, S., Francisco, A., Yu, B., Kirkendall, D., Finch, M., & Garrett, W. J. (2000). Electromyographic and kinematic analysis of cutting maneuvers: Implications for anterior cruciate ligament injury. *American Journal of Sports Medicine, 28*, 234-240.

Cortez-Cooper, M. Y., Devan, A. E., Anton, M. M., Farrar, R. P., Beckwith, K. A., Todd, J. S., & Tanaka, H. (2005). Effects of high intensity resistance training on arterial stiffness and wave reflection in women. *American Journal of Hypertension, 18*, 930-934.

Deie, M., Sakamaki, Y., Sumen, Y., Urabe, Y., & Ikuta, Y. (2002). Anterior knee laxity in young women varies with their menstrual cycle. *International Orthopaedics, 26*, 154-156.

DeMorat, G., Weinhold, P., Blackburn, T., Chudik, S., & Garrett, W. (2004). Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *American Journal of Sports Medicine, 32*, 477-483.

Dunnam, L. O., Hunter, G. R., & Williams, B. P. (1988). Comprehensive evaluation of the university of Alabama at Birmingham women's volleyball training program. *National Strength Conditioning Association Journal, 10*, 50-52.

Fleck, S. J., & Kraemer, W. J. (2003). *Designing resistance training programs* (3rd ed.). Champaign, IL: Human Kinetics.

Fleming, B. C., Ohlen, G., Renstrom, P. A., Peura, G. D., Beynnon, B. D., & Badger, G. J. (2003). The effects of compressive load and knee joint torque on peak anterior cruciate ligament strains. *American Journal of Sports Medicine, 31*, 701-707.

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sports and Exercise, 35*, 1745-1750.

Freedman, K. B., Glasgow, M. T., Glasgow, S. G., & Bernstein, J. (1998). Anterior cruciate ligament injury and reconstruction among university students. *Clinical Orthopaedics and Related Research, 356*, 208-212.

Fu, F. H., & Stone, D. A. (1994). *Sports injuries: Mechanisms, prevention, treatment*. Philadelphia, PA: Williams & Wilkins.

Gilchrist, J., Mandelbaum, B. R., Melancon, H., Ryan, G. W., Silvers, H. J., Griffin, L. Y., … & Dick, R.W. (2008). A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *American Orthopaedic Society for Sports Medicine, 36*(8), 1476-1483.

Good, L., Odensten, M., & Gillquist, J. (1991). Intercondylar notch measurements with special reference to anterior cruciate ligament surgery. *Clinical Orthopaedics, 263*, 185-189.

Harner, C. D., Paulos, L. E., Greenwald, A. E., Rosenberg, T. D., & Cooley, V. C. (1994). Detailed analysis of patients with bilateral anterior cruciate ligament injuries. *American Journal of Sports Medicine, 22*, 37-43.

Heiderscheit, B. C., Hamill, J., & Caldwell, G. E. (2000). Influence of Q-angle on lower-extremity running kinematics. *Journal of Orthopaedic and Sports Physical Therapy, 30*, 271-278.

Heidt, R. S., Sweeterman, L. M., Carlonas, R. L., Traub, J. A., & Tekulve, F. X. (2000). Avoidance of soccer injuries with preseason conditioning. *American Journal of Sports Medicine, 28*, 659-662.

Heitz, N. A. (1999). Hormonal changes throughout the menstrual cycle and increased anterior cruciate ligament laxity in females. *Journal of Athletic Training, 343*, 144-149.

Hewett, T. E., Lindenfeld, T. N., Riccobene, J. V., & Noyes, F. R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes: A prospective study. *American Orthopaedic Society for Sports Medicine, 27*(6), 699-706.

Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in neuromuscular control about the knee with maturation in female athletes. *Journal of Bone and Joint Surgery, 86*, 1601-1608.

Hewett, T. E., Myer, G. D., & Ford, K. R. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *American Journal of Sports Medicine, 33*, 492-501.

Hewett, T. E., Paterno, M. V., & Myer, G. D. (2002). Strategies for enhancing proprioception and neuromuscular control of the knee. *Clinical Orthopaedics and Related Research,* 402 , 76-94.

Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes: Decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine, 24*(6), 765-773.

Horton, M., & Hail, T. (1989). Quadriceps femoris muscle angle: Normal values and relationships with gender and selected skeletal measures. *Physical Therapy, 69*, 897-901.

Huston, L. J., Vibert, B., Ashton-Miller, J. A., & Wojtys, E. M. (2001). Gender differences in knee angle when landing from a drop-jump. *American Journal of Knee Surgery, 14*, 215-220.

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular performance characteristics in elite female athletes. *American Journal of Sports Medicine, 24*(4), 427-436.

Ireland, M. L. (1994). *Special concerns of the female athlete*. Baltimore, MD: Williams & Wilkins.

Ireland, M. L. (1996). Anterior cruciate ligament injuries in young female atheltes. *Your Patient & Fitness, 10*(5), 26-30.

Ireland, M.L. (1999). Anterior cruciate ligament injuries in female athletes: Epidemiology. *Journal of Athletic Training.* 34(2), 150-154.

Ireland, M. L. (2002). The female ACL: Why is it more prone to injury? *Orthopedic Clinics of North America, 33*, 637-651.

Ireland, M. L., Guadette, M., & Crook, S. (1997). ACL injuries in the female athlete. *Journal of Sports Rehabilitation, 6*, 97-108.

Kang, M., Ragan, B. G., & Park, J. (2008). Issues in outcomes research: An overview of randomization techniques for clinical trials. *Journal of Athletic Training, 43*(2), 215-221.

Karageanes, S. J., Blackburn, K., & Vangelos, Z. A. (2000). The association of the menstrual cycle with the laxity of the anterior cruciate ligament in adolescent female athletes. *Clinical Journal of Sport Medicine, 10*, 162-168.

Kessler, M. A., Behrend, H., Henz, S., Stutz, G., Rukavina, A., & Kuster, M. S. (2008). Function, osteoarthritis and activity after ACL-rupture: 11 year follow-up results of conservative versus reconstructive treatmen. *Knee Surgery, Sports Traumatology, Arthroscopy, 16*, 442-444.

Kim, A. W., Rosen, A. M., Brander, V. A., & Buchanan, T. S. (1995). Selective muscle activation following electrical stimulation of the collateral ligaments of the human knee joint. *Archives of Physical Medicine and Rehabilitation, 76*, 750-757.

Knapik, J. J., Bauman, C. L., Jones, B. H., Harris, J. M., & Vaughn, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *American Journal of Sports Medicine, 19*(1), 76-81.

Lambson, R. B., Barnhill, B. S., & Higgins, R. W. (1996). Football cleat design and its effect on anterior cruciate ligament injuries: A 3-year prospective study. *American Journal of Sports Medicine, 24*, 155-159.

LaPrade, R. F., & Burnett, Q. M. (1994). Femoral intercondylar notch stenosis and correlation to anterior cruciate ligament injuries: A prospective study. *American Journal of Sports Medicine, 22*, 198-203.

Liu, S. H., al-Shaikh, R., & Panossian, V. (1996). Primary immunolocalization of estrogen progesterone target cells in the human anterior cruciate ligament. *Journal of Orthopaedic Research, 14*, 526-533.

Livingston, L. (1998). The quadriceps angle: A review of literature. *Journal Orthopaedic and Sports Physial Therapy, 28*, 105-109.

Lohmander, L. S., Ostenberg, A., Englund, M., & Roos, H. (2004). High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis and Rheumatism, 50*(10), 3145-3152.

Loudon, J. K., Jenkins, W., & Loudon, K. L. (1996). The relationship between static posture and ACL injury in female athletes. *Journal of Orthopaedic and Sports Physical Therapy, 24*, 91-97.

Lund-Hassen, H., Gannon, J., Engebretsen, L., Holen, K. J., Anda, S., & Vatten, L. (1994). Intercondylar notch width and risk of anterior cruciate ligament rupture: A case-control study in 46 female handball players. *Acta Orthopaedica Scandinavica, 65*, 529-532.

MacWilliams, B. A., Wilson, D. R., DesJardins, J. D., Romero, J., & Chao, E. Y. (1999). Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *Journal of Orthopaedic Research, 17*, 817-822.

Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). Timing and sequence of changes during adolescence. In *Growth, maturation, and physical activity* (pp. 307-333). Champaign, IL: Human Kinetics.

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics, 16*, 438-445.

Malone, T. R., Hardaker, W. T., Garrett, W. E., Feagin, J. A., & Bassett, F. H. (1993). Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *Journal of Southern Orthopaedic Association, 2*, 36-39.

Mandelbaum, B. R., Silvers, H. J., Watanabe, D. S., Knarr, J. F., Thomas, S. D., Griffin, L. Y., … & Garrett, W. (2005). Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female atheltes. *American Orthopaedic Society for Sports Medicine, 33*(7), 1003-1010.

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterback, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research, 13*, 930-935.

Markolf, K. L., Graff-Redford, A., & Amstutz, H. C. (1978). In vivo knee stability: A quantitative assessment using an instrumented clinical testing apparatus. *Journal of Bone Joint Surgery, 60*, 664-674.

Martin, R. J., Dore, E., Twisk, J., Van Praagh, E., Hautier, C. A., & Bedu, M. (2004). Longitudinal changes of maximal short-term peak power in girls and boys during growth. *Medicine and Science in Sports and Exercise, 36*, 498-503.

McNair, P. J., Marshall, R. N., & Matheson, J. A. (1990). Important features associated with acute anterior cruciate ligament injury. *Medicine and Science in Sports and Exercise, 103*, 537-539.

Meyers, M. C., & Barnhill, B. S. (2004). Incidence, causes, and severity of high school football injuries on FieldTurf versus natural grass: A 5-year prospective study. *American Journal of Sports Medicine, 32*, 1626-1638.

Miyaska, K. C., Daniel, D. M., & Stone, M. L. (1991). The incidence of knee ligament injuries in the general population. *American Journal of Knee Surgery, 4*, 3-8.

Mizuno, Y., Kumagai, M., Mattessich, S. M., Elias, J. J., Ramrattan, N., Cosgarea, A .J., & Chao, E. Y. S. (2001). Q-angle influences tibiofemoral and patellofemoral kinematics. *Journal of Orthopaedic Research, 19*, 834-840.

More, R. C., Karras, B. T., Neiman, R., Fritschy, D., Woo, S. L., & Daniel, D. M. (1993). Hamstrings: An anterior cruciate ligament protagonist: An in vitro study. *American Journal of Sports Medicine, 21*, 231-237.

Moul, J. (1998). Differences in selected predictors of anterior cruciate ligament tears between male and female NCAA division I collegiate basketball players. *Journal of Athletic Training, 33*, 118-121.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2002). A comparison of medial knee motion in basketball players when performing a basketball rebound [Abstract]. *Medicine and Science in Sports and Exercise, 34*, S5.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training, 39*, 352-364.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2005). The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology, 15*, 181-189.

Myklebust, G., Engebretsen, L., Braekken, I. H., Skjolberg, A., Olsen, O. E., & Bahr, R. (2003). Prevention of anterior cruciate ligament injuries in female team handball players: A proprioceptive intervention study over three seasons. *Clinical Journal of Sports Medicine, 13*, 71-78.

National Collegiate Athletic Association. (2002). *NCAA injury surveillance system summary*. Indianapolis, IN: National Collegiate Athletic Association.

National Federation of State High School Associations. (2002*). 2002 high school participation survey*. Indianapolis, IN: National Federation of State High School Associations.

Noyes, F. R., Baber-Westin, S. D., Fleckenstein, C., Walsh, C., & West, J. (2005). The drop-jump screening test: Differences in lower limb control by gender and effect of neuromuscular training in female athletes. *American Orthopaedic Society for Sports Medicine, 33*(2), 197-207.

Noyes, F. R., Mooar, P. A., Matthews, D. S., & Butler, D. L. (1983). The symptomatic anterior cruciate-deficient knee. Part I: The long-term functional disability in athletically active individuals. *Journal of Bone and Joint Surgergy, 65*(2), 154-162.

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *American Journal of Sports Medicne, 32*, 1002-1012.

Olsen, O. E., Myklebust, G., Engebrestsen, L., Holme, I., & Bahr, R. (2003). Relationship between floor type and risk of ACL injury in team handball. *Scandinavian Journal of Medicine and Science in Sports, 13*, 299-304.

Olsen, O. E., Myklebust, G., Engebretsen, L., Holme, L., & Bahr, R. (2005). Exercises to prevent lower limb injuries in youth sports: Cluster randomised controlled trial. *British Medical Journal, 330*, 449-455.

Orchard, J., Seward, H., McGivern, J., & Hood, S. (1999). Rainfall, evaporation and the risk of non-contact anterior cruciate ligament injury in the Australian Football League. *Medical Journal of Australia, 170*, 304-306.

Orchard, J. W., & Powell, J. W. (2003). Risk of knee and ankle sprains under various weather conditions in American football. *Medicine and Science in Sports and Exercise, 35*, 1118-1123.

Paxton, E. S., Kymes, S. M., & Brophy, R. H. (2010). Cost-effectiveness of anterior cruciate ligament reconstruction. *American Journal of Sports Medicine, 38*(12), 2417-2425.

Pfeiffer, R. P., Shea, K. G., Roberts, D., Grandstrand, S., & Bond, L. (2006). Lack of effect on a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. *Journal of Bone and Joint Surgery, 88*(8), 1769-1774.

Porat, A. V., Roos, E. M., & Roos, H. (2004). High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: A study of radiographic and patient relevant outcomes. *Annals of the Rheumatic Diseases, 63*, 269-273.

Potach, D. H., Katsavelis, D., Karst, G. M., Stergiou, N., & Latin, R. M. (2009). The effects of a plyometric training program on the latency of the quadriceps femoris and gastrocnemius short-latency responses. *Journal of Sports Medicine and Physical Fitness, 49*, 35-49.

Prentice, W. E. (2009). *Arnheim's principles of athletic training: A competency-based approach* (13th ed.). New York, NY: McGraw-Hill Higher Education.

Rozzi, S., Lephart, S., Gear, W., & Fu, F. (1999). Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *American Journal of Sports Medicine, 27*(3), 312-319.

Sarwar, R., Beltran, N. B., & Rutherford, O. M. (1996). Changes in muscle strength, relaxation rate and fatiguability during the human menstrual cycle. *Journal of Physiology, 493*, 267-272.

Scranton, P. E., Whitesel, J. P., & Powell, J. W. (1997). A review of selected noncontact anterior cruciate ligament injuries in the National Football League. *Foot and Ankle International, 18*, 772-776.

Sell, T., Ferris, C. M., & Abt, J. P. (2004). Predictors of anterior tibia shear force during a vertical stop-jump [Abstract]. *Journal of Orthopaedic and Sports Physical Therapy, 34*, A56.

Shambaugh, J. P., Klein, A., & Herbert, J. H. (1991). Structural measures as predictors of injury in basketball players. *Medicine and Science in Sports and Exercise, 23*, 522-527.

Shelbourne, K. D., & Kerr, B. (1998). The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears: A prospective study. *American Journal of Sports Medicine, 26*, 402-408.

Shelbourne, K. D., & Kerr, B. (2001). The relationship of femoral intercondylar notch width to height, and sex in patients with intact anterior cruciate ligaments. *American Journal of Knee Surgery, 14*, 92-96.

Shultz, S. J., Perrin, D. H., Adams, M. J., Arnold, B. L., Gansneder, B. M., & Granata, K. P. (2001). Neuromuscular response characteristics in men and women after knee perturbation in a single-leg, weight-bearing stance. *Journal of Athletic Training, 36*, 37-43.

Shultz, S. J., Sander, T. C., Kirk, S. E., & Perrin, D. H. (2005). Sex differences in knee joint laxity change across the female menstrual cycle. *Journal of Sports Medicine and Physical Fitness, 45*(4), 594-603.

Slautebeck, J. R., Fuzie, S. F., & Smith, M. P. (2002). The menstrual cycle, sex hormones, and anterior cruciate ligament injury. *Journal of Athletic Training, 37*, 275-280.

Soderman, K., Alfredson, H., Pietila, T., & Werner, S. (2001). Risk factors for leg injuries in femal soccer players: A prospective investigation during one out-door season. *Knee Surgery, Sports Traumatology, Arthroscopy, 9,* 313-321.

Soderman, K., Werner, S., Pietila, T., Engstrom, B., & Alfredson, H. (2000). Balance board training: Prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. *Knee Surgery, Sports Traumatology, Arthroscopy, 8*, 356-363.

Solomonow, M., Baratta, R., & Zhou, B. H. (1987). The synergistic action of the anteior cruciate ligament and thigh muscles in maintaining joint stability. *American Journal of Sports Medicine, 15*, 207-213.

Souryal, T. O., & Freeman, T. R. (1993). Intercondylar notch size and anterior cruciate ligament injuries in athletes: A prospective study. *American Journal of Sports Medicine, 21*, 535-539.

Souryal, T. O., Moore, H. A., & Evans, P. (1988). Bilaterality in anterior cruciate ligament injuries: Associated intercondylar notch stenosis. *American Orthopaedic Society for Sports Medicine, 16*, 449-454.

Starkey, C., & Ryan, J. L. (2002). *Evaluation of orthopedic and athletic injuries* (2nd ed.). Philadelphia, PA: F.A. Davis Company.

Stergiou, N., Ristanis, S., Moraiti, C., & Georgoulis, A. D. (2007). Tibial rotation in anterior cruciate ligament (ACL)-deficient and ACL-reconstructed knees a theoretical proposition for the development of osteoarthritis. *American Journal of Sports Medicine, 37*(7), 601-613.

Thomas, S., Reading, J., & Shepard, R. J. (1992). Revision of physical activity readiness questionnaire (PAR-Q). *Canadian Journal of Applied Sport Sciences, 17*(4), 338-345.

Torzilli, P. A., Deng, X., & Warren, R. F. (1994). The effect of joint-compressive load and quadriceps muscle force on knee motion in the intact and anterior cruciate ligament-sectioned knee. *American Journal of Sports Medicine, 22*, 105-112.

Toth, A. P., & Cordasco, F. A. (2001). Anterior cruciate ligament injuries in the female athlete. *Journal of Gender Specific Medicine, 4*, 25-34.

Trimble, M. H., Bishop, M. D., Buckley, B. D., Fields, L. C., & Rozea, G. D. (2002). The relationship between clinical measurements of lower extremity posture and tibial translation. *Clinical Biomechanics, 17*, 286-290.

Tursz, A., & Crost, M. (1986). Sports-related injuries in children: A study of their characteristics, frequency, and severity, with comparison to other types of accidental injuries. *American Journal of Sports Medicine, 14,* 294-299.

Uhorchak, J. M., Scoville, C. R., Williams, G. N., Arciero, R. A., St Pierre, P., & Taylor, D. C. (2003). Risk factors associated with noncontact injury of the anterior cruciate ligament: A prospective four-year evaluation of 859 West Point cadets. *American Journal of Sports Medicine, 31*, 831-842.

Van Lunen, B. L., Roberts, J., Branch, J. D., & Dowling, E. A. (2003). Association of menstural-cycle hormone changes with ACL laxity measurements. *Journal of Athletic Training, 38*, 298-303.

Viitasalo, J. T., Salo, A., & Lahtinen, J. (1998). Neuromuscular functioning of athletes and non-athletes in the drop-jump. *European Journal of Applied Physiology, 78*, 432-440.

Wascher, D. C., Markolf, K. L., Shapiro, M. S., & Finerman, G. A. (1993). Direct in vitro measurement of forces in the cruciate ligaments. Part I: The effect of multiplane loading in the intact knee. *Journal of Bone and Joint Surgery, 75*, 377-386.

Wedderkopp, N., Kaltoft, M., Holm, R., & Froberg, K. (2003). Comparison of two intervention programmes in young female players in European handball: With and without ankle discs, *Scandinavian Journal of Medicine and Science in Sports*, *35*, 371-376.

White, K. K., Lee, S. S., Cutuk, A., Hargens, A. R., & Pedowitz, R. A. (2003). EMG power spectra of intercollegiate athletes and anterior cruciate ligament injury risk in females. *Medicine and Science in Sports and Exercise, 35*, 371-376.

Winter, D. A. (1990). *Biomechanics and motor control of human movement.* (2nd ed.). New York, NY: John Wiley & Sons.

Wojtys, E. M., Huston, L. J., Boynton, M. D., Spindler, K. P., & Lindenfeld, T. N. (2002). The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *American Journal of Sports Medicine, 30*, 182-188.

Wolk, R., Berger, P., Lennon, R. J., Brilakis, E. S., & Somers, V. K. (2003). Body mass index: A risk factor for unstable angina and myocardial infarction in patients with angiographically confirmed coronary artery disease. *Circulation, 108*, 2206-2211.

Woodford-Rogers, B., Cyphert, L., & Denegar, C. R. (1994). Risk factors for anterior cruciate ligament injury in high school and college athletes. *Journal of Athletic Training, 29*, 343-346.

Yu, W. D., Liu, S., Hatch, J. D., Panossian, V., & Finerman, G. A. (1999). Effect of estrogen on cellular metabolism of the human anterior cruciate ligament. *Clinical Orthopaedics and Related Research, 366*, 229-238.

Yu, W. D., Panossian, V., Hatch, J. D., Liu, S. H., & Finerman, G. A. (2001). Combined effects of estrogen and progesterone on the anterior cruciate ligament. *Clinical Orthopaedics and Related Research, 383*, 268-281.

Zazulak, B. T., Ponce, P. L., Straub, S. J., Medvecky, M. J., Avedisian, L., & Hewett, T. E. (2005). Gender comparison of hip muscle activity during single leg landing. *Journal of Orthopaedic and Sports Physical Therapy, 35*, 292-299.

APPENDIX A: RECRUITING FLYER

APPROVED
AUG 12 2011
OHIO UNIVERSITY
INSTITUTIONAL REVIEW BOARD

College Women!

Get FREE Training by Certified Personnel

Total Body Strength & Jump Training Study

HOW?:
Participate in a research study conducted by the Division of Athletic Training at OU.

ABOUT THE STUDY:
A 6-week training program that may modify knee injury risk factors.

QUALIFICATIONS:

- College woman age 18-20
- Healthy, without history of ACL injury
- Prior participation in high school athletics
- Not currently involved in intercollegiate athletics

WHAT YOU GET:

- *Free* Training by Certified Personnel
- $15 Gift Card to Dunham's Sports

If interested, e-mail Conrad Gabler by 9/23 (cg171110@ohio.edu)

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

Conrad Gabler, AT
cg171110@ohio.edu

APPENDIX B: INFORMED CONSENT FORM (ADULTS ONLY)

Title of Research: The Effectiveness of Neuromuscular Training on Modifiable Anterior Cruciate Ligament Injury Risk Factors

Researchers: Conrad Gabler B.S., AT; Brian G. Ragan, PhD, AT; Jason White, PhD; Cheryl Howe, PhD; Shannon David, M.S., AT

You are being asked to participate in research. For you to be able to decide whether you want to participate in this project, you should understand what the project is about, as well as the possible risks and benefits in order to make an informed decision. This process is known as informed consent. This form describes the purpose, procedures, possible benefits, and risks. It also explains how your personal information will be used and protected. Once you have read this form and your questions about the study are answered, you will be asked to sign it. This will allow your participation in this study. You should receive a copy of this document to take with you.

Explanation of Study
This study examines the effectiveness of an ACL prevention program on reducing risk factors for ACL injuries in female athletes. Many ACL injuries occur when landing from a jump. These programs focus on teaching better landing mechanics.

If you agree to participate, you will be asked to participate in a 6-week training program. You will be attending three sessions a week (on nonconsecutive days) for approximately 60 minutes a session. The session times will occur at multiple times of the day. This study will include both upper and lower body resistance training as well as jump training. You will be randomly assigned to either the jump training group or the resistance training group. Each training session will be supervised by licensed personnel. You will also be asked to perform drop-jumps off of a 12-inch box while being videotaped. This procedure will be performed approximately one week before and after the training program.

You should not participate in this study if you have a history of ACL rupture, underwent surgery within the past year, are pregnant, or have any of the following: a current/ongoing injury, knee pain, patellar (knee cap) instability, or knee joint effusion (swelling). Please refrain from the use of alcohol and drugs for at least 12 hours prior to each training session.

Risks and Discomforts
The potential risks of this study are nothing more than what is experienced during common athletic activity. You may be at risk of sustaining an acute injury while performing the exercises in the training program. Possible injuries include but are not limited to: contusions, abrasions, sprains, and strains. There is also a possibility that you may experience muscle soreness or fatigue from the training program. Throughout the training program proper training techniques will be emphasized to prevent unnecessary stress on the body. You will also perform warm-up exercises prior to each training session to prepare your body for physical activity. If an injury does occur at any time during training, a licensed athletic trainer will be available for care and treatment. Participants may choose to stop or withdraw from the study at any time.

Benefits

The results of this study will help indicate the effectiveness of ACL prevention programs. Individually, you will have the opportunity to participate in a training program that has been shown to decrease the risk of sustaining a noncontact anterior cruciate ligament (ACL) injury during athletic activity. This program will be free of cost to participants and has also been shown to increase lower extremity strength, power, agility, and coordination in previous participants. By partaking in six weeks of training, you will also gain physical fitness effects and improve your health.

Confidentiality and Records

Your study information will be kept confidential by using a code replacing identifiers and a master list connecting the code and the identifier. The code list will be stored securely in the filing cabinet of the advisor's room, which is under lock and key. The list will be destroyed via paper shredding following the completion of data analysis.

Compensation

As compensation for your time/effort, you will receive a $15 gift card to Dunham's Sports upon the completion your training program.

Contact Information

If you have any questions regarding this study, please email Conrad Gabler at cg171110@ohio.edu or call him at (715) 214-5875.

If you experience any problems as a result of this study, you should seek medical attention immediately and then report it to Conrad Gabler.

If you have any questions regarding your rights as a research participant, please contact Jo Ellen Sherow, Director of Research Compliance, Ohio University, (740)593-0664.

By signing below, you are agreeing that:

- you have read this consent form (or it has been read to you) and have been given the opportunity to ask questions and have them answered
- you have been informed of potential risks and they have been explained to your satisfaction.
- you understand Ohio University has no funds set aside for any injuries you might receive as a result of participating in this study
- you are 18 years of age or older
- your participation in this research is completely voluntary
- you may leave the study at any time. If you decide to stop participating in the study, there will be no penalty to you and you will not lose any benefits to which you are otherwise entitled.

Signature____ Date________

Printed Name____

Version Date: 6/02/11

APPENDIX C: CRITERIA QUESTIONNAIRE

ID #: _______ Code Name: ___________________ Age: _______

Height: _____inches Weight: _____lbs BMI: _______ BP: ___/____

Please answer the following questions honestly by checking YES or NO in the correlating boxes. Some of the questions may ask you to provide more detail.

YES	NO	
☐	☐	1. Are you a female college student at Ohio University
☐	☐	2. Are you between the age of 18-20?
☐	☐	3. Are you currently pregnant?
☐	☐	4. Have you had surgery within one year (not including facial)? If YES, please specify:
☐	☐	5. Do you have a current/ongoing injury? If YES, please specify:
☐	☐	6. Did you participate in any sports in high school?
☐	☐	7. Are you currently involved in intercollegiate athletics (not including club sports)?
☐	☐	8. Do you have a current/ongoing knee condition? If YES, please specify:
☐	☐	9. Have you ever been diagnosed with an ACL injury?
☐	☐	10. Have you previously participated in ACL prevention training?

OFFICE USE ONLY

Determined Status (circle): Eligible Ineligible

APPENDIX D: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

Physical Activity Readiness Questionnaire - PAR-Q (revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	**2. Do you feel pain in your chest when you do physical activity?**
☐	☐	**3. In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7. Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ________________________________

SIGNATURE ________________________________ DATE ________________________

SIGNATURE OF PARENT ________________________________ WITNESS ________________________
or GUARDIAN (for participants under the age of majority)

APPENDIX E: KNEE HISTORY FORM

Please read the following questions carefully and answer each one honestly.

1. Have you had surgery within the past year? If **YES**, please clarify:

2. Do you have a current/ongoing injury? If **YES**, please clarify:

3. Do you have current symptoms of knee pain, patellar (knee cap) instability, or joint effusion (swelling)? If **YES**, please clarify:

4. Have you ever been diagnosed with an anterior cruciate ligament (ACL) injury?

5. Have you ever participated in an ACL prevention (jump) training program?

APPENDIX F: ATHLETICS HISTORY FORM

Please read the following questions carefully and answer each one honestly.

1. Did you participate in high school athletics?

If **YES**, list the sports that you participated in and the number of years you were involved

Sport	**Years**
______________________	_________
______________________	_________
______________________	_________
______________________	_________
______________________	_________
______________________	_________

APPENDIX G: 1RM TESTING FORM

ID #: _______ **Code Name: ___________________**

Exercise	**1 RM**	**80% 1RM** (lbs)	**70% 1RM** (lbs)
Front Squat			
Calf Raise			
Leg Extension			
Leg Curl			
Back Squat			
Good Morning			
Body Squat			(band color)
Forward Lunge			
Back Hyperextension			
Pullover			
Bench Press			
Lat Pulldown			
Forearm Curl			

APPENDIX H: PRETESTING FORM

CODE NAME: ________________________

VERTICAL JUMP (inches)

Standing Reach:		
	Jump Height	**Vertical Height**
Trial 1		
Trial 2		
Trial 3		

DROP JUMP (%)

	Knee Separation %
Prelanding	
Landing	
Takeoff	

APPENDIX I: TRAINING PROGRAMS

Phase	Neuromuscular Training Program			Controlled Resistance Training Program		
Phase 1	Exercises	Week 1	Week 2	Compound Set Exercises	Week 1	Week 2
	Wall jumps	20 sec	25 sec	Front Squat	1x8 (BB)	1x8 (BB)
	Tuck jumps	20 sec	25 sec	+ Calf Raise	1x8 (MCH)	1x8 (MCH)
	Broad jumps	1x5	1x10	Leg Extension	1x8 (MCH)	1x8 (MCH)
	Squat jumps	10 sec	15 sec	+ Leg Curl	1x8 (MCH)	1x8 (MCH)
	Double-legged cone jumps	30sec/30sec	30sec/30sec	Back Squat	1x8 (BB)	1x8 (BB)
	180° jumps	20 sec	25 sec	+ Good Morning	1x8 (BB)	1x8 (BB)
	Bounding in place	20 sec	25 sec	Body Squat	1x8 (TB)	1x8 (TB)
				+ Forward Lunge	1x8 (DB)	1x8 (DB)
Phase 2	Exercises	Week 3	Week 4	Exercises	Week 3	Week 4
	Wall jumps	30 sec	30 sec	Front Squat	1x8 (BB)	1x8 (BB)
	Tuck jumps	30 sec	30 sec	+ Calf Raise	1x8 (MCH)	1x8 (MCH)
	3 Jumps to vertical jump	1x5	1x8	Leg Extension	1x8 (MCH)	1x8 (MCH)
	Squat jumps	20 sec	20 sec	+ Leg Curl	1x8 (MCH)	1x8 (MCH)
	Bounding for distance	1 run	2 runs	Back Squat	1x8 (BB)	1x8 (BB)
	Double-legged cone jumps	30sec/30sec	30sec/30sec	+ Good Morning	1x8 (BB)	1x8 (BB)
	Scissors jump	30 sec	30 sec	Body Squat	1x8 (TB)	1x8 (TB)
	Hop, hop, stick landing	1x5/leg	1x5/leg	+ Forward Lunge	1x8 (DB)	1x8 (DB)
Phase 3	Exercises	Week 5	Week 6	Exercises	Week 5	Week 6
	Wall jumps	30 sec	30 sec	Front Squat	1x8 (BB)	1x8 (BB)
	Step, jump up, down, vertical	1x5	1x10	+ Calf Raise	1x8 (MCH)	1x8 (MCH)
	Mattress jumps	30sec/30sec	30sec/30sec	Leg Extension	1x8 (MCH)	1x8 (MCH)
	Single-legged jumps distance	1x5/leg	1x5/leg	+ Leg Curl	1x8 (MCH)	1x8 (MCH)
	Squat jumps	25 sec	25 sec	Back Squat	1x8 (BB)	1x8 (BB)
	Jump into bounding	3 runs	4 runs	+ Good Morning	1x8 (BB)	1x8 (BB)
	Hop, hop, stick landing	1x5/leg	1x5/leg	Body Squat	1x8 (TB)	1x8 (TB)
				+ Forward Lunge	1x8 (DB)	1x8 (DB)

BB: performed with barbell; DB: performed with dumbbells; MCH: performed with machine; TB: performed with theraband

Assistance Strength Training Exercises
Abdominal Curl – 1x25+
Back Hyperextension – 1x15
Body Squat – 1x15
Calf Raise – 1x15
Pullover – 1x12
Bench Press – 1x12
Lat Pulldown – 1x12
Forearm Curl – 1x12

APPENDIX J: ATTENDANCE FORMS

Neuromuscular Training Group Attendance

Date: ________

Code Name	Time In	Time Out

Resistance Training Group Attendance

Date: ________

Code Name	Time In	Time Out

APPENDIX K: NEOURMUSCULAR TRAINING GROUP TRAINING LOG

Training Log (NMT)

Week #1 **Session Dates:** **#1________ #2________ #3________**

Code Name:______________________________

Dynamic Warm-up	Day 1	Day 2	Day 3
Move			
Heel/Toe Walk			
Hand Walk			
Forward Lunge			
Backward Lunge			
Leg Cradle Walk			
Dog & Bush Walk			

Jump Training	Time	Day 1	Day 2	Day 3
Exercise				
Wall Jumps	25 sec			
Tuck Jumps	25 sec			
Broad Jumps	1x10			
Squat Jumps	15 sec			
DL cone jumps	30/30 sec			
180 jumps	25 sec			
Bounding in place	25 sec			

A-Srength Training*	Weight	Day 1	Day 2	Day 3
Exercise				
(1) Abdominal Curl	X			
(2) Back Extension				
(3) Lat Pulldown				
(4) Pullover				
(5) Bench Press				
(6) Forearm Curl				
(7) Calf Raise				
(8) Body Squat	(color)			

70% 1RM

Static Stretching	Day 1	Day 2	Day 3
Move			
Tris			
Delts			
Traps			
Pecs			
Quads			
Hips			
Hamis			
Calfs			
Glutes			
Back			

APPENDIX L: RESISTANCE TRAINING GROUP TRAINING LOG

Training Log (RT)

Week #1 **Session Dates:** **#1________ #2________ #3__**

Code Name: ______________________________

Dynamic Warm-up	Day 1	Day 2	Day 3
Move			
Heel/Toe Walk			
Hand Walk			
Forward Lunge			
Backward Lunge			
Leg Cradle Walk			
Dog & Bush Walk			

A-Srength Training*	Weight	Day 1	Day 2
Exercise			
(1) Abdominal Curl			
(2) Back Extension			
(3) Lat Pulldown			
(4) Pullover			
(5) Bench Press			
(6) Forearm Curl			
(7) Calf Raise			
(8) Body Squat	(color)		

70 % 1RM

Strength Training*	Weight	Day 1	Day 2	Day 3
Exercise				
Back Squat				
+ Good Morning				
Front Squat				
+ Calf Raise				
Leg Extension				
+ Leg Curl				
Body Squat	(color)			
+ Forward Lunge				

80% 1RM

Static Stretching	Day 1	Day 2	Day 3
Move			
Tris			
Delts			
Traps			
Pecs			
Quads			
Hips			
Hamis			
Calfs			
Glutes			
Back			

APPENDIX M: POSTTESTING FORM

CODE NAME: ________________________

VERTICAL JUMP (inches)

Standing Reach:		
	Jump Height	**Vertical**
Trial 1		
Trial 2		
Trial 3		

DROP JUMP (%)

	Knee Separation %
Prelanding	
Landing	
Takeoff	