The Effects of Plyometric Training on Muscle Activation Characteristics in Post-Pubescent Adolescent Females

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Authorization to Submit Dissertation

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Abstract

The purpose of this study was to (a) assess the symmetry of muscle activation onset, duration, and time to peak muscle activation during a jump-landing task in the left and right vastus lateralis, vastus medialis, biceps femoris, semitendinosus, and to (b) determine how a 6-week plyometric training intervention may impact the symmetry of muscle activation. Previous research has demonstrated that females are at an increased risk for anterior cruciate ligament (ACL) injury. Both modifiable and non-modifiable risk factors have been proposed, including that of neuromuscular control. Past research has demonstrated that coactivation of the quadriceps and hamstrings is suggested to be a favorable movement strategy, thereby, reducing the risk of ACL injury. Electromyography was used to record onset, duration, and time to peak muscle activation of the right and left limbs during a jump-landing task, prior to and following a 6-week plyometric training intervention. Repeated-measures ANOVAs were used to identify if significant differences in activation characteristics were present prior to and following training, as well as between right and left limbs. Results from the present study revealed increased quadriceps activity without equivalent increases in hamstring activity following plyometric training, thus, less favorable coactivation recruitment patterns. These findings prompt inquiry into the value and merit of prescribing plyometric training programs for post-pubescent adolescent females.

Key words: *ACL, neuromuscular control, coactivation*

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Dedication

Dedicated to my almighty Savior, who always reminded me that He would never give me more than I could handle.

To husband and children who have endured this race with more strength and determination than I could have hoped for.

To my parents who continually loved, supported and prayed for me throughout all my education endeavors and encouraged me to set goals beyond what I could imagine accomplishing.

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Chapter I: Introduction

Each day human bodies perform a number of landing tasks associated with daily living such as walking down a flight of stairs or stepping out of vehicles. In athletics, landings are most often associated with descending from a jump, such as in a jump shot in basketball or jumping to spike a volleyball. Landings are considered by many researchers, practitioners, and clinicians to be very high-risk activities associated with various acute and chronic injuries, and while many individuals are able to avoid such injury in a planned landing, injury risk increases in an uncontrolled environment.

It is often assumed that bilateral movements such as landings are performed symmetrically (Arsenault, Winter, Eng, & Marteniuk, 1986). Researchers even make this assumption when investigating variables on only one side of the body during a bilateral task (Arsenault et al., 1986). However, studies (Pappas & Carpes, 2012; Schot, Bates, & Dufek, 1994) which have instrumented both lower extremities during bilateral tasks have shown that asymmetries often occur. Both kinetic (Schot et al., 1994) and kinematic (Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Kernozek, Torry, & Iwasaki, 2008; Pappas & Carpes, 2012) differences between limbs have been observed during bilateral landings. For example, Pappas & Carpes (2012) investigated sex differences in kinematic asymmetry during two types of landing. Results demonstrated that asymmetries in lower extremity kinematics during jump-landing tasks may exist and differ between male and females during the initial phase of landing (Pappas & Carpes, 2012). Some authors have suggested that asymmetrical loading during bilateral landing, jumping, and strengthening activities may impart unequal stimuli to the neuromuscular and skeletal systems over time (Fugal-Meyer, Mild, & Hornsten, 1982), thus exacerbating the condition of asymmetry.

Several sources of asymmetry in the kinematics and kinetics of landing tasks have been suggested in the literature. Some of these suggestions include muscle imbalance (Hay, De Souza, & Fukashiro, 2006; Knapik, Bauman, Jones, Harris, & Vaughn, 1991; Shenoy, Sharma, & Sandhu, 2010), greater energy storage in one limb (Brewer, 2005), or preferential use of muscles on one side, or dominance (Fugal-Meyer et al., 1982). Any of these neuromuscular asymmetries can cause concomitant alterations in force distribution amongst the joints, which has significant implications on the body's ability to dissipate these forces (Kovacs, Tihanyi, DeVita, Racz, Barrier, & Hortobágyi, 1997). Decreases in force dissipation abetted by increases in force distribution to the knee, hip, or ankle joints can affect neuromuscular control patterns and consequently increase risk of injury.

Lower extremity landings have been associated with numerous injuries, including ankle sprains, anterior cruciate ligament tears, and patellofemoral pain syndrome (Beynnon, Vacek, Murphy, Alosa, & Paller, 2005; Coplan, 1989; Ferretti, 1986; Ferretti, Papandrea, & Conteduca, 1990; Ferretti, Papandrea, Conteduca, & Mariani, 1992; Frank & Jackson, 1997; Griffin, Agel, Albohm, Arendt, Dick, Garrett…Wojtys, 2000; Hewett, Ford, Hoogenboom, & Myer, 2010; Hewett, Myer, Ford, Heidt, & Colosimo, 2005; Miyasaka, Daniel, Stone, & Hirshman, 1991; Shimokochi & Shultz, 2008). Reports illustrate that nearly 90% of all injuries during volleyball competition occur within the lower extremity (Gerberich, Luhmann, Finke, & Uhl, 1987) and 58% of all female basketball injuries occur while landing from a jump (Gray, Tauton, McKenzie, Clement, McConkey, & Davidson, 1985). Although numerous factors contribute to injury during landings, one important factor that has been investigated is strength asymmetry (Hay et al., 2006; Knapik et al., 1991; Shenoy et al., 2010). The type of muscle action, the velocity of muscle action (Koh, Grabiner, &

Clough, 1993), and joint position (Pappas & Carpes, 2012) can contribute to strength differences of between 3 to 25% between limbs (Archontides & Fazey, 1993). Side-to-side strength asymmetries have been suggested as a risk factor for anterior cruciate ligament injury in female athletes (Cowley, Ford, Myer, Kernozek, & Hewett, 2006; Hewett, Stroupe, Nance, & Noyes, 1996; Myer, Ford, & Hewett, 2004).

The importance of strength in landing activities is derived from its relationship to muscle stiffness. Muscle stiffness has two components, active and passive. Passive stiffness is the relaxation of the muscle allowing for greater range of motion; however, passive muscle stiffness still elicits a measurable amount of resistance (Schleip, Naylor, Ursu, Melzer, Zorn, Wilke … Klingler, 2005). Active stiffness is continuous tension of the muscle throughout a range of motion. Active stiffness is determined by force production and appropriate muscle activation. Muscle stiffness allows for joint range of motion. Studies have shown that activation of muscles prior to receiving impact load, such as in landing from a jump, is important in determining the stiffness of the musculotendinous unit, and that lack of activation or poor timing of activation results in higher impact forces (Chelly & Dennis, 2001; Duncan & McDonagh, 2000; McKinley & Pedotti, 1992, Melville-Jones & Watt, 1971; Wilkstrom, Tillman, Schenker, & Borsa, 2008). For example, a study conducted by Wilkstrom et al. (2008), indicated that successful jump landing trials require an earlier onset of muscle activity to resist the collapse of the lower extremity during impact. An insufficient level of muscle stiffness might not be able to provide the appropriate deceleration of joint rotations for a safe and smooth landing (Santello, 2005) and could result in injury. The absence of neuromuscular control of the knee joint may be responsible for the increased rates of knee injury in females (Hewett et al., 1996; Huston & Wojtys, 1996).

Since the passage of Title IX of the Educational Assistance Act, male participation at the high school level has increased less than 3%, whereas female participation has increased more than nine-fold, roughly doubling every ten years (0.3 to 2.8 million) (National Federation of State High School Associations, 2002). This geometric growth in participation has led to an alarming increase in the number of anterior cruciate ligament (ACL) injuries in female athletes (Hewett, Myer, Ford, Heidt, & Colosimo, 2005; Ivkovic, Franic, Bojanic, & Pecina, 2007). Anterior cruciate ligament (ACL) injuries disproportionately affect female athletes, accounting for 69.0% of serious knee injuries (Gomez, DeLee, & Farney, 1996) and 4.8% of all athletic injuries (Giza, Mithofer, Farrell, Zarins, & Gill, 2005; Oliphant & Drawbert, 1996) when compared to male counterparts. Moreover, although boys and girls have an equal number of ligament sprains prior to adolescence, girls have a higher rate immediately following their growth spurt and into maturity (Ivkovic et al., 2007; Malina & Bouchard, 1991; Tursz & Crost, 1986). Adolescent girls who participate in pivoting and jumping sports have a four to six-fold greater rate of injuries of the ACL than do adolescent boys participating in the same sports (Arendt & Dick, 1995; Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Malone, Hardaker, Garrett, Feagin, & Bassett, 1993). The increased ACL injury risk coupled with increased sports participation by young women over the last thirty years has increased public awareness and fueled many sex-specific mechanistic and interventional investigations (Myer, Ford, & Hewett, 2004). A shift in research toward injury mechanism and prevention is warranted due to an estimated 38,000 ACL injuries occurring in young female athletes each year (Toth & Cordasco, 2001).

Approximately, 70% of ACL injuries occur in non-contact situations (Krosshaug, Nakamae, Boden, Engebretsen, Smith, Slauterbeck … Bahr, 2007; McNair, Marshall, & Matheson, 1990; Myklebust, Maehlum, Holm, & Bahr, 1998), typically during deceleration, lateral pivoting, or landing tasks that are associated with high loads on the knee joint (Boden, Dean, Faegin, & Garrett, 2000; Olsen, Myklebust, Engebretsen, & Bahr, 2004). Reduced muscle strength, neuromuscular control, and postural control have been identified as potential risk factors (Alentorn-Geli, Myer, Silvers, Samitier, Romero, Lazaro-Haro, & Cugat, 2009; Barber-Westin, Noyes, & Galloway, 2006; Daniel, Stone, Dobson, Fithian, Rossman, & Kaufman, 1994; Huston & Wojtys, 1996; Myklebust, Maehlum, Engebretsen, Strand & Solheim, 1997; Myklebust, Maehlum, Holm & Bahr, 1998; Sell, Ferris, Abt, Tsai, Myers, Fu, & Lephart, 2006). However, to date, the extent to which neuromuscular control increases the risk of ACL injury in post-pubescent adolescent females is unknown.

Biomechanical and neuromuscular risk factors may be critical components of the mechanisms which underlie the higher rate of ACL injuries in female compared to male athletes (Ford, Shapiro, Myer, van den Bogert, & Hewett, 2010). The onset of these neuromuscular risk factors may coincide with rapid adolescent growth that results in the divergence of a multitude of biomechanical and neuromuscular parameters between sexes (Ford et al., 2010). Although ACL injuries increase with age in both males and females, females have higher rates immediately following the growth spurt (Admirin & Cheng, 2003; Tursz & Crost, 1986). Musculoskeletal growth during puberty, in the absence of corresponding neuromuscular adaptation, may facilitate the development of certain intrinsic risk factors (Hewett, Myer, & Ford, 2004). These intrinsic factors, if not addressed at the proper time period, may continue through adolescence into maturity and predispose athletes to ACL injuries (Ford et al., 2010). Therefore, the purpose of this study was to determine if these neuromuscular deficits exists in post-pubescent adolescent females, and how a plyometric training intervention may alter these neuromuscular characteristics.

Statement of the Problem

Currently, research demonstrates asymmetry in muscle activation onset during seemingly bilateral tasks. Furthermore, research has revealed differences in neuromuscular activation patterns among sex. Yet, to date, no research study has examined the effect of a plyometric training intervention on onset, duration, and time to peak muscle activation in a jump-landing task in post-pubescent adolescent females. The purpose of this study was to (a) assess the symmetry of muscle activation onset, duration, and time to peak activation during a jump-landing task in the left and right vastus lateralis, vastus medialis, biceps femoris, semitendinosus, and to (b) determine how a 6-week plyometric training intervention may impact the symmetry of muscle activation.

Hypotheses

Null: There will be no significant differences in right leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus onset of muscle activation relative to ground contact prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in right leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus onset of muscle activation relative to ground contact at the conclusion of a 6-week plyometric training intervention.

Null: There will be no significant differences in left leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus onset of muscle activation relative to ground contact prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in left leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus onset of activation relative to ground contact at the conclusion of a 6-week plyometric training intervention.

Null: There will be no significant differences in right leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus duration of activation relative to ground contact prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in right leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus duration of activation relative to ground contact at the conclusion of a 6-week plyometric training intervention.

Null: There will be no significant differences in left leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus duration of activation relative to ground contact prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in left leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus duration of activation relative to ground contact at the conclusion of 6-plyometric training intervention.

Null: There will be no significant differences in right leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus time to peak activation relative to ground contact prior to a 6-week plyometric intervention.

Null: There will be no significant differences in right leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus time to peak activation relative to ground contact at the conclusion of a 6-week plyometric training intervention.

Null: There will be no significant differences in left leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus time to peak activation relative to ground contact prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in left leg vastus lateralis, vastus medialis, biceps femoris, and semitendinosus time to peak activation relative to ground contact at the conclusion of a 6-week plyometric training intervention.

Null: There will be no significant differences in muscle activation onset between left and right vastus lateralis, vastus medialis, biceps femoris, and semitendinosus prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in muscle activation onset between left and right vastus lateralis, vastus medialis, biceps femoris, and semitendinosus at the conclusion of a 6-week plyometric training intervention.

Null: There will be no significant differences in duration of muscle activation between left and right vastus lateralis, vastus medialis, biceps femoris, and semitendinosus prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in duration of muscle activation between left and right vastus lateralis, vastus medialis, biceps femoris, and semitendinosus at the conclusion of a 6-week plyometric training intervention.

Null: There will be no significant differences in time to peak activation between the left and right vastus lateralis, vastus medialis, biceps femoris, and semitendinosus prior to a 6-week plyometric training intervention.

Null: There will be no significant differences in time to peak activation between the left and right vastus lateralis, vastus medialis, biceps femoris, and semitendinosus at the conclusion of a 6-week plyometric training intervention.

Significance

Researchers have investigated muscle activation patterns during jumping and landing in both males and females and have identified differences across sex. More specifically, differences in activation symmetry of the quadriceps and hamstrings between sexes has been documented. These differences have propagated knowledge of the heightened ACL injury risk for females. However, delineations of how this risk may be different due to age and maturity level has not been well researched. Moreover, investigations including plyometric training interventions have been conducted and suggest that training may promote advantageous alterations in neuromuscular function as well as reduce the risk of ACL injury. However, to date, no one has determined how plyometric training may influence symmetry of muscle activation onset, duration, and time to peak activation in the quadriceps and hamstrings during a jump-landing task in post-pubescent adolescent females. While many investigations have included the use of adult female athletes for identification of ACL injury risk, there is a gap in the literature regarding those females who are post-pubescent and in the middle and high school settings.

If neuromuscular asymmetries are present in the quadriceps and hamstrings in post-pubescent adolescent females, then it may be postulated that the onset of puberty may affect neuromuscular function strategies, collectively increasing the risk of ACL injury. If modifications in the neuromuscular activation patterns are changed following a plyometric training intervention, then support for specific neuromuscular training in reducing the risk of ACL injury may be imparted. Identification of programs that may reduce the risk of ACL injury in post-pubescent adolescent females can contribute greatly in decreasing the costs of ACL injury repair and rehabilitation, as well as preserving the recreational engagement and healthy lifestyles of young females.

Limitations, Delimitations, and Assumptions

This study was delimited to healthy, post-pubescent females ages 13 – 17 years, with no self-reported history of significant injury to their lower extremities, which may affect performance and participation in the plyometric training intervention. Post-pubescent criteria were ensured by use of the Tanner Staging self-assessment (see Appendix), with participants identifying in Tanner Stages IV or V. Previous studies have demonstrated lower extremity asymmetries associated with injury two years after the injury date (Cortes, Onate, Abrantes, Gagen, Dowling, & Van Lunen, 2007; Croisier, Frothomme, Namurois, Vanderthommen, & Crielaard, 2002; Paterno, Schmitt, Ford, Rauh, Myer, Huang … Hewett, 2007). Therefore, this study was limited to participants with no reported history of significant injury in the past two years. Additionally, participants must have reported a minimum of three hours of physical activity per week on average, which includes representation from jumping or landing type activities (jump rope, basketball, volleyball, etc.) (Kernozek et al., 2007; McLean, Felin, Suedekum, Calabrese, Passerallo, & Joy, 2007). The involvement of participants with experience in jumping and landing helps to reduce the effect of lack of training as a source of asymmetry. Therefore, the subject criteria limits the generalizability of the results to other populations such as injured or highly trained individuals.

Participants jumped from a plyometric box 63 cm in height to a distance of 50% of their reported height. Their only instruction was to land as they typically would from a jump. Limitations, therefore, existed on the control of each individual's landing mechanics (Cortes et al., 2007). It was assumed that the within-subjects design of this study would control for source of variability between subjects due to different individual mechanics, and that individual subjects would perform the jump-landing task consistently. It was also assumed that the familiarization session of the jump-landing tasks during the experimental protocol was sufficient to capture consistent performance (Bennett, Blackburn, Boling, McGrath, Walusz, & Padua, 2008).

It was assumed that all participants abided by the procedures of the study, including restricting physical activities which might produce fatigue or muscle soreness on testing days. It was also assumed that all subjects were honest in disclosing injury history information.

Chapter II: Review of Literature

Research has focused on improving muscular strength and power to subsequently improve jumping performance. However, we have fallen behind in teaching the landing portion of the jumping movement (Hauschildt, 2008). The National Federation of State High School Associations (2007) reported more than seven million athletes participate in organized high school varsity sports. Additionally, an estimated 380,000 athletes participate in intercollegiate sports, and millions of other athletes of all age levels are participating recreationally (Adirim & Cheng, 2003). Lower-extremity asymmetries in strength or functional abilities may be related to an increased risk for lower-extremity injury in athletic populations (Hewett et al., 2005; Klein, 1970; Myer, Paterno, Ford, Quatman, & Hewett, 2006; Noyes, Barber, & Mangine, 1991). As such, improper landing mechanics have been linked to numerous injuries (e.g., ankle sprains, anterior cruciate ligament tears, and patellofemoral pain syndrome), and are theorized to attribute to the task of landing from a jump (Beynnon, Johnson, Abate, Fleming, & Nichols, 2005; Feretti, 1986; Ferretti et al., 1990; Feretti et al., 1992; Frank & Jackson, 1997; Griffin et al., 2000; Miyasaka et al., 1991).

Many researchers, practitioners, and clinicians consider landings to be very high-risk activities associated with various acute and chronic injuries. While it is often assumed that bilateral landings are symmetrical, research data has shown that this is not always the case and that asymmetry in force production, kinematics, and muscle activation exist. Notably, asymmetries in performance characteristics have been implicated in the risk for injury, for example in the ligaments of the knee and ankle. While several researchers (Chimera, Swanik, Swanik, & Straub, 2004; Hewett et al., 2005; Medina, McLeod, Howell, & Kingma, 2007; Struminger, Lewek, Goto, Hibberd, & Blackburn, 2013) have investigated muscular activation with various types of landing activities and identified factors linked with the increase in ACL injury risk seen in female athletes, at present, there is a lack of information regarding neuromuscular deficits in post-pubescent adolescent female athletes and ACL injury. Moreover, there is a lack of knowledge regarding the effects of neuromuscular training and decreased risk of ACL injury in this population. The following literature review will provide background information about landing mechanics, implications of landing mechanics on injury, associated neuromuscular deficits, and the interaction of neuromuscular deficits and ACL injury in female athletes. Through these topics, the reader will acquire the framework needed to appreciate the purpose of this investigation.

Kinematics

The purpose of any planned landing is to gradually reduce the body's downward momentum, produced by a free-fall, to zero, and to do so in such a manner as to minimize injury potential. An additional consideration that may influence the landing is how the landing might be integrated into subsequent movements, such as a jump or stride. Reducing the body's momentum to zero requires the body to apply a positive impulse (force * time) through the ground or supporting surface, which in turn applies an impulse back to the body (action-reaction). The body applies force to the support surface through muscle contraction, and this force is applied over a period of time corresponding to the angular displacement and velocity of joint flexions. Thus, a landing in which a fast change in momentum is desired requires high force production about the joints and minimizing joint angular displacements (a 'stiff-legged' landing); however, such a landing situation also results in increased ground reaction forces (Ball, Stock, & Scurr, 2010; Decker, Torry, Wyland, Sterett, & Steadman, 2003; Thomas, McLean, & Palmieri-Smith, 2010; Zhang, Bates, & Dufek, 2000). If, however, it is desired to land with lowered ground reaction forces, then the body will increase the distance through which joint flexions occur (Bobbert, Huijing, & Shenau, 1987; Decker et al., 2003; Devita & Skelly, 1992; Oggero, Pagnacco, Morr, Barnes, & Berme, 1997).

Characterizing ‘typical’ landing kinematics is difficult, as it is clear that kinematics are altered according to many criteria, including drop distance (Arampatzis, Schade, Walsh, & Brüggemann, 1999; Asmussen & Bonde-Petersen, 1974; Bobbert et al., 1987; Duncan & Mcdonagh, 2000; Gollhofer, Strojnik, Rapp, & Schweizer, 1992; Goss-Sampson, Alkureishi, & Price, 2002; Kellis, Arabatzi, & Papadopoulos, 2003; Komi & Bosco, 1978; Lees & Fahmi, 1994; Minetti, Ardigo, Susta, & Cotelli, 1998; Santello & McDonagh, 1998; Viitasalo, Salo, & Lahtinen, 1998; Walsh, Arampatzis, Schade, & Bruggemann, 2004; Young, Pryor, & Wilson, 1995), landing surface characteristics (Arampatzis, Bruggemann, Klapsing, 2001; Potach & Chu, 2000; Santello, 2005), foot position (Brewer, 2005; Potach & Chu, 2000), and more. It is also clear that males and females typically demonstrate different kinematics, although it is still under investigation whether these differences are truly sex-based or are a result of intervening factors like training exposure (Ebben, Simenz, & Jensen, 2009; Lephart, Abt, Ferris, Sell, Nagai, Myers, & Irrgang, 2005), or strength imbalances (Fugl-Meyer et al., 1982; Markou & Vagenas, 2006). The following discussion of kinematics of landing will therefore consider how uninjured males versus females perform seemingly bilateral landings.

Many studies have investigated kinematic profiles (Decker et al., 2003), some specifically focused on differences seen in sex. Decker et al. (2003) conducted a study to determine whether sex differences exist in lower extremity joint motions and energy absorption landing strategies between age and skill-matched recreational athletes. The results demonstrated that females land more erect and utilize greater hip and ankle joint range of motions and maximum joint angular velocities compared to males (Decker et al., 2003). With much of the research surrounding landing mechanics and injury, specifically correlated to females and anterior cruciate ligament tears, this study suggests that the preferred shock absorption strategy for females required the ankle and knee to be in a more extended position to fully utilize the capacity of the ankle plantar-flexor muscles (Decker et al., 2003). As such, this landing technique has been proposed to provide a greater potential risk for non-contact ACL injury for females compared to males (Decker et al., 2003).

When video sequences of actual ACL injury are examined, it appears that there are four common motor performance components that occur, especially in women (Hewett, Torg, & Boden, 2009; Myer, Ford, Khoury, Succop, & Hewett, 2010). As the at-risk female athlete lands (a) her knee buckles inward, (b) the injured knee is relatively straight, (c) most if not all of her weight is on a single lower extremity, and (d) her trunk tends to be tilted laterally (Hewett et al., 2010). Consequently, there are several theories surrounding the higher incidence of ACL injury pertaining to females. Three of these have become the primary focuses of researchers. To begin, Hewett et al. (2000) proposed the ligament dominance theory. The ligament dominance theory suggests that the lower extremity muscles do not adequately absorb the impact of landing, resulting in knee valgus, which causes increased loading of the ACL (Ford et al., 2003; Hewett et al., 2000; Pappas, Sheikhzadeh, Hagins, & Nordin, 2007). The term "valgus" is used to describe the video-evidenced mechanism of injury and is visually associated with a knock-kneed position during dynamic tasks (Myer et al., 2011). Secondly, Hewett et al. (2000) also proposed the quadriceps dominance theory. The quadriceps dominance theory suggests that females tend to rely on their quadriceps more than their hamstrings creating excessive anterior translation of the tibia (Ford et al., 2003; Hewett et al., 1996; Huston & Wojtys, 1996; Pappas et al., 2007). And, thirdly, Huston and colleagues (2001) proposed the straight knee landing theory. This theory suggests that females exhibit less knee flexion at the time of impact that may lead to ACL injury either by hyperextension or by anterior tibial translation (Decker et al., 2003; Huston, Vibert, Ashton-Miller, Wojtys, 2001; Pappas et al., 2007).

Hewett et al. (1996) found that high school female athletes, regardless of their physical training level, exhibited excessive frontal plane motion (into the direction of valgus) at the knee when dropping from a 60 cm platform, which was not exhibited by aged-matched males. McLean and colleagues (2004) noted increased knee valgus kinematics in women compared to men in cutting maneuvers (McLean et al., 2007) and Ford et al. (2006) along with Freedman and colleagues (1998) suggest that athletic women in general demonstrate greater maximum hip adduction angles, torques, and excursions during agility and landing maneuvers compared to young men (Freedman, Glasgow, Glasgow, & Bernstein, 1998).

Forces

The effectiveness of the lower extremities to dissipate the forces generated during landing is essential to completing a safe landing (Lephart, Ferris, Reimann, Myers, & Fu, 2002). Subsequent to impact, the joints (ankle, hip, and knee) flex to absorb the forces generated. Although it would seem feasible to assume that all forces generated are the same regardless of the jump performed, the amount of force is altered dependent upon differing heights (McNitt-Gray, 1991), technique (Dufek & Zang, 1996; Tillman, Hass, Brunt, & Bennett, 2004), as well as the jump performed (Afifi & Hinrichs, 2011; Edwards, Steele, McGhee, Beattie, Purdam, & Cook, 2010). It has been reported (Adrian & Laughlin, 1983) that landings often result in the creation of ground reaction forces on the order of five times body weight.

Landing techniques can potentially be related to lower extremity energy absorption (Dufek & Zang, 1996). The literature differentiates between two different bilateral landing techniques: one that is made with flat feet and one that is made first with the forefoot and then with the rearfoot (Kovacs et al., 1997; Ortega, Bies, & Berral de la Rosa, 2010). These different landing strategies yield significant implications regarding the forces transmitted to the body and the body's ability to dissipate these forces (Kovacs et al., 1997). A study conducted by Stacoff and colleagues (1988), found an initial vertical impact force of approximately 1-2x body weight at forefoot touchdown for males performing a block in volleyball (Stacoff, Kaelin, & Stuessi, (1988). Heel contact resulted in a second peak force ranging between 1-7x body weight (Tillman et al., 2004).

There is a tendency to touch the feet down at different times in double leg-drop jumps; indicating that one leg may store more energy than the other, which may affect neuromuscular load and force output between legs (Ball & Scurr, 2009; Hay et al., 2006; Santello & Mcdonagh, 1998). Previous research attributed this to the lead leg when initiating the jump (Ball & Scurr, 2009), although this was only investigated at a height of

40 cm. Ten recreational active male subjects participated in the study and were asked to complete three different drop landings from 20, 40, and 60 cm. The results indicated that force and time variables increased as drop jump height increased. Force was found to be significantly different between legs at 20 cm, but not at 40 or 60 cm, probably accountable to the short time allotment to move the trailing foot into the correct landing position. These results illustrated bilateral differences in maximum force and impulse from various drop jump heights and could be linked with asymmetry in landing technique.

Forces associated with bilateral landings have been shown to be different between males and females (Colby, Francisco, Yu, Kirkendall, & Garrett, 2000; Colby, Hintermeister, Torry, & Steadman, 1999; DeVita & Skelly, 1992; Dufek & Bates, 1991; Hewett et al., 1996; Huston & Wojtys, 1996; Knapik et al., 1991; Lephart et al., 2002; McLean, Neal, Myers, & Walters, 1999; Nyland, Caborn, & Shapiro,1999; Viitasalo et al., 1998; Wojtys, Huston, Taylor, & Bastian, 1996). Lephart and colleagues (2002) evaluated kinematic, vertical ground reaction forces, and strength variables in healthy collegiate female basketball, volleyball, and soccer players compared with matched male subjects. Results of their study indicated that males had a greater amount of knee flexion subsequent to impact enabling the larger flexion displacement to attenuate impact forces reducing loads imposed on the joint (Lephart et al., 2002). However, the female subjects demonstrated an absence of the controlled knee flexion, which may be due to weaker quadriceps and hamstrings, resulting in abrupt stiffening of the knee (Lephart et al., 2002). Similarly, Nagai et al. (2013) found that individuals with less quadriceps strength landed with less knee flexion during a single-leg landing (Nagai, Sell, House, Abt, & Lephart, 2013).

Origins of Human Symmetry

The idea of human symmetry is a broad term; however, one of the most apparent forms of human symmetry can be seen in facial architecture (Scheib, Gangestad, & Thornhill, 1999). Consisting of eyes, ears, cheeks, lips, and a nose, these structures are most often aligned perfectly as to define bilateral symmetry of the face. Symmetry is seen throughout the human anatomy, including arm, leg, hip, and chest muscles which are located anatomically in nearly identical locations on either side of the body's hemispheres. Although bilateral symmetry is easily referenced to anatomical structure, the body's ability to maintain bilateral symmetry as best as possible when performing mechanical tasks is of concern for preventing and eliminating injury risk.

The deviations of an organism from perfect symmetry can be grouped into three categories; of particular concern is directional asymmetry and antisymmetry. Directional asymmetry occurs when there is normally a greater development of a character on one side of the plane or planes of symmetry than on the other (Van Valen, 1962). Antisymmetry refers to the apparently less common situation where asymmetry is normally present but it is variable which side has greater development (Van Valen, 1962). To better understand these concepts, directional asymmetry implies that internal, preexisting positional information influences the initial trigger, whereas antisymmetry typically signals that a random, external environment trigger induced one side to develop differently (Palmer, 1996). A simple example of antisymmetry would be a human population with right and left handed but few ambidextrous individuals (Van Valen, 1962).

Bilateral tasks such as squatting, jumping, and landing, often are assumed to be symmetrical (Berg, Blanke, & Miller, 1985; Goslin & Charteris, 1979; Hamill, Bates, Knutzen, 1984; Holmes & Alderink, 1984; Schot et al., 1994; Schot & Knutzen, 1989), which has been demonstrated through studies analyzing characteristics of one limb and assumed to characterize both limbs (Arsenault et al., 1986). Even so, some researchers have chosen to unilaterally analyze the limbs in seemingly bilateral tasks, and have shown that asymmetries exist (Arsenault et al., 1986). Therefore, an introduction to the origins of human symmetry will provide a greater understanding as to how these results may occur. A complete discussion of asymmetries reported associated with landing tasks will follow.

In the literature, it has been reported that a 10% difference between lower limb symmetry is significant (Bennell, Wajswelner, Lew, Schall-Riacour, Leslie, et al., 1998; Grace, Sweetser, Nelson, Ydens, & Skipper, 1984; Yoshioka, Nagano, Hay, & Fukashiro, 2010). However, this value is not backed by experimental results. Some research has demonstrated that asymmetries exist in several biomechanical variables such as decreased muscle power (Kowal, 1980), more frequent lower extremity anatomical malalignment, increased knee joint laxity (Alentorn-Geli et al., 2009 (Benke, Naesborg, Simonsen, & Klausen, 2000), decreased relative (to quadriceps) hamstring strength and recruitment, neuromuscular fatigue (Boden et al., 2000), and poor fundamental motor skills caused by poor training during the development years (Alentorn-Geli et al., 2009).

Previous studies have linked bilateral strength imbalance with injury, such as Knapik et al. (1991), who found that athletes had a higher injury rate with a knee flexor or hip extensor imbalance of 15% or more on either side of the body. Differences in bilateral symmetry and vulnerability associated with asymmetry in landing have also been investigated across sex. Side-to-side strength imbalances have been suggested as a risk factor for anterior cruciate ligament injury in female athletes (Cowley et al., 2006; Hewett et al., 1996; Myer et al., 2004). Females typically have a higher susceptibility to incurring non-contact ACL injury (Gray et al., 1985), being eight times more likely to rupture the ACL in basketball than their male counterparts (Malone, Hardaker, & Garrett, 1993).

Bilateral comparison is required because there is a tendency to touch the feet down at different times during a drop jump; therefore, one limb may store more energy than the other and this could have implications for long term training effects (Brewer, 2005). Ball and Scurr (2009) compared the neuromuscular contribution between left and right triceps surae in the pre-contact, initial, and post-contact phases of a bilateral drop jump exercise to assess the immediate implications of non-simultaneous foot placement. Researchers found significant differences between left and right triceps surae in normalized EMG activity before and directly after contact; however, differences were not evident after 40 ms of contact when loading and propulsion occur. Furthermore, within-leg differences were only present in the pre-contact phase of the drop jump. In comparisons between bilateral muscles, the normalized EMG activity indicated a disparity between left and right legs for the pre-contact and contact phases. The disparity between contralateral muscles in the initial phases of the drop jump disagrees with previous findings that showed a neuromuscular bilateral deficit in plantar flexion actions as a function of knee position and reflex excitability (Ball & Scurr, 2009). This is the first study to report bilateral differences between the same muscles when a reflex response (such as the stretch shortening cycle) is initiated as opposed to using a voluntary effort muscle action (Ball & Scurr, 2009). Bilateral deficits between left and right triceps surae in this study presented slight contact time differences; however, the longitudinal effects of the slight time differential are unknown (Ball & Scurr, 2009).

Furthermore, another study compared vertical ground reaction forces between the left and right legs to assess the symmetry of training induced by performing bounce-drop jumps from different heights (Ball et al., 2010). This study found that the lower drop jump heights may cause asymmetrical bilateral training stimulus compared with drop jumps at greater heights, as well as bilateral differences may occur in the relatively inexperienced athletes at low drop jump heights; however, the occurrence of bilateral differences in experienced jumpers is still uncertain. These observed differences are most likely due to a shortened time period allowed for the feet to synchronize when dropping from a shorter distance.

Achievement of bilateral symmetry may also be impaired due to the effect of leg dominance. Within the literature, the dominant leg has been defined as that the subject kicks a ball with (Oroshimo & Kremenic, 2006). Theories surrounding the prevalence of leg dominance include more neuromuscular development as well as the ability to mobilize the body better (Gabbard & Hart, 1996). To better illustrate these theories, a leg that has more neuromuscular development also has enhanced neuromuscular pathways, allowing for quicker reactions and greater resistance to fatigue.

Neuromuscular Control of Landings

The human body has mechanisms in place to help maintain homeostasis and prevent injury (James, Bates, & Dufek, 2003; Riemann & Lephart, 2002a). Two different mechanisms are utilized in injury prevention in response to a stressor. The first is a feedback mechanism, which is a reflexive response that occurs after sensory detection of the perturbation or stressor (Riemann & Lephart, 2002a). This mechanism identifies changes that affect the system and provides corrections (Medina et al., 2007). However, the feedback mechanism is not fast enough to provide dynamic knee joint stability and prevent collapse (Loeb & Ghez, 2000). There is also a feed-forward mechanism, an anticipatory effect that occurs before sensory detection of the perturbation (Riemann & Lephart, 2002a). When the system is perturbed, there is preparatory contraction of the muscles to stiffen the joints, a protective response to prevent injury (Loeb & Ghez, 2000; Riemann & Lephart, 2002a). The preparation contraction also provides stability and control of joint moments to prevent collapse, which is a performance response (Horita, Komi, Nicol, & Kyröläinen, 2002; Loeb & Ghez, 2000; Riemann & Lephart, 2002b). The overall effect of these mechanisms is efficient neuromuscular control and joint stability (Loeb & Ghez, 2000; Riemann & Lephart, 2002a).

Mechanical stiffness is thought to influence several athletic variables, including rate of force development, elastic energy storage and utilization of movement technique. Consequently, the relationship between mechanical stiffness and athletic performance is of great interest to the sport and research communities (Brughelli, Cronin, Levin, & Chaouachi, 2008). Depending on the task being performed, the neuromuscular system prepares for the impending load (deceleration of the body) by activating muscles before ground contact (McKinley & Pedotti, 1992). This pre-activation serves to stiffen the joint to prevent collapse immediately after contact (Duncan & McDonagh, 2000). We should therefore expect an increase in muscle stiffness prior to impact, produced by the pre-activation of the relevant musculature (Santello & McDonagh, 1998).

Thus, pre-activation of muscles is needed to regulate muscle stiffness prior to landing (Viitasalo et al., 1998). The term stiffness describes the force response that results from and resists mechanical stretch (Padua, Carcia, Arnold, & Granata, 2005). The stiffness behavior of the lower extremity during functional loading conditions is complex (Padua et al., 2005). Lower extremity stiffness during functional tasks represents the average stiffness of the musculoskeletal system and thus depends on the torsional stiffness of the joints (torsional joint stiffness) during ground contact (Arampatzis et al., 2001; Arampatzis, Bruggemann, & Metzler, 1999; Farley, Houdikj, Strien, & Louie, 1998; Farley & Morgenroth, 1999; Greene & McMahon, 1979; McMahon, Valiant, & Frederick, 1987). Torsional joint stiffness is controlled by several biomechanical factors, including muscle activation and force (Hunter & Kearney, 1982; Julian & Sollins, 1975; Lacquanti, Licata, & Soechting, 1982; Weiss, Hunter, & Kearney, 1988; Zhang, Nuber, Butler, Bowen, & Rymer, 1998), reflexes (Houk, 1979; Kearny, Stein, & Parameswaran, 1997; Nichols & Houk, 1976), antagonist muscle co-activation (Agarwal & Gottlieb, 1977; Cannon & Zahalak, 1982; Lacquanti et al., 1982), and lower extremity kinematics during ground contact (Farley & Morgenroth, 1999; Greene & McMahon, 1979; McMahon et al., 1987; Zhang et al., 1998).

The potential stiffness recruitment strategies available to an individual to modulate lower extremity stiffness are limitless (Farley et al., 1998; Farley & Morgenroth, 1999). Stiffness recruitment strategy may be operationally defined as the multijoint coordination (joint kinematics) and muscular recruitment plan (muscle activation) an individual executes to modulate joint torsional stiffness and lower extremity stiffness and, hence, to satisfy the objectives of the functional task (Farley et al., 1998; Hortobagyi & DeVita, 1999; 2000). Yet, women may use altered stiffness recruitment strategies (muscle activation, movement strategies, or both) to compensate for inherent reductions in stiffness properties during functional loading conditions (i.e., landing from a jump) (Padua et al., 2005). However, the contribution of gender differences in stiffness properties of the increased ACL injury rates observed in women has been largely overlooked (Padua et al., 2005). During controlled open-chain measurements of the isolated in vivo knee, women demonstrate less active muscle stiffness than men do (Blackburn, Riemann, Padua, & Guskiewicz, 2004; Granata, Wilson, & Padua, 2002). Granata, Padua, & Wilson (2002) observed similar findings during closed-chain, functional tasks such as two-legged hopping. Reduced stiffness properties in women may result in decreased stability and may potentially influence their elevated risk of ACL injury (Padua et al., 2005). The following is a comprehensive review of the neuromuscular deficits that influence mechanical stiffness as identified in the literature.

Neuromuscular Deficits

There has been a considerable push to understand the factors that may predispose females to non-contact ACL injuries. ACL injury likely occurs under conditions of high dynamic loading of the knee joint, when active muscular restraints do not compensate for and dampen joint loads adequately (Beynnon & Fleming, 1998). Decreased neuromuscular control of the joint may place stress on the passive ligamentous structures that may exceed their strength limit and potentially lead to mechanical failure (Li, Rudy, Sakane, Kanamori, Ma, & Woo, 1999; Markolf, Graff-Redford, & Amstutz, 1978). Neuromuscular control of high-load movements is required to maintain dynamic knee stability during landing and pivoting (Besier, Lloyd, Cochrane & Ackland, 2001; Li, Rudy, Sakene, Kanamori, Ma, & Woo, 1999) and prevent ACL injury. Deficits in the active neuromuscular control system likely affect dynamic knee stability and possibly increase the risk of an ACL injury (Myer, Brent, Ford, & Hewett, 2011).

Several intrinsic (anatomic, hormonal, neuromuscular, and biomechanical differences between genders) and extrinsic (physical and visual perturbations, bracing, and shoe-surface interaction) factors have been examined in order to explain this gender discrepancy (Hewett et al., 2010). Indeed, a number of studies have focused on anatomical or anthropometric measures, such as thigh length (Beynnon, Slauterbeck, Padua & Hewett, 2001), joint laxity (Myer, Ford, Paterno, Nick, & Hewett, 2008), and femoral notch width (Scoville, Williams, Uhorchak, Arciero, & Taylor, 2001). Even so, no specific difference between genders has been identified to explain all contribution to the greater incidence of lower extremity injuries in females (Griffin et al., 2010), however, the neuromuscular function of the muscles that help control the knee during functional tasks has gained attention (Medina et al., 2007). While the aforementioned risk factors (e.g., anatomical, anthropometric) are non-modifiable, ACL injury risks are related to measureable deficits in the modifiable risk factor of neuromuscular control in female athletes (Ford, Myer, & Hewett, 2003; Ford, Myer, Smith, Bymes, Dopirak, & Hewett, 2005; Hewett, Myer, Ford, Heidt, & Colosimo, 2005). Neuromuscular control deficits are defined as muscle strength, power, or activation patterns that lead to increased knee joint and ACL loads (Myer, Ford, & Hewett, 2004). Female athletes demonstrate neuromuscular control deficits that increase lower extremity joint loads during sports activities (Hewett et al., 1996), thereby, increasing the risk of ACL injury.

There are numerous studies evaluating the neuromuscular differences between males and females. In these studies, females demonstrated muscular recruitment characteristics that may be predispositions to ACL injury, including preferential recruitment of the quadriceps over hamstrings (Huston & Wojtys, 1996), shorter latency periods of the quadriceps (Shultz & Perrin, 1999), less muscular stiffness of the thigh muscles (Horita et al., 2002), and unbalanced quadriceps-to-hamstrings strength ratios (Hewett et al., 1996). Consequently, four neuromuscular control deficits have been identified in the literature including "ligament dominance," "quadriceps dominance," "leg dominance," and "trunk dominance/'core' dysfunction." The first, operationally termed, "ligament dominance," can be defined as an imbalance between the neuromuscular and ligamentous control of dynamic knee joint stability (Myer, Ford, & Hewett, 2004). This control imbalance results in an inability to control lower extremity frontal plane motion during landing and cutting (Myer et al., 2011). The second, a modifiable neuromuscular control deficit termed, "quadriceps dominance," is defined as an imbalance between knee extensor and flexor strength, recruitment, and coordination (Myer, Ford, & Hewett, 2004). The third, referred to as "leg dominance," is defined as an imbalance between the two lower extremities in strength, coordination, and control (Myer, Ford & Hewett, 2004). Lastly, the fourth neuromuscular control deficit termed, "trunk dominance 'core dysfunction," is defined as an imbalance between the inertial demands of the trunk and control and coordination to resist it (Myer et al., 2011). Ligament dominance, quadriceps dominance, and leg dominance will be further examined for the purposes of this discussion.

Hewett et al. (1996) tested the hypothesis that insufficient neuromuscular control of lower limb biomechanics, particularly of the knee joint, leads to high-risk patterns in female athletes during execution of common, albeit potentially hazardous, movements. The results of this study demonstrated that peak landing forces were significantly predicted by knee abduction torques (load) at the knee in women, that women developed decreased relative knee flexor torque during landing compared with men, and that women had greater side-to-side differences in normalized hamstring peak torque compared with men (Hewett et al., 1996).

Ford, Myer, & Hewett (2003) reported similar sex differences during the performance of a drop vertical jump. This study determined that female athletes landed with a greater maximum valgus knee angle and greater total valgus knee motion than male athletes (Ford, Myer, & Hewett, 2003). Female athletes also demonstrated significant differences between their dominant and non-dominant side in valgus knee angle; these differences in valgus measures (ligament dominance) and limb-to-limb asymmetries (leg dominance) reflect neuromuscular deficits that may be indicative of decreased dynamic knee joint control in female athletes (Ford, Myer, & Hewett, 2003). Moreover, investigations of gender differences in muscle activation and movement strategies have revealed that women repeatedly demonstrate greater reliance on their quadriceps muscles and move in a more erect posture (increased knee and hip extension) than do their male counterparts (Decker et al., 2003; Hewett et al., 1996; Lephart et al., 2002; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Wojtys et al., 1996), increasing the risk of ACL injury. Understanding the mechanisms that increase the risk of ACL injury is imperative for risk identification; therefore, the following discussion will provide an in-depth exploration of ligament dominance, quadriceps dominance, and leg dominance as predominant factors in risk of ACL injury.

Ligament Dominance

Often, the component of the typical injury mechanism is where the knee collapses into a valgus position. In the condition termed ligament dominance, muscles do not sufficiently absorb the ground reaction forces, so the joint and the ligaments must absorb high amounts of force over a brief period of time (Hewett et al., 2010). Moreover, this control imbalance is demonstrated by an inability to control dynamic knee valgus motion during landing and cutting (Myer et al., 2011). Higher amounts of force over a brief period of time lead to higher impulse forces, likely resulting in ligament rupture (Hewett et al., 2010).

Ligament dominance is characterized by use of anatomic (bony configuration and articular cartilage) and static stabilizers (ligaments) to absorb the ground reaction forces encountered during activity, rather than the use of the muscular prime movers of the lower extremity (Hewett et al., 2010). Of great importance for lower extremity control (and avoidance of ligament dominance) is the group of muscles that comprise the posterior kinetic chain: the gluteals (both maximus and medius), the hamstrings, and the gastrocnemius and soleus (Hewett et al., 2010). Recruitment of these posterior muscles is essential for absorption of large, powerful ground reaction forces, or they travel to the joint and ligament. The reaction force experienced by the athlete is actually significantly greater than her body weight because her body and body segments have inertia and impart a force to the ground greater than their collective mass (Hewett et al., 2010).

During all activities, the ground reaction force is directed toward the center of mass of the body (Hewett et al., 2010). However, in the context ligament dominance, if the trunk moves, the ground reaction force tracks or follows the movement of the trunk; if an athlete allows her trunk to move laterally, her center of mass moves with it (Hewett et al., 2010). As the ground reaction force tracks the center of mass, and if it progresses lateral to the center of the knee joint, the result is movement of the knee joint into a valgus alignment (Hewett et al., 2010). Typically, during single-leg landing, pivoting, or deceleration, all common ACL mechanisms, the female athlete allows the ground reaction force to control the direction of motion of the lower extremity joints (Myer, Ford, & Hewett, 2004).

Neuromuscular imbalances that repeatedly put athletes near "the position of no return" may increase the risk for ligament injury (Ireland, 2002). Furthermore, movement patterns that place an athlete in positions of high ACL load (excessive external knee-abduction moments) combined with a low knee-flexion angle may increase the risk for ligament injury or failure (Lloyed, 2001). Several authors (Chappell, Yu, Kirkendall, & Garrett, 2002; Ford, Myer, & Hewett, 2003; Hewett et al., 1996; Hewett, Myer, & Ford, 2004) have demonstrated this sex-related tendency toward imbalanced ligament dominance, as evidenced by increased knee-valgus angle, coronal-plane knee-valgus motion, and net knee-valgus torques in female athletes compared with males.

Andrews & Axe (1985) first introduced the concept of cruciate ligament dominance in their classical analysis of knee ligament stability. Hewett and colleagues (2002) expanded the concept with their description of ligament dominance during sports activities. Myer et al. (2011) synthesized in vivo, in vitro, and in silico (computer-simulated) data to delineate likely risk factors to the mechanism(s) of non-contact ACL injuries in female athletes. Myer and colleagues (2011) found that "ligament dominant" athletes lacked sufficient frontal plane control of the lower extremities during the performance of a tuck jump. In addition to the "ligament dominant" athlete demonstrating lower extremity valgus at landing, it was identified that foot placement (upon landing) was not shoulder with apart. These landing mechanics are aligned with the purported mechanisms for ACL injury.

Quadriceps Dominance

Recall that females tend to land from a jump with less knee flexion than males (Hewett et al., 2010). The extended knee joint component of injury mechanism relates to a neuromuscular imbalance that occurs in females referred to as quadriceps dominance (Hewett et al., 2010). Quadriceps dominance is the tendency to stabilize the knee joint primarily using the quadriceps muscles (Hewett et al., 2010). The trend seen in females to land from a jump more erect or, with less knee flexion, is indicative of a reliance on the quadriceps to stabilize the knee joint. When the quadriceps contract, they pull the tibia anterior (anterior tibial translation) relative to the femur (Hewett et al., 2010). The resultant biomechanical problem is that the ACL serves to hold the tibia posteriorly (or check anterior translation), and when a female uses her quadriceps to stabilize the joint she induces an anterior shear stress to the tibia and therefore also to the ACL (Hewett et al., 2010). Collectively, when females contract their quadriceps, it extends their knee, which likely relates to the more extended knee position observed during an ACL injury (Hewett et al., 2010).

Quadriceps dominance relates to ligament dominance (Hewett et al., 2010). If an athlete preferentially uses the quadriceps instead of the posterior chain muscles (hamstrings) to control the limb, she uses a single muscle with a single tendinous insertion for stability and control (Hewett et al., 2010). This is in contrast to using the group of posterior chain muscles that possess multiple muscles with varied tendon insertions that can be selectively utilized to control the limb during functional tasks (Hewett et al., 2010). Thus, the hamstrings are able to increase flexion at the knee, which provides a better position (mechanical advantage) for using the muscles to absorb force (Hewett et al., 2010).

Decreased hamstrings strength relative to the quadriceps is implicated as a potential mechanism for increased lower extremity injuries (Ford, Myer, Schmitt, van den Bogert, & Hewett, 2008; Ford, van den Bogert, Myer, Shapiro, & Hewett, 2008; Knapik, Buaman, Jones, Harris, & Vaughan, 1991; Myer, Ford, Barber Foss, Liu, Nick, & Hewett, 2009; Söderman, Alfredson, Pietilä, & Werner, 2001). Previous studies have found that female athletes have weaker hamstrings and different ratios of hamstring-quadriceps strength than male athletes (Colby et al., 2000; Lephart et al., 2002; Myer et al., 2009). As formerly noted, both neuromuscular and anthropometric factors have been suggested as sources for the increased ACL injury risk demonstrated by females. However, it is unclear if females land with less knee flexion and more knee valgus because of anthropometric traits or due to decreased hamstring-quadriceps strength ratios. Beutler et al. (2009) investigated muscle strength as a predictor of poor jump-landing technique in males and females. Results suggested that weaker hamstrings and gluteus medius strength were important predictors of poorer jump-landing in females (Beutler, de la Motte, Marshall, Padua, & Boden, 2009). Furthermore, Huston & Wojtys (1996) found that female athletes had weaker quadriceps and hamstring muscles than did male athletes when corrected for height. Anderson et al. (2001) found that the hamstring-to-quadriceps ratio was significantly lower for male athletes, indicating that the hamstring muscles in the female athletes were relatively weak when compared with the quadriceps muscles (Anderson, Dome, Guatam, Awh, & Rennirt, 2001). Reduced hamstring-to-quadriceps ratios at or below 50% to 60% may indicate a pathologic condition that predispose athletes to ACL injury (Davies, 1985; Dunnam, Hunter, Williams, & Dremsa, 1988). Female athletes tend to be quadriceps dominant in both strength and muscle firing patterns (Hewett et al., 1996; Huston & Wojtys, 1996).

Varying muscle activation in the lower extremities will influence the biomechanics associated with the required task. Hamstrings and quadriceps co-contraction may provide dynamic joint stabilization and potentially protect the knee during sports-related tasks (Li, Rudy, Sakane, Kanamori, Ma, & Woo, 1999; Ford et al., 2008; Renström, Arms, Stanwyck, Johnson, & Pope, 1986; Withrow, Huston, Wojtys, & Ashton-Miller, 2008). Previous studies have examined the purported differences between males and females in regards to muscular performance and earlier activation of the quadriceps (Huston & Wojtys, 1996; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Shultz et al., 2001), and have concluded that females may be quadriceps dominant (Hewett et al., 2010; Malinzak et al., 2001). Osternig and colleagues (1995) demonstrated an increased injury potential in association with a lack of hamstring-quadriceps co-contraction (Osternig, Caster, & James, 1995), which help to support and stabilize the knee joint (Pappas et al., 2007).

In the case of movement tasks, during landings females demonstrate greater quadriceps activity and lesser hamstring activity relative to males (Colby et al., 2000; Lephart et al., 2002; Malinzak et al., 2001). Ford and colleagues (2008) reported that female athletes used increased quadriceps activation without matched increases in hamstrings activation when they performed drop landings with increased drop height intensity (Ford et al., 2008). Immediately following ground contact during landing, the quadriceps are loaded eccentrically in an effort to dampen impact forces and counter the downward acceleration of the body (Blackburn & Padua, 2008; Hansen, Padua, Blackburn, Pretice, & Hirth, 2008). If the anterior tibial shear force generated by the quadriceps contraction is great enough, the hamstring muscles cannot provide adequate posterior tibial shear force to counter this force, and the ACL may be at risk for injury (DeMorat, Weinhold, Balckburn, Chudik, & Garrett, 2004; Griffin, Albohm, Arendt, Bahr, Beynnon, DeMaio … Yu, 2006). Therefore, the quadriceps cause significant anterior displacement of the tibia, resulting in gross ACL injury when strong quadriceps forces are simulated (DeMorat et al., 2004).

To the contrary, the hamstrings function as an ACL synergist by decreasing the anterior translation of the tibia and reducing interior tibial rotation during a simulated squat (More, Karras, Neiman, Fritschy, Woo, & Daniel, 1993). Hamstring activation also stabilizes the ACL-deficient knee, aids ligaments in maintaining joint stability, equalizes articular surface pressure distribution (Malinzak et al., 2001), and regulates the joints' mechanical impedance (Baratta, Solomonow, Zhou, Letson, Chuinard, & D'Ambrosia, 1988; Solomonow, Baratta, Zhou, Shoji, Bose, Beck … D'Ambrosia, 1987). Thus, the hamstrings and quadriceps are ACL synergists and antagonists, respectively (Ebben, Fauth, Petushek, Garceau, Hsu, Lutsch … Feldmann, 2010). Huston & Wojtys (1996) examined the muscular reactions that occurred after pushing the tibia forward with an experimental turnbuckle. In this study, the men activated their hamstrings first, while females first activated their quadriceps (Huston & Wojtys, 1996). Consequently, the delayed hamstring activation may inhibit the synergist mechanism by which prevention of anterior tibial translation occurs.

Therefore, women have been shown to activate the quadriceps more than men during functional movements (Chappell et al., 2002; Ladnry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007; Malinzak et al., 2001; Nagano, Ida, Akai, & Fukubayashi, 2007; Padua et al., 2005; Sigward & Powers, 2006; Zazulak et al., 2005) and have demonstrated lower hamstring to quadriceps activation ratios (Nagano et al., 2007; Padua et al., 2005). At present, the research regarding temporal activation characteristics and magnitude of hamstring and quadriceps activation during functional movements is largely comprised of college-aged subjects, more specifically, college-aged females. However, Medina et al. (2007) compared muscular pre-activation of lower extremity muscles (vastus medialis, rectus femoris, and medial/lateral hamstrings) in adolescent female basketball athletes, male basketball athletes, and female non-athletes in response to a drop landing. Subjects in the female non-athlete group recruited the rectus femoris significantly slower than both the female athlete and male athlete groups. The female non-athlete group also demonstrated a significantly slower recruitment of the vastus medialis compared to the female athlete group (Medina et al., 2007). No differences were found among the groups for medial or lateral hamstring activation. Furthermore, gender differences in activation patterns are not limited to jump-landing tasks. Sigward & Powers (2006) evaluated gender differences in knee joint kinematics, kinetics and muscle activation during side-step cutting. Results indicated that when compared to males, females exhibited greater quadriceps activation.

The work conducted by Medina and colleagues (2007) is important in that it is one of the only studies comparing hamstring and quadriceps activation patterns in adolescent females. These results indicated that all groups pre-activated the quadriceps first, thus supporting the concept of quadriceps dominance. Primary activation of the hamstrings is desirable because the hamstrings pull the tibia posteriorly and take stress off the ACL (Hewett et al., 2010). The quadriceps first muscular control strategy used by women, where the quadriceps pull forward adding to the anterior stress on the ACL, is exactly opposite of the preferred activation pattern typically used by males (Hewett et al., 2010). Additional research regarding quadriceps dominance is warranted due the limited scope of subjects' age and training status used previous studies.

Leg Dominance

There is a tendency among humans to preferentially use one side of the body in voluntary motor acts (Carpes, Mota, & Faria, 2010). This tendency characterizes the lateral preference (Carpes et al., 2010). Lateral preference is frequently observed among people who present the preferential use of a hand or foot associated to a motor skill (Serrien, Ivry, & Swinnen, 2006). Lateralization is thought to be established early in human development; accordingly, during the gestational period fetuses exhibit a preference for movements of one side of the body (Carpes et al., 2010). Additionally, other influences such as task complexity (Lissek, Hausmann, Knossalla, Peters, Nocolas, & Gunturnkun, 2007; Serrien et al., 2006), gender (Amunts, Jancke, Mohlberg, Steinmetz, & Zilles, 2000; Lissek et al., 2007), and developmental characteristics play an important role for the body side choice. As women tend to be more one-leg dominant than their male counterparts (Hewett et al., 2010), leg dominance is also discussed as a potential risk factor for ACL injuries (Brophy, Silvers, Gonzales, & Mandelbaum, 2010; Matava, Freehill, Grutzner, & Shannon, 2002; Negrete, Schick, & Cooper, 2007)

Leg dominance is an imbalance between muscular strength and recruitment patterns on opposite limbs, with one side often demonstrating greater dynamic control (Hewett et al., 1996; Knapik et al., 1991). Overreliance on one limb can put greater stress on that knee whereas the weaker side might not be able to effectively absorb the high forces associated with sporting activities (Ford et al., 2003). Several studies have assessed lower-limb dominance as it relates to athletic function and the risk of injury (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990; Harrison, Duenkal, Dunlop, & Russell, 1994; Herring, 1993; Stafford & Grana, 1984). Matava et al. (2002) investigated limb dominance as a possible etiological factor in noncontact ACL injuries and found no significant relationship between side of injury and dominant arm and leg. Additionally, researchers found no significant difference between males and females in the association between the injured knee and the dominant arm and leg (Matava et al., 2002). Five years later, Negrete et al. (2007) sought to reproduce the pilot study of Matava et al. (2002) with a larger number of subjects. Similar to Matava et al. (2002), Negrete and colleagues (2007) found no significant relationship between lower-limb dominance and the potential for ACL injury. However, unlike the work of Matava et al. (2002), Negrete et al. (2007) observed a strong trend for a female side-to-side distribution of ACL tears. It's important to note that 99% of female subjects in this study identified their right leg as dominant, as well as demonstrated a higher incidence of left lower-extremity injury (Negrete et al., 2007). These results are indicative of differences in neuromuscular control between dominant and non-dominant lower extremities.

When considering the imbalance of leg dominance, it should be acknowledged that most athletes have a preferred plant leg and a preferred kick or drive (in the case of a single leg jump task) leg (Hewett et al., 2010). However, the difference between limbs in muscle recruitment patterns, muscle strength, and muscle flexibility, tends to be greater in women than men (Ford et al., 2003; Hewett et al., 2006; Myer et al., 2010; Myer et al., 2010; Paterno et al., 2010). Ford, Myer, & Hewett (2003) observed that female athletes demonstrated significant differences between their dominant and non-dominant side in maximum knee valgus angle. These differences in limb-to-limb asymmetries (leg dominance) reflect neuromuscular deficits that may be indicative of decreased dynamic knee joint control in female athletes (Ford et al., 2003). In a study of forty physically active subjects who exercised at least three times per week for thirty minutes, there was a bilateral difference in hamstrings to quadriceps ratio (Kong & Burns, 2010). The dominant leg had a higher hamstring-to-quadriceps ratio. The difference in hamstrings: quadriceps ratio might also influence the occurrence of leg injuries in sports (Lanshammar & Ribom, 2011).

Moreover, when a female tears her ACL, most if not all of her weight is on a single leg (Hewett, Torg, & Boden, 2009). Brophy et al. (2010) conducted a retrospective observational study on subjects who had sustained an ACL injury due to direct participation in soccer (41 male, 52 female) (Brophy et al., 2010). While Brophy and colleagues (2010) found the ACL injured limbs were equally distributed between right and left limbs across both males and females, after stratifying the data for gender, an interesting theme emerged. Male athletes were significantly more likely to injure their preferred kicking leg while females were more likely to injure their preferred support leg (Brophy et al., 2010).

Similarly, Ruedl et al. (2012) sought to determine if leg dominance is a risk factor for a noncontact ACL injury in female recreational skiers. Researchers found that 68% of female skiers suffered from ACL ruptures of their left leg in comparison with 48% of male skiers (Ruedl, Webhofer, Helle, Strobl, Schranz, Fink … Burtscher, 2012). In accordance, Brophy et al. (2010) reported that 68% of female soccer players sustained noncontact ACL injury of their left knee, while only about 26% of male soccer players injured the left ACL. Moreover, Beynnon et al. (2006) reported that female skiers were 2.4 times more likely to injure an ACL and that ACL injuries occurred 35% more frequently in the left knee.

In double-leg landings, there is a tendency to touch feet down at different times, indicating that one leg may store more energy than the other (Ball & Scurr, 2009; Hay et al., 2006; Santello & Mcdonagh, 1998). Ball and Scurr (2009) compared the neuromuscular contribution between left and right triceps surae during a bilateral landing activity to assess the immediate implications of non-simultaneous foot placement. Significant differences between left and right triceps surae muscle activity were found before and directly after contact (Ball & Scurr, 2009). The importance of simultaneous foot placement in intense exercises is imperative to make sure that both limbs are getting equal stimulus (Ball & Scurr, 2009). The equal stimulus will serve to stiffen the joints to prevent collapse immediately after contact (Chelly & Dennis, 2001).

During a bilateral drop landing exercise, the implications of one foot contacting the ground ahead of the other may cause or contribute to a muscle imbalance, which will have negative long-term training effects (Hay et al., 2006). Preferential use of one leg over the other, or laterality, has been noted in the literature such as that seen by Ball, Stock, and Scurr (2010). Their subjects reported that when dropping off a box from 20 cm they found it difficult to bring the trailing foot into position to touch the ground at the same time as the leading foot. While these findings were that of a research study conducted in a controlled laboratory, it is commonplace to observe an athlete or individual display similar leg dominant mechanics during sport competition and everyday tasks. Therefore, exhibitions of leg dominance does affect the risk of noncontact ACL injury, however, the role of neuromuscular deficits and/or asymmetries have not been adequately identified.

Neuromuscular Training

Deficits in neuromuscular coordination and strength of stabilizing muscles around the knee have been shown to place an increased stress on the ACL and potentially predispose female athletes to injury (Griffin et al., 2000; Griffin et al., 2006). Neuromuscular training programs have been designed to modify risk factors and lower the incidence of ACL injuries (Ettinger, Johnson, & Shealy, 1995). Numerous studies of neuromuscular training programs have been conducted. Some support the hypothesis that ACL prevention programs reduce the incidence of injuries in female athletes, while others refute this claim (Stevenson, Beattie, Schwartz, & Busconi, 2015). For instance, Hewett et al. (2005) conducted the first known systematic review of the neuromuscular training programs and determined there is evidence that neuromuscular training alters muscle firing patterns as it decreases landing forces, improves balance, and reduces ACL injury incidence in female athletes. A more recent review conducted by Noyes & Barber-Westin (2012) looked at both injury reduction and athletic performance as outcomes of neuromuscular training programs. According to Noyes & Barber-Westin (2012), of 57 studies published from 1995 to 2011, only 5 published data regarding the effect of training on both criteria. Results of this systematic review determined that few published ACL intervention programs have both significantly reduced the incidence of ACL injury and improved aspects of athletic performance (Noyes & Barber-Westin, 2012). Additionally, Myklebust et al. (2003) found that the incidence of ACL injury in women's handball was reduced with training designed to improve neuromuscular knee control during cutting and landing (Myklebust et al., 2003).

Neuromuscular training that reproduces loads similar to those encountered during competitive sports may assist in the development of both feed-forward and reactive muscle activation strategies that protect the knee joint from excessive load (Dyhre-Poulsen, Simonsen, & Voigt, 1991; Winter & Brookes, 1991; Dietz, Noth, & Schmidtbleicher, 1981; Dunn et al., 1986; Greenwood & Hopkins, 1976; Thompson & McKinley, 1995). One form of neuromuscular training observed in the literature is plyometric training. Plyometrics consists of a rapid stretching of muscle (eccentric action) immediately followed by a concentric or shortening action of the same muscle and connective tissue (Baechle & Earle, 2000). This form of training is a very popular form of physical conditioning of healthy individuals and certain patient populations (e.g. osteoporotic patients) (Markovic & Mikulic, 2010). It involves performing bodyweight jumping-type exercises and throwing medicine balls using the stretch-shortening cycle (SSC) muscle action.

Plyometric training has been frequently used for improving human neuromuscular function in general (Fatouros et al., 2000; Häkkukinen, Komi, & Alén, 1985; Markovic et al., 2007), as well as a number of studies have shown that plyometric training could improve biomechanical technique and neuromuscular control during high-impact activities like cutting and landing (Chappell & Limpisvasti, 2008; Chimera et al., 2004; Hewett et al., 1996; Irmischer, Harris, Pfeiffer, DeBeliso, Adams, & Shea, 2004; Lephart et al., 2005; Myer et al., 2005).

Therefore, neuromuscular adaptations are believed to enhance dynamic knee stability and performance (Hewett, 2000). If neuromuscular training can increase neuromuscular control of the joint and decrease knee and ACL injury risk, it is likely the mechanisms underlying the increased risk are neuromuscular in nature (Hewett et al., 2005). Moreover, if lower limb neuromuscular control parameters linked directly to ACL injury could be identified, more effective screening regimens could therefore be implemented to identify those athletes who are at increased risk (Hewett et al., 2004). However, the specific adaptations responsible for the noted success of plyometric training are still theoretic (Chimera et al., 2004). The following discussion on plyometric training and neuromuscular adaptations will provide a thorough evaluation of the anticipated neuromuscular adaptations that take place due to plyometric prescription.

Plyometric Training and Neuromuscular Adaptations

Plyometric training is an established technique for enhancing athletic performance but may also facilitate beneficial adaptations in the sensorimotor system that enhance dynamic restraint mechanisms (Swanik, Swanik, Lephart, & Huxel, 2002; Swanik et al., 2002) and correct faulty jumping or cutting mechanics. Plyometric exercises subject the joint to rapid loads and can activate preparatory and feedback motor control loops by adaptation of the muscle stretch receptors (Wilk et al., 1993). Preparatory muscle activity involves feed-forward processing, in which the planning of movements is based on sensory input from previous experiences (Dunn, Gillig, Ponsor, Weil, & Williams, 1986). Reactive muscle activity involves the feedback process of motor control and the use of reflexive pathways to modify motor-unit recruitment (Swanik et al., 2002). Additionally, plyometric exercises have been credited with inducing neuromuscular adaptations to the stretch reflex, elasticity of muscle, and Golgi tendon organs (Chu, 1998; Wilk et al., 1993).

During most functional activities, the knee joint is subjected to high abduction and adduction moments, and, therefore, a theorized relationship exists between these moments and knee injuries (Buchanan & Lloyd, 1997; Kowalk, Duncan, & Vaughan, 1996; Lloyd & Buchanan, 1996; Schipplein & Andriacchi, 1991). Hewett et al. (1999) indicated that males who participated in a plyometric training program had a significant decrease in the number of serious knee injuries. Motion and force plate data after plyometric training revealed that trained female athletes had lower abduction and adduction moments at the knee and lower landing forces when compared with untrained males (Hewett, Stroupe, Nance, & Noyes, 1996). These results are believed to be evidence for increased dynamic restraint and functional knee stability (Chimera et al., 2004) as a result of plyometric training.

Plyometric exercises are defined as eccentric loading immediately followed by a concentric contraction (Anderson & Pandy, 1993; Bosco & Komi, 1979; Cavagna, Saibene, & Margaria, 1965; Wilk et al., 1993; Wilt, 1975). These exercises involve performing bodyweight jumping-type exercises and throwing medicine balls using the stretch-shortening cycle (SSC) muscle action. Two important aspects of this phenomena are (a) pre-activation and (b) variable activation of the muscles preceding the functional phase in a given movement (e.g. ground contact for the leg extensor muscles during running) (Komi, 2003). The SSC of muscle function comes from the observation that body segments are periodically subjected to impact or stretch forces (Komi, 2003). Running, walking, and hopping are typical examples in human locomotion of how external forces (e.g. gravity) lengthen the muscle (Komi, 2003). In this lengthening phase, the muscle is acting eccentrically, then a concentric (shortening) action follows (Komi, 2003). This combination of eccentric and concentric actions forms a natural type of muscle function referred to as the SSC (Norman & Komi, 1978; Komi, 1984; 2000). The true definition of the eccentric action indicates that the muscle must be active during stretch (Komi, 2000). Therefore, in preparation for landing from a jump, the SSC serves to pre-activate muscles in an eccentric (lengthened) state and stiffen the joint to prevent collapse upon impact. Pre-activation is muscle activation that occurs prior to ground impact when landing from a jump (Markovic & Mikulic, 2010).

Short-term plyometric training is said to improve the lower extremity strength, power and SSC function in healthy individuals (Markovic & Mikulic, 2010). These adaptive changes in neuromuscular function are likely the result of (a) an increased neural drive to the agonist muscles; (b) changes in the muscle activation strategies (i.e. improved neuromuscular coordination); (c) changes in the mechanical characteristics of the muscle-tendon complex of plantar flexors; (d) changes in muscle size and/or architecture; and (e) changes in single fiber mechanics (Markovic & Mikulic, 2010).

As discussed, plyometric training can induce changes in neuromuscular function by means of altered muscle activation strategies and improved neuromuscular coordination (Markovic & Mikulic, 2010). Hewett et al. (1996) conducted the first research study examining jumping and landing mechanics of the lower extremity both before and after a plyometric training program and to compare the results of untrained and trained female athletes with those of male athletes. Jump training consisted of two-hour sessions, three days a week (Monday, Wednesday, Friday) for six weeks. Three phases were implemented throughout the jump training program. Phase I, technique, focused on proper jumping technique. Phase II, fundamentals, concentrated on the use of proper technique to build a base of strength, power, and ability. Lastly, phase III, performance, focused on achieving maximal vertical jump height (Hewett et al., 1996). Results from this study demonstrated changes in the hamstrings-to-quadriceps muscle ratio that was significantly lower than the male subjects (51% versus 65%), prior to the jump training, up to an equivalent value (Hewett et al., 1996) following plyometric training. To note, it has been hypothesized that hamstrings-to-quadriceps muscle ratios lower than 60% can predispose an athlete to serious knee injury (Dunnam, Hunter, Williams, & Dremsa, 1988). Results of this study support the premise that plyometric training can change neuromuscular function attributable to altered muscle activation strategies.

Baratta et al. (1988) suggested that individuals with hypertrophied quadriceps muscles, such as high-performance athletes, have less co-activation of the hamstrings muscles because of an inhibitory effect on reciprocal antagonist muscles. Less hamstring-to- quadriceps co-activation can increase strain on the anterior cruciate ligament and predispose athletes to noncontact injuries (Cowling & Steel, 2001; Renström, Arms, Stanwyck, Johnson, & Pope, 1986). However, plyometric training may produce neuromuscular adaptations that encourage more symmetric hamstrings and quadriceps co-activation and balance joint loads for dynamic restraint (Solomonow et al., 1987) as supported by the findings of Hewett et al. (1996).

Markovic & Mikulic (2010) conducted a systematic review on neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. Within the review, much of the focus regarding neural adaptations in response to plyometric training is on that of pre-activation. One study, Chimera et al. (2004), examined the effects of plyometric training on muscle-activation strategies and performance in female athletes during jumping activities. Researchers reported earlier adductor pre-activation of greater magnitude in those subjects who underwent the plyometric training intervention in comparison with the control group. Moreover, researchers also noted more symmetric hamstrings to quadriceps muscle co-activation in the plyometric group. Furthermore, Kyrolainen and colleagues (1991) observed significant increases in the pre-activity of the leg extensors during a drop jump performance (Kyrolainen, Komi, & Kim, 1991) as a result of plyometric training. Years later, Kyrolainen et al. (2005) reported that plyometric training significantly increased both maximal voluntary contraction (MVC) and muscular activity of plantar flexors, but not of knee extensors. Lastly, Kubo et al. (2007) assessed the activation level of plantar flexors prior to and after plyometric training and reported a significant increase in both MVC (+17.3%) and activation level (+5.6%) of plantar flexor muscles (Kubo, Morimoto, Komuro, Yata, Tsunoda, Kanehisa … Fukunaga, 2007). Taken together, the reviewed studies generally suggest that plyometric training alone can increase MVC and voluntary activation of plantar flexors (Markovic & Mikulic, 2010).

As can be ascertained, there are commonalities within the literature regarding plyometric training prescription. It appears that many plyometric training interventions last approximately six weeks, and that training takes place at least two days a week. Respectively, the training volume and intensity is often determined based on the current fitness level and past training exposure of the participants. For instance, recalling Chimera et al. (2004), the sets, repetitions, and type of plyometric exercises replicated that of collegiate soccer and field hockey players. Hence, participants completed several vertical wall touches, split squat jumps, lateral cone jumps, and cone hops with a 180-degree turn (Chimera et al., 2004). This jump training utilized all three cardinal planes of movement, including both single and double-leg exercises. Alternatively, Hewett et al. (2009) prescribed a plyometric training program for high school volleyball players. Participants completed exercises such as vertical wall jumps, tuck jumps, broad jumps, and squat jumps.

This jump training utilized primarily two cardinal planes of movement (frontal, sagittal) and a markedly greater number of double-leg exercises to more precisely mimic those motions associated with playing volleyball.

The available evidence suggests that plyometric training, either alone or in combination with other typical training modalities such as weight training, elicits numerous positive changes in neural and musculoskeletal systems, muscle function, and athletic performance of healthy individuals (Markovic & Mikulic, 2010). Regarding neuromuscular adaptation to short-term plyometric training, the results generally show positive increases in lower-extremity strength, power, and SSC muscle function in healthy individuals (Markovic & Mikulic, 2010). The results of the review conducted by Markovic & Mikulic (2010) indicate that plyometric training has the potential to (a) enhance a wide range of athletic performance; and (b) reduce the incidence of lower-extremity injuries in female athletes. However, the available literature does not include an examination of the effects of plyometric training on neuromuscular activation patterns in post-pubescent adolescent females. More precisely, pre- and post-plyometric training intervention testing on post-pubescent adolescent females has not been assessed using electromyography for measuring changes in muscle activation patterns. It remains unknown how plyometric training effects neuromuscular activation patterns in post-pubescent adolescent females, and thus, increases performance and reduces the risk of injury.

Plyometric Prescription

Prescription of plyometric exercises is an integral component of reducing the risk of ACL injury. Consideration of age, fitness level, and current/past involvement in recreation is necessitated. Previous research conducted by Hewett et al. (1996) utilized a 6-week jump-training program partitioned into three distinct phases. Phase I, technique, included the initial two weeks when proper jump technique was demonstrated and drilled (Hewett et al., 1996). Four basic techniques were stressed: 1) Correct posture (i.e. spine erect, shoulders back) and body alignment (e.g., chest over knees) throughout the jump; 2) Jumping straight with no excessive side-to-side or forward-backward movement; 3) Soft-landings including toe-to-heal rocking and bent knees; and 4) instant recoil preparation for next jump (Hewett et al., 1996). Specific phrases were used by the investigators including, “on your toes,” “straight as an arrow,” “light as a feather,” “shock absorber,” and “recoil like a spring” (Hewett et al., 1996). Phase II, fundamentals, concentrated on the use of proper technique to build a base of strength, power, and ability (Hewett et al., 1996). Phase III, performance, focused on height achieved in each jump and the quality of each jump (Hewett et al., 1996).

The jump-training program employed by Hewett et al. (1996) was developed based on a review of literature and the authors’ athletic training experience (Bobbert, 1990; Dunnam et al., 1988; Marsit & Kraemer, 1992; McGown, Conlee, Sucec, Buono, Tamayo, Phillips … Beal, 1990; Pestolesi, 1989). While this jump-training program was designed for high school volleyball players, its structural foundation (i.e., exercises and volume) can be altered to suit various population groups while still maintaining the premise on which it was built. For instance, while the use of tuck jumps may be appropriate for high school volleyball players, the level of intensity necessary for this type of jump may be less appropriate for non-athletes. However, the technique, fundamentals, and performance phases of this jump-training program elicited significant changes in hamstring muscle strength and power in both the dominant and non-dominant legs (Hewett et al., 1996). Additionally, the increase in hamstring muscle peak torque and power observed in the subjects after training was considerable for a 6-week training period (Hewett et al., 1996). The female participants in this study also demonstrated a marked imbalance between hamstring and quadriceps muscle strength before training, however, this imbalance was corrected following the training program.

It should be documented that the study conducted by Hewett et al. (1996) also employed the use of strength training concurrently with plyometric training. Hence, the observed results could be a product of both of these programs. Conversely, the weight training exercises did not include any modality specifically for hamstring development other than the leg press. Moreover, the stretching regimen prior to strength training included only one stretch for the hamstrings. Consequently, it could be argued that the exercises employed within the plyometric training program had a more profound effect on hamstring activation, and, therefore, the observed changes.

From a physiological and psychological standpoint, four to six weeks of high intensity power training is an optimal length of time for the central nervous system to be stressed without excessive strain or fatigue (Adams, O’Shea, O’Shea, & Climstein, 1992). In a study conducted by Miller et al. (2006), plyometrics were only performed twice per week to allow for sufficient recovery between workouts as recommended by researchers (Miller, Herniman, Ricard, Cheatham, & Michael, 2006). This is contrary to Hewett et al. (1996) whose plyometric training program included sessions lasting one hour per day, three days a week. Training prescription amongst these studies varies due to the current fitness level of each of these population groups. For instance, Miller et al. (2006) included participants 18 years of age and above, who were not involved in any type of plyometric training at the time, while Hewett et al. (1996) included that of high school volleyball players. Thus, the training volume and intensity selected by Hewett and colleagues (1996) was more appropriate given the population group.

In addition, Miller et al. (2006) included a training volume that ranged from 90 to 140 foot contacts per session, and an intensity of exercises that increased for five weeks before tapering off during week six as recommended by Piper & Erdmann (1998) and used previously in another study conducted by Miller et al. (2002). The intensity of the training was tapered so that fatigue would not be a factor during post-testing (Miller et al., 2006). Moreover, the plyometric training group trained at the same time of the day and were under direct supervision and instructed on how to perform each exercise (Miller et al., 2006).

Prescription of plyometric training is a vital component in any study imploring its use in reducing the risk of ACL injury. Previous research studies have varied in the prescription based on age, current fitness level, and sport specificity of the population group. Careful consideration of this prescription should be of prodigious concern as it can alter neuromuscular function and reduce the risk of ACL injury if applied appropriately.

Gender and Adolescence

Biomechanical and neuromuscular risk factors may be critical components of the mechanisms which underlie the higher rate of ACL injuries in female compared to male athletes (Ford et al., 2010). Specifically, the onset of neuromuscular risk factors may coincide with rapid adolescent growth that results in the divergence of a multitude of biomechanical and neuromuscular parameters between sexes (Ford et al., 2010).

Musculoskeletal growth during puberty, in the absence of corresponding neuromuscular adaptation, may facilitate the development of certain intrinsic risk factors (Hewett, Myer, & Ford, 2004). These intrinsic risk factors, if not addressed at the proper time period, may continue through adolescence into maturity and predispose athletes to ACL injuries (Ford et al., 2010).

ACL sprains are rarer in prepubescent children than in adolescents and ruptures do not present at significantly different rates in males and females before adolescence (Andrish, 2001; Buehler-Yund, 1999; Clanton, DeLee, Sanders, & Neidre, 1979). After the onset of adolescence, which parallels the rise in sex disparity in ACL injury incidence, both females and males experience rapid musculoskeletal growth (Malina & Bouchard, 1991). During this adolescent growth spurt, the long bones of the lower extremity, the tibia and femur, grow at a rapid rate in both males and females (Tanner & Davies, 1985). This growth of the femur leads to longer lever arms at the two longest bony levers in the human body, which translates into greater potential for increased torques on individual's knee joint (Hewett, Myer, Kiefer, & Ford, 2015). While males exhibit increases in power and strength with chronological age that correlate to maturational stage after the onset of adolescence, females show little change in the neuromuscular parameters throughout adolescence (Kellis, Tsitskaris, Nikopoulou, & Moiusikou, 1999; Malina & Bouchard, 1991). Consequently, the ACL injury incidence is two to eight-fold higher in adolescent female athletes compared to males (Agel, Arendt, & Bershadsky, 2005). Cumulatively, these studies indicate a potential association between changes that occur during the onset of puberty and increased ACL injury risk in female athletes (Quatman, Ford, Myer, Paterno, & Hewett, 2008).

Hewett et al. (2005) conducted a prospective controlled cohort study, including female adolescent soccer, basketball, and volleyball players who were prospectively measured for neuromuscular control using 3-dimensional kinematics (joint angles) and joint loads using kinetics (joint moments) during a jump-landing task. During season, nine athletes had a confirmed ACL rupture. Hewett et al. (2005) reported that the nine injured athletes had significantly different knee posture and loading compared to the 196 athletes who did not have ACL ruptures. Specifically, knee abduction angle at landing was eight degrees greater in the ACL-injured than in uninjured athletes (Hewett et al., 2005). Moreover, ACL-injured athletes had a 2.5 times greater knee abduction moment, and twenty percent higher ground reaction forces. Findings from this study suggest that increased valgus motion and valgus moments at the knee joint during the impact phase of jump-landing tasks are key predictors of an increased potential for ACL injury in adolescent females (Hewett et al., 2005).

The observed increase in knee abduction motion and moments in females before ACL injury suggest decreased neuromuscular control of the lower extremity in the frontal plane (Hewett et al., 2005). However, muscular contraction can decrease the dynamic valgus laxity of the knee 3-fold (Markolf, Graff-Redford, & Amstutz, 1978). Joint compression through muscular co-contraction allows the knee adduction load to be absorbed by articular contact forces, which can protect the ligaments from high loads (Hewett et al., 2005). More specifically, coactivation of the hamstrings and quadriceps is proposed to protect the knee joint not only against excessive anterior translation but also against excessive knee abduction and dynamic lower extremity valgus (Besier, Lloyed, & Ackland, 2003).

In subsequent work, Qautman et al. (2008) studied the effects of gender and pubertal status on generalized joint laxity in young athletes. Pre-pubertal male and female athletes were not different in cumulative joint laxity scores; however, following the onset of puberty, females demonstrated a greater joint laxity score compared to males (Quatman et al., 2008). While the findings of this study support the hypothesis that generalized joint laxity increases in female, but not male, athletes during puberty, it did not include assessment of any possible associated neuromuscular deficits.

Nonetheless, as a result of maturation, neuromuscular patterns in males and females diverge substantially (Hewett, Myer, & Ford, 2004). Males demonstrate increases in power, strength, and coordination that correlate with their maturational age, whereas, on the average, girls show little change throughout maturation (Kellis et al., 1999; Beunen & Melina, 1988). Hewett and colleagues (1996) tracked the occurrence of ACL injuries in males and females through their soccer, volleyball, and basketball seasons. Untrained girls had significantly higher rates of ACL injury than did trained girls and boys, whereas the rates in trained girls were not different from those in untrained boys (Hewett et al., 1996). In a three-year study of 24,485 male and 18,289 female high school athletes, the incidence of season-ending knee injuries in female athletes was 4.6 times that of male athletes (Chandy & Grana, 1985). Chandy and Grana (1985) reported that significantly more female than male high school athletes had knee injuries that required surgery, and they suggested that "emphasis be placed on functional evaluation and conditioning of the hamstrings and quadriceps muscles to prevent these injuries." Hewett et al. (1996) demonstrated that neuromuscular training has the potential to decrease rates of ACL injury in adolescent female athletes, and that intensive neuromuscular training may induce a so-called neuromuscular spurt that would otherwise be absent in adolescent girls (Hewett et al., 1996; Kraemer, Mazzetti, Nindl, Gotshalk, Volek, Bush … Hakkinen, 2001; Tropp & Odenrick, 1988). Similarly, Haycock and Gillette (1976) attributed differences in injury rates amongst males and females to differing levels of training and coaching and not to anatomic or physiologic differences.

Hewett, Myer, & Ford (2004) studied the effects of growth and development on the mechanism of decreased neuromuscular control of the knee in 181 (100 girls, 81 boys) middle-school and high-school soccer and basketball players. Following the onset of maturation, the female athletes landed with greater total medial motion of the knees and a greater maximum lower-extremity valgus angle than did male athletes (Hewett et al., 2004). The female athletes also demonstrated decreased flexor torques compared with the boys, as well as a significant difference between the maximum valgus angles of their dominant and non-dominant lower extremities after maturation (Hewett et al., 2004). In summary, the observed changes in neuromuscular measures across maturational boundaries were very different between the boys and girls. Girls demonstrated decreased neuromuscular control of the knee from early to late puberty, whereas the boys demonstrated better neuromuscular control of the knee in late puberty than in early puberty (Hewett et al., 2004).

Hewett et al. (1996) aimed to test the effect of a jump training program on the mechanics of landing in female athletes involved in jumping sports. Female subjects participating in this study demonstrated a marked imbalance between hamstring and quadriceps co-activation before training. The training program corrected the imbalance and brought the hamstring and quadriceps co-activation to the level of the male participants. While this study offers valuable insight into possible neuromuscular adaptations specific to females following plyometric training, the average age of participants was 15 ± 0.6 years. Maturation status of these adolescent females was not controlled for, and, thus, results of this study may not be truly representative of neuromuscular adaptations that may be seen in post-pubescent adolescent females. Comparably, Baratta et al. (1988) noted the increased risk of ligamentous damage in athletes with reduced hamstring to quadriceps muscle co-activation patterns. Researchers observed an increase in co-activation of the hamstring muscles in athletes with hamstring to quadriceps muscle imbalances after hamstring muscle training exercises (Baratta et al., 1988). Similar to the work of Hewett et al. (1996), this study did not examine the possible impact of maturation status on the resulting neuromuscular adaptations seen.

The observed changes in neuromuscular measures across maturational boundaries are very different between boys and girls (Hewett et al., 2004). Hewett et al. (2004) observed decreased neuromuscular control of the knee from early to late puberty in girls, whereas boys demonstrated better neuromuscular control of the knee in late puberty than they had in early puberty. While this study advanced the knowledge of the neuromuscular changes that occur throughout puberty in boys and girls, it did not include definitive measurements of muscle activation patterns with use of EMG. Hence, neuromuscular adaptations were quantified using three-dimensional motion analysis, ground reaction force plates, and isokinetic dynamometer strength measures; however, these instruments do not specifically record muscle activation patterns that are in fact representative of neuromuscular changes. Therefore, the neuromuscular adaptations that may be seen in post-pubescent adolescent females following a plyometric training intervention have not been clearly defined.

Tanner Staging

Adolescents experience several types of maturation, including cognitive, psychosocial, and biologic (Child Growth Foundation, 2012). The complex series of biologic transitions are known as puberty. The most visible changes during puberty are growth in stature and development of secondary sexual characteristics (Child Growth Foundation, 2012). Conceptually, pubertal maturation can be described in terms of sequence, timing, and tempo. Puberty consists of a series of predictable events, and the sequence of changes in secondary sexual characteristics has been categorized by several groups (Child Growth Foundation, 2012). The staging system used most frequently is that published by Marshall & Tanner (1970) and the sequence of changes is commonly referred to as “Tanner Stages”.

Summary

It is often assumed that bilateral movements such as landings are performed symmetrically (Arsenault et al., 1986). Researchers even make this assumption when investigating variables on only one side of the body during a bilateral task (Arsenault et al., 1986). However, studies (Schot et al., 1994) which have instrumented both lower extremities during bilateral tasks have shown that asymmetries often occur. Both kinetic (Schot et al., 1994) and kinematic (Kernozek et al., 2005; Kernozek et al., 2008) differences between limbs have been observed during bilateral landings. For example, Kernozek et al. (2005) researched sex differences in lower-extremity joint kinematics and kinetics between age and skill-matched recreational athletes. Disparities were seen between sex differences as women demonstrated different knee movement profiles. Some authors have suggested that asymmetrical loading during bilateral landing, jumping, and strengthening activities may impart unequal stimuli to the neuromuscular and skeletal systems over time (Fugal-Meyer et al., 1982), thus exacerbating the condition of asymmetry.

Several sources of asymmetry in the kinematics and kinetics of landing tasks have been suggested in the literature. Some of these suggestions include muscle imbalance (Hay et al., 2006; Knapik et al., 1991; Shenoy et al., 2010), greater energy storage in one limb (Brewer, 2005), or preferential use of muscles on one side, or dominance (Fugal-Meyer et al., 1982). Any of these neuromuscular asymmetries can cause concomitant alterations in force distribution amongst the joints, which has significant implications on the body's ability to dissipate these forces (Kovacs et al., 1997). Upon reviewing the literature, it appears that females tend to rely more on their dominant than non-dominant limb, placing both extremities at an increased risk for ACL injury.

Plyometric exercises work through use of the stretch shortening cycle and the elastic components within muscles by training the neuromuscular apparatus to resist force (Lundin, 1985). The neuromuscular system prepares for the impending load by activating muscles before contact (McKinley & Pedotti, 1992). Sex differences in landing mechanics have been noted, but the origin of these differences remains uncertain. Injuries associated with landing have been linked to unfavorable landing techniques, inadequate or uncoordinated muscle activation, and the relative state of fatigue of the neuromuscular system, among others. Bilateral landings are often assumed to be symmetrical in practice and even in applied research settings; however, several studies have called this assumption into question. Moreover, provided literature indicates that while females tend to rely more on their dominant leg, they also tend to activate the quadriceps musculature prior to with much greater magnitude than that of the hamstrings, resulting in an increased risk for ACL injury.

While there appears to be an abundance of information in terms of neuromuscular deficits using EMG in the adult population, the literature is scarce with regards to the adolescent population, specifically post-pubescent adolescent females and how these factors influence ACL injury risk. Hewett et al. (2005) noted that there appears to be three major etiologic contributions to the gender disparity observed in ACL injury rates, namely, anatomical, hormonal, and neuromuscular (Hewett, 2000). A number of studies of ACL injury risk factors have focused on anthropometric/anatomical measures, such as thigh length (Beynnon et al., 2001), height, and femoral notch width (Scoville et al., 2001). Although these factors may contribute to ACL injury risk, they are in essence non-modifiable by nature (Hewett et al., 2005). Hormonal contributions have been studied and also linked with ACL injury risk (Arendt et al., 2002; Slauterbeck & Hardy, 2001; Wojtys et al., 2002), however, the precise means by which they may contribute to ACL injury risk, and, again, the extent to which these contributions can be modified remain unclear. There is increasing evidence in the literature suggesting that poor or abnormal neuromuscular control of the lower limb biomechanics, and in particular, the knee joint, during the execution of potential hazardous sporting movements, is a primary contributor to the female ACL injury mechanism (Hewett, 2000; Hewett et al., 2002; Lloyd, 2001; McLean et al., 2004). It is widely accepted in the literature that the ACL may experience potentially hazardous 3-dimensional forces during landing and twisting sports movements if the musculature that controls the knee does not sufficiently dissipate the associated torques and forces (Hewett et al., 2005). However, the majority of the research available regarding dynamic joint stabilization, utilized ground reaction force plates and 3-dimensional motion capture systems, and did not include EMG assessments.

Understanding the way neuromuscular control factors may manifest in terms of ACL injury is crucial, as it offers the greatest potential for interventional development and application in high-injury risk populations such as female athletes (Griffin et al., 2000). While measures of ground reaction forces and joint torques provide immeasurable insights in biomechanical assessments of lower extremity kinematics and force attenuation, it seems necessary to include measures of EMG of relevant musculature aiding in dynamic joint stabilization. Currently, there is a lack of evidence available pronouncing the muscle activation patterns of the quadriceps and hamstrings in post-pubescent adolescent females. Moreover, there have only been a handful of research studies that examined the effects of a plyometric training intervention on patterns of muscle activation and reducing ACL injury risk in the adolescent female population, and these studies did not include measures of EMG. EMG assessment could provide valuable information with regards to neuromuscular deficits, specifically abnormal or asymmetrical muscle activation patterns that may be placing this population group at an increased risk for ACL injury. Furthermore, knowledge of these deficits would assist greatly in the prescription of neuromuscular training programs in an effort to reduce the risk of ACL injury.

Neuromuscular training (e.g. plyometric training) has the potential to decrease ACL injury rates in female athletes. However, the efficacy and efficiency of neuromuscular training protocols could be improved considerably if they were designed specifically for pre-determined high-risk athletes (Hewett et al., 2005). Dynamic neuromuscular control parameters are rarely measured in athletes before participation, with measurements typically limited to static measures of joint stability (Smith & Laskowski, 1998). If lower limb neuromuscular control parameters linked directly to ACL injury could be identified, more effective screening regimens could therefore be implemented to identify those athletes who are at increased risk (Hewett et al., 2005).

Conclusion

It is widely accepted that female athletes are at a greater risk for ACL injuries compared to their male counterparts. There is an abundance of evidence suggesting that the kinematics and kinetics many female athletes exhibit while landing are factors contributing to higher risks of ACL injury. Some of these factors include landing more erect, landing with valgus knee motion, leg dominance, and quadriceps dominance. Currently, there is a lack of literature concerning the temporal activation characteristics of the quadriceps and hamstrings in post-pubescent adolescent females. Moreover, there is little knowledge in regards to how a plyometric training intervention may impact these activation patterns and reduce the risk of ACL injury.

It is necessary to conduct research on post-pubescent adolescent female athletes using EMG assessment in order to better understand muscle activation patterns seen in this population group. Identifying asymmetrical or abnormal activation patterns commonly seen in this group could contribute to the development of prescreening methods and neuromuscular training programs designed to reduce the risk of ACL injury.

Chapter III: Methods

The purpose of this study was to investigate the symmetry of muscle activation onset, duration, and time to peak, and how a plyometric training intervention may impact symmetry during a bilateral jump-landing task. A within-subjects, repeated-measures model design was utilized, with the dependent variables being evaluated before and after the experimental intervention (plyometric training) between muscles. The dependent variables were muscle activation onset, duration, and time to peak activation for four lower-extremity muscles for each of the right and left legs, both prior to and following a 6-week plyometric training intervention. Three 2x2x4 repeated measures ANOVAs were used to evaluate the effect of the following independent variables: time (pre- and post-plyometric training intervention), leg (right and left), and muscle (vastus lateralis, vastus medialis, biceps femoris, and semitendinosus).

The following chapter will present the tools and procedures used to assess muscle activation onset. Methods for conducting the jump-landing tests, prescribing the plyometric training, and analyzing the muscle activation onset, duration, and time to peak activation will also be presented. Finally, the statistical analyses employed will be described.

Subject Selection

Subject recruitment was achieved through verbal and written invitations to participate, presented by the investigator and physical educator, Sal Lopez, to post-pubescent adolescent females in Asotin School District (Asotin, WA). Exclusion criteria included (a) history of significant injury to the lower extremity, including dislocation, ligament sprains, or fractures; (b) current illness or other complexity that could compromise performance in the given task(s) (see Appendix A for specific questionnaire items addressing these exclusion criteria); and (c) having not met Tanner Staging (see Appendix C) classification of post-pubescent.

The target sample size for this investigation was 21 subjects. This value was based on similar studies that investigated effects of plyometric training on quadriceps-to-hamstring co-activation (Chimera et al., 2004; Hewett et al., 1996), as well as co-activation measures during or following plyometric tasks (Bennett et al., 2008; Medina et al., 2007). These studies employed sample sizes ranging from 11 subjects (female high school volleyball players) (Hewett et al., 1996) to 38 subjects (18 high school female athletes, 20 high school female non-athletes (Medina et al., 2007). Additionally, a power analysis using data from a pilot study conducted recently by the primary investigator, Jessica Savage, who tested for differences in duration of activation and time to peak activation of the quadriceps and hamstrings following a plyometric training intervention, was used to provide greater confidence in the sample size selected. The effect sizes (Cohen's *d*) calculated from the reported means and standard deviations from the pilot study were 0.20 (dominant quadriceps: vastus lateralis, vastus medialis), 0.37 (non-dominant quadriceps: vastus lateralis, vastus medialis), 0.01 (dominant hamstrings: biceps femoris, semitendinosus), and 0.09 (non-dominant hamstrings: biceps femoris, semitendinosus). Using an effect size of 0.35 and a 2x2x3 design, a sample size of 10 per group, 20 total participants, was calculated and provided a power value of 0.96 (G*Power™).

Instrumentation

A standard tool used to assess muscle activation is electromyography (EMG). Onset of muscle activation, as well as duration, magnitude, and frequency characteristics can be determined during human movement using EMG. Due to the dynamic nature of the landing task and the acknowledged discomfort associated with the use of intramuscular EMG, surface EMG was utilized to assess muscle activation. Certainly, intramuscular electrodes record from a more localized area of the muscle yielding a higher degree of specificity. However, it may be criticized on the basis that the small sample area is not representative of the whole muscle (Soderberg & Cook, 1984), while surface electrodes are used to assess overall gross function of muscles. Additionally, surface EMG can be applied in a standardized manner with virtually no subject discomfort (Soderberg & Cook, 1984).

Muscle activation was measured using a Noraxon™ MyoResearch (Noraxon USA, Inc., Scottsdale, AZ), eight-channel EMG using rectangular (4 cm x 2.2 cm) bipolar surface electrodes and further analyzed with MyoResearch software (Noraxon USA, Inc., Scottsdale, AZ). The amplifier served to isolate the signal source and the recording instrumentation, voltage conversion, noise reduction, and reproduction of the bioelectrical event (Soderberg & Cook, 1984).

Accelerometer

In the 1950s accelerometers became a viable option for capturing dynamic movement (Gage, 1964; Saunders, Inman, & Eberhart, 1953). Improvements to accelerometers, especially the evolution of the tri-axial accelerometer, have led to the development of a portable device that is able to collect the same data as foot switches, kinematic sensors, and force plates (Morgan, 2009). Two Noraxon™ 400G, DTS tri-axial accelerometers were used to identify the landing event for each leg during the jumping task. Data were sampled at 100 Hz. Identifying when pre-activation occurs, and thus activation onset, duration, and time to peak activation, can only be accurately determined when knowing when the landing event occurs. An accelerometer was placed on the tibia of both the right and left legs, approximately one-half the distance from the medial condyle to the medial malleolus. The "Y" axis of the accelerometer was placed pointing proximally, and only the "Y" axis data was used for identification of the landing event. A large spike in the "Y" axis data is indicative of the landing event.

Tanner Staging

In order to accurately identify post-pubescent adolescent females, participants completed a self-assessment employing a frequently used staging system referred to as "Tanner Stages", developed by Tanner (1965). Tanner stage can be determined by self-assessment, which has been shown to be valid and reliable (Tanner, Whitehouse, Marshall, & Carter, 1975). Participants were provided with an illustrative questionnaire depicting stages I-V of the Tanner Stages and were asked to select the stage in which best describes their pubertal development. All participants were asked to respond in accordance with their pubertal development of breast and pubic hair.

Videography

A digital camera was used to determine the actual drop height from which the participant landed. All trials were recorded for each participant, the apex from which the participant was in free fall from was identified, and the distance from the apex to the landing surface was measured. Assessment of the actual drop height allowed for accountability, discovery of possible trends, and determination of whether or not independent trials needed to be normalized to drop height. Video was recorded using a Cannon Vixia HF R800 digital camera at 1/2000 per second and a frame rate of 60P.

Exercise Intervention

For the purposes of this research study, the foundational structure of the plyometric training program crafted by Hewett et al. (2009) was adapted to suit the Asotin School District post-pubescent adolescent females. Three phases were implemented throughout the plyometric training program. First, the technique phase, focusing on correct posture and body alignment, jumping completely vertically, and landing softly, comprised the initial two weeks (Hewett et al., 2009). The second phase, the fundamentals phase, concentrated on the use of proper technique to build a base of strength, power, and ability (Hewett et al., 2009). Finally, the third phase, the performance phase, focused on achieving maximum vertical height (Hewett et al., 2009) supported by a soft landing including body alignment.

In order to prevent the risk of injury, all participants completed a 3 – 5-minute dynamic warm-up each session including running, skipping, high-knees, butt kicks, ankle hops, and body weight squats. Participants were encouraged to complete all phases of the plyometric training program with great effort, as well as instructed to stop if unable to complete each jump using the proper technique (Hewett et al., 2009). Proper technique was assessed by the primary investigator, Jessica Savage. Jessica Savage has been a Certified Strength & Conditioning Specialist through the National Strength & Conditioning

Association for the past 5 years. Additionally, she holds a Master degree in Exercise Science with an emphasis in Biomechanics and has taught courses such as Biomechanics and Strength Development at the college level for the past 5 years.

It was foreseeable that one or more participants would want to withdraw from this study, perhaps due to lack of interest, muscle soreness, or personal reasons. In order to reduce attrition rates, the primary investigator provided both the participant and her parent or legal guardian with a letter indicating the importance of completing the plyometric training intervention in its entirety in order to reduce the risk of ACL injury. Moreover, given that the participants completed the plyometric training tasks while in their regularly scheduled physical education course, the sessions occurred at the beginning of class and function as a warm-up for the remainder of class time. It was anticipated that the majority of the class would partake in the jump training, even if some have not signed and returned consent forms agreeing to participate in this study.

Procedures

All participants and participant's parent or legal guardian signed and returned a consent form describing the procedures of the study, as well as the risks associated with participation. Sal Lopez, Shari Lyons, and Beth McKarcher, physical educators at Asotin School District, and the primary investigator, Jessica Savage, distributed all consent forms. In addition, the parent or legal guardian was provided a letter (see Appendix D) describing the purpose and significance of the study. Testing occurred over three-day period, with no more than 48 hours between the first and second session, and no more than seven weeks between the second and third sessions. On the first day of participation, demographic measurements, such as height and weight were collected. Also, information such as the participant's age and responses to a required informational questionnaire (see Appendix A) were acquired. Each participant's weight was retrieved using a digital scale (Tanita Scales™, Arlington Heights, IL). Height was determined using a stadiometer (Harpenden, Hotain Ltd, UK). Participants were then familiarized with the double-leg jump-landing task to be utilized in the second day of testing. A demonstration of the jump-landing task and maximal vertical jump using the Vertec was provided by the lead investigator. Being familiarized with the tasks assisted in eliminating any learning effects during data collection. Participants performed jump-landing tasks from a plyometric box (Jfit Co., Vancouver, WA) 63 cm in height and landed at a distance equal to 50% of the participant's recorded height (Bennett et al., 2008). Participants were allowed to practice the jump-landing task, as well as the maximal vertical jump using the Vertec 5 – 7 times. In a pilot study conducted by Decker et al (2003), it was determined 5 – 7 practice trials were needed to sufficiently capture the true landing performance without fatigue or systematic performance variability. In addition, in a pilot study conducted by the primary investigator, it was determined that a maximum of five trials of the jump-landing task was needed in order to familiarize the participants. The familiarization day took place at Asotin School District gymnasium.

On both testing days (pre- and post-plyometric training intervention), participants arrived at the Movement and Sport Sciences Lab (Activity Center West 129) at Lewis-Clark State College wearing shorts or spandex and athletic shoes. The use of both bare-feet (Smith et al., 2009) and tennis shoes (Chappell et al., 2005) have been recorded in the literature, however, since all participants were completing the 6-week plyometric training intervention wearing tennis shoes, it was appropriate that participants would also complete all testing procedures in the same manner. In addition, in order to establish consistency and reliability in testing, participants were asked to wear the same shoes in which they selected to wear for pre- jump-training intervention testing. A five-minute warm-up on a Monark™ cycle ergometer (Ebben et al., 2008; Smith et al., 2009) at a comfortable pace and resistance (.5 – 1 kp) to raise core temperature was then completed. Following the five-minute warm-up, participants completed 3-max vertical jumps using a Vertec (Sports Imports, Columbus, OH, USA). Participants' reaching height was recorded with both arms upright, while standing flat-footed on the ground. The use of a Vertec for measuring maximal vertical jump height has been found to be highly correlated (*r* = 0.906) with a 3-camera motion capture analysis system (Leard, Cirillo, Katsenelson, Kimiatek, Miller, Trebincevic, & Barbalosa, 2007).

After completion of the max vertical jumps, preparation for the EMG electrodes ensued. The electrodes require a smooth, clean surface for valid measurement, and, therefore, participants were asked to shave the specified anatomical locations. As such, disposable razors and shaving cream were provided by the investigator for subjects if needed. The skin over the muscle bellies of the right and left vastus lateralis, vastus medialis, biceps femoris, and semitendinosus then underwent a light debridement with fine sand paper to rid the surface of dead skin cells and were cleaned with alcohol wipes. Additionally, EMG sensors were placed approximately 1.27 – 2.54 cm from the electrodes at each anatomical location. The anatomical locations identified for EMG placement include the right (R) and left (L) vastus lateralis (VL) (located 25% of the distance from the lateral line of the knee joint to the anterior superior iliac spine (ASIS); R/L vastus medialis (VM) (located 20% of the distance from the medial joint line to the ASIS); R/L biceps femoris

(BF) (located 50% of the distance between the ischial tuberosity and the fibular insertion site); and R/L semitendinosus (SEM) (located 50% of the distance between the ischial tuberosity and the tibial insertion point) (Ebben et al., 2010). The sensors relay information to the Noraxon™ Desktop DTS regarding muscle recruitment and activation patterns and were adhered using double-sided tape. As such, it was important that all anatomical locations were properly prepared and dry so as to not interfere with adherence of the electrodes or sensors.

Following placement of EMG electrodes on both the pre- and post-intervention testing days, participants were asked to complete a Maximal Voluntary Isometric Contraction (MVIC). One major drawback of any EMG analysis is that the amplitude (microvolt scaled) data are strongly influenced by the given detection condition: it can vary greatly between electrode sites, participants, and even day-to-day measures of the same muscle (Noraxon ™, Scottsdale, AZ). One solution to overcome this "uncertain" character of microvolt scaled parameters is the normalization to a reference value, referred to as MVIC (Noraxon™, Scottsdale, AZ). The MVIC of the VL and VM were recorded with the participant seated, with the knee and hip flexed at 90° (Rouffet, & Hautier, 2008). The MVIC for the BF and SEM were recorded with the participant seated, with the knee and hip flexed at 90° (Prukayastha, Cramer, Trowbridge, Fincher, & Marek, 2006; Rouffet & Hautier, 2008). For each MVIC, participants were instructed to slowly start increasing force, reach maximum effort after 3 – 5 seconds, hold it for 3 seconds and promptly relax (Noraxon™, Scottsdale, AZ). Resistance was provided manually by the investigator. The maximum recorded MVIC for each muscle across three trials was used. Data were collected for a 5-second window for each MVIC trial.

Next, two Noraxon™ 400G accelerometers were placed on the right and left tibias, approximately one-half of the distance from the medial condyle to the medial malleolus. As previously described, the participants then completed three jump-landing tasks from a plyometric box (j/fit Equipment™, Vancouver, WA) 63 cm in height. All participants were asked to place their hands on their hips, jump off the box following the command, "3, 2, 1, jump," and land with both feet at a distance 50% of recorded standing height. EMG recording began at the command of "1" and ceased after the participant landed. Participants were instructed to "jump and land as they normally would." There was not a specified rest time in place between jumps due their low-intensity nature. Therefore, after the completion of the jump-landing task, the participant simply stepped back onto the box and proceeded with another jump-landing until a total of three trials were completed. A "zeroing" method within the Muscle MyoResearch™ software was used to reduce artifact from the previous jumping task. The "zeroing" method is used to establish a baseline, whereby muscle activation onset is visually inspected by investigators. Visual inspection of the raw surface EMG trace remains a popular method, even though errors with this method and disagreement between experienced raters are known limitations (Hodges & Bui, 1996). After the completion of 3-jump-landing tasks, EMG electrodes, sensors, and the accelerometers were removed and the participant was free to go.

Data Reduction and Analysis

Muscle MyoResearch software (Noraxon, AZ) was utilized to record temporal characteristics of muscle activation onset, duration, and time to peak activation. The raw EMG signal was full-wave rectified and smoothed to assist in the detection of signal onset.

Additionally, filtering of the signal was performed to eliminate elements of noise that have infiltrated the signal (De Luca et al., 2010). Optimal filtering involves removing noise elements that have difference frequencies from the signal, and this can be done by setting limits at both high and low frequencies (De Luca et al., 2010). For the current study, filtering was set at a medium band pass filter of 250 Hz. Data were analyzed for 2 – 3 seconds of the MVIC, using the highest of two trials.

Temporal values were normalized to the muscle activation onset of the right vastus lateralis as be referenced as “0”. Therefore, to preclude the use of negative values, in which a muscle activated sooner than the right vastus lateralis, onset data were normalized using log transform and adding “1.0” to each reported onset value. Additionally, the height from which each participant actually fell from was analyzed using one-way ANOVAs and Cronbach’s alpha (Santos, 1999) to assess trends and intrasubject reliability.

A 2x2x4 repeated measures ANOVA was used to test for differences in muscle activation onset (pre-intervention and post-intervention) across both legs (right and left) for each muscle (VL, VM, BF, SEM). A 2x2x4 repeated measures ANOVA was used to test for differences in duration of muscle activation (pre-intervention and post-intervention) across both legs (right and left) for each muscle (VL, VM, BF, SEM). Lastly, a 2x2x4 repeated measures ANOVA was used to test for differences in time to peak activation (pre-intervention and post-intervention) across both legs (right and left) for each muscle (VL, VM, BF, SEM). A total of three repeated measures ANOVAs were used. In the case of an interaction effects, post hoc analyses for simple main effects with Bonferonni adjustment and pairwise comparisons were utilized. Moreover, Statistical Package for Social

Sciences™ Version 24 (SPSS Inc., Chicago, IL) was used to perform all statistical computations.

Chapter IV: Results

The purpose of this study was to investigate muscle activation patterns in post-pubescent adolescent females before and after a plyometric training intervention. Prior to a 6-week plyometric training intervention, surface EMG was recorded bilaterally for the following: muscle activation onset of the vastus lateralis ($VL1_o$), vastus medialis ($VM1_o$), biceps femoris (BF_o), and semitendinosus (SEM_o); duration of activation of the vastus lateralis ($VL1_d$), vastus medialis ($VM1_d$), biceps femoris ($BF1_d$), and semitendinosus ($SEM1_d$); and time to peak activation of the vastus lateralis ($VL1_t$), vastus medialis ($VM1_t$), biceps femoris ($BF1_t$), and semitendinosus ($SEM1_t$) were recorded bilaterally using surface EMG prior to a 6-week plyometric training intervention. At the completion of 6 weeks, the following was again recorded: muscle activation onset of the vastus lateralis ($VL2_o$), vastus medialis ($VM2_o$), biceps femoris ($BF2_o$), and semitendinosus ($SEM2_o$); duration of activation of the vastus lateralis ($VL2_d$), vastus medialis ($VM2_d$), biceps femoris ($BF2_d$), and semitendinosus ($SEM2_d$); and time to peak activation vastus lateralis ($VL2_t$), vastus medialis ($VM2_t$), biceps femoris ($BF2_t$), and semitendinosus ($SEM2_t$). Onset, duration, and time to peak muscle activation values were recorded for both the right (R) and left (L) legs. The following chapter will present the statistical analyses employed and concomitant results.

Demographics

This study included 19 Asotin School District post-pubescent adolescent females, with no self-reported history of significant injury to their lower extremities. Subjects reported a minimum of three hours of physical activity per week on average, which included representation or landing type activities (jump rope, basketball, volleyball, etc.,) (Kernozek et al., 2007; McLean et al., 2007). The means and standard deviations (SD) for age, height, weight, and pre-intervention and post-intervention vertical jump height are provided in Table 1.1 below. These values were recorded as a method for determining the effect of the intervention on maximum jump height. A paired samples T-test revealed significant differences (*p* = 0.034), and 11 of 19 (57.9%) participants increased their vertical jump height.

Table 4.1
Subject Demographics and Reported Vertical Jump Heights (n = 19)

Variable	Mean	SD
Age (yrs)	13.8	.9581
Height (cm)	163.4	7.2
Weight (kg)	63.7	32.7
Vertical Jump (pre-intervention) (cm)	40.6	5.5
Vertical Jump (post-intervention) (cm)	42.3	6.5

Assessments of Reliability and Normality

Muscle activation onset trials data were analyzed for trends using one-way ANOVA's across all three pre-intervention and post-intervention trials for both the right or left sides. Cronbach's alpha was utilized to assess reliability across trials. ANOVA and reliability results are provided in Tables 1.2 and 1.3 below.

Table 4.2
One-Way ANOVA for Trends and Reliability Results: Within Onset of Muscle Activation Pre-/Post-Intervention Trials (Right Side)

	df	*F*	*p*	α
RVM1$_o$	2	1.150	.329	.160
RBF1$_o$	2	.207	.814	.515
RSEM1$_o$	2	.672	.518	-.236
RVM2$_o$	2	.888	.427	.032
RBF2$_o$	2	.315	.734	-.007
RSEM2$_o$	2	1.120	.348	.271

Table 4.3
One-Way ANOVA for Trends and Reliability Results: Within Onset of Muscle Activation Pre-/Post-Intervention Trials (Left Side)

	df	*F*	*p*	α
LVL1$_o$	2	.940	.401	.393
LVM1$_o$	2	1.231	.306	.050
LBF1$_o$	2	.424	.658	.113
LSEM1$_o$	2	4.779	.015	-.092
LVL2$_o$	2	.2.086	.153	.615
LVM2$_o$	2	.020	.980	-.199
LBF2$_o$	2	.508	.610	.062
LSEM2$_o$	2	1.015	.382	.149

Duration of muscle activation trials data were analyzed for trends using one-way ANOVA's across all three pre-intervention and post-intervention trials for both the right or left sides. Cronbach's alpha was utilized to assess reliability across trials. ANOVA and reliability results are provided in Tables 1.4 and 1.5 below.

Table 4.4
One-Way ANOVA for Trends and Reliability Results: Within Duration of Muscle Activation Pre-/Post-Intervention Trials (Right Side)

	df	*F*	*p*	α
$RVL1_d$	2	6.738	.004	.677
$RVM1_d$	2	3.475	.043	.368
$RBF1_d$	2	.679	.514	.632
$RSEM1_d$	2	1.330	.279	.747
$RVL2_d$	2	.652	.533	.760
$RVM2_d$	2	.251	.781	.527
$RBF2_d$	2	.710	.505	-.562
$RSEM2_d$	2	.989	.391	-.490

Table 4.5

One-Way ANOVA for Trends and Reliability Results: Within Duration of Muscle Activation Pre-/Post-Intervention Trials (Left Side)

	df	*F*	*p*	α
$LVL1_d$	2	2.499	.098	.840
$LVM1_d$	2	.648	.530	.667
$LBF1_d$	2	.105	.901	.533
$LSEM1_d$	2	1.957	.158	.667
$LVL2_d$	2	.591	.564	.346
$LVM2_d$	2	.545	.589	.632
$LBF2_d$	2	1.545	.240	.090
$LSEM2_d$	2	.698	.511	.621

Time to peak muscle activation trials data were analyzed for trends using one-way ANOVA's across all three pre-intervention and post-intervention trials for both the right or left sides. Cronbach's alpha was utilized to assess reliability across trials. ANOVA and reliability results are provided in Tables 1.6 and 1.7 below.

Table 4.6

One-Way ANOVA for Trends and Reliability Results: Within Time to Peak Muscle Activation Pre/Post-Intervention Trials (Right Side)

	df	*F*	*p*	α
RVL1$_t$	2	1.556	.227	.391
RVM1$_t$	2	.907	.422	.538
RBF1$_t$	2	.819	.450	-.262
RSEM1$_t$	2	3.246	.052	.189
RVL2$_t$	2	.907	.422	.538
RVM2$_t$	2	.088	.916	-.933
RBF2$_t$	2	.317	.732	.228
RSEM2$_t$	2	1.636	.222	.187

Table 4.7

One-Way ANOVA for Trends and ICC Reliability Results: Within Time to Peak Muscle Activation Pre-/Post-Intervention Trials (Left Side)

	df	*F*	*p*	α
LVL1$_t$	2	1.044	.364	.330
LVM1$_t$	2	.707	.500	.459
LBF1$_t$	2	.015	.985	.756
LSEM1$_t$	2	2.284	.118	.640
LVL2$_t$	2	1.022	.380	-.291
LVM2$_t$	2	.323	.728	.410
LBF2$_t$	2	1.061	.367	-.767
LSEM2$_t$	2	.509	.609	.782

A repeated-measures ANOVA with a Greenhouse-Geisser correction determined that the mean drop height differed statistically significantly across pre-intervention and post-intervention testing trials (F(2.244, 38.155) = 6.009, *p* = .004). Post hoc tests using the Bonferroni correction revealed a statistically significant (*p* = .026) difference in drop height between pre-intervention trial 2 and post-intervention trial 2 (87.49 ± 6.28 cm compared to 83.41± 6.63 cm, respectively). Moreover, pre-intervention trial 3 was also significantly different (*p* = .023) than post-intervention trial 2 (87.81 ± 6.01cm compared to 83.41 ± 6.63 cm). Cronbach's alpha (Santos, 1999) was used to assess intrasubject reliability for drop height across all trials. The Cronbach alpha for all six trials was .934 (Cronbach alpha = .934), and therefore, reached conventional standards for reliability. EMG values were normalized to participant jump height for all pre-intervention and post-intervention trials.

Missing Data

After the removal of data discarded to disruptions in EMG signal, 87.7% of the data originally collected were viable for data analysis. These data were removed due to improper signaling and interruptions in signaling due to hardware malfunction during the movement task. The largest deficit in data collection from the BF. Approximately, 30.1% of the missing data came from the right and left legs of $BF1_o$, $BF2_o$, $BF1_d$, $BF2_d$, $BF1_t$, and $BF2_t$. In addition, 28.1% of the missing data were from the right and left legs of the $SEM1_o$, $SEM2_o$, $SEM1_d$, $SEM2_d$, $SEM1_t$, and $SEM2_t$. The VL provided the greatest return accounting for only 20.2% of the missing data across the right and left legs of the $VL1_o$, $VL2_o$, $VL1_d$, $VL2_d$, $VL1_t$, and $VL2_t$.

Onset of Muscle Activation

A 2x2x4 (time x leg x muscle) repeated-measures ANOVA was calculated to examine the effects of ‘time’ (pre-intervention, post-intervention) and ‘leg’ (right, left) on muscle activation onset (vastus lateralis, vastus medialis, biceps femoris, semitendinosus). No significant interactions were found (F(3,54) = .561, *p* = .643). However, the main effect for ‘muscle’ was significant (F(3,54) = 7.737, *p* < .001). Effect size was calculated using the formula for Cohen’s *d* (Cohen, 1988). The reported effect size for ‘muscle’ was small (*d* = 0.301) based on Cohen’s criteria (small effect size: *d* = 0.20, medium effect size: *d* = 0.50, large effect size: *d* = 0.80). Pairwise comparisons revealed a significant difference in onset of muscle activation between LVL1$_{o}$ and LSEM1$_{o}$ (*p* = .036), with LVL1$_{o}$ activating approximately 0.67 milliseconds (ms) sooner than LSEM1$_{o}$, prior to a 6-week plyometric training intervention.

Additional significant differences were identified in onset of muscle activation between RVL2$_{o}$ and RBF2$_{o}$ (*p* = .026), LVL2$_{o}$ and LBF2$_{o}$ ($_{\text{p}}$ = .010), and LVM2$_{o}$ and LBF2$_{o}$ (*p* = .018). More specifically, following a 6-week plyometric training intervention, RVL2$_{o}$ onset approximately 0.56 ms sooner than RBF2$_{o}$, LVL2$_{o}$ 1.01 ms sooner than LBF2$_{o}$, and LVM2$_{o}$ 0.98 ms sooner than LBF2$_{o}$, respectively. Mean (M) and standard deviation (SD) results are provided in Table 2.1 below. See Appendix E, Graph 4.1, for graphical representation of identified changes across pre- and post-intervention trials.

Table 4.8

Results of Descriptive Statistics: Onset of Muscle Activation for Right and Left Legs (n = 19)

	Right Leg		Left Leg	
Muscle	M (ms)	SD (ms)	M (ms)	SD (ms)
$VL1_o$	1000.00	0	999.79	.836
$VL2_o$	1000.00	0	1000.03	.573
$VM1_o$	1000.25	.750	1000.15	.332
$VM2_o$	1000.26	.515	1000.06	.536
$BF1_o$	1000.65	1.91	1000.43	.916
$BF2_o$	1000.56	1.02	1001.04	1.52
$SEM1_o$	1000.21	1.00	1000.46	.985
$SEM2_o$	999.91	8.86	1000.40	1.11

Duration of Muscle Activation

A 2x2x4 (time x leg x muscle) repeated-measures ANOVA was calculated to examine the effects of 'time' (pre-intervention, post intervention) and 'leg' (right, left) on duration of muscle activation (vastus lateralis, vastus medialis, biceps femoris, semitendinosus). A significant 'time x muscle' interaction was present (F(3,54) = 5.239, *p* = .003). The interaction effect was small, based on the reported Cohen's value (*d* = 0.225).

Post hoc testing revealed significant differences between $LVL1_d$ and $LVL2_d$ (*p* = .026). Additionally, a significant difference between $LVM1_d$ and $LVM2_d$ (*p* = .002) was identified. Duration of activation lasted approximately 1.3 ms longer in the LVL following a 6-week plyometric training intervention. Similarly, duration of muscle activation lasted approximately 1.69 ms longer in the $LVM2_d$ following a 6-week plyometric training intervention.

While the main effects of ‘time’ (F(1,18) = .353, *p* = .560) and ‘leg’ (F(1,18) = .037, *p* = .849) were not significant, ‘muscle’ had a main effect (F(3,54) = 24.817, *p* < .001). The effect size of ‘muscle’ was moderate, *d* = 0.580. Pairwise comparisons revealed significant differences were seen between the $RVL1_d$ and $RBF1_d$ (*p* = .001). Duration of muscle activation occurred for approximately 2.0 ms longer in the $RVL1_d$ than in the $RBF1_d$ prior to a 6-week plyometric training intervention. Additional significant differences in duration of activation between $LVL2_d$ and $LBF2_d$ (*p* = .003), $LVL2_d$ and $LSEM2_d$ (*p* = .001), $LVM2_d$ and $LBF2_d$ (*p* = .028), and $LVM2_d$ and $LSEM2_d$ (*p* = .003). Further investigation of the reported means for these muscles indicated duration of activation lasting approximately 4.1 ms longer in the $LVL2_d$ than in the $LBF2_d$, 4.12 ms longer in the $LVL2_d$ than in the $LSEM2_d$, 3.49 ms longer in the $LVM2_d$ than in the $LBF2_d$, and 3.43 ms longer in the $LVM2_d$ than in the $LSEM2_d$ following a 6-week plyometric training intervention. Moreover, duration of muscle activation lasted approximately 3.11 ms longer in the $RVL2_d$ than in the $RBF2_d$ (*p* = .010), 3.68 ms longer in the $RVL2_d$ than in the $RSEM2_d$ (*p* < .001), and 2.53 ms longer in the $RVM2_d$ than in the $RSEM2_d$ (*p* < .001). Mean and standard deviation results are provided in Table 2.2 below. See Appendix E, Graph 4.2, for graphical representation of identified changes across pre- and post-intervention trials.

Table 4.9

Results of Descriptive Statistics: Duration of Muscle Activation for Right and Left Legs (n = 19)

	Right Leg		Left Leg	
Muscle	M (ms)	SD (ms)	M (ms)	SD (ms)
VL1$_d$	8.04	2.57	8.29	4.00
VL2$_d$	9.13	3.49	9.59	3.62
VM1$_d$	7.30	2.18	7.21	2.55
VM2$_d$	7.98	2.31	8.90	3.30
BF1$_d$	6.86	3.34	6.24	2.57
BF2$_d$	6.02	2.97	5.49	2.00
SEM1$_d$	5.87	1.91	5.89	2.46
SEM2$_d$	5.45	1.63	5.47	2.51

Time to Peak Muscle Activation

A 2x2x4 (time x leg x muscle) repeated-measures ANOVA was calculated to examine the effects of ‘time’ (pre-intervention, post intervention) and ‘leg’ (right, left) on time to peak muscle activation (vastus lateralis, vastus medialis, biceps femoris, semitendinosus). No significant interactions were found (F(3,54) = .851, p = .472). Main effects of ‘time’ (F(1,18) = .034, p = .856) and ‘leg’ (F(1,18) = .060, p = .810) were non-significant, while the main effect of ‘muscle’ (F(3,54) = 8.414, p < .001) was. Cohen’s *d* reported a small effect size, d = 0.319.

Further analysis using pairwise comparisons revealed significant differences in time to peak muscle activation between RVL2$_t$ and RSEM2$_t$ (p = .017), RVM2$_t$ and RBF2$_t$ (p = .049), and RVM2$_t$ and RSEM2$_t$ (p = .029). Investigation of the reported means suggested that time to peak muscle activation was approximately 0.55 ms later in RVL2$_t$ than in

$RSEM2_t$, 0.39 ms later in $RVM2_t$ than $RBF2_t$, and 0.53 ms later in $RVM2_t$ than in $RSEM2_t$ following a 6-week plyometric training intervention. Additionally, time to peak muscle activation occurred approximately 0.85 ms later in $LVL2_t$ than in $LBF2_t$ ($p = .006$), 0.89 ms later in $LVL2_t$ than in $LSEM2_t$ ($p = .019$), 1.03 ms later in $LVM2_t$ than in $LBF2_t$ ($p = .006$), and 1.32 ms later in $LVM2_t$ than in $LSEM2_t$ following plyometric training. Mean and standard deviation results are provided in Table 2.2 below. See Appendix E, Graph 4.3, for graphical representation of identified changes across pre- and post-intervention trials.

Table 4.10
Results of Descriptive Statistics: Time to Peak Muscle Activation for Right and Left Legs (n= 19)

	Right Leg		Left Leg	
Muscle	M (ms)	SD (ms)	M (ms)	SD (ms)
$VL1_t$	3.17	.472	3.29	1.24
$VL2_t$	3.22	.732	3.54	1.43
$VM1_t$	3.09	.573	2.96	.457
$VM2_t$	3.20	1.02	3.72	1.37
$BF1_t$	2.99	1.10	2.77	1.73
$BF2_t$	2.81	.770	2.69	.942
$SEM1_t$	2.85	.680	2.92	1.73
$SEM2_t$	2.67	.691	2.40	1.08

Chapter V: Discussion

Anterior cruciate ligament injuries disproportionately affect female athletes, accounting for 69% of serious knee injuries (Gomez, DeLee, & Farney, 1996) and 4.8% of all athletic injuries (Giza et al., 2005; Oliphant & Drawbert, 1996). Additionally, higher rates are seen immediately following the growth spurt (Admirin & Cheng, 2003; Tursz & Crost, 1986). There have been several purported mechanisms responsible for this increased risk including anatomical, hormonal, neuromuscular, and biomechanical factors. More precisely, ACL injury risks are related to measurable deficits in the modifiable risk factor of neuromuscular control in female athletes (Ford, Myer, & Hewett, 2003; Ford et al., 2005; Hewett et al., 2005). Four neuromuscular control deficits have been identified in the literature; of particular interest are that of quadriceps and leg dominance.

Quadriceps dominance occurs when an athlete preferentially uses the quadriceps instead of the posterior chain muscles (hamstrings) to control the limb, and thus, uses a single muscle with a single tendinous insertion for stability and control (Hewett et al., 2010). Rather, when utilizing the posterior chain muscles, multiple tendinous insertions contribute to stabilization during functional tasks. Moreover, leg dominance is an imbalance between muscular strength and recruitment patterns on opposite limbs, with one side often demonstrating greater dynamic control (Hewett, Stroupe, Nance, & Noyes, 1996; Knapik et al., 1991). Overreliance on one limb can put greater stress on that knee whereas the weaker side might not be able to effectively absorb the high forces associated with sporting activities (Ford, Myer, & Hewett, 2003). The presence of neuromuscular asymmetries in the hamstrings and quadriceps, or between limbs, in post-pubescent adolescent females could indicate that the onset of puberty may affect neuromuscular function strategies, collectively increasing the risk of ACL injury. Thus, the purpose of this study was to determine if neuromuscular deficits exists in post-pubescent adolescent females, and how a plyometric training intervention may alter these neuromuscular characteristics. Specific characteristics under investigation included muscle activation onset, duration, and time to peak activation during a jump-landing task in the left and right vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), and semitendinosus (SEM).

Three prominent hypotheses laid the foundation for investigation including: 1) There will be no significant differences in right (left) VL, VM, BF, and SEM onset (duration, time to peak) of muscle activation relative to ground contact prior to (following) a 6-week plyometric training intervention; 2) There will be no significant differences in symmetry of muscle activation onset (duration, time to peak) between right and left VL, VM, BF, and SEM prior to (following) a 6-week plyometric training intervention; 3) There will be no significant differences in duration (time to peak) of muscle activation between the right and left VL, VM, BF, and SEM prior to (following) a 6-week plyometric training intervention. The following will provide an in-depth review of the findings of this investigation, limitations, and directions for future research.

Muscle Activation Characteristics

Perhaps the most surprising finding of this study was the presence of increased duration of quadriceps activation and decreased time to peak muscle activation of the hamstrings. This finding inspires deliberation of possible benefits and detriments associated with implementation of plyometric training for the post-pubescent adolescent female. Other researchers have demonstrated increased activation of the quadriceps in females, including that of Zazulak et al. (2005), Malinzak et al. (2001), Hewett et al. (1996), and Wojtys et al. (1996). For example, Zazulak et al. (2005) reported greater peak quadriceps activity in female than male subjects. Wojtys et al. (1996) reported that female athletes have a slower response of hamstring activation to anterior stress on the ACL. As a dissimilarity to the present study, these investigations did not include a plyometric training intervention, rather these findings were observed during a single testing session. However, one research study conducted by Chimera et al. (2004) evaluated the effects of plyometric training on muscle-activation strategies and performance of the lower extremity during jumping exercises. At the conclusion of a 6-week plyometric training intervention, significant changes in EMG activity were observed. Precisely, increased adductor and abductor coactivation were demonstrated. While the present study did not include measures of adductor and abductor musculature, Omstead et al. (1986) found that the tensor fascia latae (hip abductor) worked in concert with the quadriceps during knee extension, whereas the gracilis (hip adductor) acted in synchrony with the medial hamstrings in knee flexion, indicating that the hip abductor and adductor musculature have direct roles in assisting with knee joint stability. Ideally, coactivation values of 100% indicate agonist and antagonist muscle synchrony, which also increases muscle and joint stiffness (Bach, Chapman, & Calvert, 1983; Dyhre-Poulsen, Simonsen, & Voight, 1991).

While several researchers have demonstrated beneficial neuromuscular adaptations following plyometric training, debate continues regarding the components that ACL prevention training programs should contain, as well as the frequency and duration of training (Noyes & Barber-Westin, 2012). The present study consisted of plyometric jumping and landing exercises for a duration of six weeks, three days per week for approximately 15 – 20 minutes. Programming was developed based on past research including that of Hewett and colleagues (1996). The technique, fundamentals, and performance phases of this jump-training program elicited significant changes in hamstring muscle strength and power in both the dominant and non-dominant limbs (Hewett, Stroupe, Nance, & Noyes, 1996). Contrary to the current study, Hewett and colleagues (1996) also included concurrent strength training and demonstrated a corrected hamstring and quadriceps muscle imbalance at the conclusion of training. The following sections provide the results of within limb comparisons of quadriceps and hamstrings muscle groups for onset, duration, and time to peak muscle activation of the present study.

Onset of Muscle Activation

Female athletes tend to be quadriceps dominant in both strength and muscle firing patterns (Hewett et al., 1999; Huston & Wojtys, 1996). Correspondingly, women have been shown to activate the quadriceps more and have demonstrated lower hamstring to quadriceps activation ratios (Nagano et al., 2007; Padua et al., 2005). Similar to the present study, Medina and colleagues (2007) compared hamstring and quadriceps activation patterns in adolescent (non-athlete and athlete) females. Results indicated that both groups pre-activated the quadriceps first. Moreover, Fagenbaum & Darling (2003) demonstrated activation of the quadriceps prior to the hamstrings when assessing muscle timing in athletic college-aged females during a jump-landing task. Only one significant difference in onset of muscle activation in the right leg between the vastus lateralis and lateral hamstring was identified in the current study; these differences were present following a 6-week plyometric training intervention. 16 of the 19 participants identified as right leg dominant.

Interestingly, turning to the left leg, only one significant difference appeared in onset prior to training between the vastus lateralis and medial hamstring, while significant differences were seen between the vastus lateralis and lateral hamstring, as well as between the vastus medialis and lateral hamstring following training. While these were the only significant differences identified in onset of muscle activation prior to or following training, descriptive statistics of the data consistently demonstrated the quadriceps having activated prior to the hamstrings, reinforcing the findings of Medina et al. (2007) and Fagenbaum & Darling (2003).

Kain et al. (1988) suggested that a muscle recruitment strategy whereby the hamstring muscles contract before the quadriceps muscles, thereby initiating a posterior tibial drawer and negating the quadriceps initiated anterior tibial drawer, would offer optimal protection to the ACL during dynamic activities (Kain, McCarthy, Arms, Pope, Steadman, Manske, & Shively, 1988). Likewise, Wojtys & Huston (1996) demonstrated that quadriceps dominant strategies result in decreased resistance to anterior tibial shear stresses in female athletes and may place female athletes at increased risk for sustaining ACL injury. In opposition to the suggestions of Kain (1988), in the present study, the quadriceps activated before the hamstring muscles. As several researchers have advised based on findings of exploratory investigations, the onset activation patterns displayed in this study could warrant speculation as to the degree of risk these post-pubescent adolescent females may be at for ACL injury.

Duration of Muscle Activation

Other findings within this study may refute the notion of the participants being at an increased risk for injury. For example, significant differences in duration of muscle activation were identified in the right vastus lateralis when compared to both lateral and medial hamstrings. Duration of muscle activation occurred for a longer period of time in the right vastus lateralis than in the lateral and medial hamstrings following a 6-week plyometric training intervention. Comparatively, duration of muscle activation occurred for a longer period of time in both quadricep muscles, vastus lateralis and vastus medialis, when compared to both lateral and medial hamstrings. Thus, the hypotheses submitting no significant differences between these muscles following a plyometric training intervention were rejected. However, no significant differences in duration of muscle activation across quadricep and hamstring muscles were identified in either the right or left legs prior to plyometric training, resulting in the acceptance of these hypotheses. Findings of this study are supported by that of Cowling, Steele, & McNair (2003), who investigated the effects of verbal instructions on landing muscle activity. Researchers noted significantly longer burst durations of the quadriceps muscle in one condition in which the participants were verbally instructed to, “land with your knees bending.” Cowling and colleagues (2003) attributed the longer quadriceps activity to the need for the eccentric quadriceps contractions to “control” the greater knee flexion demonstrated during the landing condition. Although verbal instructions were not provided to participants during data collection in the present study, the foundational premise of training was verbal instruction throughout the 6-week period. At the core of instruction was, “land with bended knees,” “quiet landings,” and “sit back – don’t let your knees go past your toes.” Thus, the increased duration of muscle activation across both right and left legs, following a 6-week plyometric training intervention, seems fitting given the similarity of verbal instructions provided by that of the present study and of Cowling and colleagues (2003). Furthermore, although non-significant differences were found in the duration of muscle activation, prior to and following plyometric training, within the vastus lateralis of the right and left legs, notable increases were seen. The right leg exhibited an increase of 1.1 ms, and the left an increase of 1.4 ms, respectively, following a 6-week plyometric training intervention. While measures of knee flexion were outside of the scope of this study, perhaps the documented longer quadriceps muscle activity is suggestive of eccentric contractions attempting to “control” bending at the knees upon landing.

Time to Peak Muscle Activation

In the present study, muscle had a significant effect on time to peak muscle activation. Significant differences were not seen between pre- and post- plyometric training, although several significant differences across quadricep and hamstring muscles were present at the completion of plyometric training. The quadricep muscles, vastus lateralis and vastus medialis, within both the right and left limbs, consistently reached peak activation later than that demonstrated by the lateral and medial hamstrings. According to a study conducted by Gordon & Ghez (1984), an alternating triphasic pattern of EMG bursts in agonist and antagonist muscles is known to characterize rapid limb movement (Wacholder & Altenburger, 1926). An initial burst in the agonist is followed by a silent period coinciding with a burst in the antagonist and then by a second burst in the agonist (Gordon & Ghez, 1984). The agonist initially accelerates the limb, while the antagonist is generally held to be specifically responsible for terminal deceleration (Hallet, Shahani, & Young, 1975; Lestienne, 1979; Marsden, Obeso, & Rothwell, 1983). Of particular interest in the present study were the bursts in which followed the silent period. As Gordon & Ghez (1984) advised, the silent period should coincide with a burst in the antagonist and then by a second burst in the agonist. Research conducted by Mardsen, Obeso, & Rothwell (1983) determined that the action of the antagonist undoubtedly assists in halting a fast movement, but the amount and timing of such antagonist activity is subtly adjusted to circumstances. To further expand upon this topic, Reeves et al. (2013) investigated the limits of motor control bandwidth using stick balancing. Researchers hypothesized that the central nervous system would alter muscle co-activation to match the dynamics of the task (Reeves, Pathak, Popovich, & Vijayanagar, 2013). Results of the study indicated that more agonist muscle activation was required as task velocity increased, and likewise, the level of antagonist muscle activation also increased proportionally. As previous research has acknowledged, agonist-antagonist coactivation increases joint stiffness. In the current study, significant differences were identified following plyometric training with the quadriceps reaching peak activation consistently later than the hamstrings. While it would seem reasonable for these differences to appear prior to training, having not been very familiar with the jump task, they appeared after 6-weeks of plyometric training. Given this information, it may be reasonable to assume that the significant differences in time to peak activation between the quadriceps and hamstrings muscles, following training, is due in part to the training program prescribed for the participants, rather than the task assigned during testing.

In contrast, it may be postulated that since the medial and lateral hamstring muscles reached time to peak muscle activation prior to the quadriceps muscles, that they did indeed work to prevent anterior translation of the tibia. Despite the lateral hamstring having onset later than the medial hamstring and both quadriceps muscles, its role in ACL prevention may be of less concern, as activation of the medial hamstring is more imperative in reducing both anterior tibial translation and internal tibial torsion. Currently, while there is an abundance of literature available on the role of the hamstrings collectively as synergists, there is little available regarding the distinct and separate roles of the medial and lateral hamstrings in ACL injury prevention. Thus, interpreting the time to peak muscle activation results is based more on the premise of the author's knowledge of the anatomical and physiological function of these tissues rather than previously conducted research.

Between Limb Activation Characteristics

When considering the imbalance of leg dominance, it should be acknowledged that most athletes have a preferred plant leg and a preferred kick or drive (in the case of a single leg jump task) leg (Hewett et al., 2010). However, the difference between limbs in muscle recruitment patterns, muscle strength, and muscle flexibility, tends to be greater in women than men (Ford, Myer, & Hewett, 2003; Hewett, Myer, & Ford, 2006; Myer et al., 2010; Myer, Ford, & Hewett, 2010; Paterno et al., 2010). Ford, Myer, & Hewett (2003) observed that female athletes demonstrated significant differences between their dominant and non-dominant side in maximum knee valgus angle. These differences in limb-to-limb asymmetries (leg dominance) reflect neuromuscular deficits that may be indicative of decreased dynamic knee joint control in female athletes (Ford, Myer, & Hewett, 2003). Moreover, when a female tears her ACL, most if not all of her weight is on a single leg (Hewett, Torg, & Boden, 2009). Previous research conducted by Ruedle et al. (2012) found that 68% of female skiers suffered from ACL ruptures of their left leg in comparison with 48% of male skiers. Additionally, Brophy et al. (2010) reported that 68% of female soccer players sustained noncontact ACL injury of their left knee, while only about 26% of male soccer players injured the left ACL. Therefore, examination of leg dominance is essential in identifying overall risk for ACL injury.

In the present study, no significant differences between limbs were seen in onset, duration, and time to peak muscle activation prior to or following a plyometric training intervention. Several definitions have previously been used to classify the dominant lower limb, including a participant's preferred kicking leg (Ford, Myer, & Hewett, 2003; Matava, Freehill, Grutzner, & Shannon, 2002), the leg with which they can kick a ball the farthest (McLean et al., 2007), the lower limb used for support (Matava, Freehill, Grutzner, & Shannon, 2002), or the limb used to predominantly jump with (Crossley, Thancanamootoo, Metcalf, Cook, Purdam, & Warden, 2007). The present study defined the dominant lower limb as the preferred kicking leg, which coincidently was the right leg for 16 of 19 participants. Prior to and following plyometric training, results were similar to that of Edwards and colleagues (2012), who examined lower limb movement symmetry during a stop-jump landing (Edwards, Steele, Cook, Purdam, & McGhee, 2012). Edwards et al. (2012) observed no significant between-limb differences in muscle onset or peak muscle burst activity, however, this study was devoid of interventional methods. Additionally, Greska et al. (2016) examined neuromechanical differences in leg dominance of female collegiate soccer athletes during an unanticipated sidestep cutting task (Greska, Cortex, Ringleb, Onate, & Van Lunen, 2016). Although non-significant, researchers did find asymmetries in peak EMG activation time between the dominant and non-dominant legs.

The present study did not explicitly evaluate peak EMG activation between legs, however, non-significant, yet, asymmetrical, onset, duration, and time to peak activation was noted prior to and following training.

Leg dominance is an imbalance between muscular strength and recruitment patterns on opposite limbs, with one side demonstrating greater dynamic control (Hewett, Stroupe, Nance, & Noyes, 1996; Knapik et al., 1991). Ball and Scurr (2009) compared the neuromuscular contribution between left and right triceps surae during a bilateral landing activity to assess the immediate implications of non-simultaneous foot placement. Significant differences between the left and right triceps surae muscle activity were found before and directly after contact (Ball & Scurr, 2009). While the study by Ball & Scurr (2009) did not include neuromuscular activity assessments prior to and following an intervention, the fact that differences in the activation patterns were identified prior to ground contact supports the theory of leg dominance.

In the present study, following the 6-week plyometric training intervention, participants exhibited significant differences in quadriceps and hamstrings muscles. To clarify, across both limbs, the quadriceps exemplified quicker onset, longer time to peak activation, and longer duration times when compared to the hamstrings. Results of the present study oppose those of Chimera et al. (2004) who examined the effects of plyometric training on muscle activation strategies and performance in female athletes during jumping activities. Researchers reported more symmetric hamstrings to quadriceps coactivation in the plyometric group. Additionally, Hewett et al. (1996) tested the effects of a jump training program on the mechanics of landing in female athletes involved in jumping sports. Prior to jump training, the female participants demonstrated a marked imbalance between hamstring and quadriceps coactivation. At the completion of the training, the coactivation imbalance had been corrected.

The fact that non-significant differences in the activation characteristics were observed across legs prior to training could be a result of a lack of training exposure of these participants. Often, asymmetries become more apparent as training ensues due to fatigue, injury, and compensation. Non-significant differences between legs were also noted following plyometric training. Perhaps the inclusion of both bilateral and unilateral exercises within the plyometric training allowed these limbs to train more symmetrically, and thus, each experienced similar change (i.e. increased quadriceps activity).

Summary

As can be ascertained, the significant differences identified following a 6-week plyometric training intervention warrant examination of program composition. Hewett et al. (1996) utilized a 6-week jump-training program partitioned into three phases: technique, fundamentals, and performance. The training program for the present study was crafted based on these three foundational phases, as well as a completed literature review and the author’s knowledge and experience as a Certified Strength & Conditioning Specialist. As the literature review revealed, from a physiological and psychological standpoint, four to six weeks of high intensity power training is an optimal length of time for the central nervous system to be stressed without excessive strain or fatigue (Adams, O’Shea, O’Shea, & Climstein, 1992). Previous researchers who have implemented a plyometric training program have varied in the volume of training prescribed. For instance, Miller et al. (2006) had participants perform plyometrics twice per week to allow for sufficient recovery between workouts. This is contrary to Hewett et al. (1996) whose training program included sessions lasting one hour per day, three days a week. Furnished with this knowledge, the author of the present study chose a 6-week plyometric training program with sessions lasting approximately 20 minutes, three days per week. The participants, made up of post-pubescent adolescent females, ages 13 – 17, had past experience with various forms of jumping and/or were involved in sports. This plyometric prescription seemed reasonable given that the participants in Hewett's (1996) study included that of high school volleyball players, while Miller's (2006) consisted of participants 18 years and above.

Consideration of the plyometric exercises in which encompassed the training must be taken. Exercises were adapted from both Miller et al. (2006) and Hewett et al. (1996) in order to accurately fit the population group. Additional exercises were incorporated based on their level of intensity and prescribed week of training from the National Strength and Conditioning Association textbook, *Essentials of Strength Training & Conditioning* (Baechle & Earl, 2008). For instance, week one consisted of three low intensity exercises including a jump and reach, lateral hop-to-balance, and of one medium intensity, a power skip. High intensity exercises were not introduced until week four. Weeks four through six unveiled a slow transition from low and medium intensity training exercises, to medium and high intensity exercises, as it was assumed four weeks would be a sufficient amount of time for adaptation to occur. The program included both bilateral and unilateral training components, and of foremost importance was the movement actions occurring during any and all landing activities. Given the variances in quadriceps and hamstrings muscles following the training program, it may be conjectured that the intensity of the prescribed jumping exercises perhaps outweighed the intensity of the associated landing exercises.

Perhaps the apparent differences in the quadriceps activation characteristics as compared to the hamstrings was a result of an imbalance in prescribed intensities for these opposing muscle groups. However, as previously discussed, one significant finding was the medial and lateral hamstrings having reached time to peak muscle activation prior to the quadriceps muscle following the plyometric training intervention. While it may appear that the quadriceps had a greater contribution to the movement task, perhaps in the first few milliseconds of activity, when the hamstrings reached peak activity, are the most crucial for preventing anterior tibial translation and internal torsion. If true, the prescribed plyometric training program could have functioned to prevent ACL injury by initiating a neuromuscular adaptation that allowed the medial and lateral hamstrings to reach peak activation much sooner in an effort to reduce strain on the ACL.

At conception of the program, less than half of the participants had just finished participating in volleyball, and approximately one week prior to the conclusion of the training program, again, less than half of the participants had just begun participating in basketball. Given the intensity of training often associated with the first few weeks of a basketball season, some data may have been skewed due to fatigue from engaging in "new" training rather than what may have been accrued through the training they had been partaking in for the past six weeks. Therefore, a limitation of this study was not controlling for participation in organized sports throughout the six-week time period.

Preceding research concentrated on females and ACL injury prevention training programs has predominately integrated participants eighteen and older. The present study included that of post-pubescent adolescent females, ages 13 – 17, and therefore expands on the available literature of this population group. Musculoskeletal growth during puberty, in the absence of corresponding neuromuscular adaptation, may facilitate the development of certain intrinsic factors (Hewett, Myer, & Ford, 2004), and if not addressed at the proper time period, may continue through adolescence into maturity, predisposing athletes to ACL injuries (Ford et al., 2010). Hewett et al. (2005) observed increases in knee abduction motion and moments in adolescent females before ACL injury, suggesting decreased neuromuscular control of the lower extremity in the frontal plane (Hewett et al., 2005). The present study did not incorporate measures of knee abduction and adduction motion; however, a considerable portion of the plyometric training intervention was spent identifying improper, or at-risk, movement mechanics. Among these observed at-risk mechanics was severe knee abduction both during loading and landing for many of the jump types. As Hewett et al. (2005) intimated, at the origin of this activity could have been decreased neuromuscular control of the lower extremity.

As an abundance of research has indicated, coactivation of the hamstrings and quadriceps may augment faulty movements, such as knee abduction and extension upon landing, and thus, reduce the risk of injury. More specifically, coactivation of the hamstrings and quadriceps is proposed to protect the knee joint not only against excessive anterior translation but also against excessive knee abduction and dynamic lower extremity valgus (Besier, Lloyed, & Ackland, 2003). While increased coactivation following plyometric training was not a direct finding in the present study, other research (Cowling, Steele, & McNair, 2003) suggests that the observed increases in quadriceps activity may be due to the eccentric action of the quadriceps attempting to control the knee, allowing for greater knee flexion and attenuation of forces at landing. However, contrasting literature provided by Hewett et al. (2005) submits that if the hamstrings are under-recruited or weak, quadriceps activation may be reduced to provide the net flexor moment required to perform the movement. Moreover, Hewett et al. (2005) implies that if hamstring recruitment is high, the quadriceps can be activated more while still allowing for a net flexor moment. Magnitude of muscle activation was not evaluated in the present study, and while coactivation appeared to be reduced in onset, duration, and time to peak muscle activation, perhaps changes in quadriceps and hamstrings magnitude of activation ensued.

Depending on the task being performed, the neuromuscular system prepares for the impending load by activating muscles before ground contact (McKinley & Pedotti, 1992). This pre-activation serves to stiffen the joint to prevent collapse immediately after contact (Duncan & McDonagh, 2000). As the literature has indicated, we should therefore expect an increase in muscle stiffness prior to impact as a result of neuromuscular training. Measures of muscular stiffness were outside the scope of this study; however, results did demonstrate increased duration of muscle activation of the quadriceps and a decreased time to peak muscle activation of the hamstrings. These adaptations may have played a substantial role in stiffening the joint and preventing collapse upon landing. Moreover, mechanical stiffness is thought to influence several athletic variables, including rate of force development, elastic energy storage and utilization of movement technique. Following plyometric training, there was a significant difference in max vertical jump height performance. Conceivably, these changes could have occurred in light of increased mechanical stiffness as a result of neuromuscular adaptations.

Hewett et al. (1996) demonstrated that neuromuscular training has the potential to decrease rates of ACL injury in adolescent female athletes, and that intensive neuromuscular training may induce a so-called neuromuscular spurt that would otherwise be absent in adolescent girls (Hewett et al., 1996; Kraemer et al., 2001; Tropp & Odenrick, 1988). Similarly, Haycock and Gillette (1976) attributed differences in injury rates amongst males and females to differing levels of training and coaching and not to anatomic or physiologic differences. None of the participants in the present study had ever engaged in a prescribed neuromuscular training program. Many of them had been exposed to various jump-landing activities, but without any instruction as to the best and safest ways to complete those tasks.

Findings of the present study did not directly align with those of Hewett et al. (1996) or Miller et al. (2006) whose plyometric training programs were fundamental in the program crafted for these post-pubescent adolescent females. Perhaps the foremost difference was the age of participants utilized for the present study. The average age for these post-pubescent adolescent females was 13.8 (± .9581) years, while those in Hewett's (1996) study were 15 (± 0.6) years and Miller's (2006) consisted of those 18 years and older. Therefore, the present study consisted mostly of middle school aged girls, while Hewett's (1996) was comprised of those high school aged. To date, this is the first study to include neuromuscular assessments prior to and following a plyometric training intervention in post-pubescent adolescent females of primarily middle school age. Myer et al. (2015) conducted a cohort study to identify incidence rates and risk factors associated with ACL injury in middle and high school female athletes (Myer, Ford, Stasi, Foss, Micheli, & Hewett, 2015). One underscored finding was that the ACL-injured group demonstrated high quadriceps strength and a lower hamstring-to-quadriceps ratio. As noted, female athletes tend to increase quadriceps activation with increased plyometric intensity without a balanced increase in hamstrings activation (Ford, Myer, & Schmitt, 2011). Moreover, in a longitudinal study, it was noted that pubertal girls have an increase in abnormal landing mechanics over time (Ford et al., 2010). More specifically, contributing risk factors for knee injury were significantly greater across consecutive years in young post-pubertal female athletes compared to males (Myer et al., 2015). Based on these findings, it may be postulated that the optimal window of opportunity for the initiation of integrative neuromuscular training is based on measures of somatic maturity (Myer et al., 2015). To clarify, from Myer's (2015) data, it appears the most beneficial time to initiate integrative training programs may be during preadolescence prior to the period of peak height velocity, when youth are growing the fastest.

Integrative neuromuscular training programs have been shown to successfully reduce the abnormal biomechanics demonstrated by this population group (Myer et al., 2005; Myer et al., 2006; Myer et al., 2007; Myer et al., 2011). Clinical interventions that have reduced lower limb injuries appear to be most effective when implemented in younger athletes (Myer, Sugimoto, Thomas, & Hewett, 2013) and must provide adequate dosage of prescribed exercise (Sugimoto, Myer, Barber Foss, & Hewett, 2013). As denoted by Myer et al. (2015), plyometric, strengthening and proximal neuromuscular control exercises appear to reduce ACL injury incidence to a greater extent than programs without these exercise components. However, these findings were documented based on cohort and meta-analyses studies primarily consisting of measures of ground reaction forces and 3-D motion capture, and not measures of specific neuromuscular activity with use of EMG. The present study was the first to use EMG to record neuromuscular activity prior to and following a plyometric training intervention in post-pubescent adolescent females. The results of the present study revealed increased duration of muscle activation of the quadriceps, and quicker time to peak muscle activation of the hamstrings. During the 6-week training period, the author observed the participants not only being mindful of the way their bodies were moving but critiquing their peers' improper movement mechanics, thereby suggesting they had been informed and understood those mechanics that may be correlated to ACL injury risk. Moreover, 57.9% of participants increased their vertical jump height following plyometric training, suggesting increases in strength. Nonetheless, strength and qualitative measures were outside the scope of the present study.

Limitations

Although the results of this study make a novel contribution to the literature, it is not without limitations. Participation included females ages 13 – 17 with no reported history of significant injury in the past two years, who also reported a minimum of three hours of physical activity per week on average. Thus, the results of this study are not generalizable to other populations such as injured or highly trained individuals. Nonetheless, prior to commencement of this study, it was calculated that a sample size of 20 participants would provide a power value of 0.96. Nineteen participants completed pre- and post-testing, yielding a power value of 0.82, and thus, reaching statistical power.

Onset, duration, and time to peak activation were measured using surface EMG. Despite the relative ease with which surface EMG measurements can be performed, there are numerous technical and methodological issues that are recommended to maximize signal fidelity and measurement reliability (De Luca, 1997). These considerations include skin preparation, (Cram & Rommen, 1989), sensor placement (Hermens, Feriks, Disselhorst-Klug, & Rau, 2000; Rainoldi, Melchiorri, & Caruso, 2004), and the use and selection of normalization methods (Burden, 2010; Balshaw & Hunter, 2012; Buckthorpe, Hannah, Pain,

& Folland, 2012). In the present study, skin preparation included removal of hair, skin debridement, and cleaning with alcohol wipes. Sensor placement was performed solely by the investigator during both testing sessions. The raw EMG signal was full-wave rectified, smoothed, and filtered at a medium band pass filter of 250 Hz. Moreover, the between-session, as used in the present study, reliability of surface EMG measurements are sensitive to any variations in volume conduction (Rutkove, 2007), skin impedence (Hermens et al., 2000), and the skin-electrode interface at that particular recording site (Huigen, Peper, & Grimbergen, 2002), even if sensor location is precisely replicated (Balshaw, Fry, Maden-Wilkinson, Kong, Tillin, & Folland, 2016). Nonetheless, despite careful attention to these issues, the reliability of absolute surface EMG recording during both voluntary and evoked contractions remains modest (Ball & Scurr, 2010; Buckthorpe et al., 2012; Rota, Rogowski, Champely, & Hautier, 2013).

Another limitation exists due to a deficiency in controlling for engagement in organized sports. While less than half of the participants in this study took part in activity associated with organized sports, training for volleyball and basketball did impede the first two weeks and last week of plyometric training. Therefore, to declare that the results of this study were solely products of plyometric training would be misleading.

Directions for Future Research

Copious amounts of research are available with representation of the benefits associated with plyometric training; improved mechanics and concomitant reduced risk of ACL injury among them. The present study is one of a handful that have used EMG to quantify neuromuscular adaptations as a result of implementing plyometric training in post-pubescent adolescent females. Given the existent research correlating injury risk during the fundamental growth stage of this age group, it seems obligatory to more accurately characterize this heightened risk as it relates to the modifiable neuromuscular factor. While variability in EMG exists both within and between-sessions, additional research using this instrument would assist in clarifying, thus cultivating reliability, amongst findings of similar and replicable studies.

As formerly mentioned, an abundance of research exists pronouncing the associated advantages of plyometric training. However, an ample amount of this research has concentrated on college-age males and females. To date, only a few researchers have really studied the effects of plyometric prescription on adolescent females, including that of Hewett and colleagues (1996). It is important to articulate that ACL injury does not only occur within the sport context, although much of the statistics available are derived from this setting. Today's physical activity guidelines recommend that adolescent males and females engage in a minimum of 60 minutes of moderate to vigorous aerobic activity, as well as muscle strengthening activities a minimum of three days per week (American College of Sports Medicine, 2018). These guidelines are for all adolescents and are not limited to athletic adolescents. Therefore, ACL prevention programs should not be considered merely for the athletic population, rather for various population groups based on current level of fitness. Such training programs could be incorporated into school-sanctioned physical education courses, and thus, exposing both athletic and non-athletic population groups. Consequently, more research should be conducted in order to determine if such training is appropriate for these groups and if the benefits truly outweigh possible risks.

To date, research has acknowledged that adolescent females are at an increased risk for ACL injury. Specifically, the onset of neuromuscular risk factors may coincide with rapid adolescent growth that results in the divergence of a multitude of biomechanical and neuromuscular parameters between sexes (Ford et al., 2010). Quatman et al. (2008) studied the effects of gender and pubertal status on generalized joint laxity in young athletes. Pre-pubertal male and female athletes were not different in cumulative joint laxity scores; however, following the onset of puberty, females demonstrated a greater joint laxity score compared to males (Quatman et al., 2008). Further research should concentrate on identifying any noteworthy delineations between stages of pubertal development experienced by adolescent females. Any recognized differences could impact the prescription of plyometric activity and projected neuromuscular adaptations. As such, caution should be taken when crafting prescription of neuromuscular training for adolescent females of varying development stages.

Lastly, augmented feedback was provided to the participants during all training sessions, but not during testing sessions. When provided with augmented feedback given after each task that includes verbal and visual cues, the pediatric population is better able to reproduce and retain information regarding their motor skills (Janelle, Champenoy, Coombes, & Mousseau, 2003; Sullivan, Kantak, & Burtner, 2008). The effects of simple instruction on landing strategies have been shown to successfully decrease landing forces and increase muscle activation required for dynamic stability (Cowling & Steele, 2003; McNair, Prapavessis, & Callendar, 2000; Prapavessis & McNair, 1999; 2003). Perhaps if methods of augmented feedback were provided during testing sessions, similar to training sessions, the results of the present study would have differed. Thus, research should further investigate the role of augmented feedback as included and excluded in testing sessions to determine if differences exist.

Practical Application

Results of the present study revealed increased onset and duration of muscle activation of the quadriceps, and quicker time to peak muscle activation of the hamstrings . The prescribed plyometric training intervention may have brought about increased knee flexion angles upon landing in the participants, however, measures of knee flexion angles were outside the scope of this study. Even so, the increased duration of muscle activation as exhibited by the quadriceps muscles could be directly correlated to changes in knee flexion following the plyometric training. Perhaps the increased duration of muscle activation was a direct response to an eccentric muscle contraction in attempt to control increased knee flexion angles. Additionally, the fact that the hamstrings demonstrated a shorter time to peak muscle activation suggests there was an increased neural drive to these muscles following the plyometric training intervention that may have allowed them to function more effectively in reducing the strain often placed on the ACL due to anterior tibial translation and internal torsion.

Provided these findings, consideration should be taken in the practical application of plyometric training in both the physical education and athletic settings for post-pubescent adolescent females. While the results of this study yielded both significant and non-significant differences of asymmetry in onset, duration, and time to peak muscle activation, it appears that possible beneficial neuromuscular adaptations occurred with the presence of increased quadriceps duration and shorter time to peak muscle activation of the hamstrings.

Thus, coaches, practitioners, and clinicians should consider the prescription of plyometric training when working with this population, however, adaptation of previously crafted plyometric training programs should be applied with delicate and meticulous thought given the background experience of possible participants. The length, volume, and intensity of the prescribed tasks should suit the participant's current physical fitness level. Rest periods between tasks as well as rest days should be substantial in order to allow neuromuscular adaptation to occur.

Conclusion

The purpose of this study was to determine if neuromuscular deficits exist in post-pubescent adolescent females, and how a plyometric training intervention may alter such neuromuscular characteristics. Previous research has revealed differences in neuromuscular patterns among gender, yet, this was the first study to investigate the effects of a 6-week plyometric training intervention on onset, duration, and time to peak muscle activation in a jump-landing task in post-pubescent adolescent females. Results of this study indicate that neuromuscular deficits were present in all dependent variables: onset, duration, and time to peak muscle activation.

Asymmetry in onset, duration, and time to peak activation was present both prior to and following plyometric training, although some non-significant differences in these variables were identified. One insightful finding was the presence of asymmetry across the quadriceps and hamstrings muscle groups within limbs. Significant differences in quadriceps and hamstrings onset, duration, and time to peak muscle activation, more specifically, were apparent following a 6-week plyometric training intervention. It was anticipated that inclusion of the plyometric training intervention would propagate more symmetrical activation characteristics, and that participants would then demonstrate coactivation of the quadriceps and hamstrings muscle groups, thereby reducing their ACL injury risk. Moreover, this is the first study to investigate neuromuscular activity prior to and following plyometric training in this population group, and thus, represents a novel contribution to the literature.

Evidence was presented to suggest that following plyometric training, adolescent females experienced increased quadriceps duration of activation when evaluating quadriceps and hamstrings activation characteristics within leg. While this increase in quadriceps activity could be construed as a successive increase in ACL injury risk, other research findings intimate that this increase could be a result of the eccentric quadriceps action controlling flexion at the knee joint. Increased flexion at the knee joint is an anticipated adaptation following plyometric training. Examination of knee flexion angles was outside the scope of this study, therefore, the proposed eccentric quadriceps action due to increased knee flexion angles cannot be substantiated.

As several studies have revealed improved coactivation following plyometric training, various programs have been suggested. The plyometric training program used in the present study was crafted from similar studies that reported improved coactivation at the completion of the program. Increases in duration of muscle activation of the quadriceps and shorter time to peak muscle activation of the hamstrings were observed in the present study. Prior to this study, none of the participants had engaged in a structured plyometric training program. Selection of the participants was merely based on their pubertal development, with disregards to current or previous participation in sport. While some of the participants were athletes, the majority were not and were only involved in jumping type activities as directed in a physical education course. Precaution in exercise prescription should always be taken and consideration of age and prior experience of participants should be of upmost concern. In the present study, following a 6-week plyometric training intervention, the author observed a heightened awareness of movement mechanics within the participants; nonetheless, qualitative measures were outside the scope of this study.

Several limitations were described that should be readily acknowledged when interpreting the results of this study. Nevertheless, the results represent a framework for future investigations that could inform female adolescents, physical educators, coaches, physical therapists and the like. Most importantly, though, are the implications for the practitioners who occupy a central role in prescribing best practices to reduce injury risk for these adolescents. These practitioners often adopt and employ the use plyometric training programs to improve performance and reduce injury risk in their athletes. Therefore, these practitioners should carefully examine the use of any previously crafted plyometric training program to ensure alignment with the intendent participant's age, background, and current fitness levels.

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Appendix A

HEALTH QUESTIONNAIRE
FOR PARTICIPATION IN HUMAN SUBJECTS RESEARCH STUDY

Project Title: Neuromuscular Deficits and ACL Injury Risk in Post-Pubescent Adolescent Females

Lewis-Clark State College/University of Idaho

Name: ___________________________________ **Age**: _____________

Height: __________________________________ **Weight**: _____________

Please use the box below to provide injury (ankle sprain, knee injury, etc…) history in the last 2 years:

Leg Dominance

L: ______________ R: ______________

*If you are uncertain of your leg dominance, please ask the researcher for assistance.

Please use the box below to provide information regarding years of sport play. Include type and how many years you have/did engage(d) in this activity

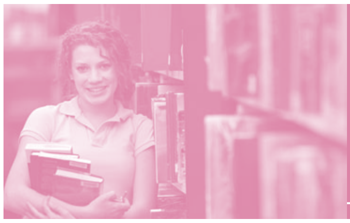
Appendix B

PLYOMETRIC TRAINING INTERVENTION FOR POST-PUBESCENT ADOLESCENT FEMALES

Training Week	Training Volume (Foot Contacts)	Plyometric Drill	Sets X Reps	Training Intensity
Week 1	90	Single-Leg deadlift Jump & Reach Lateral Hop-to-Balance Power Skip	2 X 10 2 X 10 1 X 15 (each) 1 X 10 (each)	Low Low Low Medium
Week 2	140	Single-Leg Deadlift Jump & Reach Lateral Hop-to-Balance Jump to Box Power Skip	2 X 10 2 X 10 (each) 2 X 10 (each) 1 X 10 (each) 1 X 10 (each)	Low Low Low Low Medium
Week 3	120	Squat Jump Single-Leg Squat Jump to Box Lateral Box Jump Jump from Box Power Skip	2 X 10 1 X 10 (each) 2 X 10 1 X 10 (each) 2 X 10 2 X 10	Low Medium Low Medium Medium Medium
Week 4	134	Jump & Reach Single-Leg Deadlift Split Squat Jump Lateral Box Jump Single-Leg Hop Depth-Jump	3 X 10 2 X 10 2 X 6 (each) 2 X 6 (each) 2 X 6 (each) 2 X 6	Low Medium Medium Medium High High
Week 5	136	Jump to Box – SL Jump from Box Double-Arm Bound Single-Leg Hop Depth Jumps	2 X 10 3 X 10 2 X 8 (each) 2 X 6 (each) 3 X 5 3 X 5	High Medium Medium High High High

		Depth Jump to 2nd Box		
Week 6	132	Jump to Box – SL Jump from Box Single-Leg Hop Depth Jumps Depth Jump to 2nd Box Depth Jump w/ LJ	3 X 10 3 X 10 2 X 8 (each) 3 X 5 3 X 5 2 X 5	High Medium High High High High

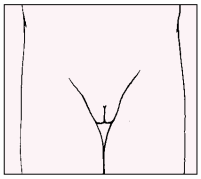
Appendix C



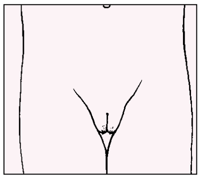
TOOL KIT FOR TEEN CARE, SECOND EDITION

Tanner Staging

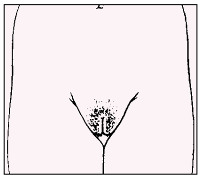
Staging Pubic Hair Development



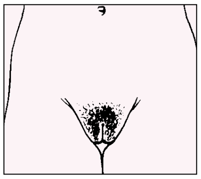
Pubic Hair Stage 1
Prepubertal. The vellus over the pubis is no further developed than that over the abdominal wall, ie, no pubic hair.



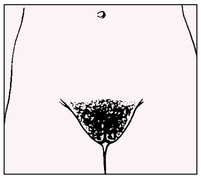
Pubic Hair Stage 2
Sparse growth of slightly pigmented, longer but still downy hair, straight or only slightly curled, appearing chiefly along the labia.



Pubic Hair Stage 3
The hair is considerably darker, coarser, and more curled. The hair spreads sparsely over the mons.

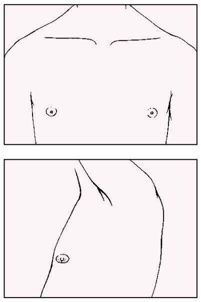


Pubic Hair Stage 4
The hair now resembles adult type. The area covered is still smaller than that in the adult, but the hair is beginning to spread across the mons. There is no hair spread to the medial thighs.

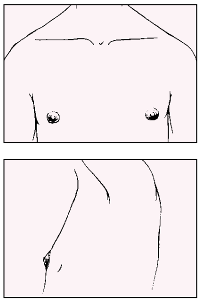


Pubic Hair Stage 5
The hair is adult in type and quantity; darker, coarse, and curled; and distributed in the classic female triangle. Some individuals may have hair spread to the medial thighs.

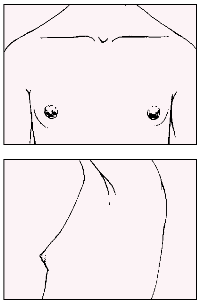
Staging Breast Development



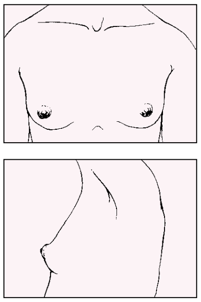
Breast Stage 1
There is no development. Only the papilla is elevated.



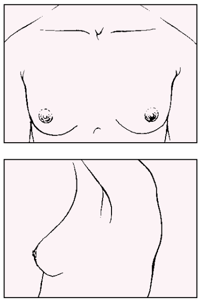
Breast Stage 2
The "breast bud" stage. The areola widens, darkens slightly, and elevates from the rest of the breast as a small mound. A bud of breast tissue is palpable below the nipple.



Breast Stage 3
The breast and areola further enlarge and present a rounded contour. There is no separation of contour between the nipple and areola and the rest of the breast. The breast tissue creates a small cone.



Breast Stage 4
The breast continues to expand. The papilla and areola project to form a secondary mound above the rest of the breast tissue.



Breast Stage 5
The mature adult stage. The secondary mound made by the areola and nipple, present in Stage 4, disappears. Only the papilla projects. The diameter of the breast tissue (as opposed to the height) has extended to cover most of the area between the sternum and lateral chest wall.

Determining the degree of development of pubic hair and the breasts in adolescents is an essential part of the physical examination. Accurate staging provides an important basis for the management of certain clinical problems that may arise throughout puberty. In addition, counseling regarding the expected timing and sequence of pubertal development depends on recording and understanding the stages of development. The above diagrams detail the various stages of secondary sexual development using the system described by Tanner.

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THE AMERICAN COLLEGE OF OBSTETRICIANS AND GYNECOLOGISTS

Appendix D

500 8th Ave
Lewiston, ID 83501

Dear Parent or Legal Guardian,

It is with great excitement that I contact you in regards to a great opportunity for your teenage daughter or dependent. My name is Jessica Savage and I am a Doctoral Candidate in the College of Education and Department of Movement Sciences at the University of Idaho. I am also a full-time faculty member at Lewis-Clark State College where I teach in the Division of Movement and Sport Sciences.

As part of my doctoral program, I am required to complete a Dissertation study. My interests and experience has led me to learning more about the higher incidence and risk of anterior cruciate ligament (ACL) injury in females, and training methods for reducing this risk. Female adolescents who participate in pivoting and jumping activities suffer ACL injuries at a 4- to 6-fold greater rate than do male adolescents participating in the same activities (Hewett et al., 2005). Moreover, most ACL injuries occur during a noncontact episode. At a national level, the cost per injury is estimated at approximately $17,000 (Hewett et al., 1996); surgery and rehabilitation costs associated with female ACL injuries total approximately $646 million annually (Hewett et al., 2005).

Several factors have been suggested as possible links for this increased risk including anatomical, hormonal, and learned movement patterns. While some of these suggested factors are non-modifiable (e.g., anatomical, hormonal), the muscle activation patterns established based on how the adolescent learned to walk, run, jump, etc., is a modifiable factor. If the muscle activation patterns that are in place are faulty, asymmetrical, or non-economical, then the adolescent could be at a risk for an ACL injury. For instance, if an adolescent continually lands from a jump while using more of her front thigh muscles (quadriceps) than she does using her posterior thigh muscles (hamstrings), then there is asymmetry in the muscle activation patterns. This type of asymmetry is very, very common – in fact, everyone has some sort of muscle activation asymmetry present. Even so, the extent of this asymmetry is crucial in identifying at-risk individuals and reducing the risk of ACL injury.

The purpose of this letter is to provide information about the risk of ACL injury and how that risk may be reduced. Plyometric training (jump training) has been suggested as a possible method for remedying some of these muscle activation asymmetries and movement patterns, thereby reducing the risk of ACL injury. As such, it is my hope that you may consider allowing your daughter or dependent to take part in my dissertation study, where I will: a) identify muscle activation asymmetries; b) identify faulty or at-risk movement patterns; and c) use plyometric training to reduce her risk of ACL injury.

This study will be approximately 8 weeks in length, however, plyometric training will comprise 6 of these. Allowing your daughter or dependent to participate in this study would mean the following: a) she will take part muscle activation testing prior to the start of plyometric training; b) she will take part in plyometric training 3 days a week, approximately 15 minutes per session in her physical education class; c) she will take part in muscle activation testing after the 6-week plyometric training is completed.

Muscle activation testing will take place at Lewis-Clark State College in the Kinesiology Laboratory, located in ACW 129. I have worked closely with Sal Lopez and the administration to arrange for transportation from Asotin School District to Lewis-Clark State College, therefore, as the parent or guardian, your involvement in this study is minimal. All participants will make two trips to Lewis-Clark State College, approximately 4 hours in length each visit (one visit prior to the start of plyometric training and one visit after the completion of plyometric training). Muscle activation testing will only take 5-10 minutes per participant. Muscle activation testing is non-invasive and uses surface electrodes adhered to the skin to record muscle activation patterns. Your daughter or dependent will feel nothing in regards to the electrodes recording signals. While your daughter or dependent is not being tested, she will have the opportunity to take a campus tour, visit college courses underway, learn about various degree programs on campus, and participate in physical activity.

My hope is that you will have trust and confidence in my abilities to accurately identify any faulty movement patterns as well as prescribe plyometric training methods which will improve your daughter or dependent's movement mechanics, and inherently decrease her risk of ACL injury. My knowledge and experience is supported by 5 years teaching in movement sciences at the college level, being a Certified Strength and Conditioning Specialist, and being a former high school and collegiate athlete. Moreover, I recently conducted a similar study using plyometric training which involved the Lewis-Clark State College Girls' Basketball team. While the team was very successful this past year, they only sustained one ACL injury, which, ironically, occurred in a contact situation.

Please consider allowing your daughter or dependent to take part in this study. To date, little is known about the effects of plyometric training on muscle activation patterns and reducing the risk of ACL injury in post-pubescent adolescent females. If this risk can be reduced even by a fraction, not only will the emotional and monetary costs associated with ACL injury be lessened, but girls may more confidently and enthusiastically participate in recreational activities – fundamental in living a healthy lifestyle.

Attached you will find a consent form. Details regarding the procedures of the study are explained in greater detail. Please feel free to sign and have your daughter or dependent return the consent form. Additionally, if you have any questions or concerns regarding this study, please feel free to contact me at 208.412.2650 or jjsavage@lcsc.edu. I am more than happy to provide you with any information you would like.

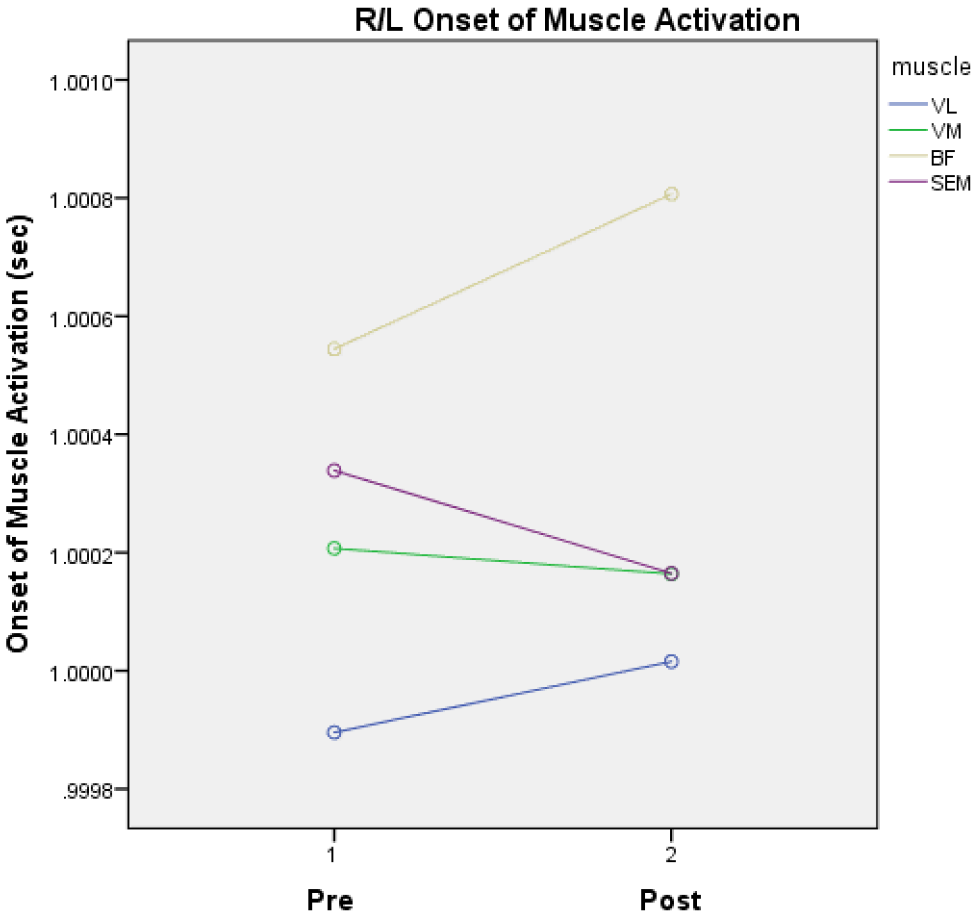
Thank you for your time and consideration,

Jessica Savage, M.S., CSCS
Department of Movement and Sport Sciences
Lewis-Clark State College
Ph.D. Candidate, University of Idaho

Appendix E

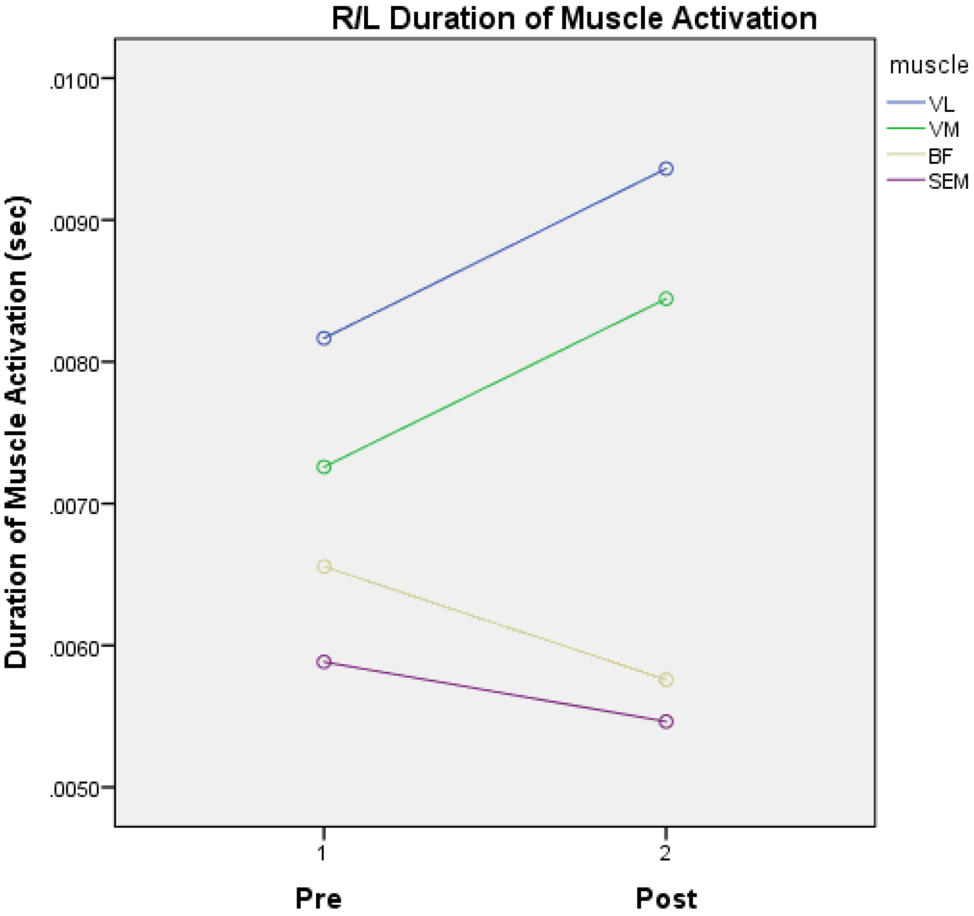
Graph 4.1

Right/Left Leg Onset of Muscle Activation (Pre-/Post-Intervention): VL, VM, BF, SEM



Graph 4.2

Right/Left Leg Duration of Muscle Activation (Pre-/Post-Intervention): VL, VM, BF, SEM



Graph 4.3

Right/Left Leg Time to Peak Muscle Activation (Pre-/Post-Intervention): VL, VM, BF, SEM