INFLUENCE OF CORE NEUROMUSCULAR CONTROL ON PELVIC POSITION
DURING AN OVERHEAD SQUAT

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ABSTRACT

John Bonney: Influence of Core Neuromuscular Control on Pelvic Position during Overhead
Squat
(Under the direction of Darin Padua)

Anterior Pelvic Tilt (APT) is theorized to be an intrinsic risk factor for anterior

cruciate ligament (ACL) injury. There is little research to substantiate this claim, and no

reliable, valid, easy, and clinically relevant test to assess it. The purpose of this study is to

determine what correlations exist between APT, and various bony and neuromuscular

characteristics. To accomplish this, differences in Lumbo-Pelvic Hip Complex (LPHC)

electromyography (EMG), kinematics, Range of Motion (ROM), boney alignment, and the

Double Leg Lowering Test (DLLT) will be compared among physically active participants.

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CHAPTER 1

INTRODUCTION

Between 1999 and 2008 over 6 million knee injuries were treated in emergency rooms, with 49% related to sport or recreation, and 15-24 year olds showing the highest injury rate (Gage, McIlvain, Collins, Fields, & Comstock, 2012). Knee injuries make up a significant percentage of injuries suffered by college athletes, and of those injuries, anterior cruciate ligament (ACL) injury is one of the most devastating an athlete can suffer. ACL injury rates are estimated at 80,000 to 250,000 a year, with 50% of these injuries occurring in young athletes ages 15-25(Griffin et al., 2006).

Multiple neuromuscular risk factors have been proposed for ACL injury, including greater knee valgus angle and knee valgus moment (Hewett et al., 2005), greater hip internal rotation (Besier, Lloyd, Cochrane, & Ackland, 2001), less knee flexion angle (Walsh, Boling, McGrath, Blackburn, & Padua, 2012), smaller hip flexion angle (Blackburn & Padua, 2009), greater proximal tibia anterior shear force (Chappell, Yu, Kirkendall, & Garrett, 2002), lower gluteus maximus activation (Bohdanna T. Zazulak et al., 2005), and greater quadriceps-to-hamstring activation ratio (Chappell, Creighton, Giuliani, Yu, & Garrett, 2007). Each of these proposed neuromuscular risk factors may directly or indirectly increase strain in ACL and predispose one to an ACL injury (Dai, Herman, Liu, Garrett, & Yu, 2012; Hashemi et al., 2011). Thus, understanding factors associated with these proposed neuromuscular risk factors for ACL injury may improve our understanding of ACL injury risk management and prevention strategies.

Lumbo-pelvic hip complex (LPHC) neuromuscular control has gained increased attention as an important factor associated with those proposed neuromuscular risk factors for ACL injury (Bell, Padua, & Clark, 2008; Ingram, Fields, Yard, & Comstock, 2008; Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; Noehren, Hamill, & Davis, 2012; Padua, Bell, & Clark, 2012; B. T. Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). The LPHC is defined anatomically as the abdominals, paraspinals and gluteals, pelvic floor musculature, hip flexors, abductors, and rotators, diaphragm, and hamstrings. Numerous research studies have demonstrated that movement of the LPHC can alter knee kinematics and kinetics, indicating that deficits in LPHC neuromuscular control could increase the risk of knee injury (Jamison, Pan, & Chaudhari, 2012; Popovich & Kulig, 2012; Shirey et al., 2012). For example, Blackburn et al. (2008) demonstrated that an increased trunk flexion angle during a drop landing task was associated with increased hip and knee flexion angles which decreased the forces contributing to ACL loading. Kulas et al. (2012) also demonstrated that increased forward trunk lean during a single leg squat decreased ACL loading. In a separate study by Kulas et al. (2010), increasing trunk load by 10% of body mass resulted in an increase in anterior tibial shear forces and hamstring force dependent on landing posture. In general, these studies demonstrated those who landed in a more erect or extended posture experienced greater forces during functional landing tasks.

Trunk positioning in the frontal and transverse planes has also been shown as a risk factor, with Dempsey et al. (2012) finding that torso lateral flexion and torso rotation in the direction of the catch were significantly correlated with peak knee valgus moment during an overhead catch and landing task. Jamison et al. (2012) conducted a correlational study in which participants performed cutting maneuvers that suggested lateral torso lean may

increase ACL load and risk of injury. Frank et al. (2013) conducted a study looking at the LPHC influence on triplanar knee moments. They found that a greater internal knee varus moment was associated with a greater internal hip adduction moment and trunk rotation displacement away from the stance leg during a side step cutting task. Shirey et al. (2012) found that increased activation of the abdominal musculature during a single leg squat decreased lateral hip displacement. Zazulak et al. (2007) found that increased trunk displacement during a sudden force release task predicted knee injury risk as well, specifically in females. Specifically, those who showed an increased lateral displacement following the release of a counterweighted isometric hold were more likely to suffer a knee injury.

With so much research demonstrating the impact the LPHC has on knee kinematics and kinetics, it has become increasingly clear that there is a detrimental impact on knee motion in individuals with poor LPHC neuromuscular strength and control. One component in particular that has not been studied in depth is the effect anterior pelvic tilt (APT) has on the knee.

Increased APT is frequently theorized to be an underlying factor associated with altered LPHC neuromuscular control and thus may be a risk factor for ACL injury. This concept is based on the fact that as the pelvis is tilted anteriorly, it forces the femoral head posteriorly, which causes internal rotation and adduction (Duval, Lam, & Sanderson, 2010; Hruska, 1998; Ireland, 2002). These two motions are key contributors to the "position of no return" (Ireland, 2002) which has been shown to be a severely detrimental position for the ACL. However, we are unaware of any research that has specifically examined the

relationship between increased APT and lower extremity biomechanics, such as hip internal rotation and adduction.

Several underlying muscle imbalances are proposed to explain the presence of increased APT. Specifically, range of motion deficits in the musculature could contribute to the aforementioned risk factors of excessive APT and femoral internal rotation and adduction. A tight iliopsoas pulling the lumbar spine anteriorly, coupled with a tight erector spinae group bowing the lumbar spine anteriorly could increase lumbar lordosis (LL), while a tight rectus femoris could tilt the pelvis anteriorly, causing femoral internal rotation and knee valgus (Neumann, 2010). The lattisimus dorsi originates from the thoracolumbar fascia, and when tight, can contribute to lumbar lordosis when the arms are forward flexed such as in an overhead squat assessment (OSA) (Neumann, 2010) or when jumping for a rebound in basketball or a block in volleyball. This occurs because the vector of force created by the lats is superior and anterior to the lumbar spine, causing the spine to be pulled in that direction. If these muscles are not lengthened to a functional point, then in theory dynamic motion, such as increased APT, may be altered.

Excessive anterior pelvic tilt could be influenced by the interaction between the muscle activity of agonists and antagonists. Increased activation of the erector spinae and/or hip flexors (rectus femoris and/or iliopsoas) combined with decreased activation of the abdominal and/or hip extensors (gluteus maximus and/or hamstrings) muscles is believed to lead to increased APT (Tateuchi, Taniguchi, Mori, & Ichihashi, 2012). Tateuchi et al. demonstrated that increased activity of the tensor fasciae latae relative to the gluteus maximus and semitendinosus muscles was significantly associated with APT. In addition, decreased gluteus maximus activity in relation to the semitendinosus was indicative of

increased activity of the ipsilateral erector spinae, which again, could contribute to APT. The combination of these muscle imbalances could lead to altered force couples acting on the pelvis in the sagittal plane, thus facilitating increased APT and subsequently altering lower extremity biomechanics associated with ACL injury (Mayer, Verna, Manini, Mooney, & Graves, 2002).

Assessing the LPHC to determine which, if any, of the aforementioned variables are present is an important task that the clinician faces. Several different means have been used to quantify core stability, such as McGill's endurance protocols, the prone plank, the Davies or closed kinetic chain upper extremity stability test, the functional movement screen, sudden force release apparatuses, and video analysis. Among all assessment tools, the double leg lowering test (DLLT) has been shown to be a very reliable predictor of lumbo-pelvic motor control (Krause, Youdas, Hollman, & Smith, 2005). The time required to administer this test is not excessive, but the patient must be trained to posteriorly tilt the pelvis while lowering the legs, and requires two clinicians if a sphygmomanometer is not used. If the sphygmomanometer is used, the clinician must be adept at its utilization while also monitoring the participant's leg angle. Although this test challenges the abdominals effectively (Shields & Heiss, 1997), the body should be positioned in supine, therefore it is not very functional and may not be as applicable to the athletic population. However, because of its reliability, it will be the assessment tool of choice for LPHC neuromuscular control in this study.

The OSA has been used to assess and identify trunk and lower extremity faulty movement patterns in the sagittal and frontal planes (Bell et al., 2008; Butler, Plisky, Southers, Scoma, & Kiesel, 2010; Macrum, Bell, Boling, Lewek, & Padua, 2012; Padua et

al., 2012). It is functional in nature, requires very little equipment or set up, takes very little time, and can be used to assess multiple factors related to dynamic movement based on the relationship between tight/overactive and weak/underactive muscles (Neumann, 2010). However, there has been little research on the validity of the OSA in relation to the LPHC and its strength and neuromuscular control capabilities. To validate the OSA, muscle activity, ROM, and neuromuscular control and strength need to be compared between individuals with excessive APT and those without to determine if there are significant differences between the two.

If the OSA was found to be a valid assessor of LPHC neuromuscular control and strength, it would give further credence to its use as an assessment technique, and provide the clinician with a quick and easy tool to utilize when attempting to assess the LPHC in the sagittal plane for ACL risk factors.

In summation, the purpose of this study is to validate the OSA as a tool to measure APT. Differences between groups of individuals with and without significant APT will be quantified by observing LPHC motion during an OSA (lumbar lordosis), LPHC neuromuscular control during a DLLT, flexibility, EMG activity of trunk and hip flexors and extensors, and trunk and lower extremity kinematics. To date, there is little research looking at the relationship between anterior pelvic tilt and lower extremity kinematics. However, based on what research there is, screening for sagittal plane LPHC neuromuscular control is warranted in ACL injury prevention, and a quick, easy, reliable, and valid tool is needed.

1.1   Variables

- Anterior Pelvic Tilt (in degrees)

- LPHC neuromuscular control score

    o DLLT (in degrees)

- Joint Ranges of Motions

    o Hip Flexors

    o Knee Extensors

    o Knee Flexors

    o Lattisimus Dorsi

    o Triceps Surae

- Kinematics

    o Anterior Pelvic Tilt (Peak)

    o Hip Internal Rotation (Peak and displacement)

    o Hip Adduction(Peak and displacement)

- EMG

    o Erector Spinae

        ▪ Iliocostalis, longissimus

    o Gluteus Maximus

    o Hamstrings

        ▪ Semitendinosus

        ▪ Biceps Femoris

    o Rectus Femoris

1.2 Hypotheses

RQ1: Were there differences in neuromuscular control characteristics in participants with varying levels of APT during an overhead squat?

- o **H$_{A1}$**: Sagittal plane APT angle would be positively correlated with hip adduction and hip internal rotation angle.

- o **H$_{O1}$**: Sagittal plane APT angle will not be positively correlated with hip adduction and hip internal rotation angle.

- o **H$_{A2}$**: Sagittal plane APT angle will be positively correlated with rectus femoris and erector spinae activity, and negatively correlated with gluteus maximus and medial and lateral hamstrings.

- o **H$_{O2}$**: Sagittal plane APT angle will not be positively correlated with rectus femoris and erector spinae activity, and will not be negatively correlated with gluteus maximus, medial and lateral hamstrings activity.

- o **H$_{A3}$:** Sagittal plane APT angle will be negatively correlated with rectus femoris, iliopsoas, triceps surae and lattisimus dorsi ROM, and positively correlated with hamstring ROM.

- o **H$_{O3}$**: Sagittal plane APT angle will not be negatively correlated with rectus femoris, iliopsoas, triceps surae and lattisimus dorsi ROM, and will not be positively correlated with hamstring ROM.

- o **H$_{A4}$**: Sagittal plane pelvic angle during the OSA will be positively correlated with DLLT.

- o **H$_{O4}$**: Sagittal plane pelvic angle during the OSA will be positively correlated with DLLT.

1.3   Operational Definitions

LPHC – the definition provided by previous study (Bliss & Teeple, 2005) will be used to build a case for the Lumbo-Pelvic Hip Complex (LPHC) as the preferred term. The definition is as follows:

> "Anatomically, the core is the musculature that surrounds the lumbopelvic region and includes the abdominals anteriorly, the paraspinals and gluteals posteriorly, the pelvic floor musculature inferiorly, the hip abductors and rotators laterally, and diaphragm superiorly."

In addition, the hip flexors and extensors should be added to this definition, as they play a significant role in pelvic position.

Poor Lumbar Lordosis - Defined relative to parallel longitudinal lines through the trunk and shank in reference to a grid. A distinct curvature of the lumbar spine in reference to a line drawn from C7 to S1 will be denoted as poor.

Good Lumbar Lordosis - Defined relative to parallel longitudinal lines through the trunk and shank in reference to a grid. Little to no curvature of the lumbar spine in reference to a line drawn from C7 to S1 will be denoted as good.

Good Pelvic Control – The pelvis maintains a neutral position with little to no anterior tilt visually determined in reference to the lumbar spine and kinematically determined via the electromagnetic motion capture system.

Poor Pelvic Control – The pelvis tilts anteriorly and is visually determined in reference to the lumbar spine and kinematically determined via the electromagnetic motion capture system.

Assessment Technique – A test designed to assess the degree of core stability present in an individual. The DLLT will be used.

Flexibility – Flexibility will be measured via goniometry using the Thomas test for the hip flexors and rectus femoris, the 90/90 straight leg raise test for the hamstrings, the lat length

test for the latissimus dorsi, and weight bearing, straight, and bent knee measurements of ankle dorsiflexion from 90 degrees.

Muscle Activation – EMG activity of the, erector spinae, gluteus maximus, rectus femoris, rectus abdominis, and medial and lateral hamstrings, which is normalized to EMG activity of maximal voluntary isometric contraction of the designated muscle group.

Physically Active – Participating in physical activity for at least 30 minutes a day 3 times a week.

1.4   Assumptions

o   The instruments used to collect kinematic and EMG data are reliable.

o   The core stability test is a reliable and valid measure of LPHC stability and neuromuscular control.

1.5   Delimitations

o   18 males and 20 females will be selected from a physically active population.

o   Individuals recruited for the study are Division I athletes or physically active students.

o   No history of injury in the last 6 months or current pain in the shoulder, low back, or lower extremity.

o   No history of shoulder, back, abdominal, hip, or knee surgery.

o   All participants will be between the ages of 18 and 25.

1.6   Limitations

o   Unable to control current training status

o   Will not take into account the lateral musculature of the LPHC

- The result of this study will not apply to individuals with LPHC or lower extremity pathologies.
- Excessive foot pronation can affect anterior pelvic tilt.
- Excessive femoral anteversion can affect anterior pelvic tilt.

CHAPTER II

LITERATURE REVIEW

Introduction

The purpose of this literature review is to gain an understanding of the Lumbo-Pelvic Hip Complex (LPHC), specifically current definitions, relation to Anterior Cruciate Ligament (ACL) injury, and assessment techniques. The information gathered will be used to make a case for the need of a simple, timely, reliable, and valid assessment tool that clinicians may use when screening athletes for ACL injury risk. The Overhead Squat Assessment (OSA) has become a valid and reliable tool in assessing faulty movement patterns in participant's trunk and lower extremities (Bell et al., 2008; Butler et al., 2010; Macrum et al., 2012; Padua et al., 2012). However, there has been little, if any, research on the validity of the OSA in relation to the LPHC and its strength and neuromuscular control capabilities in the sagittal plane, specifically in regards to Anterior Pelvic Tilt (APT). If the OSA was found to be a valid assessor of LPHC neuromuscular control and strength, it would give further credence to its use as an assessment technique, and provide the clinician with a quick and easy tool to utilize when screening for ACL injury risk.

Epidemiology

Between 1999 and 2008 over 6 million knee injuries were treated in emergency rooms, with 49% related to sport or recreation, and 15-24 year olds showing the highest injury rate (Gage et al., 2012). Knee injuries make up a significant percentage of injuries

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suffered by college athletes, and of these injuries, ACL injury is one of the most devastating an athlete can suffer. ACL injury rates are estimated at 80,000 to 250,000 a year, with 50% of these injuries occurring in young athletes ages 15-25(Griffin et al., 2006). Females suffer ACL injury at a rate two to eight times higher than males (Toth & Cordasco, 2001). Over a 13 year period, Agel et al. (2005) tracked ACL injury rates in males and females in NCAA basketball and soccer and found that females had a higher injury rate than males in these two sports. Hootman et al. (2007) found that over a 16 year period, out of 5000 ACL injuries suffered by collegiate athletes, female gymnastics had the highest rate of ACL injury, and along with female soccer and basketball, comprised the top four sports for ACL injury including football. Other data has shown that males have a higher overall injury rate, accounting for 57-69% of ACL injuries, but this is for a more diverse population and is based off of surgical databases and insurance records (Csintalan, Inacio, & Funahashi, 2008; Gianotti, Marshall, Hume, & Bunt, 2009; Granan, Bahr, Steindal, Furnes, & Engebretsen, 2008). In addition to the increased rate of ACL injury among females, the re-injury rate is also high. Using the Swedish National ACL Register, Ahlden et al. (2012) found that, out of all female soccer players 15-18 years old who underwent ACL reconstruction, 22% suffered another ACL injury.

Regardless of the injury rates between sexes, ACL injury has been shown to increase the risk for osteoarthritis and thus decrease the quality of life in those with the condition. Thelin et al. (2006) conducted a survey of 825 participants with x-ray verified osteoarthritis using matched controls for age, sex, and residential area. Of those 1650 contacted, 1437 responded. After analyzing the data and accounting for confounding variables, it became apparent that knee injuries, such as a fracture, ligament, or meniscus tear diagnosed by a

physician, were significantly related to the prevalence of osteoarthritis, especially as a result of injuries suffered playing soccer and ice hockey (Thelin et al., 2006).

In addition to the physical harm, ACL injury causes emotional disturbances as well. The immobilization, extensive rehabilitation, and removal from sport and the accustomed lifestyle an athlete is familiar with all contribute to depressive manifestations. In a comparison of emotional responses to concussion and ACL injury, Mainwaring et al. (2010) found that ACL injured patients suffered significantly longer from depression. Whereas the concussed patients showed similar depressive states to the ACL patients close the to the injury, as time progressed depression levels remained higher for ACL injured patients, while depression levels decreased for the concussed, and even ceased, long before the ACL patients.

Another major consideration with respect to ACL injury is the financial impact. The cost of an ACL reconstruction can be upwards of approximately $9,000 for the surgery alone, to say nothing of the rehabilitation and future health care costs. Even when treated conservatively, the cost is still well over $2000 per incident (Farshad et al., 2011). At an estimated rate of 200,000 injuries in the U.S. alone each year, the cost of this injury is substantial to say the least (Brophy, Wright, & Matava, 2009).

With the multitude of factors contributing to the impact that ACL injury has on patients, preventative measures should be pursued to reduce the frequency of these in both sexes, minimize the impact on quality of life, decrease the emotional impact, and curtail costs associated with the injury. A thorough understanding of the risk factors involved with ACL injury and how they can be modified is an important component to this task. Specifically for

this literature review, neuromuscular risk factors will be addressed, as this is related to the

direct purpose of the study, and are perhaps the easiest to modify.

Potential Neuromuscular Risk Factors for ACL Injury

Multiple kinematic risk factors have been proposed for ACL injury, particularly in

females, including greater knee valgus (Ford, Myer, & Hewett, 2003; Malinzak, Colby,

Kirkendall, Yu, & Garrett, 2001; McLean, Huang, Su, & Van Den Bogert, 2004); lesser knee

and hip flexion angle (Blackburn & Padua, 2008, 2009; Chappell et al., 2007; McLean,

Lipfert, & van den Bogert, 2004; Walsh et al., 2012); greater hip adduction(Frank et al.,

2013; Padua et al., 2012) greater hip internal rotation (Ireland, 2002; Pollard, Sigward, &

Powers, 2007); greater proximal tibia anterior shear force (Chappell et al., 2002), and

delayed co-contraction of the hamstrings and quadriceps (Chappell et al., 2007).

One of the most researched kinematic risk factors is knee valgus (Besier et al., 2001;

Brazen, Todd, Ambegaonkar, Wunderlich, & Peterson, 2010; Cashman, 2012; Chappell et

al., 2007; Chappell et al., 2002; Dempsey et al., 2012; Ford et al., 2003; McLean, Huang, &

van den Bogert, 2005; McLean, Lipfert, et al., 2004; Padua et al., 2012; Pantano, White,

Gilchrist, & Leddy, 2005; Pollard et al., 2007) Knee valgus loads the ACL beyond capacity

primarily while the knee is in a partially or fully extended position, and with the additional

component of knee rotation, can apply enough load beyond the normal capabilities of the

ACL to cause a rupture (Besier et al., 2001). Several studies have shown that in vivo, the

ACL is tightest at full extension (Iwahashi et al., 2008; Jordan et al., 2007; Yoo et al.,

2010)which ties in with evidence of lesser knee and hip flexion angles during a jump landing

being a concern (Blackburn & Padua, 2008, 2009). The screw home mechanism in relation to

ACL tension must also be considered. The tibia externally rotates in relation to the femur as full knee extension is reached in an open kinetic chain, providing an added stress to the ACL. In a closed kinetic chain, increased femoral internal rotation accomplishes the same thing (Neumann, 2010). Because of the orientation and attachment of the ACL, anterior tibial translation puts a direct load on the ACL. This may be caused by planting and cutting, anterior force produced by the quadriceps as extension is neared, and/or delayed co-contraction of the hamstrings and quadriceps. Although computer simulations suggest that anterior tibial shear force alone will not rupture an ACL (McLean, Huang, et al., 2004), in conjunction with knee valgus, hip internal rotation, and a latency in hamstring activation, the ACL can easily reach a failing point.

LPHC Contribution to Lower Extremity Neuromuscular Deficits

The core has been described a multitude of ways in the literature. For the purpose of this literature review, the definition provided by Bliss and Teeple (Bliss & Teeple, 2005) will be used to build a case for the Lumbo-Pelvic Hip Complex (LPHC) as the preferred term. The definition is as follows:

> "Anatomically, the core is the musculature that surrounds the lumbopelvic region and includes the abdominals anteriorly, the paraspinals and gluteals posteriorly, the pelvic floor musculature inferiorly, the hip abductors and rotators laterally, and diaphragm superiorly."

In addition to the above, the hamstrings, hip flexors, adductors, and obliques should be included as they play an important role in stabilizing the LPHC. This definition takes into account the fact that the core itself is not solely composed of muscles in the trunk, but muscles of the hip and pelvis as well. This is an important distinction as the muscles of the trunk never act alone, but rather in concert with those of the hip and pelvis to provide both

static and dynamic stability. All these muscles must work together as functional agonists and antagonists to maintain proper musculoskeletal alignment and force couples during movement (Patla, 2003). The term core can lead to vague and imprecise notions when describing this area of the body, and invariably narrows the scope of the discussion. It is with this purpose that LPHC will be used throughout the remainder of this literature review.

Trunk Motion

Lumbo-pelvic hip complex (LPHC) neuromuscular control has been shown to have a significant effect on hip and knee kinematics and kinetics, which may be associated with knee injury if it is not functionally sound (Blackburn & Padua, 2008; Kulas et al., 2012). If the trunk is not held in an advantageous position during dynamic activity, the forces acting on the lower extremities can increase beyond the limits of ACL tissue resilience. An ever expanding amount of research has shown a relationship between the LPHC neuromuscular control hip and knee kinematics and injury risk. The majority of this research has focused on frontal plane risk factors, including knee valgus and hip adduction, but less so on sagittal plane risk factors. Numerous studies are outlined in the following paragraphs to give a more comprehensive picture of this area of study, and are organized by kinematic motions that were of primary interest of this research study.

Sagittal Plane Trunk Motion

Blackburn et al. (2008) showed that an increased trunk flexion angle during a drop landing task was associated with a decreased ACL injury risk. By allowing the trunk to flex more and at the same time the knees, the amount of time the ACL would be subjected to a load would increase, and therefore decrease the amount of force it would have to withstand. This would also help to avoid the high load position of full knee extension discussed earlier.

Kulas et al. (2012) also showed that forward trunk lean during a single leg squat decreased ACL load. In another study, Kulas et al. (2010) concluded that trunk loads increased knee anterior sheer and muscle forces, specifically when the trunk extensors were dominant and the trunk flexors less so. This could theoretically cause a more erect landing posture. The hamstrings also showed greater activation with a flexion dominant strategy, which would help to stabilize the knee and prevent further anterior shear force.

Shirey et al. found that core activation during a single leg squat decreased hip frontal plane motion. After assessing the core neuromuscular control of 14 participants, each subject completed a single leg squat with and without the core engaged. Performance on the single leg squat as measured by medial hip displacement and knee flexion increased significantly, lending credence to the idea that the core does indeed play a significant role in lower extremity kinematics. (Shirey et al., 2012).

Frontal Plane Trunk Motion

Trunk positioning in frontal plane has also been shown as a risk factor for injury, with Dempsey et al. (2012) finding that torso lateral flexion and torso rotation were significantly correlated with peak knee valgus moment. As the trunk is moved away from the body's center of mass, the lower extremities are put into compromising situations which are difficult to recover from. If the athlete does not have the capabilities to correct this position before landing the risk of injury is increased.

Popovich et al. (2012) compared single leg landing kinematics in two groups, one with normal gluteus medius and maximus strength and one with poor strength. They found significant differences between the two groups in peak frontal plane angular displacement,

and total angular excursion in all planes of motion. In other words, weak gluteus medius and maximus muscles allowed for greater trunk motion and affected knee kinematics adversely.

Jamison et al. (2012) conducted research that suggested torso lean may increase ACL load and risk of injury. Specifically, as trunk lateral flexion occurs, the hip is adducted and the foot abducted without proper hip abductor activation, contributing to the aforementioned position of no return.

Leetun et al. (2004) looked at LPHC factors contributing to injury and found that male and female athletes who suffered injury had significantly less hip external rotation and hip abduction strength than the uninjured athletes. Additionally, females displayed decreased side bridge endurance.

Zazulak et al. (2007) found that deficits in trunk neuromuscular control predicted injury risk as well, particularly in females. By utilizing a sudden force release apparatus to measure the core musculatures ability to activate quickly and control trunk displacement, 277 collegiate athletes were assessed. 25 injuries were recorded over a 3 year period, with those who had poor trunk activation suffering more knee, ligament, and ACL injuries than uninjured athletes.

Frontal and Transverse Plane Knee and Hip Motion

Padua et al. (2012) looked at muscle activation patterns for healthy participants during a double leg squat task and found that the hip adductors, gastrocnemius, and tibialis anterior had increased activation levels in those displaying medial knee displacement. The tight adductors could in theory lead to inhibited hip abductors, and thus compound the issue.

With this growing body of evidence pointing to a relationship between trunk position and ACL loading during dynamic activity, further research to aid in assessing this risk factor

must be undertaken. A relationship between anterior pelvic tilt and femoral internal rotation

has been suggested (Duval et al., 2010; Hruska, 1998; Ireland, 2002), and a study by

McKeon et al. (2009) showed significantly more anterior pelvic tilt in women compared to

men, which could be a contributing factor to the increased ACL injury rates in women.

Anterior pelvic tilt is associated with increased lumbar lordosis, femoral internal rotation,

tibial external rotation, and foot pronation (Duval et al., 2010; Hruska, 1998; Ireland, 2002;

Joseph et al., 2008; Khamis & Yizhar, 2007; Pinto et al., 2008). These all contribute to the

"position of no return" in which video analysis has shown to be the most common position

for non-contact ACL injury. In short, anterior pelvic tilt may cause a host of lower extremity

kinematic changes.

Range of Motion

Range of motion deficits in the musculature of the LPHC can contribute to

many of the aforementioned risk factors. Overactive hip flexors, knee extensors, or

trunk extensors can increase anterior pelvic tilt and lumbar lordosis (Neumann, 2010;

Tateuchi et al., 2012). A tight iliopsoas pulling the lumbar spine anteriorly, coupled

with a tight erector spinae group bowing the lumbar spine anteriorly could increase

APT, while a tight rectus femoris could tilt the pelvis anteriorly as well as causing

femoral internal rotation and knee valgus (Neumann, 2010). The lattisimus dorsi

originates from the thoracolumbar fascia, and when tight, could contribute to lumbar

lordosis when the arms are forward flexed such as in an overhead squat assessment

(OSA) (Neumann, 2010) or when jumping for a rebound in basketball or a block in

volleyball. Tight or overactive triceps surae can contribute to knee valgus during

double leg squat tasks as well, further enhancing the negative impact tight

musculature has on kinematics (Bell et al., 2008; Macrum et al., 2012; Padua et al., 2012). If these muscles are not lengthened to a functional point, dynamic motion will be altered to a potentially injurious point.

Electromyography

Assessing the level of activation for the erector spinae, gluteus maximus, rectus femoris, and medial and lateral hamstrings through electromyography (EMG) will allow for possible differentiation between contributing factors to anterior pelvic tilt. If the longissimus and rectus femoris muscles become tight they can lead to inhibited antagonists, specifically the gluteus maximus, hamstrings, and rectus abdominus, which further contribute to anterior pelvic tilt (Neumann, 2010; Workman, Docherty, Parfrey, & Behm, 2008)

If the erector spinae and rectus femoris muscles are found to be overactive and the gluteus maximus, rectus abdominis, and hamstring muscles are found to be underactive in participants with an increased anterior pelvic tilt, the connection could be made that a weak LPHC (specifically in the sagittal plane) is a risk factor for ACL injury. Mayer et al. (Mayer et al., 2002) looked at EMG activity for the erector spinae, gluteus maximus, and hamstrings during a Roman chair back extension exercise. It was found that femoral internal rotation caused an increase in trunk extensor activity, theoretically because the gluteus maximus was put at a biomechanical disadvantage as an extensor. It could then be theorized that an athlete with a weak gluteus maximus would tend to display an increased anterior pelvic tilt. This could in turn contribute to femoral internal rotation and the rest of the precipitating factors associated with the position of no return.

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EMG analysis during the OSA itself would shed further light on the activation levels of the hip and spinal flexors and extensors during dynamic motion. Clark et al. (Clark, Manini, Mayer, Ploutz-Snyder, & Graves, 2002) looked at activation patterns during a trunk extension exercise regimen that was based on different percentages of maximum voluntary isometric contraction. It was discovered that at varying intensities the spinal extensors and hip extensors had varying degrees of activation. Although this can be used to make a general statement about the role the muscles play, it cannot be extrapolated to functional movement. In order to accomplish this, valid and reliable assessment techniques for the LPHC must be utilized. The Overhead Squat Assessment (OSA) has become a reliable tool in assessing faulty lower extremity movement patterns in participants (Bell et al., 2008; Butler et al., 2010; Macrum et al., 2012; Padua et al., 2012). It is functional in nature, requires very little equipment or set up, takes very little time, and can be used to assess multiple factors related to dynamic movement based on the relationship between tight/overactive and weak/underactive muscles. However there has been little, if any, research on the validity of the OSA in relation to the LPHC and its strength and neuromuscular control capabilities. If the OSA was found to be a valid assessor of LPHC neuromuscular control and strength, it would give further credence to its use as an assessment technique, and provide the clinician with a quick and easy tool to utilize.

While there are clearly multiple factors to take into account, anterior pelvic tilt is one that has garnered little, if any, interest. The ability to quickly and accurately assess this with a simple clinical tool could help identify those individuals at risk and allow appropriate interventions to be applied. With this in mind, this study will look at how anterior pelvic tilt

is affected by LPHC neuromuscular control, and flexibility, and whether an overhead squat

assessment (OSA) can be a valid tool to assess this potential risk factor.

LPHC Assessment Techniques

Assessing the level of activation for the erector spinae, gluteus maximus, and

medial and lateral hamstrings through electromyography (EMG) will allow for

possible differentiation between contributing factors to APT. If the erector spinae

muscles are found to be overactive and the gluteus and hamstring muscles are found

to be underactive in participants with an increased APT, the connection could be

made that a weak LPHC (specifically in the sagittal plane) is a risk factor for ACL

injury. Mayer et al. (Mayer et al., 2002) looked at EMG activity for the erector

spinae, gluteus maximus, and hamstrings during a Roman chair back extension

exercise. It was found that femoral internal rotation caused an increase in trunk

extensor activity, theoretically because the gluteus maximus was put at a

biomechanical disadvantage as an extensor. It could then be theorized that an athlete

with a weak gluteus maximus would tend to display an increased APT. This could in

turn lead to an increased APT, which would then contribute to femoral internal

rotation and the rest of the precipitating factors associated with the position of no

return.

APT has been shown to increase femoral internal rotation which has been shown as a

risk factor for knee injury (Hruska, 1998; Ireland, 2002; Walker, Rothstein, Finucane, &

Lamb, 1987). EMG analysis during the OSA itself would shed further light on the activation

levels of the hip and spinal extensors during dynamic motion. Clark et al. (Clark et al., 2002)

looked at activation patterns during a trunk extension exercise regimen that was based on

different percentages of maximum voluntary isometric contraction. It was discovered that at varying intensities the spinal extensors and hip extensors had varying degrees of activation. Although this can be used to make a general statement about the role the muscles play, it cannot be extrapolated to functional movement. In order to accomplish this, valid and reliable assessment techniques for the LPHC must be utilized. The Overhead Squat Assessment (OSA) has become a reliable tool in assessing faulty lower extremity movement patterns in participants (Bell et al., 2008; Butler et al., 2010; Macrum et al., 2012; Padua et al., 2012). It is functional in nature, requires very little equipment or set up, takes very little time, and can be used to assess multiple factors related to dynamic movement based on the relationship between tight/overactive and weak/underactive muscles. However there has been little, if any, research on the validity of the OSA in relation to the LPHC and its strength and neuromuscular control capabilities. If the OSA was found to be a valid assessor of LPHC neuromuscular control and strength, it would give further credence to its use as an assessment technique, and provide the clinician with a quick and easy tool to utilize.

While there are clearly multiple factors to take into account, anterior pelvic tilt is one that has garnered little, if any, interest. The ability to quickly and accurately assess this with a simple clinical tool could help identify those individuals at risk and allow appropriate interventions to be applied. With this in mind, this study will look at how anterior pelvic tilt is affected by LPHC neuromuscular control, and flexibility, and whether a dynamic overhead squat assessment (OSA) can be a valid tool to assess this potential risk factor.

The current favored LPHC assessment tools are the double leg lowering test, McGill's endurance protocols, variations of the prone plank, the Davies test, video analysis, certain aspects of the functional movement screen (FMS), and sudden force release

apparatuses. There are reasons for and against the use of each, which are briefly discussed below.

Double Leg Lowering Test (DLLT)

The DLLT has been shown to be a very reliable predictor of lumbo-pelvic motor control(Krause et al., 2005). It is similar in execution to the Sahrmann core stability test (Aggarwal, Kumar, Madan, & Kumar, 2011), but is simpler and requires fewer steps. Krause et al (2005) found an intratester reliability of 98% with the DLLT. The drawbacks with this test are the time, tools, and precision involved with its execution. In order to accurately use the test, one must have a method for measuring the angle of the legs. Multiple options have been employed, including digital goniometers, handheld goniometers, and angle charts set up on the opposite side of the participant from the clinician. The question of how to determine the level of LL which is cause for cancelation of the test is an issue as well. Some research has suggested that pelvic tilt occurs immediately upon lowering of the legs, and therefore needs to be assessed with more than just palpation of the lumbar spine by the clinician(Zannotti, Bohannon, Tiberio, Dewberry, & Murray, 2002). To accomplish this, a pressure cuff must be used, adding yet another confounding element to the testing procedure. In addition, if a participant has inflexible hamstrings the starting position of the legs will be less than 90° and variable between patients.

McGill's Endurance Protocols

McGill's endurance protocols are used to test for gross endurance of the LPHC (S. M. McGill, Childs, & Liebenson, 1999). The flexion, extension, and lateral flexion tests have all been found to be very reliable predictors of LPHC endurance. The drawback to these tests is the amount of time and set up required to carry them out, and does not necessarily show the

level of LPH neuromuscular control a participant may have in the same manner the DLLT does. Although the side bridge is quickly administered, the flexion and extension tests require more setup and planning, and all the tests are isometric contractions timed to fatigue and therefore non-functional.

Prone Plank

One of the most common tests of LPHC endurance is the prone plank. Despite its popularity as an assessment tool, very little research has been done on its reliability. There are multiple start positions and multiple deviations from that position that can confound the results. In order to control these problems, an objective measure of termination such as the one used by Cowley et al. (2009) must be employed. Again, this is time consuming and requires extra equipment and training in its use.

Davies Test

The Davies Test, or closed kinetic chain upper extremity stability test (Goldbeck & Davies, 2000) looks at a more dynamic assessment of the LPHC, and incorporates the shoulders. Although primarily a test for upper body functional stability, the test has been used to assess the LPHC because of the high stabilization demand on the LPHC during its execution as a result of only having three points of contact with the ground in a non-linear relationship.

Video Analysis

Video analysis tools have been used to assess LPHC endurance as well. In one study (McDonald et al., 2011), gymnasts were recorded performing isometric endurance exercises and then analyzed with a software program that measured the participants deviation from the

start point to objectively give an end time for the test. It was shown to be very reliable, but clearly was much more involved than the tests mentioned previously.

Functional Movement Screen

The Functional Movement Screen has been used to assess LPHC stability(Butler et al., 2010; Minick et al., 2010; Onate et al., 2012; Smith, Chimera, Wright, & Warren, 2012; Teyhen et al., 2012) via the rotary stability test and the trunk stability pushup. While these assessments are purported to provide information on functional asymmetries that may lead to injury, they have not been validated as tests for LPHC stability in any research to this point. Further research is needed before the FMS can be validated as a tool to assess LPHC stability.

Sudden Force Release Apparatuses

Sudden force release apparatuses have been used to assess neuromuscular control in the trunk specifically (B. T. Zazulak et al., 2007). Participants that demonstrated delayed firing patterns in their trunk were found to be at higher risk for knee injury. Although this assessment technique shows promise, it is a sophisticated laboratory tool, and does not allow the hip musculature to play any part in the assessment.

Overhead Squat Assessment

The overhead squat assessment has become a valuable tool in the clinician's arsenal for determining faulty movement patterns so that a proper intervention may be prescribed. Although there have been studies showing its efficacy for the assessment of lower extremity dysfunction (Bell et al., 2008; Macrum et al., 2012; Padua et al., 2012; B. T. Zazulak et al.,

2007), no studies were found validating its use to assess the sagittal plane motor control of the LPHC.

In theory, excessive APT would be associated with weak glutes, hamstrings, rectus abdominis, and the deeper muscles of the LPHC as discussed earlier. Possible overactive muscles would include the hip flexors, erector spinae, and latissimus dorsi. Therefore it would seem plausible to say that a participant with a weak LPHC would display APT. This basic theoretical model would allow the OSA to be used as an assessment tool.

A drawback to using this technique would be the lack of assessment for the lateral musculature of the trunk, particularly the internal and external obliques, and quadratus lumborum (QL). The QL has been shown to play an important role in spinal stability, primarily in the frontal plane (S. McGill, Juker, & Kropf, 1996; S. M. McGill et al., 1999), but is out of the scope of this study.

Proposed Assessment Techniques

There are numerous assessment techniques available for evaluation of the LPHC, and there is minimal literature to link the different tests together in terms of their validity (Aggarwal et al., 2011). In addition, many of these tests require more time and effort than many clinicians have to devote to the assessment, and therefore are less likely to be used. By assessing APT during an OSA, and comparing the results with those of a battery of tests designed to encompass multiple aspects in the sagittal plane musculature (McGill's endurance protocols, DLLT), a relationship may be found which would enable the clinician to make a direct connection to lumbo-pelvic motion and LPHC neuromuscular control in the sagittal plane.

In summation, the purpose of this study is to validate the OSA as a tool to measure APT. Differences between groups of individuals with and without significant APT will be quantified by observing LPHC motion during a OSA, LPHC neuromuscular control and endurance, flexibility, EMG activity of trunk and hip extensors, and trunk and lower extremity kinematics. To date, there is little research looking at the relationship between APT and lower extremity kinematics. However, based on what research there is, screening for sagittal plane LPHC neuromuscular control is warranted, and a quick, easy, simple, and valid tool is needed.

CHAPTER III

METHODS

Experimental Design

A correlational study design was used to investigate relationships between LPHC neuromuscular control and boney characteristics in individuals with varying degrees of APT. During the testing session, each participant underwent a series of tests, including a navicular drop assessment, femoral anteversion assessment, ROM assessment of the lower extremity and lattisimus dorsi, three-dimensional motion analysis of APT, and EMG assessment of the erector spinae, gluteus maximus, rectus femoris, rectus abdominis, and medial and lateral hamstrings during an OSA, and the DLLT test.

Participants

To achieve a power of 0.80 for the study, a sample of 40 participants were chosen based on research by, Ford et al. (2003), McLean et al. (2005), and Pantano et al. (2005) and the study conducted in our laboratory. 18 male and 20 female participants with varying degrees of APT were selected for the study. Participants were selected from a convenience sample of Division I athletes taken from all available sports and the physically active (3 times a week for at least 30 minutes) student population.

Inclusion and Exclusion Criteria

- Participants were included in the study if they meet the following criteria:
    - Ages between 18 and 25.

- o Athletes who played sports at the Division I level or physically active individuals who were active at least 3 times a week for 30 minutes.
- Participants were excluded if they meet at least one of the following:
  - o History of low back, abdominal, hip, knee, ankle or shoulder injuries (ligament sprains, muscle strains, and any chronic pain) within 6 months prior to the testing session.
  - o

Instrumentation

- Electromagnetic motion capture system (MotionStar, Ascension Technology Corporation, Burlington, VT.) integrated with extended range transmitter (Ascension Technology Corporation, Burlington, VT) and 5 Ascension Flock of Birds electrical magnetic trackers will be used to sample Lumbar, hip, and knee kinematics during the task at a sampling frequency of 100 Hz (Blackburn & Padua, 2009).
- Surface electromyography (Delsys, Inc., Boston, MA; amplification factor = 1,000 (20 – 450 Hz); CMRR @ 60 Hz > 80 dB; input impedance > 10^{15}//0.2 Ω//pF) will be used to record muscle activity of the rectus femoris, gluteus maximus, medial and lateral hamstrings, and erector spinae at 1000 Hz (Blackburn & Padua, 2009; Padua et al., 2012)
- A nonconductive force plate (4060-08, Bertec Corporation, Columbus, Ohio, USA) will be used to sample ground reaction forces using a sampling frequency of 1000 Hz (Blackburn & Padua, 2009; Kulas et al., 2010).
- A digital inclinometer (12-1057, Baseline Evaluation Instruments) was used to hip flexor/rectus femoris, hamstring, triceps surae, and latissimus dorsi range of motion.

- Participants performed the DLLT on a 1.5cm thick dense foam exercise pad.

Procedures

The participants reported for one testing session. The primary investigator provided an overview of the study, had participants complete a consent form, and provided an opportunity for participants to ask questions. Once consenting to participate in the study, participants were asked to remove their shoes and fitted with compression shorts and a sports bra for females, and compression shorts for males. Each participant's height and weight was recorded. The participant completed a five minute stationary cycle warmup before being taught how to perform an overhead squat. While in front of a black background, the participant stood with feet shoulder width apart, toes pointed straight ahead, and arms fully flexed overhead. The participant was instructed to squat as if they were sitting down in a chair and was encouraged to reach 90° of knee flexion by lightly touching a box with their buttocks. Each participant performed 5 overhead squats to the beat of a metronome set at approximately 25 squat cycles/minute (scm) or 80 bpm to control the velocity of performance across the participants (Boling, Padua, Blackburn, Petschauer, & Hirth, 2006).

Boney Alignment Assessment

The navicular drop test was used to classify participants as having normal or clinically relevant pronation. The clinician palpated the most medial aspect of the navicular tuberosity while the participant was non-weight bearing and in subtalar joint neutral. This spot was marked and the distance from the floor recorded on an index card. The participant then stood in full equal bilateral weight bearing on the foot being measured and the distance from the marked spot to the ground was recorded again (Gross, 1995).

The femoral anteversion test, or Craig's test, was used to assess the degree of femoral anteversion in each participant. The participant lay prone with the knee flexed to 90°. The clinician then palpated the greater trochanter while rotating the femur internally and externally. When the trochanter was at its most lateral aspect the angle of the tibia from vertical was measured using a digital inclinometer zeroed at vertical and aligned with the shank (Gross, 1995).

Range of Motion Assessment

Each participant was assessed for hip flexor, rectus femoris, hamstring, triceps surae, and latissimus dorsi ROM. An average of three trials wasrecorded as the passive range of motion in degrees.

The hip flexor and rectus femoris were assessed using the Thomas test. Each participant stood with his/her gluteal crease on the edge of a table, pulled one knee as close to their chest as possible, and lay back supine allowing one leg to slowly extend as the clinician palpated the anterior superior iliac spine to ensure lumbar lordosis remained minimal (Harvey, 1998). A digital inclinometer wwas zeroed along the horizontal world axis and aligned with the femur at the midpoint between the ASIS and the patella, and the angle recorded. The inclinometer was thenplaced on the anterior edge of the mid-tibia and the angle recorded (Ferber, Kendall, & McElroy, 2010). (Figure 1)

Hamstring range of motion for each participant was measured using a passive 90/90 hamstring assessment. The participant lay supine on a table, and a digital inclinometer with a straight edge attached to it was used to ensure the femur a\was at 90°. The research assistant then passively extended the knee until reaching the end range of motion, at which point the

primary investigator placed the digital inclinometer on the anterior edge of the mid-tibia and record the angle as measured from 0° at vertical (Fasen et al., 2009). (Figure 2)

To assess range of motion for the triceps surae, each participant wasinstructed to lay supine with the heels off the edge of the table. A goniometer aligned with the fibula and centered at the distal malleolus was set parallel to the 5th metatarsal and all measurements taken from 90° as the participant was passively dorsiflexed (Figure 3). The participant lay prone with the knee bent to 90° as determined by the goniometer, with the fixed arm parallel to the femur and the movement arm parallel with the fibula, and the same measurement was taken as with the supine assessment (Figure 4). The weight bearing dorsiflexion range of motion assessment required the participants to stand with their second toe on a line bisecting their heel, and attempt to touch the knee to another vertical line on the wall in front of them. They gradually slid their foot away from the wall until they could barely touch the wall with their knee. At that point the digital inclinometer was placed at approximately the midway point of the anterior tibia and the result recorded (Rabin & Kozol, 2012). (Figure 5)

For latissimus dorsi range of motion, each of the participants was instructed to stand with their feet far enough from a wall so that the lower back could be flattened against it. The participant was instructed to actively forward flex the shoulders so that the thumbs were in the sagittal plane and to attempt to touch the wall behind them. The clinician palpated the lumbar spine and asked the participant to stop in the position at which he/she could no longer maintain wall contact so that the angle could be recorded. A digital inclinometer zeroed at vertical and attached to a straight edge was aligned with the participant's humerus. (Borstad & Briggs, 2010; Rose, 2006) . (Figure 6)

Electromyography (EMG)

Electrode placement sites for GMAX, medial and lateral hamstrings, rectus femoris, and erector spinae were shaved if needed, abraded with a coarse sponge, and cleaned with isopropyl alcohol and allowed to dry before electrode placement. Electrodes were placed parallel with the muscle fibers, with the reference electrodes on the bilateral acromion processes. The electrodes were fixated to each muscle using a double-sided adhesive skin interface (Delsys, Inc., Boston, MA) and secured using surgical tape and non-woven retention tape (Hartmann USA, Inc., Rock Hill, SC). An active contraction through the muscles full ROM was used to confirm EMG placement for all muscles tested. Activity of each muscle was recorded during maximal voluntary isometric contraction (MVIC) and OHA described below.

MVIC was collected post-assessment using the techniques described by Bolgla et al. (Bolgla & Uhl, 2007). Participants generated maximum force over a two second period and held it for five seconds while the clinician provided strong verbal encouragement.

For the rectus femoris, the participant was positioned supine with the knee in slight flexion. The electrodes were positioned half way between the anterior superior iliac spine and the superior pole of the patella. The participant extended the knee against manual resistance to confirm electrode placement and then MVIC was collected at the end of the session.

Erector spinae electrode placement was broken into the illiocostalis and longissimus muscles. For the illiocostalis, the participant lay prone in a slightly flexed position and the electrodes were placed approximately one finger width medial from the line between the posterior superior iliac spines to the lowest point of the lower rib at the L2 level. The participant then lifted the trunk off the table to confirm EMG placement and then MVIC was

collected at the end of the session. For the longissimus, electrodes were placed 2 finger widths lateral from the spinous process of L1. The participant again lifted the trunk to confirm EMG placemen and then MVIC was be collected at the end of the session.

For GMAX, electrodes were placed halfway on the line between the sacral vertebrae and the greater trochanter. From a prone position, the participant lifted the leg with the knee flexed to 90° against manual resistance to confirm EMG placement and then MVIC was collected at the end of the session.

Hamstring electrode placement was broken into the biceps femoris and semitendinosus muscles. For the biceps femoris, electrodes were placed halfway between the ischial tuberosity and the lateral epicondyle of the tibia. From a prone position, the participant attempted to flex the knee at 90 degrees against manual resistance to confirm EMG placement. For the semitendinosus, electrodes were placed halfway between the ischial tuberosity and the medial epicondyle of the tibia. From a prone position, the participant attempted to flex the knee at 90 degrees against manual resistance to confirm EMG placement and then MVIC was collected at the end of the testing session. All electrode placements were determined through guidelines set forth by the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles organized by the Biomedical Health and Research Program (BIOMED II) of the European Union(Freriks)..

Wires and sensors were secured to the skin with non-woven retention tape and surgical tape to prevent motion artifact. All wires were held together by Velcro ties to prevent excess noise in the EMG signal.

Kinematics Assessment

All kinematic sensors were applied using double sided tape, non-woven retention tape, prewrap, and athletic tape to achieve secure fixation. A segment linkage model was used, with the spinal sensors placed on the T2 and T10 spinous process, and spinal column landmarks digitized at T12-L1 and C7-T1. The sacral sensor was placed directly over the S1 spinous process and both ASIS were digitized. The femoral sensor was placed at approximately the midpoint of the right shank, at the space between the vastus lateralus and biceps femoris on the midpoint of the right lateral thigh. The shank sensor was placed on the midpoint of the medial tibia and the foot sensor was placed on the dorsum of the foot over the navicular. A right hand coordinate system was used to establish a world and segment axis system in which the positive direction for the x-axis was anterior, the y-axis was medial, and the z-axis was superior (Blackburn & Padua, 2008, 2009; Padua et al., 2012).

Each participant performed 5 overhead squats to the beat of a metronome set at approximately 25 scm. The participants stood with feet shoulder width apart, toes pointed straight ahead, and arms fully flexed overhead. The participants were instructed to squat as if they were sitting down in a chair and were encouraged to reach 90° of knee flexion as determined by a box placed behind the participant which they touched lightly each time. Joint angle displacement wasmeasured starting at the first movement of the participant's knee to the peak flexion angle during the decent phase.

DLLT

Each selected participant underwent a DLLT. The average of 2 trials was taken with a 1 minute rest between each trial. The participant lay in the hook lying position and transverse abdominis activation was taught through demonstration by the investigators, verbal cueing including "pull your belly button to your spine," "make yourself as skinny as possible," and

"swallow your stomach," and tactile cueing through palpation of the lower abdominals just medial to the anterior superior iliac spines. Patients were then instructed on how to posteriorly tilt the pelvis and flatten the lumbar spine against the table through demonstration and verbal cueing including "tuck your tailbone," and "roll your hips back." Next, the primary investigator placed one hand under the lumbar spine and palpated the spinous processes. The participants legs were passively raised as close to 90° as possible, and then actively lowered during a 10 second countdown. As soon as the lumbar spine came off the primary investigators finger tips, the research assistant held the legs, and the angle was measured using a digital inclinometer zeroed at horizontal taped to a straight edge and aligned with the femur (Krause et al., 2005; Stanton, Reaburn, & Humphries, 2004). (Figure 7)

Data Processing and Reduction

Data was synchronized using the Motion Monitor software for kinematics, and EMG. Kinematic data was low pass filtered at 10 Hz with a 4th order, zero phase lag Butterworth filter (Blackburn & Padua, 2009).

A right hand coordinate system was used to establish a real world axis system in which the positive direction for the x-axis is anterior, the y-axis is medial, and the z-axis is superior. A segment linkage model was used. Pelvic tilt angle was determined using the pelvic segment relative to the world. The joint center for the hip was estimated by using the Bell method Joint displacement was determined by subtracting minimal joint angle at the first movement of the participant during the decent phase of the overhead squat task from the peak knee flexion angle (Joint displacement = Max joint angle during descending phase – initial joint angle).

EMG was bandpass filtered (20-350Hz) and notch filtered (59.5-60.5Hz) using a 4th order Butterworth filter. EMG was smoothed using a 25ms root mean square sliding window function. Mean EMG amplitude of each muscle during the OSA was normalized to mean amplitude of each muscle during MVIC (% MVIC). Range of motion assessments were averaged over 3 trials, and DLLT scores were in displacement in degrees from horizontal.

Statistical Analysis

Our primary aim was addressed by calculating Pearson product moment correlation coefficients between sagittal plane pelvic angle during the descending phase of an overhead squat with lower extremity kinematics, range of motion, and muscle activation measures. Our secondary aim was addressed by calculating Pearson product moment correlation coefficients between sagittal plane pelvic angle and the double leg lowering test measure. For both our primary and secondary aims, we hypothesized that correlation coefficients would range from $r = 0.50$ to $r = 0.75$ (moderate to strong relationships) for each of the different dependent variables. Based on a sample size of 38 participants and a probability of Type 1 error (a) rate of 0.05, our Correlation (ρ) are all greater than 0.95P.

CHAPTER 4

RESULTS

APT has been proposed as a possible risk factor for ACL injury, although there is little

research to support this . The purpose of this study was to determine what neuromuscular and bony

characteristics are associated with APT and if APT could be determined via lumbar lordosis during an

overhead squat. Subject's flexibility, bony characteristics, muscle activity, and trunk and lower

extremity kinematics were used to look for correlations with APT.

Twenty females (age=20.35 yrs ± 0.88, height=166.96 ± 6.88, weight=62.51 ± 9.91) and 18

males (age=21.00 yrs ± 1.37, height=177.54 ± 7.23, weight=75.29 ± 8.66) participated in the study

(Table 1). EMG data were eliminated once for the rectus femoris, erector spinae, illiocostalis, and

medial hamstrings, and 3 times for the biceps femoris because of values outside the normal range.

We observed significant correlations between anterior pelvic tilt and EMG of the gluteus

maximus ($r_{(38)}$=0.40, p=0.01)(**Figure 8**) and the longissimus ($r_{(37)}$=0.33, p=0.05)(**Figure 9**). We did

not observe any significant correlations between anterior pelvic tilt and any of the other EMG values,

range of motion, boney alignment, kinematics, or double leg lowering test.

Table 1 – Age, height, weight, sex, navicular drop, Craig's test, and amount of peak APT during
descending phase.

Variable	Mean	SD
Age (years)	20.66	1.17
Height (cm)	171.97	8.77
Weight (kg)	68.56	11.25
R Navicular Drop (mm)	7.29	2.63
L Navicular Drop (mm)	6.50	2.60
R Craig's Test (Deg)	9.53	3.70
L Craig's Test (Deg)	7.32	3.12
Peak APT During Descending	32.16	7.19

Phase (Deg)

Table 2 – ROM, DLLT

Range of Motion/DLLT (Degrees)	Mean	SD
R Hip Flexor	0.54	7.79
L Hip Flexor	1.54	8.59
R Rectus Femoris	63.04	10.40
L Rectus Femoris	63.79	9.07
R Hamstring	13.35	9.25
L Hamstring	11.29	8.34
R Gastrocnemius	15.44	5.54
L Gastrocnemius	11.95	6.20
R Soleus	27.83	7.31
L Soleus	26.75	8.09
R Weight Bearing Dorsiflexion	44.50	5.92
L Weight Bearing Dorsiflexion	44.71	6.66
R Latissimus Dorsi	19.52	9.07
L Latissimus Dorsi	18.51	9.00
Double Leg Lowering Test	30.49	14.75

Table 3 – EMG during descending phase of OSA

EMG	Mean	SD
Rectus Femoris	44.32	24.60
Lateral Hamstring	9.88	5.03
Medial Hamstring	8.43	6.04
Gluteus Maximus	9.49	8.55
Illiocostalis	30.57	20.67
Longissimus	35.01	12.78

Table 4 – Joint angles during descending phase of OSA

	Descending Phase Peak Value		Descending Phase Displacement	
	Mean	SD	Mean	SD
Hip Adduction	-0.35	4.85	1.12	3.00
Hip Abduction	-9.47	7.04	-8.00	4.95
Hip Internal Rotation	17.45	15.98	11.36	9.53

Table 5 – Correlations between APT and Boney Characteristics

Variable	R-Value	P-Value
R Navicular Drop (mm)	-.11	.51
L Navicular Drop (mm)	-.07	.68
R Craig's Test (Deg)	.20	.23
L Craig's Test (Deg)	.21	.21

Table 6 – Correlations between Peak APT and . ROM

	R-Value	P-Value
R Hip Flexor	.13	.43
L Hip Flexor	.09	.58
R Rectus Femoris	.20	.23
L Rectus Femoris	.15	.36
R Hamstring	-.25	.13
L Hamstring	-.23	.17
R Gastrocnemius	.07	.70
L Gastrocnemius	.07	.68
R Soleus	.05	.79
L Soleus	.19	.27
R Weight Bearing Dorsiflexion	-.06	.72
L Weight Bearing Dorsiflexion	-.03	.87
R Latissimus Dorsi	-.10	.54
L Latissimus Dorsi	-.16	.35
Double Leg Lowering Test	-.21	.21

Table 7 – Correlations between APT and. EMG

EMG	R-Value	P-Value
Rectus Femoris	.15	.36
Lateral Hamstring	.03	.86
Medial Hamstring	.16	.34
Gluteus Maximus	.40	.01*
Illiocostalis	.21	.22
Longissimus	.33	.05*

Table 8 – Correlations between APT and hip kinematics

	Peak		Displacement	
	R-value	P-Value	R-Value	P-Value
Hip Front Descending	-.07	.69	-.05	.76
Hip Trans Descending	.28	0.09	.20	.23
Hip Trans Ascending	0.33	0.04*	0.29	.07

Table 9 – Correlations between APT and. Rectus Femoris ROM in Females

	Peak Descending Phase		Peak Ascending Phase	
	R-Value	P-Value	R-Value	P-Value
R Rectus Femoris	.39	.09	.470	0.04*
L Rectus Femoris	.56	.01*	.64	.002*

CHAPTER 5

DISCUSSION

Our research showed a significant positive correlation between increased activity in the gluteus maximus and longissimus muscles and anterior pelvic tilt. This is contrary to our original prediction for the gluteus maximus but consistent with that for the longissimus. It does not appear as though bony characteristics, range of motion, the double leg lowering test, kinematics, or other muscle activity are associated with anterior pelvic tilt during the descending phase of an OSA in this particular group of individuals. Because increased gluteus maximus and erector spinae activity are not considered risk factors for ACL injury, anterior pelvic tilt during the OSA does not appear to be a relevant risk factor to screen for. Although our results showed only two significant associations between these factors during the descending phase of the squat, we did notice a trend toward significance in the correlation between anterior pelvic tilt and peak hip internal and external motion. Based on this information we decided to look at the correlations during the ascending phase of the overhead squat assessment, and this time the correlations became significant. (**Table 8)**

Integrate

These findings moderately support the previous findings and theories of authors who reported associations between anterior pelvic tilt and femoral internal rotation (Duval et al., 2010; Hruska, 1998; Ireland, 2002). These authors also suggested that anterior pelvic tilt could be caused by pronation or femoral anteversion but our results did not support those theories.

Previous literature has suggested and our hypothesis predicted, increased activity of the rectus femoris and erector spinae paired with decreased gluteus maximus and hamstring activity could contribute to anterior pelvic tilt (Mayer et al., 2002; Neumann, 2010),. Our results agree with Mayer

et al. (2002) in regards to increased erector spinae activity being associated with femoral internal rotation. In Mayer's study, internally rotating the participant's legs during a back extension exercise increase lumbar extensor activity by 18% compared to external rotation. Ours results showed a correlation between longissimus activity and hip internal rotation ($r_{(38)}$=0.33, p=0.04), although only during the ascending phase of the overhead squat assessment, which was not part of our hypotheses. In addition, what is presented as common knowledge in Neumann (2010) with regards to agonist/antagonist interactions and muscular inhibitions, did not play out in exactly the same fashion in our study, with the increased longissimus activation being the only expected significant relationship found with anterior pelvic tilt.

Range of motion showed no significant associations with anterior pelvic tilt in the group as a whole, but when the males and females were separated, there was a significant positive correlation between increased anterior pelvic tilt and increased rectus femoris range of motion, which is opposite of what we expected to find. **(Table 9)** In theory as the rectus femoris is shortened, it should draw the pelvis into a more anteriorly rotated position, but in our study increased anterior pelvic tilt was associated with those females who had a greater range of motion, suggesting that potentially different neuromuscular factors could contribute to increase APT in males and females.

It does not appear as though anterior pelvic tilt is associated with tight triceps surae either. Bell et al. (2008) and Macrum et al. (2012) found correlations between decreased ankle dorsiflexion and medial knee displacement, which in theory could increase anterior pelvic tilt, but our results showed no such association. Padua et al. (2012) found increased activity of the gastrocnemius and tibialis anterior in participants displaying medial knee displacement during an overhead squat, suggesting that this would be associated with decreased ankle range of motion, but once again there was no apparent consequence up the kinetic chain to the pelvis in our results as we had theorized would occur.

The latissimus dorsi does not appear to play any role in influencing anterior pelvic tilt, as none of our results showed any significance. This again goes against our theory that decreased range of motion in the latissimus dorsi could lead to an increased lordotic curve and therefor increased anterior pelvic tilt.

The double leg lowering test showed no significant correlations with anterior pelvic tilt despite the theory that weak abdominals would allow for a greater degree of anterior pelvic tilt along with increased activity in the erector spinae.

The lack of significance between the navicular drop test and anterior pelvic tilt could potentially be the result of the fact that our sample on average did not have a clinically relevant drop. Without excessive navicular drop to cause changes up the kinetic chain it would stand to reason that nothing out of the ordinary would be observed. Similarly, in regards to femoral anteversion, our sample did not have one participant who displayed excessive anteversion. On the contrary, the average for our sample was retroverted.

Interpret

The two significant findings in this study both related to EMG activity, specifically the gluteus maximus and longissimus muscles. It is important to keep in mind that increased activity does not necessarily mean that the muscle is also creating more force. As stated before, the increased longissimus activity was predicted by our hypothesis, but the gluteus maximus activity was opposite of what we had anticipated. This could potentially be due to the fact that as the pelvis tilts anteriorly, the gluteus maximus is lengthened eccentrically, thereby eliciting the stretch reflex, which leads to increase GMAX activity. It could also mean that the gluteus maximus was weak in our participants and therefore must work harder during the overhead squat assessment. Because of the increased activity of the gluteus maximus, the hamstrings may not need to do as much work, and most likely functions more as a stabilizer at the knee, having no real effect on pelvic tilt. The lack of correlation between the illiocostalis and anterior pelvic tilt could be attributed to the fact that the muscle lies most

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laterally of the three erector spinae muscles and therefore would contribute least to an increase in the lordotic curve. Finally, the lack of correlation between rectus femoris activation level and anterior pelvic tilt could be attributed to the fact that because the gluteus maximus was so active it reciprocally inhibited the rectus femoris.

The lack of correlations between anterior pelvic tilt and range of motion could be explained by several instances. On average our participants had tight iliopsoas' and tight rectus femoris (except when compared to values given by Harvey (1998)), which in theory should increase anterior pelvic tilt.   However, if there is a certain point in passive hip range of motion where inflexibility no longer has an effect on anterior pelvic tilt, or there is a point beyond the average range of motion into flexion than what our participants displayed, this could potentially explain the lack of correlations. The fact that our subjects operated primarily in the midrange of motion at minimal load during the overhead squat assessment could also provide an explanation. If the muscles aren't being used to achieve end range of motion at any given joint and there is not sufficient load to cause a challenge, any deviations from the norm would be unlikely to show up. All other range of motion values were, on average, within normal limits, so again, the lack of correlations could be the result of a lack of non-normative participants.

The double leg lowering test did not show any significant correlations for perhaps two reasons. In order to achieve the posterior rotation of the pelvis during an overhead squat assessment, the rectus abdominis would have to overcome the reciprocal inhibition caused by the increased activation of the erector spinae. Because none of the subjects were consciously recruiting the abdominals during the overhead squat assessment and there was minimal load, it wouldn't necessarily matter how well they performed in the much more difficult double leg lowering test, as the difficulty of the two tasks are disparate. On the other hand, it could be that since our participants were all physically active individuals, they may have been quite adept at controlling their pelvic tilt. In a study by Zannotti et al. (2002) kinematic analysis of the DLLT showed that anterior pelvic tilt

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occurred almost immediately upon lowering of the legs and continued to increase as the legs were lowered. Although we did not assess joint kinematics during DLLT, many of the participants were able to maintain consistent pressure on the clinician's hand until reaching the failing point. In addition, Zannotti had participants hold onto the table above their heads in a shoulder flexed position, potentially contributing to increased lumbar lordosis and pelvic tilt, while our participants kept their arms at their sides.

Implications

Based on our results, several things are worth noting. First of all, it does not appear as though the LPHC muscles function together as is commonly thought. The increase in gluteus maximus activity in those with increased anterior pelvic tilt raises the question of just how much reciprocal inhibition and agonist antagonist interactions come in to play at lower levels of physical activity. While we tend to view these relationships as all-encompassing scenarios, perhaps they only take effect when a certain stress threshold is reached, for example during actual sport participation or weightlifting.

Second, if increased activity in a muscle is taken to mean that muscle is also in a shortened position, the erector spinae should be stretched to minimize its effect on anterior pelvic tilt, as this could theoretically decrease ACL injury risk. This seems counter-intuitive to the gluteus maximus though, as it is not a commonly thought of as being inflexible, therefore the potential that the muscle is weak and operating at near maximal capacity must be acknowledged.

Thirdly, in order for many risk factors to become apparent, fatigue or increased load may need to be introduced to any assessment technique. Faulty movement patterns may not be apparent during an overhead squat assessment, but may become blatantly obvious if weight is added or a jumping task is used. The fitness level of our participants may have been a large part of the reason we did not see the correlations we expected, as they were simply not challenged enough.

Fourthly, anterior pelvic tilt during an overhead squat assessment does not necessarily translate to faulty thigh or knee motion. Although we did see a correlation between peak transverse plane hip motion and anterior pelvic tilt during the ascending phase, this is likely not enough to make a solid connection between the two.

The most significant limitations of our study are the age and physical activity level of our population, and the controlled and relatively easy task of performing an overhead squat assessment. Future research should look to establish correlations across different groups, especially those displaying more abnormal characteristics in range of motion and boney alignment, and those who are more or less physically active than our group was. Adding a dynamometry variable to the study would also help to clarify the relationship between activation levels and force generated. The intensity and type of the assessment tool should be experimented with to truly amplify any correlations, and differences between sexes should also be researched. Activation of the rectus abdominis using fine wire EMG would help to establish its contribution to pelvic tilt during dynamic activity, and using a broader range of participants to observe double leg lowering test performance would help shed light on its contributions as well. Interventional research involving corrective techniques for faulty movement patterns and proper LPHC activation should be undertaken to determine what truly has an effect on pelvic tilt.

Overall more questions were raised than answered in this study. The only significant correlation observed that we predicted was the positive association between anterior pelvic tilt and longissimus activity, which makes sense and helps to support previously accepted theories. Clinicians should consider keeping the erector muscles properly stretched to avoid contributing to excessive anterior pelvic tilt. However, the positive association between gluteus maximus activity and anterior pelvic tilt warrants further investigation, as this is counterintuitive to previously accepted theories. The lack of abnormal bony and neuromuscular characteristics in conjunction with the relative ease of our assessment tool may not have been enough to give a true representation of just

how much these factors can contribute to pelvic tilt. Continued research in this area is necessary to

shed further light on the workings of the lumbopelvic hip complex area and its role in upper and

lower extremity function.

1: Thomas Test Hip Flexor and Rectus Femoris ROM Assessment
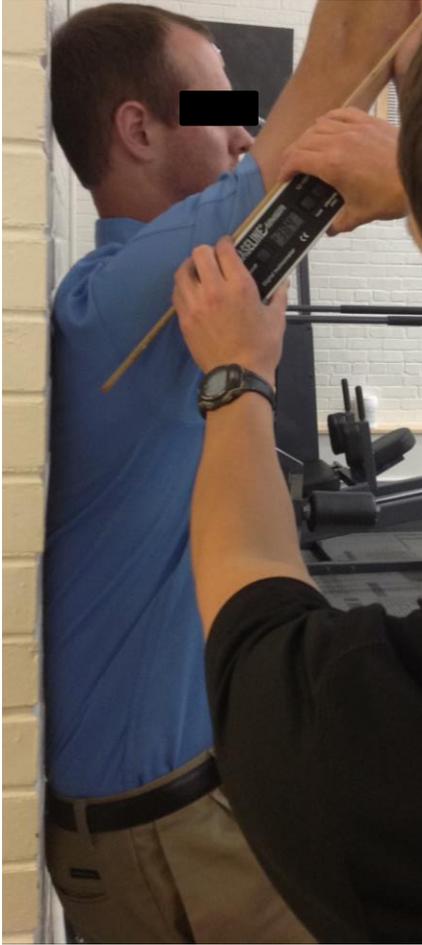

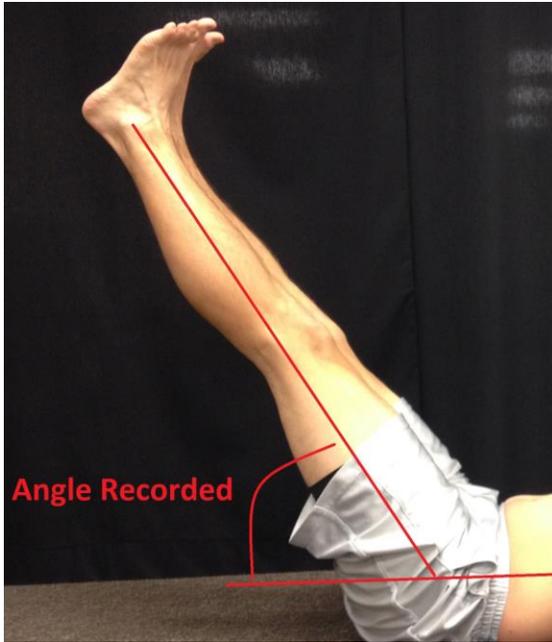2: 90/90 Hamstring ROM Assessment

3: Prone Gastrocnemius ROM Assessment

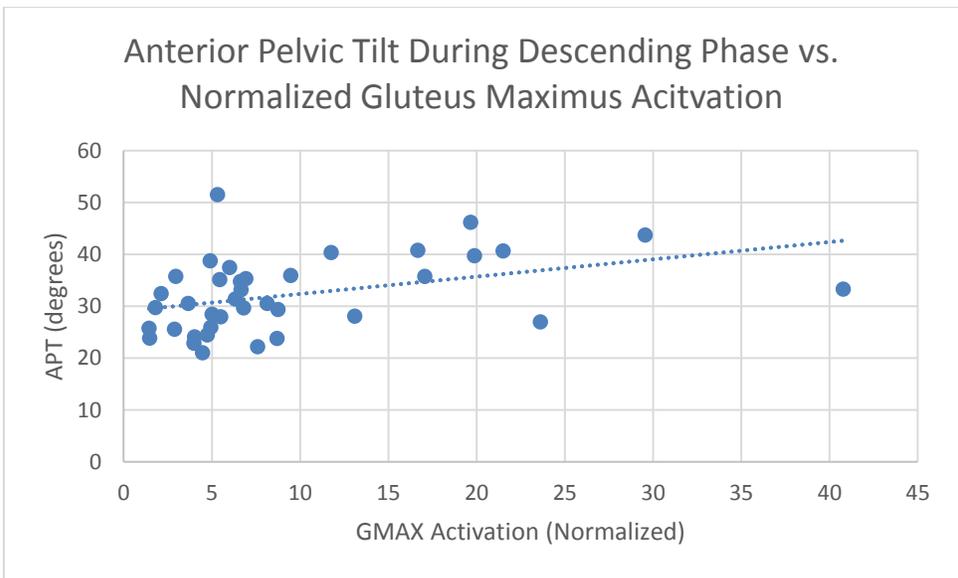4: Prone Soleus ROM Assessment

5: Weight Bearing Soleus ROM Assessment

6: Lat Length Test ROM Assessment

Angle Recorded

7: DLLT Assessment

8: APT vs Gluteus Maximus

Anterior Pelvic Tilt During Descending Phase vs. Normalized Longissimus Acitvation
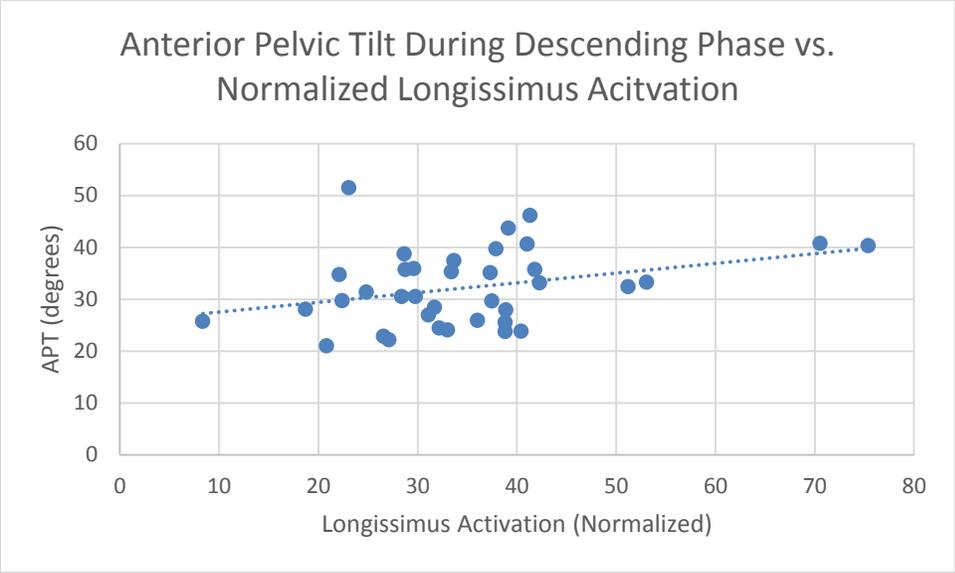
8: APT vs Longissimus

REFERENCES

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. [Comparative Study]. *Am J Sports Med, 33*(4), 524-530. doi: 10.1177/0363546504269937

Aggarwal, A., Kumar, S., Madan, R., & Kumar, R. (2011). RELATIONSHIP AMONG DIFFERENT TESTS OF EVALUATING LOW BACK CORE STABILITY. *Journal of Musculoskeletal Research, 14*(02), 1250004. doi: doi:10.1142/S0218957712500042

Ahlden, M., Samuelsson, K., Sernert, N., Forssblad, M., Karlsson, J., & Kartus, J. (2012). The Swedish National Anterior Cruciate Ligament Register: a report on baseline variables and outcomes of surgery for almost 18,000 patients. [Research Support, Non-U.S. Gov't]. *Am J Sports Med, 40*(10), 2230-2235. doi: 10.1177/0363546512457348

Bell, D. R., Padua, D. A., & Clark, M. A. (2008). Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement. [Comparative Study

Research Support, Non-U.S. Gov't]. *Arch Phys Med Rehabil, 89*(7), 1323-1328. doi: 10.1016/j.apmr.2007.11.048

Besier, T. F., Lloyd, D. G., Cochrane, J. L., & Ackland, T. R. (2001). External loading of the knee joint during running and cutting maneuvers. [Clinical Trial]. *Med Sci Sports Exerc, 33*(7), 1168-1175.

Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon), 23*(3), 313-319. doi: 10.1016/j.clinbiomech.2007.10.003

Blackburn, J. T., & Padua, D. A. (2009). Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. [Comparative Study]. *J Athl Train, 44*(2), 174-179. doi: 10.4085/1062-6050-44.2.174

Bliss, L. S., & Teeple, P. (2005). Core stability: the centerpiece of any training program. [Review]. *Curr Sports Med Rep, 4*(3), 179-183.

Boling, M., Padua, D., Blackburn, J. T., Petschauer, M., & Hirth, C. (2006). Hip Adduction Does not Affect VMO EMG Amplitude or VMO:VL Ratios During a Dynamic Squat Exercise. *J Sport Rehabil, 15*, 195-205.

Borstad, J. D., & Briggs, M. S. (2010). Reproducibility of a measurement for latissimus dorsi muscle length. *Physiother Theory Pract, 26*(3), 195-203. doi: 10.3109/09593980903015250

Brazen, D. M., Todd, M. K., Ambegaonkar, J. P., Wunderlich, R., & Peterson, C. (2010). The effect of fatigue on landing biomechanics in single-leg drop landings. *Clin J Sport Med, 20*(4), 286-292. doi: 10.1097/JSM.0b013e3181e8f7dc

Brophy, R. H., Wright, R. W., & Matava, M. J. (2009). Cost analysis of converting from single-bundle to double-bundle anterior cruciate ligament reconstruction. *Am J Sports Med, 37*(4), 683-687. doi: 10.1177/0363546508328121

Butler, R. J., Plisky, P. J., Southers, C., Scoma, C., & Kiesel, K. B. (2010). Biomechanical analysis of the different classifications of the Functional Movement Screen deep squat test. [Research Support, Non-U.S. Gov't]. *Sports Biomech, 9*(4), 270-279. doi: 10.1080/14763141.2010.539623

Cashman, G. E. (2012). The effect of weak hip abductors or external rotators on knee valgus kinematics in healthy subjects: a systematic review. *J Sport Rehabil, 21*(3), 273-284.

Chappell, J. D., Creighton, R. A., Giuliani, C., Yu, B., & Garrett, W. E. (2007). Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. *Am J Sports Med, 35*(2), 235-241. doi: 10.1177/0363546506294077

Chappell, J. D., Yu, B., Kirkendall, D. T., & Garrett, W. E. (2002). A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. [Comparative Study]. *Am J Sports Med, 30*(2), 261-267.

Clark, B. C., Manini, T. M., Mayer, J. M., Ploutz-Snyder, L. L., & Graves, J. E. (2002). Electromyographic activity of the lumbar and hip extensors during dynamic trunk extension exercise. *Arch Phys Med Rehabil, 83*(11), 1547-1552. doi: http://dx.doi.org/10.1053/apmr.2002.34828

Cowley, P. M., Fitzgerald, S., Sottung, K., & Swensen, T. (2009). Age, weight, and the front abdominal power test as predictors of isokinetic trunk strength and work in young men and women. *J Strength Cond Res, 23*(3), 915-925. doi: 10.1519/JSC.0b013e3181a06f59

Csintalan, R. P., Inacio, M. C., & Funahashi, T. T. (2008). Incidence rate of anterior cruciate ligament reconstructions. *Perm J, 12*(3), 17-21.

Dai, B., Herman, D., Liu, H., Garrett, W. E., & Yu, B. (2012). Prevention of ACL injury, part I: injury characteristics, risk factors, and loading mechanism. [Review]. *Res Sports Med, 20*(3-4), 180-197. doi: 10.1080/15438627.2012.680990

Dempsey, A. R., Elliott, B. C., Munro, B. J., Steele, J. R., & Lloyd, D. G. (2012). Whole body kinematics and knee moments that occur during an overhead catch and landing task in sport. [Research Support, Non-U.S. Gov't]. *Clin Biomech (Bristol, Avon), 27*(5), 466-474. doi: 10.1016/j.clinbiomech.2011.12.001

Duval, K., Lam, T., & Sanderson, D. (2010). The mechanical relationship between the rearfoot, pelvis and low-back. [Randomized Controlled Trial

Research Support, Non-U.S. Gov't]. *Gait Posture, 32*(4), 637-640. doi: 10.1016/j.gaitpost.2010.09.007

Farshad, M., Gerber, C., Meyer, D. C., Schwab, A., Blank, P. R., & Szucs, T. (2011). Reconstruction versus conservative treatment after rupture of the anterior cruciate ligament: cost effectiveness analysis. [Comparative Study

Review]. *BMC Health Serv Res, 11*, 317. doi: 10.1186/1472-6963-11-317

Fasen, J. M., O'Connor, A. M., Schwartz, S. L., Watson, J. O., Plastaras, C. T., Garvan, C. W., . . . Akuthota, V. (2009). A randomized controlled trial of hamstring stretching: comparison of four techniques. [Comparative Study

Randomized Controlled Trial]. *J Strength Cond Res, 23*(2), 660-667. doi: 10.1519/JSC.0b013e318198fbd1

Ferber, R., Kendall, K. D., & McElroy, L. (2010). Normative and critical criteria for iliotibial band and iliopsoas muscle flexibility. [Comparative Study

Research Support, Non-U.S. Gov't]. *J Athl Train, 45*(4), 344-348. doi: 10.4085/1062-6050-45.4.344

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. [Research Support, Non-U.S. Gov't]. *Med Sci Sports Exerc, 35*(10), 1745-1750. doi: 10.1249/01.MSS.0000089346.85744.D9

Frank, B., Bell, D. R., Norcross, M. F., Blackburn, J. T., Goerger, B. M., & Padua, D. A. (2013). Trunk and Hip Biomechanics Influence Anterior Cruciate Loading Mechanisms in Physically Active Participants. *Am J Sports Med*. doi: 10.1177/0363546513496625

Freriks, H. J. H. a. B. Biomedical Health and Research Program (BIOMED II) of the European Union Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles, from http://seniam.org/

Gage, B. E., McIlvain, N. M., Collins, C. L., Fields, S. K., & Comstock, R. D. (2012). Epidemiology of 6.6 million knee injuries presenting to United States emergency departments from 1999 through 2008. *Acad Emerg Med, 19*(4), 378-385. doi: 10.1111/j.1553-2712.2012.01315.x

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. *J Sci Med Sport, 12*(6), 622-627. doi: 10.1016/j.jsams.2008.07.005

Goldbeck, T. G., & Davies, G. J. (2000). Test-retest reliability of the closed kinetic chain upper extremity stability test: a clinical field test. / Verification de la fiabilite test-retest d'un test de stabilite des membres superieurs en chaine cinetique fermee. *J Sport Rehabil, 9*(1), 35-45.

Granan, L. P., Bahr, R., Steindal, K., Furnes, O., & Engebretsen, L. (2008). Development of a national cruciate ligament surgery registry: the Norwegian National Knee Ligament Registry. [Research Support, Non-U.S. Gov't]. *Am J Sports Med, 36*(2), 308-315. doi: 10.1177/0363546507308939

Griffin, L. Y., Albohm, M. J., Arendt, E. A., Bahr, R., Beynnon, B. D., Demaio, M., . . . Yu, B. (2006). Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. [Consensus Development Conference]. *Am J Sports Med, 34*(9), 1512-1532. doi: 10.1177/0363546506286866

Harvey, D. (1998). Assessment of the flexibility of elite athletes using the modified Thomas test. *Br J Sports Med, 32*(1), 68-70.

Hashemi, J., Breighner, R., Chandrashekar, N., Hardy, D. M., Chaudhari, A. M., Shultz, S. J., . . . Beynnon, B. D. (2011). Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. *J Biomech, 44*(4), 577-585. doi: 10.1016/j.jbiomech.2010.11.013

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Jr., Colosimo, A. J., McLean, S. G., . . . Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee

predict anterior cruciate ligament injury risk in female athletes: a prospective study. [Research Support, N.I.H., Extramural

Research Support, U.S. Gov't, P.H.S.]. *Am J Sports Med, 33*(4), 492-501. doi: 10.1177/0363546504269591

Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. [Review]. *J Athl Train, 42*(2), 311-319.

Hruska, R. (1998). Pelvic Stability Influences Lower-Extremity Kinematics. *Biomechanics*, 6.

Ingram, J. G., Fields, S. K., Yard, E. E., & Comstock, R. D. (2008). Epidemiology of knee injuries among boys and girls in US high school athletics. [Research Support, U.S. Gov't, P.H.S.]. *Am J Sports Med, 36*(6), 1116-1122. doi: 10.1177/0363546508314400

Ireland, M. L. (2002). The female ACL: why is it more prone to injury? [Review]. *Orthop Clin North Am, 33*(4), 637-651.

Iwahashi, T., Shino, K., Nakata, K., Nakamura, N., Yamada, Y., Yoshikawa, H., & Sugamoto, K. (2008). Assessment of the "functional length" of the three bundles of the anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc, 16*(2), 167-174. doi: 10.1007/s00167-007-0456-z

Jamison, S. T., Pan, X., & Chaudhari, A. M. (2012). Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. [Research Support, Non-U.S. Gov't]. *J Biomech, 45*(11), 1881-1885. doi: 10.1016/j.jbiomech.2012.05.031

Jordan, S. S., DeFrate, L. E., Nha, K. W., Papannagari, R., Gill, T. J., & Li, G. (2007). The in vivo kinematics of the anteromedial and posterolateral bundles of the anterior cruciate ligament during weightbearing knee flexion. [Research Support, N.I.H., Extramural

Research Support, Non-U.S. Gov't]. *Am J Sports Med, 35*(4), 547-554. doi: 10.1177/0363546506295941

Joseph, M., Tiberio, D., Baird, J. L., Trojian, T. H., Anderson, J. M., Kraemer, W. J., & Maresh, C. M. (2008). Knee valgus during drop jumps in National Collegiate Athletic Association Division I female athletes: the effect of a medial post. *Am J Sports Med, 36*(2), 285-289. doi: 10.1177/0363546507308362

Khamis, S., & Yizhar, Z. (2007). Effect of feet hyperpronation on pelvic alignment in a standing position. *Gait Posture, 25*(1), 127-134. doi: 10.1016/j.gaitpost.2006.02.005

Krause, D. A., Youdas, J. W., Hollman, J. H., & Smith, J. (2005). Abdominal muscle performance as measured by the double leg-lowering test. *Arch Phys Med Rehabil, 86*(7), 1345-1348.

Kulas, A. S., Hortobagyi, T., & Devita, P. (2010). The interaction of trunk-load and trunk-position adaptations on knee anterior shear and hamstrings muscle forces during landing. [Clinical Trial]. *J Athl Train, 45*(1), 5-15. doi: 10.4085/1062-6050-45.1.5

Kulas, A. S., Hortobagyi, T., & DeVita, P. (2012). Trunk position modulates anterior cruciate ligament forces and strains during a single-leg squat. [Research Support, Non-U.S. Gov't]. *Clin Biomech (Bristol, Avon), 27*(1), 16-21. doi: 10.1016/j.clinbiomech.2011.07.009

Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc, 36*(6), 926-934.

Macrum, E., Bell, D. R., Boling, M., Lewek, M., & Padua, D. (2012). Effect of limiting ankle-dorsiflexion range of motion on lower extremity kinematics and muscle-activation patterns during a squat. *J Sport Rehabil, 21*(2), 144-150.

Mainwaring, L. M., Hutchison, M., Bisschop, S. M., Comper, P., & Richards, D. W. (2010). Emotional response to sport concussion compared to ACL injury. [Comparative Study]. *Brain Inj, 24*(4), 589-597. doi: 10.3109/02699051003610508

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. [Comparative Study]. *Clin Biomech (Bristol, Avon), 16*(5), 438-445.

Mayer, J. M., Verna, J. L., Manini, T. M., Mooney, V., & Graves, J. E. (2002). Electromyographic activity of the trunk extensor muscles: effect of varying hip position and lumbar posture during Roman chair exercise. [Research Support, U.S. Gov't, P.H.S.]. *Arch Phys Med Rehabil, 83*(11), 1543-1546.

McDonald, D. A., Delgadillo, J. Q., Fredericson, M., McConnell, J., Hodgins, M., & Besier, T. F. (2011). Reliability and accuracy of a video analysis protocol to assess core ability. [Research Support, Non-U.S. Gov't

Validation Studies]. *PM R, 3*(3), 204-211. doi: 10.1016/j.pmrj.2010.12.007

McGill, S., Juker, D., & Kropf, P. (1996). Quantitative intramuscular myoelectric activity of quadratus lumborum during a wide variety of tasks. *Clin Biomech (Bristol, Avon), 11*(3), 170-172.

McGill, S. M., Childs, A., & Liebenson, C. (1999). Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. [Research Support, Non-U.S. Gov't]. *Arch Phys Med Rehabil, 80*(8), 941-944.

McLean, S. G., Huang, X., Su, A., & Van Den Bogert, A. J. (2004). Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. [Clinical Trial

Comparative Study

Controlled Clinical Trial

Research Support, U.S. Gov't, P.H.S.

Validation Studies]. *Clin Biomech (Bristol, Avon), 19*(8), 828-838. doi: 10.1016/j.clinbiomech.2004.06.006

McLean, S. G., Huang, X., & van den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. [Clinical Trial

Controlled Clinical Trial

Research Support, N.I.H., Extramural

Research Support, U.S. Gov't, P.H.S.]. *Clin Biomech (Bristol, Avon), 20*(8), 863-870. doi: 10.1016/j.clinbiomech.2005.05.007

McLean, S. G., Lipfert, S. W., & van den Bogert, A. J. (2004). Effect of gender and defensive opponent on the biomechanics of sidestep cutting. [Research Support, U.S. Gov't, P.H.S.]. *Med Sci Sports Exerc, 36*(6), 1008-1016.

Medina McKeon, J. M., & Hertel, J. (2009). Sex differences and representative values for 6 lower extremity alignment measures. *J Athl Train, 44*(3), 249-255. doi: 10.4085/1062-6050-44.3.249

Minick, K. I., Kiesel, K. B., Burton, L., Taylor, A., Plisky, P., & Butler, R. J. (2010). Interrater reliability of the functional movement screen. [Research Support, Non-U.S. Gov't]. *J Strength Cond Res, 24*(2), 479-486. doi: 10.1519/JSC.0b013e3181c09c04

Neumann (Ed.). (2010).

Noehren, B., Hamill, J., & Davis, I. (2012). Prospective Evidence for a Hip Etiology in Patellofemoral Pain. *Med Sci Sports Exerc*. doi: 10.1249/MSS.0b013e31828249d2

Onate, J. A., Dewey, T., Kollock, R. O., Thomas, K. S., Van Lunen, B. L., DeMaio, M., & Ringleb, S. I. (2012). Real-time intersession and interrater reliability of the functional movement screen. *J Strength Cond Res, 26*(2), 408-415. doi: 10.1519/JSC.0b013e318220e6fa

Padua, D. A., Bell, D. R., & Clark, M. A. (2012). Neuromuscular characteristics of individuals displaying excessive medial knee displacement. [Research Support, Non-U.S. Gov't]. *J Athl Train, 47*(5), 525-536. doi: 10.4085/1062-6050-47.5.10

Pantano, K. J., White, S. C., Gilchrist, L. A., & Leddy, J. (2005). Differences in peak knee valgus angles between individuals with high and low Q-angles during a single limb squat. [Research Support, Non-U.S. Gov't]. *Clin Biomech (Bristol, Avon), 20*(9), 966-972. doi: 10.1016/j.clinbiomech.2005.05.008

Patla, C. F. (2003). Diagnosis and treatment of movement impairment syndrome. (Review). *J Orthop Sports Phys Ther, 33*(5), 295.

Pinto, R. Z., Souza, T. R., Trede, R. G., Kirkwood, R. N., Figueiredo, E. M., & Fonseca, S. T. (2008). Bilateral and unilateral increases in calcaneal eversion affect pelvic alignment in standing position. *Man Ther, 13*(6), 513-519. doi: 10.1016/j.math.2007.06.004

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2007). Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. [Comparative Study]. *Clin J Sport Med, 17*(1), 38-42. doi: 10.1097/JSM.0b013e3180305de8

Popovich, J. M., Jr., & Kulig, K. (2012). Lumbopelvic landing kinematics and EMG in women with contrasting hip strength. [Research Support, Non-U.S. Gov't]. *Med Sci Sports Exerc, 44*(1), 146-153. doi: 10.1249/MSS.0b013e3182267435

Rabin, A., & Kozol, Z. (2012). Weightbearing and nonweightbearing ankle dorsiflexion range of motion: are we measuring the same thing? [Comparative Study]. *J Am Podiatr Med Assoc, 102*(5), 406-411.

Rose, D. G. (2006). Level One TPI Certified Gof Fitness Instructor Manual (Vol. 2008, pp. 135-138): Titleist Performance Institute.

Shields, R. K., & Heiss, D. G. (1997). An electromyographic comparison of abdominal muscle synergies during curl and double straight leg lowering exercises with control of the pelvic position. [Comparative Study

Research Support, U.S. Gov't, Non-P.H.S.]. *Spine (Phila Pa 1976), 22*(16), 1873-1879.

Shirey, M., Hurlbutt, M., Johansen, N., King, G. W., Wilkinson, S. G., & Hoover, D. L. (2012). The influence of core musculature engagement on hip and knee kinematics in women during a single leg squat. *Int J Sports Phys Ther, 7*(1), 1-12.

Smith, C. A., Chimera, N. J., Wright, N., & Warren, M. (2012). Interrater and Intrarater Reliability of the Functional Movement Screen. *J Strength Cond Res*. doi: 10.1519/JSC.0b013e3182606df2

Stanton, R., Reaburn, P. R., & Humphries, B. (2004). The effect of short-term Swiss ball training on core stability and running economy. [Clinical Trial

Controlled Clinical Trial]. *J Strength Cond Res, 18*(3), 522-528. doi: 10.1519/1533-4287(2004)18<522:TEOSSB>2.0.CO;2

Tateuchi, H., Taniguchi, M., Mori, N., & Ichihashi, N. (2012). Balance of hip and trunk muscle activity is associated with increased anterior pelvic tilt during prone hip extension. *J Electromyogr Kinesiol, 22*(3), 391-397. doi: 10.1016/j.jelekin.2012.03.003

Teyhen, D. S., Shaffer, S. W., Lorenson, C. L., Halfpap, J. P., Donofry, D. F., Walker, M. J., . . . Childs, J. D. (2012). The Functional Movement Screen: a reliability study. [Validation Studies]. *J Orthop Sports Phys Ther, 42*(6), 530-540. doi: 10.2519/jospt.2012.3838

Thelin, N., Holmberg, S., & Thelin, A. (2006). Knee injuries account for the sports-related increased risk of knee osteoarthritis. [Research Support, Non-U.S. Gov't]. *Scand J Med Sci Sports, 16*(5), 329-333. doi: 10.1111/j.1600-0838.2005.00497.x

Toth, A. P., & Cordasco, F. A. (2001). Anterior cruciate ligament injuries in the female athlete. [Review]. *J Gend Specif Med, 4*(4), 25-34.

Walker, M. L., Rothstein, J. M., Finucane, S. D., & Lamb, R. L. (1987). Relationships between lumbar lordosis, pelvic tilt, and abdominal muscle performance. *Phys Ther, 67*(4), 512-516.

Walsh, M., Boling, M. C., McGrath, M., Blackburn, J. T., & Padua, D. A. (2012). Lower extremity muscle activation and knee flexion during a jump-landing task. *J Athl Train, 47*(4), 406-413. doi: 10.4085/1062-6050-47.4.17

Workman, J. C., Docherty, D., Parfrey, K. C., & Behm, D. G. (2008). Influence of pelvis position on the activation of abdominal and hip flexor muscles. [Research Support, Non-U.S. Gov't]. *J Strength Cond Res, 22*(5), 1563-1569. doi: 10.1519/JSC.0b013e3181739981

Yoo, Y. S., Jeong, W. S., Shetty, N. S., Ingham, S. J., Smolinski, P., & Fu, F. (2010). Changes in ACL length at different knee flexion angles: an in vivo biomechanical study. *Knee Surg Sports Traumatol Arthrosc, 18*(3), 292-297. doi: 10.1007/s00167-009-0932-8

Zannotti, C. M., Bohannon, R. W., Tiberio, D., Dewberry, M. J., & Murray, R. (2002). Kinematics of the double-leg-lowering test for abdominal muscle strength. *J Orthop Sports Phys Ther, 32*(9), 432-436.

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. [Research Support, N.I.H., Extramural]. *Am J Sports Med, 35*(7), 1123-1130. doi: 10.1177/0363546507301585

Zazulak, B. T., Ponce, P. L., Straub, S. J., Medvecky, M. J., Avedisian, L., & Hewett, T. E. (2005). Gender Comparison of Hip Muscle Activity During Single-Leg Landing. *J Orthop Sports Phys Ther, 35*(5), 292.