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Range of Motion and Plantar Foot Pressures in Those with and without a Lateral Hip Shift during an Overhead Squat

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RANGE OF MOTION AND PLANTAR FOOT PRESSURES IN THOSE WITH AND WITHOUT A LATERAL HIP SHIFT DURING AN OVERHEAD SQUAT

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66 Pages

Context: Asymmetrical loading between lower limbs can theoretically be explained as an inequality of strength, neuromuscular control, or subconscious reliance on one leg more than the other. Asymmetries are often identified utilizing costly equipment such as force plates and 3D motion analysis cameras. It is important to establish less costly ways of identifying movement and loading asymmetries for clinicians to utilize. One qualitative assessment that may identify asymmetries is a 'lateral hip shift' during an overhead squat. **Objective:** To identify differences in lower extremity range of motion (ROM) and plantar foot pressures in individuals with and without a lateral hip shift during an overhead squat. **Design:** Cross-Sectional Observation. **Setting:** Lab. **Participants:** Twenty-nine (14 males and 15 females) physically active individuals participated in this study. Seventeen individuals with a lateral hip shift during an overhead squat (LAT; Age = 21.2 ± 2.1 years, Height = 175.1 ± 9.1 cm, Mass = 77.6 ± 14.2 kg) and twelve without (CON; Age = 20.8 ± 2.1 years, Height = 177.4 ± 6.8cm, Mass = 77.8 ± 11.1kg) were identified through screening.

Interventions: Participants were screened for a lateral hip shift while performing five overhead squats to determine group allocation (LAT, CON). All ROM measures were performed in a randomized order followed by additional trials of the overhead squat while standing on the pressure sensor mat. **Main Outcome Measures:** Active, passive, and weight-bearing ROM for ankle dorsiflexion (DF) and passive hip abduction, internal, and external rotation were measured. Plantar pressure variables were captured via a pressure sensor mat during the overhead squat, including side-to-side weight bearing %, anterior-posterior excursion (cm), left-right excursion (cm), and center of force (COF) distance (cm). **Results:** A significant group-by-limb interaction for active DF ROM, such that the LAT group had less active DF ROM with the knee flexed on the limb they shifted away from in comparison to the assigned CON limb (mean difference = 6.87º ± 0.2). The LAT group also had less active DF ROM with the knee extended (3.07° ± 1.25) compared to the CON group (8.30° ± 1.49). No differences were observed on other ROM variables. The LAT group demonstrated greater movement in their center of force on the plantar pressure mat for total distance (mean difference = 24.27 cm ± 0.4) and LR excursion (mean difference = 2.96 cm ± 3.2). **Conclusion:** Participants with a lateral shift during an overhead squat generally had decreased active ankle DF ROM and greater movement of their center of force. Clinically, addressing active DF ROM may promote more symmetrical loading during an overhead squat.

KEYWORDS: Asymmetry, Lateral Hip Shift, Overhead Squat, Plantar Foot Pressure, Range of Motion.

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CHAPTER I

INTRODUCTION

Asymmetrical movement and loading between limbs during lower extremity movements may pose a risk for individuals to sustain lower extremity injury. Asymmetrical loading following injury, such as anterior cruciate ligament (ACL) rupture, may be an underlying contributor for the high re-injury rates observed in an athletic population.[1] Previous research has demonstrated greater weight distribution on the contralateral (previously uninjured) limb during double leg squats and double leg jump landing tasks.[1-5] While these studies provide relevant information on bilateral asymmetry, laboratory force plates may be unattainable to clinicians due to the high cost. Pressure sensor mats may provide a more cost effective means of identifying loading asymmetries in addition to providing detailed information on pressure distribution under each foot and potentially retraining movement in a clinical setting. Plantar pressure mats have the potential to identify weight bearing percentages (WB%) between limbs during activity. They can also be utilized to identify and track movement of patient's center of force (COF). Identifying asymmetries with plantar pressure mats may be advantageous for clinicians in the attempt to improve rehabilitation and long term outcomes following ACL injury and surgical reconstruction. Often times in research bilateral comparisons of limbs in the control or ACL reconstruction (ACLR) population are not drawn.[6] Therefore, presence of side-to-side asymmetries cannot be investigated.

Research has shown that a combination of greater hip adduction and internal rotation (IR) of the hip is linked with a decreased DF at the ankle.[7] The combination of these movement patterns during functional activity may cause an increased medial displacement of the knee, which can be an injury risk. This movement pattern may also present clinically as a lateral hip shift during an overhead squat, which has been utilized during clinical movement screens to identify injury risk. More research should be dedicated to understanding the relationship of deficits in ROM in functional movements, such as a lateral hip shift. Research has established relationships between range of motion and dysfunctional movement patterns, such as knee valgus.[8-11] During an overhead squat, those with dynamic knee valgus had less passive ankle dorsiflexion ROM while the knee was flexed and extended.[9, 10] There is relevance in investigating potential ROM characteristics that may manifest as different dysfunctional movement patterns, such as the lateral hip shift, as well.

Additional research on ROM and plantar pressure characteristics will help develop theories on causes of injurious lower extremity motions. Unveiling potential causes of risky lower extremity motion will provide information to clinicians and potentially guide treatments in order to prevent initial or subsequent injury.

The purpose of this study is to identify lower extremity ROM and plantar foot pressure distributions that may contribute to a lateral hip shift during an overhead squat. Identifying deficits in these variables could provide helpful information to clinicians as these factors are modifiable. We hypothesized that subjects with a lateral hip shift during an overhead squat would demonstrate decreases in ankle DF and hip ROM on the side shifted toward and greater hip IR on the side shifted away from. We also hypothesized that those with a lateral hip shift would have greater side to side asymmetry in WB% and movement of the COF in plantar pressure measurements.

CHAPTER II

REVIEW OF RELATED LITERATURE

In the athletic community, injury to the ACL is one of the most prevalent injuries of the lower extremity. The literature on ACL injuries has grown immensely in the medical field to provide clinicians with information they can apply to their practice. The existing research is primarily dedicated to giving insight on risk factors of ACL injury, prevention of these injuries, identifying injurious movement patterns, and potential corrections of these risk factors and movement patterns. There is limited research on comparing side-to-side asymmetries in control populations versus populations that exhibit a visually identifiable injurious movement patterns. Specifically, there is limited research on the musculoskeletal characteristics of patients that display injurious lower extremity movement patterns.

An overhead squat can be quickly and easily used to identify dynamic knee valgus, a main contributor to ACL injury. Dynamic knee valgus may present itself as a lateral hip shift during dynamic tasks, such as the overhead squat. Clinicians can visually assess for this specific movement pattern while patients perform an overhead squat in all settings of practice. Once a lateral hip shift has been identified, it is important that clinicians know what deficits can contribute to this movement pattern. Therefore, the importance not only lies in the identification of injurious movement patterns, but the knowledge of what interventions to take once a lateral hip shift has been presented. In order to provide the proper treatment to counteract the causes of this poor movement pattern, research needs to be done on characteristics of populations with a lateral hip shift during an overhead squat.

Additionally, there is little evidence on how to reliably use any type of feedback while performing the overhead squat task. This type of information is relevant to clinicians that are re-educating post-operative ACLR patients during rehabilitation programs. Using devices that display comparisons of bilateral symmetry of limbs, such as a pressure sensor device, can change the way clinicians provide care to patients. These devices are more available to a wider variety of sport settings due to lower cost and ease of transfer. Evidence on how to properly and reliably identify asymmetrical loading patterns during double leg tasks with plantar foot pressure mats is relevant to clinical practice. The goal of this literature review is to examine the current research available on ACL injury risk factors, how to prevent ACL injuries, the best strategies to identify injurious lower extremity biomechanics, and how to best correct poor movement patterns.

Functional Anatomy

The knee joint is considerably protected by the musculature that surrounds it. However, there are many factors that contribute to how the knee joint maintains stability and remains efficient during sport specific activity. To understand the injuries that may occur at this joint it is important to understand the functional anatomy of the joint.

Bony

The knee is comprised of the distal femur, proximal tibia, proximal fibula, and the patella. The femur is the longest bone in the body.[12, 13] The tibia is considered the weight bearing bone of the shank. The medial and lateral tibial condyles articulate with the medial and lateral femoral condyles. The femoral condyles are separated by the femoral notch.[12] Sitting anterior to the medial and lateral tibial condyles is the tibial tuberosity. The tibial tuberosity is the attachment site of the quadriceps muscle, via the patellar tendon. The congruency of the medial tibiofemoral articulation is greater than the lateral articulation.[13] The tibia is connected to the fibula by the interosseous membrane. The fibula is the lateral bone of the shank. The fibula is responsible for minimal weight bearing during closed chain activity.

The patella is the largest sesamoid, or free floating, bone in the human body.[12] One of the primary purposes of the patella is to serve as a means to increase the mechanical advantage of the quadriceps muscle.[12, 14] The patella also serves to decrease friction and protect the bones.[12] The patella articulates with the anterior portion of the femoral condyles. This articulation is described as the patellofemoral joint. The area the patella glides through as flexion and extension occur is called the femoral trochlea. The trochlea sits higher on the lateral side, meaning the patella has greater bony stability in the lateral direction. The patellar tendon also has attachments onto the patella and the tibial tuberosity. This tendon's role is to serve as the muscular attachment of the quadriceps muscle group.

The bones of the lower extremity rely on the assistance of soft tissue, such as muscle to provide smooth, efficient movement. These bones have important attachment sites for muscles that act on the knee joint including the quadriceps, hamstrings, gluteus maximus, gluteus medius, popliteus, and tensor fascia latae (TFL). When these muscles are not working efficiently the stability of the lower extremity is far less, potentially being a harmful factor in sports competition.

Muscular

The tibiofemoral joint is heavily dependent on dynamic stability rather than bony stability. The tibiofemoral joint is classified as a diarthrodial, synovial, hinge joint. The tibiofemoral joint has 3 degrees of freedom, indicating flexion/extension, IR/ER, and varus/valgus motions occur at this joint.

Several muscles and muscle groups provide support to the knee. Anteriorly is the quadriceps muscle group. Four muscles make up this group including the rectus femoris, vastus lateralis, vastus medialis, and the vastus intermedius.[12] The rectus femoris muscle crosses both the hip and the knee joints. This muscle originates on the anterior inferior iliac spine of the ilium, and inserts onto the tibial tuberosity of the tibia and patellar tendon. Therefore, this muscle performs the two actions of hip flexion and knee extension. The vastus lateralis originates on the greater trochanter, linea aspera and intertrochanteric line of the femur and inserts on patella and patellar tendon. The vastus medialis originates on the linea aspera and intertrochanteric line and inserts on the patellar tendon. Lastly, the vastus intermedius originates on the anterior aspect of the femur and inserts on the patellar tendon. These three muscles of the quadriceps only perform knee extension. The quadriceps also provide an anterior translation of the tibia upon contraction.[13]

The hamstrings are considered the antagonist muscle group of the quadriceps. This muscle group lies posterior to the femur and made up of three muscles including the biceps femoris, semitendinosis, and semimembranosus. The origin of the heads of the biceps femoris include the ischial tuberosity and linea aspera of the femur and the insertion is the head of the fibula and the proximal, lateral tibia. The origin of the semimembranosus and semitendinosis muscles is the ischial tuberosity of the ischium and the insertions are the pes anserine of the tibia and the medial proximal tibia. These muscles all work together to extend the hip and flex the knee.[12, 13] The hamstring muscle group also provides a posterior translation of the tibia upon contraction.

The popliteus is a posterior muscle of the knee. The origin of the popliteus is the distal, posterolateral femur and the insertion is on the proximal, posteromedial tibia. This muscle is small but plays a role in flexing the knee. This muscle is also important for the facilitation of the arthrokinematics of the knee and allows for fluid motion in the joint.[12] The gastrocnemius also assists with flexion of the knee. This muscle lies on the posterior side of the lower leg. This muscle has two heads that originate on the medial and lateral condyles of the femur and inserts on the Achilles tendon and calcaneus.

There are also muscles at the hip that impact motion and forces at the knee. Some of these muscles are the gluteus maximus, gluteus medius, gluteus minimus and tensor fasciae latae. These muscles are located on the posterior aspect of the pelvis and femur. The gluteus maximus originates on the ilium, sacrum, and coccyx and inserts on the proximal femur and iliotibial tract, also known as the IT band. This muscle extends the hip and externally rotates the hip. The gluteus medius and gluteus minimus originate on the lateral surface of the ilium and insert on the greater trochanter of the femur. These muscles work together to abduct and IR the hip. The TFL originates on the iliac crest and the anterior superior iliac spine and inserts on the IT band. This muscle flexes and abducts the hip.

Musculature at the hip and knee is very significant in regards to how ACL injuries occur. The presence of deficits or imbalances in strength or ROM of these muscles can have a direct effect on movement patterns and potentially contribute to injury of the lower extremity. The way these muscles are developed and recruited during activity plays a significant role on the capsular and ligamentous alignment, and the arthrokinematics that occur at the joint.

Joint Capsule

The capsule surrounding the knee is the largest in the body. This capsule surrounds the posterior margins of the femoral and tibial condyles and the patella. The synovial capsule surrounds the knee with the exception of the intercondylar notch, cruciate ligaments, and extrasynovial space.[12] The synovial fluid moves around in this capsule based on the motion and position of the knee. Structures that are major contributors to the static stability of the knee include the menisci, the medial and lateral collateral ligaments, and the anterior and posterior cruciate ligaments.

Meniscus

The menisci are fibrocartilage discs that lie in between the femoral condyles and the tibial condyles. The menisci assist in creating a deeper, more stable joint. The menisci bring nutrients to the knee joint. They also help with creating more fluid movement for the knee joint. There are two portions of the meniscus. The lateral menisci are more mobile and described as “O” shaped. The popliteus has attachments to the lateral meniscus. The lateral portions of the menisci are more vascular than the medial and can often be treated conservatively or repaired with surgery, in contrast to the medial portions. The medial menisci are described as more avascular and “C” shaped.[12] The medial meniscus has attachments to the semimembranosus muscle, synovial capsule and the medial collateral ligament (MCL). The medial meniscus is the larger of the two portions to accommodate the larger medial femoral condyle. The blood flow to the meniscus is poor, which limits the ability to heal after an injury occurs.[12] The menisci both attach to the surface of the tibia through tiny ligaments referred to as the coronary ligaments.[12] These ligaments attach deep into the bone and the meniscus. During flexion of the knee, the menisci must move to avoid becoming pinched between the femur and tibia. The lateral meniscus moves posterior with the assistance of the popliteus muscle.[12] The medial meniscus is not as moveable when compared to the lateral because of the ligament attachment sites. However, the medial meniscus is pulled posterior by the semimembranosus muscle.[12] Due to this lack of movement the medial meniscus is more often injured.

Ligaments

The MCL is considered a capsular ligament. It has attachments on the synovial joint capsule surrounding the knee and medial meniscus. The MCL attaches to the femur at the medial femoral epicondyle. The anterior band attaches to the medial tibial shaft and the posterior band attaches to the tibial condyle, the capsule, and the medial meniscus.[12] Some of the MCL fibers are taut during flexion and extension. The superficial fibers of the MCL are the primary stabilizers against valgus and external rotation motion.[12] This ligament becomes injured when an excessive valgus motion occurs. While the knee is in a position of full extension and a valgus force is applied the ACL, MCL, and the medial joint capsule will be stressed. When put in about thirty degrees of knee flexion, valgus forces applied to the knee will be stressing the medial collateral ligament only.[12]

The lateral collateral ligament (LCL) of the knee is described as extracapsular. This ligament attaches to the lateral epicondyle of the femur through the ligament of Wrisberg and the fibular head.[12] The main function of this ligament is to resist varus forces at the knee. This ligament is stressed while the knee is fully extended and relaxed when the knee is in flexion.[12] Excessive varus force is the most common mechanism of injury for the LCL. The angle of knee flexion effects the stress of the lateral structures. While the knee is in full extension the LCL, the lateral synovial capsule and the posterior cruciate ligament undergo stress. When placed in about thirty degrees of knee flexion the LCL undergoes the stress of a varus force applied.[12]

The posterior cruciate ligament (PCL) attaches to the anteromedial aspect of the femoral condyle and the posterior intercondylar region of the tibia. There are two bundles of this ligament: the anterolateral bundle, becomes taut when the knee is in flexion and the posteromedial bundle, becomes taut when the knee is extended. The PCL resists posterior translation of a fixed tibia and hyperextension of the knee. When the ACL fails the PCL takes over to resist that motion, as well.

The ACL attaches to the posteromedial aspect of the lateral femoral condyle and anterior intercondylar surface of the tibia. There are two bundles of the ligament: the anteromedial, becomes taut when the knee is flexed and the posterolateral bundle becomes taut in extension.[15-20] There are recent findings that show there are three bundles of the ACL: the anteromedial, posterolateral, and intermediate bundles.[20-22] In another instance, there has been evidence that there are four bundles: anterolateral, anteromedial, central, and posterior.[23] The most common bundle that is injured in athletics is the anteromedial bundle. The ACL functions to prevent anterior translation and IR of the tibia.[19, 24] As the knee moves into greater degrees of flexion the tension on the anteromedial bundle of the ACL increases and the tension on the posterior bundle decreases.[20] At about thirty degrees of knee flexion the bundles share an equal load. At this 30 degree angle clinical tests are performed to test the integrity of the ACL.

To keep the ligaments, capsule, and menisci intact the knee joint has developed efficient joint movement called, arthrokinematics. The importance of the proper arthrokinematics is important to a functioning lower extremity. It is imperative to understand the proper arthrokinematics of the knee joint to understand the injury that can potentially harm the aforementioned structures of the knee if disruptions in these subtle movements is present.

Arthrokinematics

The arthrokinematics, or rolling, gliding, and sliding of the knee occur in many different planes of motion. As the tibia is moving into extension on a fixed femur the tibia rolls and glides anteriorly. If the femur is moving into extension on a fixed tibia an posterior glide takes place.[12] The different size of the medial and lateral femoral condyles do not allow for strictly one plane of motion. Therefore, additional movements must occur at the joint to utilize the full medial surface of the condyle. During open chain activity the tibia is moving about a fixed femur so it must externally rotate the last 15 degrees of knee extension to get into a closed pack position. During closed chain movements, which describes most of the athletic activity in which an ACL injury occurs, the femur is moving about a fixed tibia. Therefore, the femur must internally rotate during the last 20 degrees to reach a closed pack position.[12] As the knee moves into flexion and extension the patella goes through different points of contact with the trochlea. In an extended position the patella has no contact with the trochlea. As the knee moves into flexion the contact force increases and the patella becomes more compressed into the trochlea. When the knee is in the end range of flexion the patella is in complete contact with femoral condyles. These arthrokinematics can be disrupted by a number of things and potentially cause injury due to the compensations patients must then make to overcome the deficits.

Prevalence of Anterior Cruciate Ligament Injury

There is an increasing number of ACL injuries throughout various populations, including athletic, recreationally active, and military personnel. [25-27] Experiencing these ACL injuries in conjunction with surgical repair of the ligament are reported to be on the rise over the last 12 years significantly.[27] Specifically, these increases are seen in patients younger than 20 years old and athletic females.[27] It has been reported that 80% of knee injuries include compromise to the ACL and a subsequent surgery.[25]

The most common mechanism of injury to the ACL is non-contact in a "positon of no return" defined as an ACL injury that occurs when there has been no contact between players. Non-contact injuries typically occur upon landing, during a deceleration or a change in direction when the foot is planted in a fixed position.[28-31] Since most of these injuries are non-contact mechanisms, inferences can be made about specific movement patterns that may be related to ACL injuries. Movement patterns and neuromuscular aspects are risk factors that clinicians can modify. Therefore, the more information given on how best to modify these poor movement patterns the better outcome of decreasing these non-contact ACL injuries. To help understand why ACL injuries are prevalent, intrinsic and extrinsic factors for this injury must be examined.

Etiology of Anterior Cruciate Ligament Injury

Extrinsic Risk Factors

Extrinsic risk factors can be defined as risk factors that have an effect on the athlete "from without" that increase risk of injury.[32] In regards to ACL injury these factors include environmental factors.

There are certain researchers that have found weather/environment to influence ACL injury.[33, 34] Orchard[33] found an increase in ACL injury during high evaporation and low rain time frames. However, it could be due to the surface changing and becoming harder, decreasing shock absorption at the knee. The problem with the evidence about weather causing increases in ACL injury is that the confounders are impossible to account for making these hypotheses difficult to prove.

Perhaps the most influential extrinsic risk factors for ACL injury are playing surface, footwear and weather. On surfaces such as natural grass and wood floors, the injury risk is less.[35, 36] The interaction between the shoes of the athlete and the playing surface seem to give us a good idea about how the injury risk will be affected. Certain research that analyzes footwear have been able to confidently say the interaction between the playing surface and the footwear is the relevant information.[37] For example, it has been found that shorter cleat length will reduce the risk of knee and ankle injuries, most likely due to the lower amount traction shorter cleats allow for. [38, 39]

Olsen et. al.[35] found the greater the coefficient of friction, the more traction the shoes have and, in turn, the more chance for an interaction with intrinsic risk factors of the athlete to occur and cause an injury.[35] Therefore, the actual risk is the interaction and not the variables of the shoe type or the playing surface individually. With the previous information mentioned on the interaction of the floor and shoes, the type of footwear being worn is of equal importance when discussing injury risk. With both of these topics it is difficult to account for confounders, therefore evidence should be interpreted with caution. Another reason to interpret this information with caution is due to the natural ability of an athlete to adjust for variables such as these. In cases, the altered biomechanics of an athlete maybe the reason we see an increase in injury.[37]

Intrinsic Risk Factors

Intrinsic risk factors can be defined as internal risk factors to an athlete that predispose them to an injury.[32] Anatomical factors that have been found to increase the risk for ACL injury include Q- angle, size and shape of the femoral intercondylar notch, ligamentous properties, hormonal changes, history of injury, natural joint laxity, sex, body mass index (BMI), increased static valgus positions, excessive pronation, and genetic predispositions.[2, 40-70]

There are several incidences when an individual can be classified as having natural joint laxity. Natural joint laxity can have an impact on the likelihood to sustain an ACL injury. Dr. James Nicholas implemented a list of criteria to classify natural joint laxity. The classifications of joint integrity included: 1) loose 2) loose to moderate 3) moderate 4) moderate to tight 5) tight The five indices used to characterize tightness or looseness were as follows: 1) capability of placing palms on the floor with locked knees 2) presence of genu recurvatum 3) knee and ankle rotation 4) hip rotation 5) upper extremity laxity[61] Football players that met three or more of the criteria for laxity were at a 72% higher risk for a ligamentous knee injury.[61] The KT 1000 is a clinical instrument used to measure joint laxity at the knee. When an individual is measured as unstable by this standardized machine there is a greater increase in risk of an ACL tear.[62] Stability or general joint laxity has also been assessed using physical examinations including: Lachman's special test, pivot shift, anterior drawer, posterior drawer, and varus/valgus stress tests. Research has shown that joint laxity is a risk factor for ACL injury.[44]

The geometry and ligamentous properties of the ACL combined with the shape and size of the femoral intercondylar notch has a significant effect on an individual's risk for ACL injury. Individuals with a smaller intercondylar notch, relative to body size are at an increased risk for non-contact ACL injury. Anterior intercondylar notch stenosis is associated with increased risk of ACL tear in cutting and pivoting sports, specifically in a non-contact mechanism of injury. The result of a smaller intercondylar notch is an increased impingement on the ACL before any activity is carried out.[46] When researchers have compared notch size within patients that have sustained bilateral ACL injuries with patients that have only a unilateral injury and a control group notch sizes were found to be smallest within the bilateral ACL injury group.[45] Some forms of measuring this type of data include radiograph, MRI, calipers, and digital data. Otherwise, data is collected and analyzed using cadaver tissue, which is not easily accessible and difficult to discern from live tissue cultures. However, since some studies have found no differences between groups there is contradictory evidence and more need for research regarding and regulating these types of factors.[71, 72] The interpretation should also be made with caution.

The effect of hormones on ligamentous properties and ACL injury has been a focus of research in the female population. Once again, it is difficult to standardize recent studies on hormonal effects as data is collected at various times of the menstrual cycle and it is unknown which phase or phases are optimal for data collection. Another difficulty in this area of research is finding the optimal number of hormone samples to collect, due to variance in the cycle time frames among females. There is also the problem of not being able to compare data and analyze between sexes. Due to these confounding factors, some research has been collected on animal models. For example, when rabbits were treated with estradiol for thirty days the load to failure was at a much lower threshold.[48] However, some studies report no differences in ligament qualities when animals were treated with hormones over time.[73] Hormonal treatment simulating the female menstrual cycle influenced ACL metabolism and collagen synthesis. During various phases of the menstrual cycle, knee laxity seems to be effected more so than in other phases. Specifically, increased knee laxity will occur during the periovulatory and luteal phases of menstrual cycle when compared to mensus.[74-76] However, there is no evidence that changes in laxity are correlated with the menstrual cycle. Therefore, more research needs to be dedicated to finding the effects of hormones on ACL ligamentous properties, as well as standardized procedures for data collection.

BMI is also risk factor for ACL injury, in that as BMI increases the risk for injury. There are also movement adjustments that occur when BMI is increased, such as a more extended lower extremity position causing decreased knee flexion in velocity upon landings.[77]. When compared to females with average BMI levels of 18.5-24.9 it was found that females with an above average BMI level had a higher rate of ACL injury[44]. This may be due to the lower muscle mass strength present when there is an increased

BMI or fat mass.[78] However, there are several studies that have found no relationship between injury risk and BMI.[40, 79, 80]

The little research that has been done on familial dispositions of ACL injury risk yields that there may be some sort of genetic impact on the likelihood of sustaining an ACL injury. When patients with bilateral ACL ruptures were analyzed, there was a significantly higher incidence of ACL ruptures in immediate family members.[81, 82] More research should be conducted on this risk factor to understand if sustaining the injury is the risk factor, or if it is due to an anatomical risk.

One of the most accessible ways to determine an increased risk for ACL injury is to measure Q- angle. The Q- angle is described as the angle between the anterior superior iliac spine, the midpoint of the patella, and the tibial tuberosity.[83, 84] As Q- angle increases the position of the knee rests in a more static valgus position. The normal ranges for Q- angle lie between ten and fifteen degrees. Over fifteen to twenty degrees is considered abnormal or excessive, with women having an increased Q-angle when compared to men on average.[85-87] In the athletic population, an increased Q-angle is problematic due to the decrease in stability and the compensations that must be made as a result of the malalignment in static position. Individuals with increased Q- angle have shown decreased vastus medialis activation and increased vastus lateralis activation during activity.[86] This weakness causes genu valgum static posture and an imbalance at the knee.

Excessive pronation is a risk factor for ACL injury.[65-70] To identify excessive pronation, measuring navicular drop has proven effective throughout research. The correlation between an excessively pronated posture and excessive navicular drop angle were highly correlated when investigated.[67, 69, 70] Athletes that exhibit a greater degree of navicular drop are classified as having excessive pronation. Multiple researchers have found excessive navicular drop and subtalar pronation in patients that have a history of ACL injury when compared to athletes that have remained healthy.[65, 67, 69] When an individual is in a postural position throughout life the proprioceptors in their body recognize that position as “normal”.[67] As a person increases the amount of pronation at the subtalar joint, the amount of tibial IR also increases. When the tibia internally rotates the ACL ligament becomes stressed. A constant position of tibial IR will increase the amount of constant stress on the ACL, which will become the normal position of the ligament. Once the athlete performs activity the ACL is at an even greater disadvantage than when they are in a static stance, hence, at an increased risk.

It is known that women are more likely to sustain an ACL injury than men.[5, 52, 53] Not only do women appear to have more of the intrinsic risk factors associated with ACL injury, but there is evidence that female movement patterns put them at even more of a disadvantage.[55, 88, 89] The anatomical factors present in women that put them at an increased risk for ACL injury include larger Q-angle measurements, higher incidence of navicular drop, and weaker hamstrings.[57, 90, 91] Once the intrinsic factor is present, the interaction between movement patterns is added and the injury risk is further increased.

Neuromuscular Control and Biomechanical Risk Factors

The neuromuscular components of research provide the strongest theoretical evidence to support clinical observations of risk factors for ACL injury occurrence. Neuromuscular risk factors can be generally categorized into three groups: altered movement patterns, altered activation patterns, and inadequate muscle stiffness.[37] There are various movement patterns during athletic activity that have been linked to injury. The most common altered movement patterns are less knee and hip flexion, increased knee valgus, increased hip IR, increased tibial ER, less knee joint stiffness, and high quadriceps activity in comparison with hamstring activity. Females tend to exhibit more of these patterns than males.[56, 92, 93 57, 90, 94-98]

Increased knee valgus angle during functional activity is a predisposing risk factor to ACL injury.[30, 58, 63, 64] In recent years, analyzing motion during physical activity, specifically landing from vertical jumps, has yielded applicable knowledge for clinicians. It appears that females tend to exhibit more knee valgus motion and higher knee valgus angles when compared to males. Since clinicians now know that dynamic knee valgus angle, also known as medial knee collapse, during landing is a potential cause of injury there have been strides by many to correct these positions in those athletes who exhibit it. Analyzing athletes in real time, through video, or 3D motion analysis have all proven effective in identifying dynamic knee valgus.

One reason for altered movement patterns is leg dominance in sports, which can impact strength, flexibility, and coordination between limbs, this cause imbalances and increases the chance of injury in the weaker limb.[2, 58, 99-101] Another cause of the altered movements related to ACL injury risk is fatigue. Fatigue that comes with athletic activity decreases the efficiency of the muscles and ultimately increases the chance of injury. [37, 102] It has been shown that when fatigued, the occurrence of altered mechanics, specifically internal knee varus moment, tibial anterior translation, and decreased knee flexion angle during landing increase.[102] During athletic activity an overwhelming recruitment of the quadriceps can increase injury risk. The hamstring muscle assists the

ACL in limiting anterior tibial translation while the quadriceps promote anterior tibial translation potentially loading the ACL.[28] An eccentric quadriceps contraction that overcomes the opposite hamstrings contraction creates an excessive anterior translation of the tibia.[56, 94, 103, 104 90, 105, 106]

Females are not only at a disadvantage in regards to anatomical risk factors for ACL injury, but also in neuromuscular and biomechanical aspects, as well. Males experience a rapid increase in growth more defined than females during puberty. Females may not experience the sudden increase in muscle development that males do.[88] Research shows that boys and girls exhibit fairly similar knee flexion angles during a stop-jump task before the age of 12- 13. However, after the age of 13, girls begin to exhibit decreased knee flexion angles, which is an ACL injury risk factor.[107] Females exhibit a higher quadriceps activation rate and quadriceps to hamstring strength ratio when compared to males creating an increased anterior translation of the tibia. Inadequate muscle stiffness around the knee is another cause of increased anterior translation.[108 109] Females exhibit decreased stiffness when compared to males, leading to a decreased response to an anterior force.[108-112]

The information that we have been provided about all these risky movement patterns has been detrimental to the break though in identifying these movements effectively in clinical settings. Females tend to exhibit stiff landing patterns, which can be described as less knee flexion and more knee valgus upon landing, causing a decreased ability to absorb ground reaction forces during deceleration.[57, 58, 93] The location in which women and men absorb absolute energy has an effect on the injuries they sustain. It was found that women will absorb more energy at the knee when compared to men, increasing the potential for injury. [60] However, there is evidence that is not the case.[78] A common finding is that women will absorb less energy at the hip than men do. [60, 78] More research determining which joint impacts are absorbed between sexes can lead to more insight on why females tend to have more frequent, more severe knee injuries than men do.

Anterior Cruciate Ligament Reconstruction Surgery Outcomes

After an ACLR has been performed there are many aspects to reconsider. In an athletic population that want to continue to compete surgical repair is the option with the best long term outcomes. Unfortunately, with reconstruction surgery there are associated risks. As research continues to develop findings on these outcomes the surgical procedure may begin to improve, which is why continual research on methods or surgical repair and graft types is extremely relevant to clinical practice.

Long term consequences of ACLR include early onset of knee osteoarthritis (OA), high rates of second ACL injury, and a decreased ability to participate in sport or physical activity. The likelihood of a patient with a history of ACLR to develop OA is reported to be at about 50 percent. [113] [114] This statistic climbs to 70% likelihood of OA at 15 to 20 years after the initial injury occurs when there is presence of a meniscal injury.[113, 114] These high occurrences of OA between 10 to 15 years after surgery can be occurring in ages as young as 25 years in certain patients. The overall quality of life of these young individuals is severely affected. There are instances when a patient undergoes a primary reconstruction and still experiences anterior instability. In these cases, a revision ACLR can be done. However, research has found that these types of reconstructions are not as effective in reducing instability and increasing quality of life when compared to primary ACLR.[27, 115-118] Research that utilized animal subjects has found that the mechanical properties of a normal ACL are much stronger than that of the ACLR graft.[119-121] It can be interpreted that an ACL that hasn't undergone surgical reconstruction is less likely to become injured when compared to a reconstructed ligament. This may be why a history of ACL reconstruction is a significant risk factor to having another ACL injury.

Re-injury tends to occur in the populations that remain active. Most of these re-injuries tend to occur within two years of the reconstruction. Not only is the risk of injury applied to the recently injured ACL but the contralateral ACL, as well. Perhaps some of the highest re-injury rates are recorded in female athletes when compared to female non-athletes, and those that return to sports or physical activity. Annual injury rates have been recorded to be as high as 80,000 tears in the United States alone.[122] It is known that after an athlete sustains an ACL rupture, there is a decrease in the level of performance and frequency of sports activity relative to previous levels due to reports of decrease in quality of life.[62, 123, 124]An alteration in neuromuscular control, specifically during landing and deficits in postural stability, are also a big contributor to subsequent ACL injuries.[124] Examples of altered neuromuscular control include patients that begin to favor their injured limb or exhibit more of the poor movement patterns that may have caused initial injury due to weakness. Patients that do not adopt new and improved movement patterns that put them at a less chance for injury may likely suffer a second ACL injury to either limb.

Prevention and Rehabilitation Programs

The best way to combat subsequent injury of the ACL is to prevent initial injury from occurring in the first place. Unfortunately, this task is not easily done. Therefore, there has been a lot of research devoted to preventing ACL ruptures through various training methods and programs. Several studies have found an increase in performance once a prevention program concludes. Examples of increased performance have varied from increased hamstring strength, improvements in postural control and balance, and even increased vertical jump height.[54, 125, 126] It is discussed that the timeline and the point in time are important in the results of the program. However, the research is varied in time points and duration as of now. More research should be conducted on how these effects make an impact on the results of prevention programs.

It is difficult to control for all the factors that can disrupt an effective prevention program, however, there have been many research studies that have demonstrated reliability.[37] The gold standard of prevention research studies is particular. Most of the prevention programs have been implemented on a female population, due to the increased risk that females have been shown to have.[37] Common themes in the prevention programs that have been successful contain stretching and strengthening activities, aerobic conditioning, agility training, plyometric exercises, and risk awareness training.[37, 127] There have been no documented or published incidences of a prevention program creating a higher rate of ACL injury. However, there have been instances that programs implemented did not yield a decreased rate of knee injuries.[126, 128] Reasons that these programs may have been unsuccessful include: high dropout rates and the training style selected was strength training and plyometrics, which creates an abundance of fatigue.

Strengthening in rehabilitation or prevention programs has been found to decrease the risk of an initial or subsequent ACL injury. Since the internal rotator muscles in the hip are highly associated with knee valgus kinematics it can be inferred that intervention at the hip may have significant effects at the knee.[96] Specifically if there is a deficit of hip muscle strength during the early phases of landing there is a high risk of ACL injury.[129] Strength training of the lower extremity alone has been shown to decrease ACL injury in groups put through a prevention program. It is common to target the hamstrings during strengthening due to the posterior tibial shear force the hamstrings provide at the knee. [127]

Plyometric training is important to include in a prevention or rehabilitation program based on the evidence that the stretch shortening cycle activates neural, muscular, and elastic components of soft tissue fibers. Therefore, the knee becomes more stable due to the education of the muscles to anticipate perturbation and respond accordingly. Not only have these programs decreased overall injury but severity of injury, as well. It is argued that balance can lead to increased trunk control and when used in combination with plyometric exercise there are positive effects on asymmetrical landing patterns.[56, 127] Balance and postural training will also stimulate the somatosensory systems and increase co-activation of the muscles protecting the joint in response to perturbations. Recently, rehabilitation programs have been accelerated to push patients back into athletic activity.[130] However, recent research debates if the patient is truly ready for return to sport after these types of rehabilitation protocols. Finding ways to intervene during rehabilitation of ACLR patients is relevant from the standpoint that it could help decrease re-injury rates significantly.

Movement Screening Assessments

Screening assessments of movement can be implemented in clinical settings to identify patients at risk for an ACL injury. There are a variety of reliable ways to identify certain movement patterns that may put an individual at risk for an ACL rupture.[11, 64, 131-133] The Landing Error Scoring System (LESS) is a standardized screening process that has been used to identify injury risk based on observations of movement. Some of the categories in this scoring system include: initial foot contact symmetry, maximum foot rotation position, stance width, maximum knee valgus angles, initial landing of feet, amount of knee flexion, amount of trunk flexion, totally displacement of knee joint in the sagittal plane, and overall impression. The examiner has the patient perform a jump off a box three times. The movements are analyzed in the frontal and sagittal planes. Once the movements of the patient have been analyzed and scored the score is interpreted and risk of injury is noted.[64] This system serves as mostly a way to identify the poor movements and correct them to decrease injury risk.

Using a simple single leg squat is cost effective and has been found to be reliable in identifying knee valgus angles.[11] The Trendelenburg test is used to identify gluteus medius weakness that may cause an increase in knee valgus. However, because an individual presents with knee valgus and a positive Trendelenburg tests it does not indicate that the only problem is hip abductor weakness. Often researchers use a single leg squat to identify these deficits. Insight provided by analyzing the single leg squat is certainly relevant to sport activity. In the areas concerning bilateral asymmetrical landing and loading patterns a single leg squat does not allow bilateral leg comparisons that need to be drawn. Analyzing bilateral limb loading patterns during an overhead squat can be an effective alternative and will provide information about bilateral loading asymmetries and imbalances that may crossover to sport activity.

The Overhead Squat

The standard overhead squat can be defined as a multiple joint, closed kinetic chain activity occurring in a sitting posture that requires dorsiflexed ankles and deeply flexed hips and knees.[134] Squats are a popular, low risk task that allows for bilateral symmetry comparisons of the lower extremity.[135-137] When a squat is taut properly it can increase strength of the lower extremity, decrease risk of strain on the joints of the lower extremity, and minimize risk of injury of the lower back and knee.[135, 137-139] The criteria for a properly performed squat is as follows: hips, knees, ankles, in parallel alignment, no presence of mediolateral movement, and heels remaining on the ground throughout the entire movement.

Faulty squat mechanics include: mediolateral hip rotation and knee alignment inside or outside of the hip during the movement. The examples of poor squatting mechanics can increase compressive and shear forces at the knee, putting an individual at an increased risk for injury.[140] Poor squatting mechanics have been shown in individuals that have decreased strength in the hip and ankle musculature. These decreases in strength have a negative effect on the ability to stabilize the lower extremity and can cause risky movement patterns such as hip adduction, hip rotation, and knee valgus positions.[134, 141] Due to the kinetic chain, the hip and ankle play an extremely important role in performance of lower extremity physical activities. For example, limited DF capability can contribute to decreased knee flexion and increased knee valgus.[9, 142, 143] Another example was shown by Chiais et al.[8] concluding limited two joint hip flexors and limited external rotation range of motion will cause deviations at the hip and knee that increase injury risk

Asymmetry in Anterior Cruciate Ligament Reconstruction Patients

Individuals with a history of ACL injury surgical reconstruction have been shown to decrease the loading on the injured limb compared to their previously uninjured limb during physical activity.[144-146] Whether the compensation is due to weakness or a protective mechanism of the injured limb is still up for debate. Holsgaard- Larsen et. al.[147] was one of the first studies to use a dual platform approach to investigate what types of bilateral asymmetry ACLR patients exhibited during bilateral and unilateral countermovement jumps and a one leg maximal hop for distance.[147] This study found the most asymmetry in the contractile strength of the hamstring muscle. This information gives us a good idea why there may be so many subsequent ruptures of the ACL in an ACLR patients. However, this study also provides a good basis for future research. Using a dual platform approach to identify risk in post-operative patients may help prevent future injury. This study also notes that future research should focus on how to remove the presence of asymmetry through training or feedback.

Functional hop tests, such as the single leg hop test is deemed a reliable functional test used to determine when ACLR patients are ready to return to play according to some research.[148] Single leg hop tests are conducted by instructing the patient to use one leg to hop as far as the patient can go with a controlled landing and the distance hopped is measured.[148, 149] The single legged timed hop test is conducted by instructing the patient to perform one legged hops in a series and timed and rounded to the nearest tenth of a second. A crossover hop test is conducted by instructing the patient to hop over a designated line on the floor with one foot, three times and the total distance hopped is measured. The limb symmetry index that are observed from the single hop test and crossover test is calculated by taking the mean of the involved limb and dividing it by the noninvolved limb then multiplying that value by 100. The contrary is done for the timed hop test, the mean of the noninvolved limb is divided by the mean of the involved limb and the value is multiplied by 100.[148, 149] The value that is determined normal is 85% limb symmetry index. This does not take into account level of activity in sport or leg dominance. The problem with these return to play methods is that some research studies have found an excessive amount of patients that cannot pass with higher than 85% symmetry between limbs in all the categories. Noyes et. al.[149] discovered that of the population that was put through the functional hop tests, 50% demonstrated abnormal symmetry between limbs on the single hop test. Therefore, it can be presumed that ACLR population are exhibiting asymmetrical movement patterns that can lead to a subsequent injury.

Correction of Faulty Lower Extremity Biomechanics

The knowledge that asymmetries and other injurious lower extremity biomechanics exist has made it apparent to clinicians that corrections of movement patterns need to be made to prevent injury. Verbal feedback has been used on landing techniques and other athletic activities. Main strategies of verbal feedback can be divided into internal focuses and external focuses. Internal focuses of attention focus on the movement themselves, such as, the instruction of “bend your knees more when you land”. These instructions can also use a more external focus of attention, such as, “run to the line and pivot”.[150, 151] Certain verbal cues have been linked to decreased knee valgus angles, increased knee flexion, and decreased vertical ground reaction force.[89, 127, 152, 153] Using visual feedback, such as video footage, to try and stimulate a change in poor movement patterns during side step maneuvers has also been proven effective.[154] However, there are not many research studies that have dedicated their efforts to correcting bilateral asymmetry during tasks with verbal or visual feedback.

A tool that can potentially be used to measure bilateral asymmetry is the TekScan Mobile Mat. This tool is a pressure sensor mat used to measure plantar pressure during normal tasks, such as walking or squatting. This tool has been proven reliable in measuring plantar pressure and can be used in the investigation of clinical populations.[155-157] The TekScan software has been used for detecting risk of neuropathy and foot ulcers by assessing different aspects of the foot and the peak pressures that occur.[158] Similarly, there have been more dynamic research studies that investigated foot pressure. Such activities include walking, running, and sit to stand performance.[159-162] Certain studies have identified populations that have already sustained injuries and then compare their plantar pressure profiles to receive information on the biomechanics of injury. These types of technology have been compared and proven just as reliable as force plates. The data that can be interpreted can allow for clinicians and patients to view the degree of asymmetry. Possibly, this technology can be implemented to educate clinicians and patients on how to correct their movements for more ideal limb symmetry. The TekScan is not made for hard landing, such as a vertical jump. However, an overhead squat is a stationary, athletic activity that may be able to give feedback on how an individual carries their weight.

Analyzing Asymmetry with Overhead Squats

Analyzing overhead squats using plantar foot pressure sensor mats can allow for data on differences in side-to-side loading patterns between limbs throughout the task. The presence of a lateral hip shift in an overhead squat is easily identifiable through a visual movement screening of a double leg squat. A lateral hip shift is often associated with knee valgus or imbalanced movement patterns. After the asymmetries in loading have been detected it is a clinician's responsibility to communicate to the patient how to correct the causes of the asymmetrical movement. However, research must be done to give clinicians the proper knowledge on causes and characteristics of the patients that have asymmetrical movement patterns, such as a lateral hip shift. This study will provide insight on lower extremity ROM and plantar foot pressure characteristics in populations that exhibit a lateral hip shift and populations that do not have a lateral hip shift during overhead squats. Eventually, the evidence of this article can help clinicians to understand the causes that may be contributing to lateral hip shifting, and ultimately asymmetrical movement patterns in patient.

CHAPTER III

METHODS

Study Design

The current study was a cross-sectional research design. All subjects reported to the athletic training research laboratory for a single testing session lasting approximately forty-five minutes. The independent variables were Group (lateral shift and control) and Limb (limb shifted ‘toward’, limb shifted ‘away’ from). The dependent variables included, active and passive ankle DF range of motion (ROM), passive hip ABD, active hip IR and external rotation (ER) ROM, and WB%, left- right (LR) excursion, anterior-posterior (AP) excursion during an overhead squat.

Participants

Twenty-nine healthy collegiate students volunteered to participate in this study. Through a screening process, seventeen individuals (7 males and 10 females) were identified that had a lateral hip shift (LAT; Age = 21.3 ± 2.05 years, Height = 175.1 ± 9.10 cm, Mass = 77.6 ± 14.2 kg) during an overhead squat and 12 individuals (7 males and 5 females) were identified that did not (CON; Age = 20.8 ± 2.1 years, Height = 177.4 ± 6.8cm, Mass = 77.8 ± 11.1kg). Subjects were excluded from the study if they had a lower extremity musculoskeletal injury within the past 3 months that kept them from participating in physical activity. Subjects were also excluded if they had a functional leg length discrepancy, a known neurologic condition resulting in decreased balance and/or proprioception, or were knowingly pregnant.

All subjects involved in the data collection were required to read and sign an IRB approved informed consent document prior to testing. Participation in this study was voluntary and subjects were able to withdraw from the study at any time.

Instrumentation

Plantar Pressure Mat

The plantar pressure mat system (TekScan, MobileMat, Boston, MA) included a mobile pressure mat with a platform sensor area of 0.76 ^{2} cm, scanning speed up of up to 100 Hz, a sensing area of 2,176.9 cm, a pressure range of 125 psi/862 kPa, and 2,112 sensels. The plantar pressure mat system was paired with the FootMat Research Software 7.0 (TekScan, Boston, MA., USA) to measure pressure between the foot and the ground beneath the platform. Data was sampled at 30 Hz over a 30-second time period. The plantar pressure mat was synched with a laptop for data acquisition and processing via a standard USB port.

Goniometry

A standard 19-inch plastic goniometer was utilized to assess active and passive ankle DF ROM and passive hip abduction ROM. A digital inclinometer (SPI-Tronic, Garden Grove, California) was utilized to assess the weight bearing lunge (WBL), hip internal rotation (IR), and hip external rotation (ER) ROM. The same investigator performed all ROM measurements bilaterally on all subjects. Intrarater reliability was established prior to data collection with ICCs ranging from (0.96-0.99)

Procedures

Subjects reported to the lab and were asked to wear athletic shorts and a t-shirt that allowed for free movement. The researcher measured the subject's bilateral leg length using a standard cloth tape measure. Leg length was measured bilaterally as the distance from the subject's anterior superior iliac spine (ASIS) to the lateral malleolus. A difference of greater than 20 mm from side to side was a positive finding for a true leg length discrepancy.[84] No potential subjects were excluded based on this criteria.

Additional demographic information was recorded for each subject, including body mass (kg), height (cm), dominant 'balance' limb, and dominant 'kicking' limb. Dominant balance limb was operationally defined as the leg chosen for optimal stability during a stationary single leg stance. Dominant kicking limb was operationally defined as the leg chosen to kick a soccer ball for maximal distance. Subjects were then asked to begin a 5 minute warm- up on a stationary bike (Life Fitness, 9500 Upright Bike, Bencia, CA). Subjects were instructed to maintain a speed of 70 rotations per minute with no additional resistance added.

Range of Motion Measurements

All ROM measurements were performed immediately following the 5-minute warm- up. The order of ROM assessments was randomized for each subject to control for any potential order affects. Randomization was performed prior to each testing session by pulling slips of paper out of a box to determine the order. Bilateral active ROM (AROM) and passive ROM (PROM) measurements at the ankle and hip were measured and recorded for each subject. For the purpose of this study, AROM was described as the point of neutral joint position to the point the subject can no longer move their limb without assistance from a clinician.[83, 84] All PROM measurements were described as the beginning neutral joint position to the point of first resistance. The point of first resistance was defined as the point where the examiner felt resistance from tension in the muscle or the subject expressed discomfort.[83, 84] For ROM that required both active and passive measurements AROM measurements were always taken first followed by PROM measurements. Three trials were taken for each assessment and the average was used for statistical analysis.

Active & Passive Ankle Dorsiflexion: The subject was asked to lay in a supine position on a treatment table with both legs fully extended. A bolster was placed under the distal shank of the limb being measured. The examiner instructed the subject to pull their toes as far toward their head as they could. Once this point was reached, the examiner placed a standard goniometer fulcrum on the lateral malleolus, the stationary arm bisecting the fibula, and the movement arm bisecting the long axis of the 5th metatarsal.[83, 84] This angle was then recorded as the AROM measurement and repeated three times. The same procedure was used to assess PROM, but the clinician provided an overpressure on the joint until the point of first resistance was reached. This angle was then recorded as the PROM measurement and repeated three times. The same AROM and PROM procedures were repeated while lying supine, with the knee flexed to 90 degrees to isolate the soleus.[84]

Weight-Bearing Lunge (WBL): For purposes of this study, the WBL was described as the patient lunging forward as far as they could without allowing their back?

heel to leave the ground. Once this point was reached, the examiner placed the digital inclinometer just below the tibial tuberosity and measured the angle of the front lower leg relative to the vertical.[163] This measurement was recorded three times on each leg.

Passive Hip Abduction (ABD): The subject was asked to lay in a supine position with both legs fully extended. The examiner grasped the medial thigh and brought the leg passively into hip ABD until the first resistance was reached. Once this point was reached, the examiner placed a goniometer fulcrum on the ASIS of the limb that was being measured, the stationary arm was placed in line with the opposite ASIS and the movement arm along the long axis of the femur.[83, 84] The angle was read and then recorded for three trials.

Active Hip Internal Rotation (Hip IR): The subject was lying prone with their knee flexed to 90 degrees on the treatment table. While stabilizing the pelvis, the subject was instructed to actively move their lower leg as far toward the outside as possible. A demonstration was done if needed. The examiner placed the digital inclinometer just above the subject's lateral malleolus and measured this angle relative to the vertical.[164] This was done three times on each limb.

Active Hip External Rotation (Hip ER): The subject was lying prone with their knee flexed to 90 degrees on the treatment table. While stabilizing the pelvis, the subject was instructed to actively move their lower leg as far to the inside as possible. [164] A demonstration was done if needed. The examiner placed the digital inclinometer just above the subject's medial malleolus and measured this angle relative to the vertical. This was done three times on each limb.

Overhead Squat Screening for Group Allocation

One set of five consecutive overhead squats were performed by each subject to determine eligibility for the current study as well as group allocation based on the presence or absence of a lateral shift. Squats were performed bare foot while standing atop the plantar pressure mat to a standardized cadence of 60 beats per second. The laptop and researcher were positioned so the subject could not see the laptop screen and the researcher could observe the subject for a successful trial during all sessions. Plantar pressure data was not recorded during the screening process, but was used to familiarize the subjects during screening. A standard metronome set at 60Hz was utilized to provide audible cues for squat tempo. The subjects were asked to step onto the plantar pressure mat, place feet shoulder distance apart, facing forward, with the tip of their great toe touching a horizontal line placed on the mat with a piece of white athletic tape. Once the subject was in this position, two additional vertical pieces of tape were placed on the mat even with the medial aspect of the foot. The tape was used as a reference to ensure consistency in foot placement between the screening and data collection trials. The subjects were instructed on how to perform the overhead squat with the following verbal instructions: “You will squat down to a depth that is comfortable for you, with at least 60 degrees of bend in your knees. Your toes should face forward. Heels should remain on the mat at all times. Your arms must remain straight up above your head. Perform the five squats fluidly, without hesitation.” Knee flexion to a minimum of sixty degrees was confirmed visually by the investigator.

Verbal cues also assisted in standardizing the squat cadence with the metronome. The clinician turned on the metronome and instructed the subject with the following direction: “I want you to go down into the squat for two beats and rise for two beats. Then pause for one beat.” The subject was then allowed to practice the squats with the metronome and the verbal cues given by the researcher. Verbal cues that were given simultaneously with the metronome were: “Down, down. Up, up. Pause.” The subject was allowed as many trials as they needed to get accustomed to the proper form and speed of the squat.

Demonstration and feedback were not provided. Squats were considered successful if the following criteria were met: 1) toes remained forward, 2) heels remained on the ground, 3) arms remained above the head, 4) squats were completed at the correct speed and to proper depth, 5) and the task was completed in a fluid motion (no hesitation).

The primary investigator visually observed the subjects performing the squat task and group assignment was determined. Subjects’ whose mid-sagittal line through the trunk shifted laterally towards one leg during at least 3 out of the five squats were placed in the LAT group. Subjects who shifted in both directions were disqualified so that the hip shift movement would be isolated to one limb. One potential subject was eliminated from the study due to these criteria. Subjects were placed in the CON group if they did not shift laterally and they maintained proper form in at least 3 out of 5 squats. All subjects included in the study were not informed of what group they were placed into to avoid influencing the performance of the overhead squat in future trials. No data from the plantar pressure mat was collected during this screening trial, but was used to allow the subject to become accustomed to performing the squats on the mat.

Plantar Foot Pressure Measurements

At the conclusion of the group allocation session, each subject performed an additional set of 5 overhead squats while plantar pressure data were captured. The plantar pressure mat was calibrated for each individual subject. The subject was asked to step onto the mat. The sensitivity of the mat was assessed for each subject to ensure the amount of pressure the subject places on the mat did not exceed the sensitivity of the mat. The subject was asked to perform a single leg calf raise and then to rock back onto their heels. If no pink areas illuminated on the real-time pressure sensor screen that setting was determined suitable for data collection. The point calibration method was utilized prior to testing by asking the subject to stand on both feet, shoulder distance apart, and remain still while the software calibrated the mat.

The subject was instructed to perform the overhead squat task in the exact same manner as described previously. Data were recorded for a 30 second time period (900 frames) or until the subject completed the full set of five consecutive squats.

Data Reduction

All trials of ROM measurements were recorded into an Excel spreadsheet. The average of 3-trials was calculated for all variables and utilized for data analysis. The four plantar pressure mat variables were exported from the software and entered into the same Excel spreadsheet. Bilateral limb data for each subject was coded as the limb shifted toward (1) or the limb shifted away from (2). The limbs of the CON subjects were assigned to serve as the ‘toward’ and ‘away’ limb to match the distribution of LAT subjects that shifted toward their right or left. Specifically, 9 subjects in the LAT shift group shifted toward their right leg and away from their left, while 8 subjects shifted toward their left leg and away from their right. Therefore, 6 CON subjects were assigned so that the right leg was the shifted 'toward' and 6 were assigned so that the left leg was the shifted 'toward.' All but one subject reported their right leg as their dominant kicking leg. Therefore, we felt the limb dominance was not a strong factor for assignment purposes.

WB% under each foot, COF distance travelled (cm), LR excursion (cm), AP excursion were recorded and analyzed using the average generated by the plantar pressure sensing mat software. These variables can be defined as follows: WB% was described as the percentage of the subject's body weight that was supported on each foot throughout the duration of the five consecutive squats. COF distance traveled is the scalar distance that the subject's COF traveled in cm throughout the duration of the five consecutive squats. LR excursion is the scalar distance that the subject's COF traveled, specifically in the frontal plane (left to right), throughout the duration of the five consecutive squats.

Statistical Analysis

Separate mixed-model Analyses of Variance (ANOVA) with 1-between subject factor (Group: LAT and CON) and 1-within subject factor (Limb: limb shifted toward and limb shifted away from) were used to compare each of the ROM dependent variables and weight bearing %. The alpha level was set a priori at $\alpha \leq 0.05$ for the ANOVA models. Post hoc analyses were performed using t-tests to identify the location of differences when a significant interaction was observed.

Independent samples t-tests were performed to identify group differences (LAT, CON) in the center of force pressure measures of distance (cm) and LR Excursion (cm). Statistical analyses were performed using the SPSS statistical package (version 21.0; IBM, Inc.). Effect sizes were estimated using Cohen’s method for any significant differences. Cohen d effect size was used to determine the magnitude of difference based on the following criteria: small = 0.2; moderate = 0.5; large = 0.8.

CHAPTER IV

RESULTS

Range of Motion

There was a significant group-by-limb interaction for active DF ROM with the knee flexed ($F_{(1,27)}$ =6.23, p=0.02). Individuals in the LAT shift group had less active DF ROM with the knee flexed on the limb shifted away from in comparison to the limb assigned to serve as the limb shifted away from in the CON group (t (1,27) = -3.03, p < 0.01; d=0.45; Mean Diff = 6.87°). All descriptive data for group and limb are reported in Table 1 and 2.

Table 1

LAT vs. CON Group ROM Measures and WB% of Limb Shifted Toward, Mean ± SD

Measurements	Lateral Shift	Control
Active Ankle DF Flex	7.95±5.39	12.22±5.74
Active Ankle DF Ext	3.61±4.91	8.77±3.94
Passive Ankle DF Flex	2.42±8.60	7.20±6.91
Passive Ankle DF Ext	-4.25±8.65	-1.77±7.83
WBL	39.59±7.53	42.03±6.42
Hip ABD	30.32±8.26	32.23±5.80
Hip IR	36.00±16.72	34.16±16.69
Hip ER	39.04±14.37	38.76±11.86
WB % (Plantar Pressure)	49.65±7.28	50.75±7.31

Note. * indicates statistical significance (p<0.05)

Table 2

LAT vs. CON Group ROM Measures and WB% of Limb Shifted Away, Mean ± SD

Measurements	Lateral Shift	Control
Active Ankle DF Flex	*6.44±5.92	*13.31±6.13
Active Ankle DF Ext	2.53±6.93	7.83±5.04
Passive Ankle DF Flex	2.41±7.75	5.88±8.06
Passive Ankle DF Ext	-4.44±10.44	-3.73±7.74
WBL	39.28±7.30	41.75±6.61
Hip ABD	31.69±7.61	31.89±7.61
Hip IR	39.62±15.42	36.79±13.28
Hip ER	36.95±13.00	38.88±14.29
WB % (Plantar Pressure)	50.25±7.28	49.25±7.31

Note. * indicates statistical significance ($p<0.05$)

There were no significant group-by-limb interactions for any of the other ROM dependent variables: Hip Abduction ($F_{(1,27)} = 0.77$, $p = 0.39$), Hip ER ROM ($F_{(1,27)} = 0.28$, $p = 0.60$), Hip IR ROM ($F_{(1,27)} = 0.11$, $p = 0.75$), Passive DF ROM with the knee flexed ($F_{(1,27)} = 1.09$, $p = 0.31$) or extended ($F_{(1,27)} = 0.53$, $p = 0.47$), active DF ROM with the knee extended ($F_{(1,27)} = 0.01$, $p = 0.92$), and WBL ($F_{(1,27)} = 0.00$, $p = 0.99$).

A main effect for Limb was found for Hip IR ROM ($F_{(1,27)} = 4.28$, $p = 0.04$; $d = 0.10$; Mean Diff = 3.21°), such that regardless of group, the limb shifted toward (35.24 ± 16.43) had less active hip IR ROM in comparison to the limb shifted away from (38.45 ± 14.39). There was also a significant main effect for Group for active DF ROM with the knee extended ($F_{(1,27)} = 7.23$, $p = 0.01$; $d = 0.45$; Mean Diff = 5.23°), such that the CON group had greater active DF ROM with the knee extended (8.3 ± 1.5°) in comparison to the LAT shift group (3.1 ± 1.3°).

Plantar Pressures

There was no significant group-by-limb interaction ($F_{(1,27)} = 0.16$, $p = 0.69$) or main effect for weight bearing % during the overhead squat.

The LAT shift group demonstrated greater total Distance (cm) travelled by the COF ($t_{(1,27)} = 2.21$, $p = 0.04$; $d = 0.38$; Mean Diff = 24.27cm) and greater LR excursion (cm) of the COF ($t_{(1,27)} = 2.30$, $p = 0.03$; $d = 0.37$; Mean Diff = 2.96cm) in comparison to the CON group. All descriptive data for plantar pressure variables are reported in Table 3.

Table 3

LAT vs. CON Group Plantar Pressure Measures (cm), Mean ± SD

Measurements	Lateral Shift	Control
COF Distance (cm)	*198.14± 29.03	*173.87±29.39
COF LR Excursion (cm)	*8.45±4.91	*5.49±1.71

Note. * indicates statistical significance ($p<0.05$)

CHAPTER V

DISCUSSION AND CONCLUSION

Discussion

The purpose of this study was to identify lower extremity ROM and plantar foot pressure distributions that are present in individuals with and without a lateral hip shift during an overhead squat. We hypothesized that the subjects with a lateral hip shift during an overhead squat would demonstrate decreased ankle DF, decreases in hip ER in the limb shifted toward, and increased hip IR in the limb shifted away from. The results of the study confirmed that a portion of our hypothesis was accurate. Subjects with a lateral hip shift did exhibit a decreased DF when compared to the CON group in the limb shifted away in the limb shifted away. We also hypothesized that the LAT group would present with greater side to side asymmetry in weight bearing %. While we did not find statistical significance in weight bearing %, we did observe greater movement of the COF in individuals in the LAT shift group.

Range of Motion

Our results revealed that the LAT group had a decreased active DF ROM with the knee flexed in the limb shifted away from when compared to those in the limb assigned as the limb shifted away from in the CON group. Research has previously shown that passive DF ROM has an effect on how an individual will perform a double leg squat.[9] In contrast to our hypothesis, passive ankle DF did not have a significant difference between groups. The WBL also showed no differences between groups. Information such as this may help to support that passive ROM is not the only factor that can cause compensations in the lower extremity during functional movements.

Perhaps the lateral hip shift compensation does not occur due to soft tissue restraints, but instead muscle activation deficits or abnormalities. Research has shown that an increased muscle activation of plantarflexors may cause a faulty movement during lower extremity activities.[165] Our study may support that finding due to the lack of active DF subjects with a lateral hip shift displayed. During functional activity these physically active individuals may be relying more heavily on their plantarflexors for muscular control. Therefore, they may display an overall decrease in their ability to actively contract their ankle DF muscle group, whether it is in a functional activity or a non-weight bearing measurement. This study shows that, although limited passive ankle DF and WBL have been associated with other lower extremity compensations, they may play no role on a lateral hip shift during an overhead squat. Additional research should be done on the lower extremity neuromuscular characteristics of those that display a lateral hip shift during overhead squatting.

This information can allow for an observation to be made about those who display a lateral hip shift, which is easily identified visually by a clinician. Clinicians may be able to use a simple overhead squat to screen for a lateral hip shift. If a lateral hip shift is found in a screening, this pattern may be able to be related to a decreased strength of dorsiflexors, or a restriction in a knee flexed position that does not allow for proper DF.

Ultimately, active ankle DF deficits may be an indicator in those that clinically present with a lateral hip shift and can also help direct interventions for corrections for patients.

Our results revealed that both groups had an increased hip IR ROM on the limb they shifted away from (contralateral). These findings in the current study should be taken with caution due to the nature of the statistical analysis. Limbs of subjects in the LAT group had to be assigned with the limbs of the CON group. Increased hip IR ROM may not be as true to an individual with a lateral hip shift. Additionally, when reading further into the differences, the effect size is unremarkable. Clinically, this may not be viewed as a significant enough increase in IR to have a true effect on motion that can be observed in squatting mechanics.

Plantar Pressure Data

This study utilized a more mobile and affordable technology to bilaterally compare the left and right limbs in a population that is classified as having a lateral hip shift. These bilateral comparisons are extremely important to draw as bilateral asymmetry loading has been linked to high re-injury rates in ACLR populations.[1] Using more affordable equipment can provide clinicians with information on how to identify and then reeducate patients that have sustained an ACL injury.

Our results found consistent differences in bilateral plantar pressure variables between the LAT and CON group, specifically the distance (cm) and the LR excursion (cm) of COF. The LAT group had a greater amount of both overall distance translation and LR excursion throughout the duration of their squat compared to the CON group.

Clinically, this means an individual with a lateral hip shift may have more movement of the COF from left to right and general distance, overall. It can be inferred that some sort of compensation of the body will follow this greater excursion since the body feels most stable when the COF lies within the base of support.[166] It should be noted that LR movement of the COF will be carried out in the frontal plane, similar to the plane that dynamic knee valgus is observed in. In contrast, there were no differences found in AP excursion. Not only did the plantar foot pressure mat allow us to make the comparison of how much the COF traveled, but specifically which direction. Clinically this information may be able to link a lateral hip shift to an increased LR distance traveled, which clinicians recognize as a risk factor for lower extremity injury. In general, more research should be done using these variables and technology. Further, more research should be done to find which lower extremity compensations may be associated with AP excursion, as they may too be harmful. This study has begun to use plantar pressure mats, to start drawing comparisons and making inferences on those that exhibit, increased injury risk movement patterns.

Limitations

Subjects in the current study were a sample of convenience. Therefore, results from this study cannot be generalized to an injured population or a healthy population outside of the healthy college aged sample.

We were unable to look at pressure data at specific time points during the five consecutive squats. Rather, we looked at the overall pressure during the entire time period the five consecutive squats were performed. Breaking up the squats into the descent and ascent phase may provide further information about pressure distributions in this population. Unfortunately, the technology at this time is not able to do that with squats. This study was novel in the use of the pressure sensor mat during squats.

Conclusion

In conclusion, this study suggests that a patient exhibiting a lateral hip shift during an overhead squat may have restrictions in active ankle DF. Active ankle DF ROM is modifiable through rehabilitation and clinicians should use this information to help eliminate side to side asymmetries during functional movements. This study also provided insight on how a patient's COF moves during a squat with a lateral hip shift. Clinicians may now begin to understand biomechanically what is occurring in the LE when there is a lateral hip shift present.

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