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Hip Muscle Activity During a Functional Movement Assessment

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Hip Muscle Activity During a Functional Movement Assessment

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Abstract

Hip Muscle Activity During a Functional Movement Assessment
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CONTEXT: Neuromuscular control throughout functional movement is a risk factor for lower extremity injury. When implemented correctly, some preventive training programs (PTPs) decrease injury risk while focusing on strengthening the gluteus medius. Specific changes to faulty biomechanics are typically not accomplished. Understanding the causes of these risk factors, and techniques to manipulate them are crucial in injury prevention. **OBJECTIVE:** To evaluate potential differences in hip musculature activation, gluteus medius (GMed), gluteus maximus (GMax), and adductor magnus (ADD), during a jump-landing task between females with and without medial knee displacement (MKD). Additionally, to determine associations between hip muscle activation, vertical ground reaction force (vGRF), and movement control during a jump-landing task. **STUDY DESIGN:** Cross-Sectional Study. **SETTING:** Research laboratory. **PARTICIPANTS:** Thirty-one recreationally active female volunteers (age: 24 ± 5years; height: 167.3 ± 6.8cm; mass: 66.4 ± 10.0kg). **MAIN OUTCOME MEASURES:** Landings were scored for "errors" in technique using the Landing Error Scoring System (LESS). The activity (uV) of the gluteus medius (GMed), gluteus maximus (GMax), and adductor magnus (ADD) were recorded using surface electromyography (EMG); and, landing forces (% bodyweight) were recorded through force-plates. **RESULTS:** No significant differences observed between groups for age, mass, and peak vGRF. In the MKD group, negative correlations were seen between: GMed loading activation and vGRF ($P=0.03$; $R^2=-0.41$); and, GMed:ADD preparatory activation and vGRF ($P=0.04$; $R^2=-0.36$). In the control group, negative correlations were observed between GMed loading activation and LESS scores ($P=0.02$; $R^2=-0.28$); GMed:ADD loading activation and LESS scores ($P=0.01$; $R^2=-0.32$). A positive correlation was observed between GMed and GMax loading activation ($P=0.01$; $R^2=0.30$). **CONCLUSIONS:** Individuals with MKD decrease their vGRF through higher activation of ADD as compared to their gluteus muscles. PTPs and rehabilitation efforts may be more effective with reducing MKD if GMax muscle activity is encouraged instead of ADD.

KEY WORDS: Landing Error Scoring System, LESS, Vertical Ground Reaction Force, vGRF, Gluteus Maximus, Gluteus Medius, Adductor Magnus, Neuromuscular Control

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Review of the Literature

Introduction

When an individual participates in athletic activities at any level, he or she assumes the risk of sustaining an injury. Approximately 7 million high school students participate in team sports each year in the United States, and, between 3 – 11% of these students advance to the NCAA college athletics level.[1–3] Each athletic event, including practice, strength training, conditioning or games, constitutes an exposure to a risk of injury; therefore, as individuals mature through the ranks of athletics and the number of athletic exposures they have increases, so does their risk of sustaining an injury.

Universally, there is an increased awareness of the health benefits of an active lifestyle more and more individuals are participating in physical activity each year; additionally the age range of active individuals is constantly expanding.[4] This constant growth in the active population suggests a constant growth in the incidence of injury.[4] In an attempt to combat the rising injury rates across the nation, researchers have focused their efforts on identifying risk factors of injury and implementing prevention efforts.

Neuromuscular Control

Neuromuscular characteristics, such as muscle activation, strength, and flexibility, have been found to have a strong effect on lower extremity biomechanics; while certain dysfunctional characteristics have been shown to directly relate to the risk of sustaining an injury.[5–15] To assess these potentially high risk biomechanics, many functional assessment tools have been developed for clinicians.[16–21] Neuromuscular training programs have been developed for athletes at any level to focus on general balance and body control training, strengthening and agility exercises, stretching, running, cutting, and landing techniques.[22–28] [24,1,29–34] Regrettably, these preventative efforts are not widely used in athletics; however, the increase of neuromuscular control that comes from the programs could greatly decrease the risk and incidence of many lower extremity injuries.

Osteoarthritis

Osteoarthritis (OA), is a degenerative disease where there is excessive wear on the articular surface of the bones in addition to joint line changes.[35] It is often seen in the knee following traumatic injury, most commonly Anterior Cruciate Ligament (ACL) injury, and has been suggested that as many as 80% of patients with previous ACL injury will develop OA within 5 to 15 years after the initial injury.[35–40] Osteoarthritis is often classified by severity upon diagnosis based on a well-recognized grading system, the Kellgren & Lawrence classification.[41–44] This classification consists of 5 different grades (0, I, II, III, and IV) that represent ‘‘normal,’’ ‘‘doubtful significance,’’ ‘‘minimal changes,’’ ‘‘moderate changes,’’ and ‘‘severe changes,’’ respectively.[41–44] Approximately 20% of ACL deficient (ACL-D) knees exhibit severe or moderate (grade III or IV) radiologic changes as compared to the 5% in the contralateral uninjured knee; in other words, moderate to severe changes are nearly 5 times more likely to occur in the ACL injured knee as compared to an uninjured knee.[35,41] Osteoarthritis is found in 57% of knees of patients who have undergone ACL-R surgery and only in 18% of the uninjured knees.[35,45] The risk of developing OA following an ACL injury is also increased with the presence of concomitant injuries, such as meniscal tears or bone bruises.[35–40,46,47]

Inactivity and Obesity

Injury to the lower extremity can be devastating to an athlete as it often results in extended time out of participation. On average, an individual who sustains an ACL injury sees a decrease in their activity levels for at least 6 to 9 months due to treatment and rehabilitation. One to two thirds of individuals never return to their previous peak activity levels despite successful surgery and rehabilitation.[48–54] For other lower extremity injuries, the time in rehabilitation may not be as long; however, there is a commonly reported fear of re-injury as well as lack of trust in the previously injured joint that cause patients to not return to previous athletic or recreational activity levels.[41,50,51,55] These fears have been associated with inactivity or a drastic decrease in activity for up to seven years after injury.[51–53,56–59]

It is commonly accepted that the United States is struggling with obesity on a national level and inactivity is a large contributor to this issue.[60] Current data shows that failure to maintain a healthy and physically active lifestyle is directly associated with cessation of activity due to an injury or fear of re-injury.[61–63] Approximately one quarter of active individuals report getting injured during athletic activity and, of this group, one third report a complete end to their exercise program due to self-perceived severe injury.[61,64–68] A complete cessation to physical activity due to a lower extremity injury holds an individual back from receiving the health benefits of regular exercise such as a risk reduction of cardiovascular disease, diabetes, obesity, hypertension, and cancer.[61,69–71] Furthermore, if individuals do not properly rehabilitate and return to some level of activity, injury to the lower extremity can result in lifelong compensations in an individual's movement patterns.

Monetary Cost of Lower Extremity Injury

On top of a taxing physical burden, lower extremity injury results in a large financial burden. Taking into account diagnostic measures, surgical procedures, protective bracing, rehabilitation processes, and other long term costs, the United States spends over $3 billion annually on lower extremity injuries alone.[46] Due to an increased societal focus on the importance of a healthy lifestyle, the number of individuals participating in high-level athletics is continually increasing at every age range. With this increase in participation, the incidence of injuries, as well as the money spent on injuries, continues to increase exponentially.[4]

Lower Extremity Injury

Common Injuries

Stress Fractures

Stress fractures are defined as overuse injuries of the skeletal system due to the consistent breakdown of bone outpacing bone remodeling.[72] Lower extremity biomechanics directly affect how forces are absorbed throughout the limbs, and, these forces are important in the development stress fractures.[72] Stress fractures typically occur 6-8 weeks after a change or increase in training and can be exacerbated by poor bone quality or poor nutritional intake.[72] Diagnosis and prognosis of stress fractures depend on location as well as their risk classification, low or high.[72] High-risk stress fractures of the lower extremity include those in the femoral neck, anterior cortex of the tibia, tarsal navicular, and the base of the fifth metatarsal. These stress fractures are more prone to unfavorable outcomes and are treated slightly more aggressively, with surgery.[72] Low risk stress fractures include those in the posteromedial tibial cortex, fibula, and metatarsal shafts.[72] Low risk stress fractures are commonly treated with functional progression based on symptoms.[72]

Ankle Sprains

The ankle is one of the most commonly injured joint in the body not only in the athletic population, but also in the general population.[12,13] It has been reported that 70% to 80% of these ankle injuries are inversion type sprains that are likely caused by more proximal muscle weakness.[12,13] The lower extremity acts as a functional kinetic chain where there is a direct relationship between the mechanics at the ankle and the mechanics of more proximal joints.[12,73–77] Active individuals who suffer from ankle sprains show significant hip weakness in the hip abductor muscles on the involved limb as compared to the uninvolved limb.[12] Strength and stability of the musculature at the hip joint are vital aspects of proper gait mechanics and lower extremity positioning throughout functional movement.[12,13] In particular, it has been shown that stability of the hip is important for control of foot positioning during heel strike.[12] Weakness of the hip musculature leads to faulty foot positioning during heel strike and places the foot in a more vulnerable position for sustaining an injury such as an inversion ankle sprain.[12,78]

It has been found that up to 70% of acute ankle injuries result in recurrent ankle sprains; and, up to 74% of ankle sprains result in residual symptoms.[79] These residual symptoms are referred to as chronic ankle instability (CAI).[79] Investigators have shown that individuals who suffer from CAI report decreased ability to perform activities of daily living; consequentially reporting a lower health-related quality of life.[79] Ankle laxity is oftentimes an objective variable that directly influences the subjective function in individuals with CAI.[79]

Patellofemoral Pain Syndrome and Iliotibial Band Syndrome

Of all the lower extremity joints, the knee has been shown to have the highest injury rate, especially in active individuals.[80] Patellofemoral pain syndrome (PFPS) is a common term used for anterior knee pain that causes individuals to decrease or modify their normal activity levels[81–83] PFPS is mainly seen in athletes who lack any structural changes such as increased Q-angle or significant pathological changes in articular cartilage.[81,83–87] Due to this broad definition, PFPS is commonly used as a diagnosis of exclusion.[81,83–87] Individuals who exhibit symptoms of PFPS tend to demonstrate less strength in hip abduction and external rotation.[88,89] On average, those experiencing knee pain have an average hip abductor strength deficit of 26%, and an external rotation strength deficit of 36% as compared to their pain free counterparts.[15,88,90] Similarly, Iliotibial band (ITB) syndrome often occurs due to weakness of the gluteus medius muscle, causing over-firing and tightness of the ipsilateral tensor fascia lata and ITB.[14,15] ITB syndrome is a common source of general knee pain for many athletes resulting in an increased compressive force on a highly innervated fat pad that sits between the ITB and the lateral epicondyle.[12,15,91]

Anterior Cruciate Ligament Injury

The anterior cruciate ligament (ACL) is a double bundle ligament that runs anteromedially through the knee joint, originating from the posteriomedial corner of lateral femoral condyle and inserting on the anterior intercondyloid eminence of the tibia where it blends with the anterior horn of the medial meniscus and acts as one of the primary stabilizers of the knee joint.[92] The ACL stabilizes the knee against anteroposterior translation of the tibia on the femur, providing more than 80% of the resistance when the knee is flexed between 30 to 90 degrees.[35,93] When fully taught, the ACL also assists in the arthrokinematics of the knee joint, providing rotation between the tibia and the femur between 20 degrees of flexion and full extension.[35] This rotation is known as the “screw home mechanism” and is vital for stability of the knee when standing upright.[35] As it is such a crucial part of the knee, injury to the ACL results in lifetime functional anomalies.[35]

Epidemiology

It is commonly reported that between 200,000 to 350,000 ACL injuries occur annually in the United States;[1,4,48,94–99] therefore, approximately 1 in every 3,000 active individuals will sustain an ACL injury.[48] It has been shown that increased frequency of sports participation in addition to increased intensity puts an athlete higher risk of sustaining an ACL injury.[100,101] As athletes mature, the intensity and frequency of their participation steadily increases in conjunction with their level of competition. Each athletic exposure, including practice, strength training, conditioning or games, constitutes risk of an injury, and specifically ACL injury; therefore, when the frequency of an individual's athletic exposures increases, so does their risk of injury. It has been shown that 6.5 ACL injuries occur for every 100,000 athletic exposures.[102] A similar increase in risk is seen when individuals are performing at high level activities later in life whether it be recreationally or competitivetly.[4,103,104] In 1994, the average age of patients who suffered an ACL injury was 28±10 years; however, more recent data shows a slight increase to an average age of 29 ± 13 years.[4] This increase accounts for the injury risk associated with the higher lifetime athletic exposures seen in the recent population of the United States.

The highest incidence of ACL injury is seen in college aged individuals, 19-25 years;[98,105] nevertheless, it has been reported that 14-18 year old females are of the highest risk of sustaining such an ACL injury.[105] This increased risk is due to biomechanical risk factors in conjunction with greater participation in sports that involve jumping and cutting motions.[105,106] Since the passing of Title IX legislation in 1972, the number of females who participate in athletics has steadily risen.[4] It has been found that females have a 1.5 to 4.6 fold increased risk of ACL injury as compared to their male counter parts of the same sport.[102,107–110] Of the ACL injuries suffered in the male population, a majority are contact injuries; conversely, females sustain more non-contact ACL injuries.[106] The difference seen between men and women has led to an immense amount of research looking into specific sex differences that predispose females to ACL injury. Proposed reasons for this gender discrepancy include ACL and knee joint anatomy, lower extremity strength, and sports participation.[41,111–116]

Injuries, especially to the ACL, are a common concern for athletes participating in all types of sports. The risk of ACL injury is highest, however, in sports that require large amounts of jumping and pivoting, as this places the ACL on increased levels of stress.[105,106] Contact sports have also been shown to place an individual at increased risk for ACL injury due to external forces that can act on the knee joint during activities of increased levels of stress.[24,117] When comparing sports in the United States, the highest risk of ACL injury can be seen among soccer players,[118] followed by basketball, volleyball, and football athletes.[24,117] It is important to note there is a risk of ACL injury with participation in any sport or athletic activity.

Non-Contact, Contact, and Indirect Contact Injury

Injury to the ACL occurs due to excessive loading of the knee, specifically with knee valgus, extension, and rotation; in addition to anterior tibial shear force as the combination of these movements imposes the greatest strain on the ligament.[49,119–122] The mechanism of injury for an ACL injury is categorized into non-contact, contact, or indirect contact injuries. Non-contact injuries occur due to the athlete's inherent movement patterns, without extrinsic contact to the knee from another player or object;[123,124] whereas, contact and indirect contact ACL injuries occur due to extrinsic forces on the knee. Non-contact ACL injuries are the most prevalent mechanism, accounting for approximately 70% of all reported injuries These often result from movements such as landing from a jump, cutting, pivoting and forceful deceleration.[120,123,125,126] Contact ACL injuries can happen during a football tackle when one player's foot is planted and another player hits him directly on the lateral aspect of the knee joint. An indirect contact mechanism is defined as contact to another body region other than the lower extremity resulting in injury to the ACL.[127] For example, an athlete being hit on the trunk causing them to lose their balance and stability resulting in faulty biomechanics subsequently injuring the ACL. As non-contact and indirect contact ACL injuries occur due to intrinsic factors, they are the types of ACL injury mechanisms that have a strong potential for prevention.

Concomitant Injuries

An isolated ACL injury is rare; rather, they are frequently accompanied by other concomitant injuries. When the ACL is compromised, anterior tibial subluxation often occurs, leading to impact between the posterior lateral tibial plateau and the anterior aspect of the femoral condyle thus causing further injuries to these areas.[35,128] This results in the often-termed injury "kissing bruise".[129] The most common concomitant injuries seen with ACL injuries are bone bruises, and damage to cartilage, the menisci, and the medial collateral ligament.[4] As many as 54% of patients with ACL injuries also have lateral meniscus injuries;[4,129] and, between 80% - 90% of patients will suffer from bone bruises, most commonly seen on the posterolateral tibial plateau and the anterolateral femoral condyle.[130,131] These concomitant injuries often lead to increased pain and more extensive rehabilitation.

Management Strategies

There are many different methods to restoring knee function following injury to the ACL; however, current best practice management does not diminish the lifelong debilitation caused by such an injury. Treatment of ACL injuries can be either surgical, with ligamentous reconstruction (ACL-R) and rehabilitation, or non-surgical, with rehabilitation only. In the United States, ACL-R is more commonly used in an attempt to protect the surrounding joint structures including the menisci and articular cartilage, in addition to return the individual to athletic activity at a competitive level.[46] ACL reconstruction surgeries incorporate a graft into the injured knee as a replacement for the torn ACL ligament. ACL grafts are harvested from one of two sources: a donor cadaver (allograft) or the patient's own body (autograft). The more commonly used method of ACL-R incorporates autografts; however, the use of allografts has been slowly gaining popularity and each choice has different pros and cons.[132,133] Allografts are chosen over autografts in an attempt to diminish symptoms at the donor site, reduce operative time and incisions, and often when return to high levels of activity is not of importance.[132,133] Disadvantages of allografts include negative immune responses, disease transmission, delayed graft incorporation, reduced availability, and high cost as compared to the autograft options.[132] Autografts have low failure rates, rapid incorporation into the knee, minimal symptoms at the donor site, wide availability, and a lower cost as compared to an allograft.[134] Patients with an autograft ACL-R tend to experience a quicker return to sport as compared to patients who undergo allograft reconstruction.[132] The most commonly used grafts are bone-patellar-bone (BTB) grafts (harvested from the central third of the patellar tendon), hamstring tendon (HS) grafts (harvested from portions of the medial hamstrings;semitendinosis and gracilis), and quadriceps grafts (harvested from the quad tendon just proximal to the patella).[134–140] For those patients who choose to avoid surgical treatment, ACL injuries can be treated with consistent structured rehabilitation. Typically, patients who choose this option place a lower demand on their knee joints than the generally active population.[46,141] Oftentimes, this is the elderly, and they experience a decrease in functional stability of the joint throughout the rest of their lives.[46,141] After a long rehabilitation process, there is little to no return to sporting activity when ACL injuries are treated non-surgically due to a significant decreases in joint stability.[14]

Surgical reconstruction provides a base of static stability; but, dynamic stability is provided by muscle strength and firing patterns.[142,143] Rehabilitation post-ACL injury, regardless of whether it is preceded by surgical intervention or not, typically lasts 6-8 months and includes exercises that focus initially on regaining normal joint movement, with the focus on knee extension for a successful outcome for the patient.[143] Progressive weight bearing exercises are utilized to maintain neuromuscular activation patterns; and, regardless if the patient underwent surgery or not, strength training, low impact aerobic activity, proprioceptive, neuromuscular, and stability exercises are vital progressions the patient must take to return to any level of activity successfully.[143,144] As rehabilitation progresses, functional based movements are emphasized in conjunction with sport-specific movements in hopes of the patient returning to full pre injury participation levels eventually.[143,144] Oftentimes, ACL injury prevention interventions are used in ACL injury rehabilitation in an attempt to protect the patient from the pain of a subsequent ACL injury or other lower extremity injury.[143]

Risk Factors for Lower Extremity Injury

Non-Modifiable

Non-modifiable risk factors are the anatomical characteristics of an athlete that they cannot change that place them at a greater risk of injury. As previously stated, females are at a higher risk of sustaining an ACL injury as compared to males,[102,107–110] factors including posterior tibial slope differences, size of ACL in relation to the intercondylar notch, and genetic predisposition.[41,111–116145,146]

Contact forces are spread throughout the tibial plateau and a strain is placed upon the ACL as the lower extremity moves through the gait cycle.[147,148] When the compressive force is applied to the knee, as with normal weight bearing motion, an increased posterior tibial slope causes an increased anterior shear force., Adding this to normal anterior directed forces, places the ACL under more stress than typically necessary.[147,149,150] If the magnitude of these anterior forces exceeds the tensile strength of the ACL, an injury occurs.[147,148] Further, after adjusting for age and body anthropometrics, it has been found that individuals with smaller ACL's,in length, cross-sectional area, volume, and mass, are at an increased risk for ACL injury compared to the overall larger ACL's in healthy counterparts.[145,146,151] A smaller ACL contains a lower fibril concentration and therefore a lower percentage of collagen fibers, thus decreasing the ACL's tensile stiffness, or stability.[145,146] This decrease in stability can result in ACL injury at a shorter length and lesser forces as compared to a 'healthy' ACL size.[146,152,153] The intercondylar notch serves as the attachment site of the ACL and is a deep groove on the posterior aspect of the femur between the medial and lateral condyles and it has been suggested that there is a positive correlation between intercondylar notch size and the cross sectional area of the ACL.[146,154] A smaller intercondylar notch has been shown to cause an impingement of the ACL during tibial external rotation and abduction, thus adding additional stress to the ligament during functional movements.[146,154,155] Many studies have shown that a smaller notch size in addition to a smaller ACL size are non-modifiable risk factors of ACL injury.[145,146,151,156,157]

Recently, it has been reported that previous ACL injury increases an individual's risk of sustaining a subsequent ipsilateral or contralateral non-contact ACL injury.[158–161] Wright *et al.* reports that approximately 6% of patients (1 in 17) sustains a second ACL injury within two years after the initial ACL injury.[160] Additionally, it has been shown that within 15 years post-primary ACL reconstruction surgery (ACL-R) approximately 29% to 34% of patients have suffered a second ACL injury, with all studies reporting seeing no difference in which side the secondary ACL injury is reported.[158–161] Overall, patients who have previously undergone ACL-R are far more likely to sustain a second ACL injury in their lifetime.[158–161]

Modifiable

Many of the factors that place an individual at a higher risk of lower extremity injury are modifiable, implying that it is possible to change them. Currently, movement technique is the most supported modifiable risk factor, as they have been reported to cause many lower extremity injuries such as ACL injuries, patellofemoral pain, and acetabular labral tears.[5–10] Hamstring stiffness has been shown to be inversely related to knee injury;[162] meaning, the more taught the hamstring muscles are, the less stress is placed on the ACL and surrounding structures.[162] It has been suggested that decreased hamstring stiffness can increase an individual's risk of ACL injury, as hamstring stiffness is inversely related to ACL loading.[162] The ACL is loaded in the sagittal, frontal, and transverse plane; and, due to the insertion of the hamstrings on the posterior medial and lateral aspects of the lower leg, they have the ability to influence joint loading in these three dimensions.[121,162–166] Conversely, quadriceps dominance refers to the tendency of an individual to primarily rely on the quadriceps muscles to stabilize the knee joint throughout movement, [100] rather than utilizing other muscle groups, such as the hamstrings, fluidly through motion. The main action of the quadriceps muscles is knee extension, and when they contract, the quadriceps extend the knee but in doing so also pull the tibia anteriorly in relation to the femur, stressing the ACL, the main action of which is to limit excessive anterior translation of the tibia. If an individual has quadriceps dominance, stress is placed on the ACL more frequently and more intensely thus increasing the risk of sustaining an ACL injury.[100,167]

Association with High Risk Biomechanics

The muscles of the hip joint, specifically the gluteus muscle group, play a pivotal role in lower extremity kinematics.[123] Weakness at the proximal end of the femur alters the forces acting on the knee joint and therefore leads to compensatory stress at the distal aspect of the femur, such as a knee valgus positioning.[89,168,169] It has been speculated that the strength of the posterior lateral gluteal musculature greatly influence the biomechanics of the lower extremity.[9,89,170–173] Weakness of the gluteus medius and gluteus maximus have been reported to be a major contributor of various lower extremity injuries, such as stress fractures, ankle sprains, and patellofemoral pain syndrome due to a lack of control over the lower extremity.[9,80,89,170,173,174] Individuals with weak gluteal musculature tend to laterally flex their trunk towards the weak side during functional movements in an attempt to reduce the demands on their weak hip musculature.[174,175] When the lower extremity is fixed on the ground, this lateral trunk flexion greatly increase the valgus movement at the knee causing medial knee displacement with dynamic movements.[80,174] Medial knee displacement in conjunction with trunk flexion has been proven to be predictive of ACL injuries with a sensitivity of 78% and a specificity of 73%.[8,49,123]

Stiffness in the knee upon landing, decreased hip and knee flexion, that is, causes excessive loading throughout the lower extremity, thus increasing the risk of lower extremity injury.[176–181] Stiff landings have been shown to produce a higher vertical ground reaction force (VGRF) as compared to softer landings with greater hip and knee flexion.[176,179,182,183] With every step- or landing, a vertical force, he vertical ground reaction force (VGRF), is thrust up through the lower extremity, causing an increased stress and a higher potential for damage.[100]

Medial Knee Displacement and Vertical Ground Reaction Force

Medial knee displacement, seen as knee valgus, is the result of hip internal rotation and adduction while the foot is fixed on the ground and is clinically assessed through excessive knee valgus.[184–186] Current literature demonstrates that an increase in MKD during functional task is a reliable risk factor for not only non-contact ACL injuries, but general lower extremity risk of injury as well.[8,24,49,123,187] When examining varus and valgus motion of the knee, individuals who exhibit a more neutral alignment show incidence rates for stress fractures that are 43% to 53% lower than those with greater than 5° of knee valgus.[11] It has been hypothesized that MKD is not the result of gluteus musculature weakness, rather, is a result of a relative correlation between hip adductor and abductor-external rotator muscles.[185] An increased adductor activation in relation to abductor-external rotator activation increases the internal hip adduction movements during functional activities, thus, displaying MKD.[185] It has been shown that individuals who exhibit MKD showed 4 times more adductor activation relative to the abductor-external rotator (gluteus) musculature.[185]

Another biomechanical factor that affects lower extremity injury risk is the landing itself, whether it is softer or more stiff, stiff landings have been associated with an increased risk of lower extremity injury.[176] Stiff landings are the result of decreased hip and knee flexion during the landing maneuver and cause a higher VGRF through the lower extremity.[176] The most functional application of landing seen in every sport is running. At a basic level, running is consecutive single leg landings. Sending the strong VGRF through the lower extremity with stiff landings causes immense amounts of stress at each joint thus increasing the risk of injuring the lower extremity.

Functional Movement Assessments

Basic movement patterns commonly seen in athletics have been shown to exhibit signs of intrinsic risk for injury based on the athlete's ability to perform the movements with or without compensation.[16–21] In an attempt to qualitatively assess and screen these basic movement patterns to uncover high risk mechanics, clinical movement assessments, such as the Functional Movement Screen™ (FMS), the Selective Functional Movement Assessment (SFMA), and the Landing Error Scoring System (LESS), have been developed and tested.[16–21,49]

Functional Movement Screening and the Selective Functional Movement Assessment

The FMS assesses seven fundamental movements: deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotational stability; and, each of the movements are scored using a 4 point scale (0 – 3) and added together for a total score (0- 21).[16–19] Each of the movements is scored based off of specific criteri, a score of 1 corresponds to the inability to perform the movement, 2 corresponds to performing the movement with compensation, and 3 corresponds to the ability to correctly complete the movement.[16] A functional score of 0 is given to any movement that evokes pain.[16] Three clearing tests, shoulder impingement test, spinal extension test, and spinal flexion test, are done to provoke pain that may not be induced through the 7 functional movements.[16] Current literature demonstrates that athletes who score 14 or below on the FMS have an increased rate of injury.[16,188–190] Furthermore, the FMS requires very minimal equipment and has been shown to have good interrater reliability;[16] therefore, it is easily applicable to clinical practice.

In conjunction with the FMS, the Selective Functional Movement Assessment (SFMA) was developed to aid in the clinical identification of movement dysfunctions in populations with known musculoskeletal injuries.[191] The SFMA described movements as either functional of dysfunctional based on specific criterion defined for each movement.[191] If a particular movement is shown to be functional and not painful, then further investigation is unnecessary; however painful movement patterns are further assessed.[191] This assessment is to be done with caution as pain is known to alter movement control, and continued movement may exacerbate more pain.(6-11)[191] Treatments and modalities to decrease pain in these movements may be done in an attempt to alleviate the dysfunctions. Movements that are dysfunctional and not painful are further assessed for instability, mobility limitations, and strength that may be causing the movement dysfunctions.

Landing Error Scoring System

The Landing Error Scoring System (LESS) specifically assesses high-risk movement patterns during a jump landing maneuver.[49] A highly dichotomous scoring rubric is used when evaluating the jump landing of an individual; therefore, a one point difference of the possible seventeen points may be associated with a large change in certain biomechanical variables.[49,192] Movement errors are assessed and given a score of 0 or 1 depending on the presence of the faulty mechanics. An individual with poor jump landing technique and therefore a large number of landing errors will indicate a higher LESS score.[49] There is a lack in precision associated with LESS scores due to the fact that all errors are grouped into a single overall score; therefore, the LESS is most effective in separating athletes into high risk and low risk subgroups.[49] Total LESS scores can be assigned into one of four categories of jump landing biomechanics: excellent (≤4), good (>4 to ≤5), moderate (>5 to ≤6), and poor (>6).[192,193] The LESS can be applied clinically as it requires little to no equipment and, after a few hours of training, can take less than 5 minutes to complete per person.[49,194]

Jump Landing Task

During a jump landing task, individuals are instructed to jump forward off of a 30-cm box leaving with both feet at the same time to a horizontal distance equal to 50% of their height; then, immediately on ground impact, rebound into a maximal vertical jump in one fluid motion.[193] The LESS score assesses the biomechanics of a jump landing task using four set of items.[49,192] Items 1-6 address lower extremity and trunk positioning at the time of initial contact with the ground.[49,192] This group of items assesses faulty mechanics such as knee flexion less than 30°, trunk extension or side bending, and heel to toe or flat foot landing.[49,192] Items 7-11 specifically assess errors in positioning of the feet both at initial contact with the ground, and the time between initial contact to maximal knee flexion.[49,192] The focus of these items include stance width, the symmetry of landing, and foot rotation.[49,192] The third set of items, numbers12-15, assesses lower extremity and trunk positioning between initial contact with the ground and the moment of maximum knee flexion angle or the moment of maximum knee valgus angle; such as, knee flexion displacement, hip flexion displacement, trunk flexion displacement, and medial knee displacement.[49,192] Lastly, there are 2 “global” items, numbers 16-17, that address overall joint displacement and the general perception of landing quality.[49,192]

When analyzing LESS scores, every movement error noted increased the incidence of lower extremity stress fractures by about 15%.[195] Medial knee displacement is one of the most cited movement errors leading to an increased risk of injury, whereas other factors include lack of ankle flexion at initial contact, stance width at initial contact, trunk flexion at initial contact, and overall impression were shown to increase risk for stress fracture.[195] Individuals who are noted to land flat-footed or heel-to-toe are approximately 2.33 times more likely to sustain a lower extremity stress fracture, while those who consistently land asymmetrically are 2.53 times more likely.[195]

Injury Prevention

Many theories about preventing ACL and other lower extremity injuries exist based on manipulating modifiable risk factors. The most widely accepted method of injury prevention is neuromuscular training programs that include balance and body control, strengthening and agility exercises, stretching, running, cutting, and landing techniques.[22–28] Preventive training programs (PTPs) are developed with the intention of replacing current team warm up programs with exercises that emphasize proper neuromuscular and proprioceptive biomechanics in order to reduce landing forces and abnormal movement patterns therefore decreasing an individual's risk of injury.[1,196,197] Ultimately, these programs aim to improve an athlete's self-awareness of high- risk biomechanics while also preparing them for peak performance.[1] Numerous lower extremity PTPs have been developed and introduced to various athletic populations in hopes of improving high risk movement patterns and therefore reducing the incidence of injury. The most commonly researched and validated programs include SPORTSMETRICS,[198] Frappier Acceleration Training Program (FATP),[8] Prevent Injury and Enhance Performance (PEP),[24,31] Knee Ligament Injury Prevention (KLIP),[199] and the "FIFA 11+".[29,200] Well-rounded and effective protocols tend to focus on similar concepts of training: plyometric, dynamic stabilization, sport specific agility paired with education and feedback on correct technique, and strength training for the trunk in addition to the upper and lower extremities.[29] When successful, PTPs improve modifiable risk factors ultimately decreasing their overall risk of sustaining an ACL injury.

Effectiveness

Despite a relatively new introduction into athletic populations, neuromuscular-based PTPs have proven to decrease the overall incidence of lower extremity injury in addition to decreasing an individual's risk of injury.[1,24,29–34] Irrespective of which sport these programs are used for, athletes who utilize PTPs are reported to be 1.7 times less likely to suffer an ACL injury.[24,30–34] Following implementation of a neuromuscular training PTP, knee injuries are shown reduce by 27% where ACL injuries can be reduced by 51% to 70% overall,[1,24,29] and by up to 88% during the first season alone.[31,34] Thus far, the research on PTPs points towards a decrease in ACL and other lower extremity injury over time if used by general athletic populations

The effects of an injury prevention program can be seen as soon the first season following implementation; however, it has been discovered that, in all patient populations, the effectiveness of the programs increases over the time that they are utilized. [29,31,34,201,202]Therefore, interventions that began in the preseason, rather than during the season have been proven to be significantly more effective at preventing knee injuries.[1,34] Furthermore, the earlier in life an athlete begins practicing injury prevention programs they see a greater decrease in risk factors than those who begin implementing these protocols later in their athletic careers.[201] Although it has been shown that PTPs significantly decrease athletes' risk of injury;[31,34] they have not been shown to specifically correct faulty biomechanics such as medial knee displacement directly.[167,197,203–216]

Compliance is vital to the success of a PTP; in order for maximum effectiveness, athletes need to not only complete the program on a regular basis, but also complete the components of the program correctly. This is where constant feedback needs to be given to the athletes performing the programs. In order to ensure compliance, many programs have been designed with the intention of replacing pre-participation warm ups. Additionally, the current literature suggests that performing prevention programs three times a week for at least six weeks yields the best outcomes through noticeable biomechanical improvements.[29,32,217,218] When PTPs are used as warm ups they have been proven to be effective in reducing the incidence of ACL injuries as they are monitored by the coaching or athletic training staff in addition to being a mandatory part of everyday participation. [29–31,33] A caveat to incorporating a PTP as a warm up is fatigue. As a major component to PTPs is strengthening, and an athlete is adding to the already high demand on his or her musculature when a PTP is added. In order to reduce this fatigue, a successful prevention program should start during pre-season, at least six weeks before the start of the season at a relatively high intensity, daily, then continue in-season with less frequency, 1 to 2 times a week.[29] In reality, most pre-seasons do not last six weeks; rather, they are about two weeks of very intense training. For most athletic populations, a six week pre-season program is too high of a goal; therefore, time to complete the PTPs is often cited as a barrier to completing them. Implementing a PTP is a relatively small adjustment for a sports team; however, it can have a profound effect on the reduction of lower extremity injuries, including ACL injuries.

Commonly Used Rehabilitation Exercises

Single Limb Squat

Standing on one leg with knees and hips in full extension and hands on hips, to complete a single limb squat, one is instructed to squat down as if sitting in a chair and return to the starting upright position.[171] Presence of Trendelenburg sign, or a drop of the hip, noted in real-time by study personnel has been reported consistently as a sign of functional weakness of the gluteus medius.[219–221] With the use of cues, patients who are able to complete the exercise without the presence of a Trendelenburg sign are targeting their gluteus medius musculature.

Hip Hike

To complete a hip hike, patients are instructed to standing with equal weight on both legs with their feet hip width apart, hands on their hips, and their knees slightly bent. A hip hike is done by lifting the contralateral leg off the ground with no sagittal plane movement (i.e. hip flexion, hip extension, or hip abduction) and pushing through the stance leg, thus elevating the hip. The hip hike is commonly done on a 6-inch box.

Single Limb Dead Lift

To complete a single limb deadlift, standing on one leg with knees and hips in full extension and hands on hips, one is instructed to slowly flex at the hip and touch the floor, with the hand opposite the stance leg, and return to the upright posture through hip extension. Due to various hamstring tightness, knees can remain either straight or slightly bent to compensate for limitations touching the floor.[222]

Lateral Band Walks and Monster Walks

When completing lateral band walks and monster walks, resistance tubing is typically placed around the feet and the amount of resistance varies.[223] To complete lateral band walks, the subject is instructed to stand with 30° hip flexion, an athletic stance, with feet together, toes pointed straight ahead and knees over the toes throughout the whole exercise. From this stance, one side steps, stepping shoulder width apart and slowly following with the hind leg. This is typically completed in two directions so that each leg leads.

Instructions for monster walks dictate forward ambulation in an athletic stance where the movement limb moves medially first and then forward and lateral before stepping on to the ground followed by a similar step with the standing limb and repeated as needed.

Walking Lunges

To complete walking lunges, the patient is instructed to stand with feet hip-width with hands on hips. Slowly lunging forward at an even pace, bend knees and hips until the leading knee is flexed to 90° without the bent knee progressing beyond the toes. It is vital to not let the leading knee buckle inwards, keep the core contracted, and maintaining the pelvis in a neutral position.

Side Lying Hip Abduction and Side Lying Hip Clam Shells

Side lying hip abduction has been shown to be one of the best exercises for targeting gluteus medius activation.[171] During this exercise, the patient is instructed to start in the side lying position with the knees in full extension and the pelvis in neutral. From this position, the patient is dictated to slowly abduct the hip without any tibial or femoral rotation. The exercise is done to 30° of hip abduction before returning to the starting position.

Side lying hip clam shells also begin side lying; however, for this exercise the knees are flexed to 90° and hips flexed to 60°. The patient is instructed to abduct the top knee off of the bottom knee while keeping the heels together and the hips stacked. Both of these exercises are commonly done bilaterally.

Conclusion

Injury to the lower extremity can be a life-changing event for any individual. While short-term symptoms can be treated, and function can be restored, individuals who suffer severe injuries, such as ACL injuries, are predisposed to a lifetime of subsequent injuries and sequela. With the already high rates of injury steadily increasing, sports medicine research has seen a strong shift towards injury risk assessment and prevention strategies. Through wide acceptance of neuromuscular training programs, high risk biomechanics that place individuals at a higher risk of sustaining a lower extremity injury can be modified and the incidence of non-contact injuries may decrease. By avoiding injuries, individuals, and the United States as a whole, would see many benefits including money saved. The risk of sustaining an injury is multifactorial; however, with the advancement in research of lower extremity injuries, injury prevention and injury rehabilitation, primary and secondary injury risk may soon decrease drastically.

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Introduction

Neuromuscular control is a risk factor for many lower extremity injuries, such as ACL injury, patellofemoral pain, stress fractures, and ankle sprains.[1–11] Consequently, prevention efforts for these injuries focus on improving neuromuscular control, specifically movement control during sport-specific tasks. Neuromuscular training programs that integrate balance, strengthening, plyometric, flexibility, and agility exercises while teaching appropriate cutting and landing techniques is a widely accepted method of injury prevention and rehabilitation.[12–18] Ultimately, neuromuscular training aims to improve an athlete's self-awareness of high- risk biomechanics while also preparing athletes for peak performance,[19] while also being effective with reducing injury rates when used as a sport warm-up.[14,19–25] Despite this evidence, preventive training programs are not widely adopted in high risk female athletic populations and time to complete is frequently described as a barrier.[26,27] More knowledge about the underlying causes of poor neuromuscular control in female athletes may improve the efficiency and effectiveness of neuromuscular training programs thus leading to an increased widespread adoption of these programs.

The most common component to neuromuscular training programs focus on reducing medial knee displacement (MKD) and optimizing sagittal plane motion during functional tasks.[4,28,29] Medial knee displacement, or dynamic knee valgus, is the result of hip internal rotation and adduction coupled with tibial external rotation and abduction while the foot is fixed on the ground.[30,31] Additionally, sagittal plane movement control can affect an individual's injury risk by influencing force absorption.[32–36] Stiffness in the knee upon landing, or decreased hip and knee flexion, causes excessive loading throughout the lower extremity, thus increasing the risk of lower extremity injury.[32,37–41] Stiff landings have been shown to produce a higher vertical ground reaction force (vGRF) as compared to soft landings with greater hip and knee flexion.[32,39,42,43] The gluteal muscles contribute to this need of multiplanar stability and function, thus reducing injury risk.

The gluteal musculature, specifically the gluteus medius, has a pivotal role in controlling frontal and transverse plane lower extremity kinematics.[28] The main action of the gluteus medius during functional movement is to stabilize the pelvis and control femoral motion; [5,7,8,44–56] the gluteus maximus, however, is the primary hip extensor and external rotator muscle throughout functional movement; its main function is to eccentrically control femoral internal rotation.[53–55,57] Therefore, alterations in neuromuscular control may result in abnormal lower extremity joint loading and stress throughout all planes of motion.[5,7,8,44–56] Numerous studies suggest that diminished hip strength influences abnormal movements at the trunk, hip and knee.[28,58–62] Further studies have demonstrated that it may not be a weakness of the musculature, rather, the abnormal movements may stem from poor muscular recruitment or activation.[30,57,63–65] A clearer understanding of gluteal muscle activation and signs of dysfunctional activation during functional movement is vital to prevent lower extremity injuries.

The adductors provide stabilization of the lower extremity and contribute to hip adduction, internal rotation, and extension throughout functional movement. These actions, in relation to that of the external rotating forces of the gluteal musculature may affect movement control. It has been hypothesized that movement dysfunctions, such as MKD, are not the result of just gluteus musculature weakness, rather, a result of a relative dysfunction between hip adductor and abductor-external rotator muscles.[30] Increased adductor activation in relation to abductor-external rotator activation likely increases hip adduction movements during functional activities, thus, resulting in MKD.[30] Individuals who exhibit MKD possessed 4 times more adductor activation relative to the abductor-external rotator (gluteus) musculature during a controlled squat, however, these muscle relationships have not been studied during dynamic sport-specific tasks.[30]

The primary purpose of this exploratory study is to evaluate if there are differences in hip muscle activation during a jump-landing task between female athletes with and without MKD. A secondary purpose is to determine if there are associations between hip muscle activation, vGRF, and movement control during a jump-landing task in athletes with and without MKD. We hypothesize that the activation patterns of the hip musculature during a jump-landing task will vary between females with and without MKD. Specifically, we hypothesize that there will be decreased gluteus medius activation in those with MKD as compared to those without. Further, we hypothesize that there will be an association between hip muscle activation, vGRF, and movement control in that, those with MKD will exhibit higher LESS scores and vGRF measurements as well as decreased hip muscle activation as compared to the control group.

Methods

Design and Participants

This study design utilized a cross-sectional design to evaluate differences in hip muscle activation between individuals with and without MKD, and the associations between hip muscle activity and neuromuscular control in these individuals. Thirty-one recreationally active females (mean ± SD age: 24 ± 5 years; height: 167.3 ± 6.8 cm; mass: 66.4 ± 10.0 kg) volunteered to participate in this study. Participant inclusion criteria included: 1) female, 2) 18 – 40 years old, and 3) recreationally active for at least 30 minutes per day, 3 days per week. Participants were excluded if they reported a history of lower extremity injury within the past six months or if they were actively suffering from a self-reported injury or illness that prevented them from physical activity on the day of the test session. All participants completed an informed consent form prior to data collection, which was approved by the university's Institutional Review Board.

Procedures

Participants wore their own t-shirt, shorts and athletic shoes to a single 1.5-hour test session. At the beginning of the test session, participant height, mass, and dominant limb (defined as the limb used to kick a ball for maximal distance) were idenitified. Prior to testing, participants performed a self-selected warm-up consisting of a 5-minute walk, jog or bike at a submaximal speed.

Surface electromyography (EMG) electrodes (DTS System, Noraxon) were placed over the muscle bellies of the gluteus medius, gluteus maximus, and adductor magnus according to the techniques described by Delagi *et al.*[66] To reduce impedance to the EMG signal and to allow for proper electrode fixation, the skin for each electrode site was cleaned with isopropyl alcohol and a piece of tape, designed for use on the skin, secured the electrode sensor. To ensure consistency between participants, a single researcher (E.B.) placed all electrodes on all participants and performed manual resistance to confirm placement. Proper location of the EMG electrodes was confirmed by viewing the EMG signals on an oscilloscope while the participant activated the muscles against manual resistance. Testing for the gluteus medius involved the participant side-lying with their hip slightly extended and in neutral rotation, MVIC was measured during active hip abduction to end range with resistance applied just proximal to the ankle.[67] For adductor magnus testing, the participant was side-lying with their hip in neutral and the researcher holding the upper leg in abduction while the partcipant performed adduction against resistance applied to the medial aspect of the distal thigh.[67] Gluteus maximus MVIC was measured with the participants in a prone position with the knee flexed to 90°. Resistance was applied just proximal to the knee as the participants actively extended the hip.[67]

Participants performed three trials of a jump-landing task. They began standing with equal weight on both legs with their feet hip width apart on a 30cm high box. The high box was placed approximately half of the participant's body height behind two force plates. Participants were instructed to jump forward from the box, leaving with both feet at the same time, onto the force plates. Upon landing, they immediately recoiled and performed a vertical jump for maximum vertical height. Participants received standardized instructions of the jump-landing task followed by as many practice trials as they indicated they needed to perform the task correctly. Trials were repeated if participants did not jump forward the correct distance, jumped off the box with one foot before the other foot, or if the participants jumped vertically off the box.

Two force-plates (Bertec Corp., Columbus, Ohio) synchronized with a wireless EMG system (DTS System, Noraxon Inc, Scottsdale, AZ) were used for data collection. MotionMonitor (Innovative Sports Technology, Chicago, IL) and Noraxon were used for data processing. vGRF data and EMG data were sampled at 1500Hz and filtered using a fourth-order, zero-lag, low-pass Butterworth filter at 12 Hz cut-off.frequency.

Using an Xbox Kinect camera (Microsoft, Redmond, WA) and a laptop computer (Dell, Round Rock, TX), Physimax software (PhysiHome Technologies LTD, Tel Aviv, Israel), was used to automate scoring of the Landing Error Scoring System (LESS). The LESS has been shown to be valid and reliable method of movement assessment.[68] The LESS analyzes a jump landing tasks and highlights seventeen observable items of human movement. A binary system is used to determine whether the participant demonstrated the movement errors, or not. A higher LESS score indicates poor technique in landing from a jump; a lower score indicating better technique.[69]

Data Reduction

EMG data collected during the jump-landing task were analyzed to determine if hip musculature activation affected vGRF and LESS scores. The raw EMG signals were band-pass filtered 6 to 1,000 Hz, rectified, and then processed using a root-mean-square algorithm with a 50-milisecond moving window. EMG data were divided into two phases- preparatory activation (100 milliseconds prior to ground contact until initial contact) and loading activation (between initial ground contact and 50% stance)[70–72] Initial contact was defined as when the vGRF exceeded 10N; whereas, take-off occurred when the vGRF was below 10N.[72] The stance phase was defined as between initial contact and take-off. The mean muscle activation across trials was calculated and normalized using measured peak activation levels during the jump-landing task. Ratios for gluteus maximus and gluteus medius activity relative to hip adductor activity were calculated. This co-activation ratio was estimated using the equation developed by Rudolph *et al.*: EMGS/EMGL×(EMGS+EMGL).[73] In order to avoid division by zero, EMGS represents the level of activity in the less active muscle and EMGL is the level of activity in the more active muscle.[73] This equation provided an estimate of relative activation of the muscles, as well as the magnitude of the co-activation.[73] The participants were assigned to groups based on landing performance: those with medial knee displacement (MKD, n=12) and those without medial knee displacement (CON, n=19) during a jump-landing task. Medial knee displacement was determined via the Physimax LESS score grading for that specific variable. The average peak vGRF and LESS total score were used for all analyses.

Independent t-tests were used to evaluate group differences in demographic variables (age, height, mass) and dependent variables (LESS score, peak vGRF, muscle activity during each phase of the landing). Associations between average muscle activation for the gluteus medius, gluteus maximus, and adductor magnus during both landing phases (preparatory, loading), as well as vGRF and LESS scores, were evaluated separately for MKD and CON using bivariate correlations. All statistical analyses were performed using SPSS (version 21.0, SPSS Inc, Chicago, IL) with an a priori level of significance of α = 0.05.

Results

No significant differences were observed between groups for age, mass, and peak vGRF (P>0.05) (Table 1). The MKD group was significantly shorter than the Control group (P=0.02). The MKD group also landed with more errors on the LESS (P=0.04). No significant differences were observed between the MKD and Control groups for preparatory or loading activation of any of the muscles (P>0.05) (Table 1).

For the MKD group (Table 2), there were negative correlations between GMed loading activation and vGRF (P=0.03); and GMed:ADD preparatory activation and vGRF (P=0.04). A positive correlation was observed between GMax:ADD preparatory activation, but this was not statistically significant (P=0.07).

In the control group (Table 3), there were negative correlations observed between GMed loading activation and LESS scores (P=0.02), as well as between GMed:ADD loading activation and LESS scores (P=0.01). There were positive correlations observed between GMed loading activation and GMax loading activation (P=0.01), and between GMed:ADD preparatory activation and vGRF, although this correlation was not statistically significant (P=0.056).

Discussion

Impaired neuromuscular control during sport-specific tasks (i.e., jump landing), including MKD, is associated with abnormal joint loading and may predispose an individual for lower extremity injury.[4] A multitude of clinical assessment tools have been established to identify impairments associated with injury risk in athletes, specifically the LESS is a valid and reliable clinical assessment tool to assess movement control during a jump landing maneuver.[69] Padua *et al.*[69] recently demonstrated that youth athletes who land with fewer than 5 movement errors, out of a possible 17**,** have a lower risk of ACL injury than those with LESS scores above 5.[74] One of these errors, MKD, is commonly described to be a major factor associated with injury risk and altered movement efficiency.[4,14,28,29,69] Gluteus medius strength and recruitment have traditionally been thought to have a primary role in reducing MKD. The findings of this study support this critical role of the gluteal muscles in controlling lower extremity movement control, as represented by landing forces and the LESS. However, these findings also highlight the influence of the hip adductor muscles in movement control.

The muscles of the hip joint, especially the gluteal muscle group, are theorized to have a pivotal role on lower extremity movement control, and MKD. Although the use of preventive training programs has been shown to decrease injury risk, their ability to specifically alter frontal and transverse plane kinematics is inconclusive.[75–90] Prevention programs and rehabilitation plans often emphasize strengthening the gluteus medius in an attempt to alleviate MKD and promote normal joint loading; however, this may be insufficient. Using a prospective design, Khayambashi *et al.*[28] suggested that strengthening of the gluteal musculature improves many of the lower extremity kinematics that are associated with increased risk of injury, including trunk flexion, pelvic drop, and MKD. They established a link between baseline hip strength and noncontact ACL injury.[28] It has been observed that athletes are at an increased risk of injury when they have poor movement control, including medial knee displacement, and have weak gluteal musculature compared to individuals with proper control.[5,28,47,53,56,91–93] Despite this evidence, previous literature reports inconsistent findings as to whether or not those with MKD have weaker gluteus medius muscles as compared to their counterparts without MKD. For example, some studies report neural recruitment of the gluteus medius as the main difference between the affected and unaffected groups.[30,57,64,65]

Due to inconsistencies in the literature regarding the role of gluteal muscles on movement control, this study aimed to evaluate the influence of gluteal muscle activation specifically on landing technique. Our findings demonstrate that individuals without MKD in the jump landing task exhibited strong loading activation of the gluteus medius in relation to their decreased LESS scores. This finding supports the original hypotheses of this study in demonstrating the positive role gluteus medius activation has on movement control. These results also agree with the work of Lepley *et al.*[94] In this particular study, Lepley *et al.*[94] investigated gluteus activation in relation to LESS scores; however, their focus was the central nervous system's role in the activation. They reported only a moderate positive association (r=0.562) between activation and landing biomechanics as measured by the LESS score.[94] Future research should focus on how gluteal muscle activation affects landing mechanics and address ways to manipulate this.

The significant findings of this study show that the gluteus medius serves different purposed in individuals with and without MKD. In those with MKD, the gluteus medius activates and directly affects vGRF during landing; whereas, in individuals without MKD, the gluteus medius activates and has a direct effect on LESS scores. This study looks at the gluteus maximus and adductors to explain this discrepancy across groups; however, neither was seen to correlate with vGRF or LESS scores. Further studies should look into complete lower extremity muscle activation, including knee and ankle musculature, to determine if the gluteus medius activated to absorb landing forces as a frontal plane compensation for a lack of sagittal plane motion at the knee and knee, or, if individuals with MKD have generally poor hip mechanics. Although the hip has been shown vital in controlling lower extremity biomechanics, perhaps knee and ankle neuromuscular control has just as strong of an effect.

This current study supports previous work in emphasizing the need for proper gluteus medius recruitment, but also expands it to suggest the need to reduce the impact of the hip adductors. Padua *et al.*[30] hypothesized that MKD is not the result of gluteus musculature weakness, rather, is a result of a relative correlation, or functional co-activation ratio, between hip adductor and abductor-external rotator muscles. This ratio highlights the activation of the two muscle groups compared to each other (ADD:Glutes).[30] An increased adductor activation in relation to abductor-external rotator activation increases the internal hip adduction movements during functional activities, and thus, MKD.[30] It has been shown that individuals who exhibit MKD had 4 times more adductor activation relative to the abductor-external rotator (gluteus) musculature.[30] The results of this study address the co-activation ratio of the gluteus medius in relation to the adductor magnus and further support the findings of Padua *et al.*[30] Due to these findings, evaluating the relationship of the gluteal muscles to the adductors may be more important than previously established. It has been shown that individuals who exhibit MKD showed 4 times more adductor activation relative to the abductor-external rotator (gluteus) musculature.[30] Future research should keep this ratio in focus in an attempt to accuarately assess an athlete's risk of lower extremity injury.

Adductor muscle recruitment, relative to gluteus medius and maximus activation, was moderately associated with the ability to absorb landing forces. Specifically, these findings suggest individuals with MKD may be preferentially recruiting their hip adductor muscles as a synergistic hip extensor to decelerate hip flexion during landing. While this method appears to be effective with reducing landing forces, adductor muscle recruitment is also likely responsible for the observed MKD. Similarly, Padua *et al.*[30] found that those with MKD had a hip adductor activation that was 34% greater when compared to the control group lacking MKD. In contrast, there appears to be a strong association between gluteus medius and gluteus maximus activation in individuals without MKD, which is not present in individuals with MKD. This co-activation has a benefit on greater overall movement control, as demonstrated by lower LESS scores in the individuals without MKD. These findings are important for clinicians attempting to modify poor movement control, specifically MKD, as a greater emphasis may need to be placed on encouraging the use of the gluteus maximus to decelerate hip flexion compared to the adductors.

Limitations

A few limitations need to be considered in the analysis of these results. First, the activation of other hip and thigh muscles were not measured. Muscles such as the quadriceps and hamstrings are also believed to have an important role in lower extremity biomechanics and MKD control. Lastly, this study does not indicate causation of these functions and dysfunctions. Further research should evaluate how these activation patterns relate to lower extremity injury risk as a whole. We recognize that this is a small sample of healthy females and, thus, caution should be used in generalizing this information to other populations. However, the difference in gluteus medius activation between those with and without MKD warrants further investigation because it effects training methods of athletes at all levels.

Conclusion

To date, the literature suggests that strengthening the hip musculature, may limit the amount of knee valgus observed during functional movements such as gait or landing patterns.[4,94,95] Gluteus medius activation is negatively associated with vGRF in those who exhibit MKD during a jump-landing task. The results of this study suggest a relationship between the activation of the gluteus medius and the gluteus maximus during functional movement in those without MKD. A decrease in LESS scores of this population indicate that there is a dysfunction in the activation of the gluteal musculature in those individuals with MKD. As MKD and increased vGRF have been associated as strong predictors of injury risk. By focusing rehab efforts on functional gluteal co-activation, this may allow clinicians to decrease their athletes' injury risk. Evaluating functional movement patterns may enable clinicians to predict dysfunctions that increase an athlete's risk of lower extremity injury and work towards correcting faulty biomechanics. Overall, these findings support our original hypotheses and encourage future research to delve further into the clinical assessment of functional movements and how they relate to overall injury risk.

Appendix

Table 1: Group Differences (n = 31)					
		Mean	**P-Value**	**Mean Difference**	**95% Confidence Interval**
Age (years)	MKD	23 ± 1	0.75	2.3 ± 1.7	-1.21 to 5.78
	Control	25 ± 1			
Height (cm)	MKD	163.8 ± 6.5	0.02*	5.6 ± 2.3	0.83 to 10.40
	Control	169.5 ± 6.3			
Mass (kg)	MKD	63.3 ± 10.1	0.19	4.94 ± 3.63	-2.50 to 12.37
	Control	68.3 ± 9.7			
vGRF (% BW)	MKD	1.6 ± 0.2	0.24	0.12 ± 0.10	-0.08 to 0.31
	Control	1.7 ± 0.2			
LESS	MKD	5.6 ± 1.4	0.04	-1.15 ± 0.54	-2.26 to -0.05
	Control	4.4 ± 1.5			
GMed Preparatory Activation (uV)	MKD	0.2 ± 0.1	0.74	-0.01 ± 0.04	-0.10 to 0.07
	Control	0.2 ± 0.1			
GMed Loading Activation (uV)	MKD	0.3 ± 0.2	0.9	0.00 ± 0.06	-0.11 to 0.12
	Control	0.3 ± 0.1			
GMax Preparatory Activation (uV)	MKD	0.2 ± 0.1	0.76	0.02 ± 0.06	-0.10 to 0.14
	Control	0.2 ± 0.2			
GMax Loading Activation (uV)	MKD	0.2 ± 0.2	0.83	-0.01 ± 0.05	-0.12 to 0.10
	Control	0.2 ± 0.1			
ADD Preparatory Activation (uV)	MKD	0.3 ± 0.2	0.27	-0.06 ± 0.05	-0.16 to 0.05
	Control	0.2 ± 0.1			
ADD Loading Activation (uV)	MKD	0.3 ± 0.2	0.93	0.01 ± 0.06	-0.11 to 0.13
	Control	0.3 ± 0.2			
GMed : ADD Preparatory Activation (uV)	MKD	1.0 ± 0.7	0.27	0.54 ± 0.47	-0.43 to 1.50
	Control	1.5 ± 1.5			
GMed : ADD Loading Activation (uV)	MKD	1.2 ± 0.8	0.43	0.64 ± 0.79	-0.98 to 2.26
	Control	1.8 ± 2.7			

*Significant difference (P < 0.05)

Table 2: Associations between Variables in Participants with Medial Knee Displacement			
		R-value	**R^2**
LESS	vGRF	0.44	0.19
GMed Preparatory Activation	vGRF	-0.03	0.00
GMed Loading Activation	vGRF	-0.64*	0.41*
GMax Preparatory Activation	vGRF	-0.11	0.01
GMax Loading Activation	vGRF	-0.22	0.05
ADD Preparatory Activation	vGRF	-0.32	0.10
ADD Loading Activation	vGRF	-0.27	0.07
GMed : ADD Preparatory Activation	vGRF	-0.60*	0.36*
GMed : ADD Loading Activation	vGRF	-0.47	0.22
GMax : ADD Preparatory Activation	vGRF	-0.54	0.29
GMax : ADD Loading Activation	vGRF	-0.12	0.02
GMed Preparatory Activation	LESS	0.32	0.10
GMed Loading Activation	LESS	-0.06	0.00
GMax Preparatory Activation	LESS	-0.16	0.03
GMax Loading Activation	LESS	-0.17	0.03
ADD Preparatory Activation	LESS	0.11	0.01
ADD Loading Activation	LESS	0.01	0.00
GMed : ADD Preparatory Activation	LESS	0.00	0.00
GMed : ADD Loading Activation	LESS	0.10	0.00
GMax : ADD Preparatory Activation	LESS	0.08	0.01
GMax : ADD Loading Activation	LESS	-0.21	0.04
GMed Preparatory Activation	GMax Preparatory Activation	0.03	0.00
GMed Preparatory Activation	ADD Preparatory Activation	0.01	0.00
GMed Loading Activation	GMax Loading Activation	0.35	0.12
GMed Loading Activation	ADD Loading Activation	0.23	0.05
GMax Preparatory Activation	ADD Preparatory Activation	0.01	0.00
GMax Loading Activation	ADD Loading Activation	0.19	0.04

*Significant correlation ($P < 0.05$)

Table 3: Associations between Variables in Participants Without MKD			
		R-value	R^2
LESS	vGRF	0.31	0.10
GMed Preparatory Activation	vGRF	-0.05	0.00
GMed Loading Activation	vGRF	0.50	0.25
GMax Preparatory Activation	vGRF	0.18	0.03
GMax Loading Activation	vGRF	0.16	0.03
ADD Preparatory Activation	vGRF	-0.39	0.15
ADD Loading Activation	vGRF	-0.36	0.13
GMed : ADD Preparatory Activation	vGRF	0.45*	0.20*
GMed : ADD Loading Activation	vGRF	0.19	0.03
GMax : ADD Preparatory Activation	vGRF	-0.15	0.02
GMax : ADD Loading Activation	vGRF	-0.18	0.03
GMed Preparatory Activation	LESS	0.06	0.00
GMed Loading Activation	LESS	-0.53*	0.28*
GMax Preparatory Activation	LESS	0.01	0.00
GMax Loading Activation	LESS	-0.10	0.01
ADD Preparatory Activation	LESS	-0.27	0.07
ADD Loading Activation	LESS	-0.25	0.06
GMed : ADD Preparatory Activation	LESS	0.06	0.00
GMed : ADD Loading Activation	LESS	-0.56	0.32
GMax : ADD Preparatory Activation	LESS	-0.16	0.02
GMax : ADD Loading Activation	LESS	-0.15	0.02
GMed Preparatory Activation	GMax Preparatory Activation	0.19	0.04
GMed Preparatory Activation	ADD Preparatory Activation	-0.28	0.08
GMed Loading Activation	GMax Loading Activation	0.55*	0.30*
GMed Loading Activation	ADD Loading Activation	0.00	0.00
GMax Preparatory Activation	ADD Preparatory Activation	-0.39	0.15
GMax Loading Activation	ADD Loading Activation	-0.9	0.81

*Significant correlation ($P < 0.05$)

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