5-7-2016

Changes in Power and Movement Strategy Over One Athletic Season

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B.S., University of Vermont, 2010

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

At the

University of Connecticut

2016

APPROVAL PAGE

Master of Science Thesis

Changes in Power and Movement Strategy Over One Athletic Season

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ACKNOWLEDGEMENTS

Dr. Lindsay DiStefano: Thank you for your tremendous support, encouragement, and patience. I am so thankful to have had the opportunity to learn from you as an advisor and mentor. I truly appreciate your willingness to do whatever is needed for student success, and am grateful for your guidance in every step of this process! You are an exemplary role model and I am so glad to have had the chance to be a DiStefano student!

Dr. Craig Denegar: Thank you for always making each of your students feel valued and important. I am so appreciative of your vast knowledge and willingness to share it. You have helped me grow clinically and academically, and always with a smile on your face.

Dr. Giselle Aerni: Thank you for being a phenomenal role model and mentor. The last two years would have been a lot more challenging without you, and I certainly owe a very large part of my professional growth to your leadership and support.

Catie Dann: Thank you for always providing a listening ear and good advice- no matter what I've come at you with, you've kept me on the right path. You inspire me every day to follow my dreams because you set a shining example of what can happen when you set your mind to something.

Nora Beltz: There are no words strong enough to accurately portray how thankful I am to have had you as my mentor- but I'll start with Thank You. You have been an incredible rock the past two years. Your patience, guidance, and efforts are what make you an exceptional researcher, educator, and advisor. There are a million other qualities that make you one of my best friends. Peaches. For. Free.

My Family: Thank you all for cheering me on, supporting me, and inspiring me to achieve success. To my Mom, thank you for being my loudest cheerleader, my harshest critic, and an incredible role model. To John, for keeping everybody level headed- it means more than could ever be put into words. To my Dad, thank you for guiding me down this path. Stuart, thank you for supporting my dreams and always encouraging me to work hard but never lose sight of what makes me truly happy. Ramsey, thank you for sitting dutifully by my side while I paid more attention to my computer than you. Jackie, thank you for providing insight from the other side and all your efforts in helping me get through!

My UCONN Family: Thank you to my friends, mentors and colleagues in Kinesiology and Sports Medicine for helping to make the most challenging two years of my life also two of the best. Thank you to my athletes and coaches for making me smile every single day. I have gotten so much more from you than I could ever give back, and I am so appreciative of the opportunity I've had to learn from you and develop lifelong friendships.

My UVM Family: Thank you to all of my teachers and mentors who helped me build the foundation I needed to get to this point. Thank you especially to Tim Tourville, who was part of a team that first ignited my passion for biomechanics and lower extremity injuries 10+ years ago, and has continued to provide professional guidance that has served me well in all aspects of my professional life.

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ABSTRACT

Context: Female collegiate soccer athletes sustain injuries at a concerning rate, often with severe short and long-term consequences. Identifying changes in movement control and power that inherently occur over an athletic season may improve our ability to predict and ultimately prevent injury. **Objective:** The purpose of this study was to evaluate movement control and power over the course of an athletic season in female collegiate soccer athletes. **Design:** Repeated measures **Setting:** Field Study **Participants:** 25 female athletes (age: 20±1years, mass: 66.5 ±6.6kg, height: 1.7±0.1m) **Intervention(s):** None **Main Outcome Measure(s):** Participants performed jump-landing and vertical jump (VJ) tasks five times (preseason (T1), end of preseason (T2), mid-season (T3), beginning of post-season (T4), end of post-season (T5).The jump-landing task was scored using an automated Landing Error Scoring System (LESS) grading system (*PhysiMax Technologies Ltd., Tel Aviv, Israel*), which is a movement control assessment. A high score on the LESS indicates a large number of movement errors, or poor movement control. The average LESS score and VJ was calculated for each athlete at each time point. Injury data were also collected throughout the season. Separate repeated measures ANOVAs were used to evaluate changes in LESS and VJ scores between the test points (α=0.05). Participant's LESS score for each time point was dichotomized into a GOOD (LESS>5) or POOR (LESS≤5) movement category. Each time point was coded as INJURY or NO INJURY A chi-square analysis was used to evaluate the association between movement category (GOOD, POOR) and the incidence of a non-contact lower extremity injury following each test point for each participant. **Results:** LESS scores were significantly different between T1 and T2 (1.73±2.02), T3 (1.73±2.22)(P=0.046). VJ performance significantly differed between T2 and all other time points (P < 0.001). There was a significant association between movement category and subsequent injury ($\chi^2_{(1)}$ = 3.96, p=0.047, OR: 3.34, 95% CI [0.97, 11.49]) Participants were more likely to sustain an injury when their LESS score was >5 than when it was <5. **Conclusions:** Movement technique and VJ performance inherently vary over the course of one collegiate women's soccer season, and may be the result of training intensity. Female soccer athletes were more susceptible for sustaining a non-contact lower extremity injury when their movement control was poor, as measured by a LESS score>5. Monitoring movement control during a soccer season may improve efforts to prevent injury. **Key Words:** Landing Error Scoring System, LESS, vertical jump, soccer, female athletes

REVIEW OF LITERATURE

Injury in Sport

Between the 2009-2010 and 2013-2014 academic years, 1,053,370 injuries were recorded in 478,869 NCAA athletes. Of these injuries, 46,231 required at least 7 days to return to full participation and 4% required surgery.[1] Approximately half of the injuries in the previously noted NCAA study were sprains or strains, including full rupture of a ligament, tendon, or muscle, and more than half of the injuries sustained requiring surgery were recorded as sprains or strains.[1] In the high school population, 60% of sport-related surgeries are attributed to knee injuries.[2] With regard to anterior cruciate ligament (ACL) tears in the United States alone, the estimated lifetime burden is over $25 billion annually.[3] Identifying the athletes most at risk for both acute and overuse injury, and implementing prevention injury strategies, including rule changes and injury prevention programs, is essential.[2]

In collegiate athletics, women's soccer was found to have the highest rate of injuries sustained in preseason participation at 9.5 injuries per 1,000 athlete exposures.[4] Women's soccer is also the sport with the highest rate of injury sustained in competition, estimated at 8.4 per 1,000 athlete exposures, and accumulating 15,113 total injuries documented between the 2009-2010 and 2013-2014 in NCAA programs.[1] In comparison, Men's soccer has an estimated injury rate of 8.0 per 1,000 athlete exposures, with 13,435 documented injuries in the same study.

Seventy percent of overuse injuries occur in the lower extremity in both high school and college aged athletes, with overuse injuries to the knee being most common in the collegiate setting (20%), and injuries to the lower leg more prevalent in high school athletes (22.5%).[5] One in four active people across all age ranges suffer from patellofemoral pain syndrome (PFPS).[6–8]

There is little insight into the risk factors for developing PFPS,[6] and the long term effects commonly persist for several years after the onset of symptoms.[6,9] Furthermore, the development of patellofemoral osteoarthritis and PFPS have been associated.[6,10]

Collegiate athletes suffer from overuse injuries more frequently and with more severe consequences, such as surgical intervention and time loss, than high school athletes. Tibial stress fracture is the most common diagnosis requiring greater than 21 days before full return to activity in both high school and collegiate athletes.[5] In both populations, females and athletes participating in running sports may be at a higher risk for overuse injury.[5] Overuse injuries are more common in females versus males in sex-comparable sports at both the high school and collegiate level in all sports with the exception of soccer.[5]

Acute injuries to the lower extremity are very common as well. Across populations, ankle sprains are one of the most common musculoskeletal injuries,[11] and are the most common injury sustained in collegiate soccer.[12] Ankle sprains are approximately twice as prevalent in females and males (13.6 vs. 6.94 per 1,000 exposures) in the general population.[11] Ankle sprains can occur in the lateral ankle, medial ankle, and at the syndesmosis, however, lateral ankle sprains are significantly more common than medial and syndesmotic sprains.[11] Chronic ankle instability (CAI) is a condition characterized by recurrent ankle sprains and may or may not also include functional impairment and functional instability.[13–15] Up to 73% of individuals who sustain a lateral ankle sprain go on to develop chronic ankle instability.[13,16,17] CAI has been identified as a predisposing factor in the development of post-traumatic ankle joint arthritis[11,13,18] Furthermore, Terada et al suggest that patients with CAI may have some of the same biomechanical alterations in the sagittal plane as those sustaining ACL injury.[13]

Knee Anatomy & Physiology

The primary joint of the knee, the tibiofemoral joint, is a nearly vertical hinge joint between the condyles of the femur and plateau of the tibia.[19] The patellofemoral joint of the knee is comprised of the patella, a sesamoid bone encased in the distal tendon of the quadriceps, sliding within the femoral condyles. The patellofemoral joint provides a mechanical advantage to the knee extensor mechanism and transmits tensile forces from the quadriceps.[20]

There are four primary ligaments that help to stabilize the knee. The aptly named medial and lateral collateral ligaments reside on the medial and lateral sides of the tibiofemoral joint, and help to protect against valgus and varus forces, respectively. Near the midpoint of the tibiofemoral joint, the anterior and posterior cruciate ligaments cross, and primarily act to protect against anterior and posterior translation of the tibia, respectively. The proximal attachment of the ACL resides within the femoral notch, while the distal attachment is on the tibial plateau. Extensive research has been conducted identifying the anatomy of these attachment sites and their impact on the risk of ACL injury.[21–31] In addition to these structures, the knee joint has menisci to provide additional stability and cushioning for the tibiofemoral joint, as well as several smaller ligaments. There are also a number of muscles that provide force generation and dynamic stabilization of the knee. Of these noted structures, the ACL specifically functions to provide primary anteroposterior stability and secondary rotary stability to the knee joint.[32] The ACL is comprised of two functional bundles, the anteromedial bundle and the posteromedial bundle, as well as a secondary bundle termed the intermediate bundle, which impacts anterior instability.[19,32]

The anteromedial band serves as the center of rotation of the ACL. It inserts on the medial aspect of the intercondylar eminence of the tibia, and is the primary structure preventing anterior translation of the tibia on the femur when the knee is flexed. The anteromedial band is tight in flexion up to 30°. From 30°-70° of flexion, it lengthens, and stretches from 80°-120° of flexion, therefore, it is most vulnerable to injury when the knee is flexed.[19,32]

The posterolateral bundle is responsible for limiting anterior translation, hyperextension, and rotation for the knee. Its' fibers are oriented posteriorly, and attach immediately lateral to the midline of the intercondylar eminence of the femur and slightly lateral to the most lateral attachment point of the intermediate bundle of the ACL. Positioned obliquely compared to the anteromedial bundle, it plays a bigger role in controlling rotation of the knee. The posterolateral bundle is at its' maximal length and strain when the knee is fully extended. It shortens with knee flexion, and is under the least amount of strain when the knee is flexed to 120°. It is most at risk of injury when the knee is hyperextended and internally rotated.[19,32]

The two primary bundles twist upon each other with knee motion. In extension, the anteromedial and posterolateral bundles are parallel. As the knee moves into flexion, the posterolateral bundle shifts anteriorly from the femoral insertion. The bundles cross, and the anteromedial bundle tightens while the posterolateral bundle loosens.[19] When the knee is flexed to 90°, the femoral posterolateral attachment moves anteriorly, and the attachment sites of the anteromedial and posterolateral bundles align horizontally.[32] The literature suggests that ACL reconstruction using a double-bundle graft is more effective at recreating the inherent anatomy of the ACL than a single-bundle graft.[33,34]

The strain on the ACL varies depending on the position of the knee joint. Passive range of motion exerts about 100N of force on the ACL. In contrast, walking exerts approximately 400N of force. Motions common in sport, such as acceleration, deceleration, and cutting, can exert up to 1700N of force on the ACL.[32] The normal tensile load of the ACL ranges from approximately 2000-2300N. The ACL can withstand up to approximately 20% strain before it ruptures.[32]

Epidemiology & Implications of Anterior Cruciate Ligament Injury

Over 200,000 ACL injuries are sustained annually in the United States.[35] It is estimated that more than 120,000 of these injuries affect athletes, with over 50% of patients between the ages of 15 and 25 years old.[36,37] Female soccer and basketball players have an approximately three-times higher risk of ACL injury than males, with these sports having the highest rates of ACL injury.[38] Some of the literature citing these statistics is based on predictions and literature dating back over 20 years, thus it must be emphasized that these are estimates and the true incidence of ACL injury is unknown.[35,37,39]

Females are widely reported to be at an increased risk of noncontact ACL injuries.[2,5,21–23,35,40–52] From 1994 to 2006, the rate of ACL reconstruction in females nearly doubled.[35] When compared to men performing the same activities, female athletes were found to be at a two to eight times higher risk of sustaining ACL injury.[6] Furthermore, when examining cutting sports, female athletes were identified as having a four to six times higher risk of sustaining a noncontact ACL injury.[38] Females also demonstrated a disproportionate risk of ACL injury after puberty begins.[53]

Impact on Health and Activity

When an ACL injury is sustained, it can take upwards of six months to return to athletic activity.[23] In a study by McAllister et al, the majority of ACL injured patients competing in elite college athletics did not return to full, unrestricted participation in sport for at least 8 months following surgery.[54] A meta-analysis conducted in 2010 found that 82% of athletes returned to sports participation following ACL reconstruction surgery, however, only 63% returned to participation at preinjury levels.[55] Surgical reconstruction of the injured ligament is standard practice, particularly in young, active persons.[3] Regardless, a randomized controlled trial of physically active adults with acute ACL rupture demonstrated that there was not a significant improvement 2 years after injury in a rehabilitation-only approach.[56]

While ACL injury may be isolated, concomitant injuries are common. The most frequently injured structures associated with ACL injury are to the cartilage, meniscus, and MCL.[35] The most common procedures associated with ACL reconstruction are partial meniscectomy and chondroplasty.[35] Regardless of treatment, ACL injuries are associated with early onset osteoarthritis of the knee.[3,10,30,40,41,57–62] Osteoarthritis contributes an additional $9,801-$22,111, depending on the progression of the disease.[3]

Financial Implications

ACL injury is not only debilitating and potentially devastating to the daily life, knee health, and athletic capabilities of the individual, but is also fiscally burdensome. The average lifetime cost to society for an ACL Reconstruction (ACLR) is approximately $38,121[3] In the United States alone, the lifetime burden of ACL tears is over $25 billion annually. Approximately $17.7 billion of that is attributed to ACL tears treated with rehabilitation only, with the remaining $7.6 billion allocated towards ACL injuries treated with surgical reconstruction.[3]

Mechanism of Injury

Anterior Cruciate Ligament

Anterior Cruciate Ligament injuries occur in two ways: contact injuries and non-contact injuries. ACL injuries associated with athletics are predominately due to non-contact mechanisms.[25,46,47,63,64] Approximately 70% of ACL injuries are noted as such.[65] The most common non-contact mechanism is when performing side-step and cutting maneuvers.[46,57,66] The remaining 30% are attributed to contact mechanisms of injury[48], however, one study examining injury in the high school setting found that up to 60% of ACL injuries are due to contact mechanisms of injury[2,37].

ACL injuries occur when the knee is forced into a valgus position combined with anterior translation of the tibia on the femur and internal rotation of the tibia, which results in ACL rupture.[67] Contact ACL injuries occur when an outside force, such as another player or an object, impact the knee and force a combination of the aforementioned positions. Rule changes in sport are the most likely area to decrease the prevalence of contact ACL injuries.[1,2,12,49]

A combination of several biomechanical positions in multiple planes are believed to be common in non-contact ACL injuries.[68] Movements that mimic taut positions on the ACL put the athlete at risk of injury. Even cognitive perturbation,[68] such as a lapse in concentration,[23] may also play a role. The most common mechanism of injury for non-contact ACL injury is a sudden deceleration and a sudden change of direction with a planted foot.[48] Many non-contact ACL injuries involve significant forward momentum of the individual in conjunction with side-cutting and cross-cutting. Deceleration, lateral pivoting, and landing tasks associated with high external knee joint loads are also cited as common components of a non-contact ACL mechanism of injury.[69] Review of video footage of non-contact ACL injuries confirms that sharp deceleration or landing with the knee close to extension at initial ground contact, and an erect body position are commonly present when the ACL is injured via a non-contact mechanism of injury.[64,69] Landing from a jump in a position where the knee and hip are near full extension is a modifiable behavior that is known to be present in many non-contact ACL injuries.[23,68]

Center of mass (COM) is an important factor in ACL injury. Ground reaction force (GRF) is directed toward the COM in landing.[69] Females who are at an increased risk of ACL injury, tend to land with their COM outside the base of support, with the knee straight, the majority of their weight on one extremity, and/or their trunk laterally tilted. Valgus collapse of the knee is also noted. Similar, but less exaggerated landing mechanics have been found in men.[69] Controlling trunk motion is essential for control of ground reaction forces on the body. Ground reaction forces follow the movement of the trunk, so if the trunk moves, the center of mass moves, and ground reaction force will follow to a less advantageous location, potentially contributing to injury.[69]

Overuse Injuries

Overuse injuries are injuries that develop over time with no one specific incident precipitating the onset of symptoms.[5,70,71] These injuries are widespread in sports at all levels and can have significant impacts on the athletes affected.[5,12,70,71] Because of the gradual onset of these injuries, many go unreported until the injury becomes severe in nature.[5,72] Rest and a progressive return to activity is the typical treatment for most overuse injuries.[73]

Sport specialization is defined as “intense, year-round training in a single sport with the exclusion of other sports.”[74,75] Research in the area of early sport specialization is limited, however, an increasing body of literature suggests that early sport specialization leads to an increased rate of injury, particularly overuse injury.[76] PFPS and apophysitis of the knee (Osgood-Schlatter and Sinding Larsen-Johansson) have been associated with sport specialization in adolescent females.[76]

Risk Factors for Injury

There are two main categories for differentiating injury risk factors: non-modifiable, and modifiable. Non-modifiable risk factors are things that cannot be changed, such as anatomy and genetics.[24] Modifiable risk factors are things that can be changed through intervention, such as an injury prevention program.[24] In order to effectively implement changes to decrease the prevalence of modifiable risk factors, understanding the risk factors for injury is paramount.[23,43,68,77]

Patellofemoral Pain Syndrome

The factors that contribute to patellofemoral pain syndrome are poorly understood.[6] Lower extremity structural abnormalities including femoral neck anteversion, patellar malalignment, knee hyperextension, genu valgum, increased Q-angle, excessive rearfoot pronation, and tibia varum have been associated with PFPS.[78] In addition, decreased quadriceps flexibility, shortened reflex time of the vastus medialis oblique (VMO) muscle, increased medial patellar mobility, increased medial tibial intercondylar distance, reduction of vertical jump performance, and increased quadriceps strength have been associated with the incidence of PFPS.[6,79,80] Boling et al identified individuals who developed PFPS as having significant weakness in hip abduction, knee flexion, and knee extension as well as lower vertical ground-reaction force, hip external rotation moment, knee extension moment, and navicular drop in baseline assessments.[6] In the same study, utilizing the jump-landing task, decreased peak knee flexion angle and decreased peak vertical ground-reaction force were identified as risk factors for developing PFPS.[6]

Lower Extremity Stress Fractures

Stress fractures result from repetitive microtrauma and chronic submaximal loading of tissues.[71] They may be associated with factors such as nutritional insufficiency,[71,81,82] low level fitness, strength, and endurance, poor flexibility, lower BMI, amenorrhea and menstrual irregularity, footwear, rapid changes in training volume, intensity, duration, frequency, and/or distance, pes cavus, high Q-angle, leg length discrepancy and bone geometry.[81,82] Several modifiable biomechanical factors have also been linked to lower extremity stress fractures including greater peak hip adduction angle, greater peak rear foot eversion angle, increased sagittal plane stiffness, increased absolute free movement, increased vertical force impact peak, increased peak positive acceleration of the tibia, increased tibial shock, and increased peak vertical loading rate. In a jump-landing task, increased peak vertical ground reaction force, increased medial ground reaction force, increased knee valgus, and increased knee internal rotation are known risk factors for lower extremity stress fracture.[81,82]

Anterior Cruciate Ligament Non-Modifiable Risk Factors

Anatomic features of the bony structure of the knee, as well as variations in ACL composition, hormones, sex, biomechanics, genetics, and cognitive function have been cited as potential non-modifiable risk factors for ACL injury[23,24,30,36,41,69,83,84].

Anatomical Features

ACL-injured patients have demonstrated multiple architectural differences with regard to the tibia as compared to non-injured knees. One area of substantial focus is the tibial slope, which is defined as the angle between the perpendicular to the middle part of the diaphysis of the tibia and the line representing the posterior inclination of the tibial plateau. There are three parts that make up the tibial slope: the medial tibial slope, lateral tibial slope, and coronal slope. The coronal slope spans the lateral and medial slopes. A decreased depth of concavity of the medial tibial plateau[26,28,40,52] as well as an increase in posterior-inferior directed slope of the tibial plateau[22,25,28,31,41,52,83,84] have both been consistently identified in subjects who have a history of ACL injury. In pathologic knees, the posterior tibial slope has been identified as having an anterior elevation higher than the posterior elevation.[26,30,40] Additionally, ACL injured females have been identified as having greater lateral and medial posterior-inferior tibial slopes and coronal tibial slopes (Shultz). There is a direct relationship between anterior translation of the knee and tibial plateau slope. As the knee transitions from non-weight bearing to weight-bearing conditions, an anterior shear force occurs, which results in the tibia shifting anteriorly on the femur.[26]

The intercondylar notch width of the femur has also been examined as a possible non-modifiable risk factor. A smaller femoral notch width, or notch width index, has been observed in ACL-injured knees.[21–23,29–31,36,40,48,51,52,85] Other observed anatomical differences seen in ACL-injured knees are the presence of an anterior medial ridge on the intercondylar notch[51,86], as well as taller femoral notch height[52,87] and a smaller femoral notch.[21,30,36,40,48,51,52]

Van Eck *et al*. established three categories of notch shapes in ACL-injured patients, named for resemblance to the letters U, W, and A. When comparing these different notch shapes, no statistical significance (p= 0.514) was found comparing notch height among the shapes. The median height for A-shaped notches was 19mm, U-shaped notches was 21mm, and W-shaped notches 20mm. There was also no statistical significance relating notch shape and gender (P = 0.056); however, a trend was identified, indicating female subjects had more A-shaped notches than U-shaped notches. Patient height was the only demographic that was shown to influence notch height: taller patients had U and W-shaped notches. With regard to notch width, an A-shaped notch was the narrowest shape overall, including at the base. In females, the notch width was smaller at both the middle and the base compared to men, regardless of notch shape.[29]

Hormonal Influence

Hormonal influences on ACL injury risk have also been studied. It has been reported that the risk of sustaining ACL injury appears to be greater during the preovulatory phase than during the postovulatory phase of mensturation.[52,88–92] A limitation of this finding is that a validated measure has not been identified to characterize menstrual cycle phase status.[41] The risk of ACL injury may be higher in elite athletes who have higher serum levels of the hormone relaxin.[23,30,48,51,52,93,94] In some women, variations in knee laxity due to cyclic hormonal changes may be substantial enough to affect the mechanics of the knee.[51,52,90,91] Sex hormones may also have the potential to influence skeletal muscle as well as the ACL via sex hormone receptors. [52,95–98]. Interactions between several sex hormones, remodeling proteins, mechanical stresses, and secondary messengers are all thought to influence the molecular and mechanical properties of the ACL, which may also affect ACL injury risk.[52] Lastly, there has been no evidence to support the use of oral contraceptives to stabilize hormones with the intent of reducing the risk of ACL injury.[52]

Postural Deformities

Several postural deformities of the lower extremity have been identified in subjects with a history of non-contact ACL injury, including increased contralateral anterior knee laxity,[42,52,99] genu recurvtum,[52,99–103] internal rotation,[52,104] and general joint laxity.[52,99,100,103,105] Additionally, females demonstrated greater generalized joint laxity[52,99,106] as well as specific laxity in the sagittal[52,99,106–109], greater frontal and transverse planes.[52,110–112] Furthermore, females at risk of ACL injury demonstrated greater anterior pelvic tilt, hip anteversion, tibiofemoral angle, and quadriceps (Q) angle.[52] It should be noted that no one lower extremity alignment factor has been clearly identified across the literature to predict ACL injury risk.[52]

Cognitive Risk

Studies have also addressed cognitive risk factors for non-contact ACL injury. Correlations have been found between ACL injury risk and significantly slower reaction times and processing speeds, as well as lower scores on verbal and visual memory tests, and overall total scores on neurocognitive tests, such as those designed to assess cognitive function after concussion.[41]

Family History of ACL Injury

Family history of ACL injury has been correlated with a higher incidence of ACL injury.[41,113] The familial predisposition to ACL injury is thought to be multifactorial and includes decreased intercondylar notch width, increased general joint laxity, increased knee abduction angle, and low hamstring/quad ratios.[105]

Myer et al found that males with a family history of ACL injury were more likely to sustain ACL injury than females with a family history of injury.[114] In a case-control study of 171 ACL injured patients matched with 171 uninjured patients, Flynn et al found that patients with ACL injury were twice as likely to have a relative with a history of ACL injury.[113] Additional genetic links have been identified; multiple genes have been associated with a risk of ACL rupture, and several genes have also been associated with known risk factors such as increased range of motion and joint laxity.[41] It must be noted that these studies have predominately been done on European white populations, so it cannot be assumed that the results would translate to other ethnicities.[24,51]

Previous ACL Injury

Prior history of ACL is an independent, significant risk factor for ACL injury.[41,115] History of ACL reconstruction is a well-supported risk factor for ACL injury to both the ipsilateral and contralateral leg. [41,115] Athletes who have sustained a previous ACL injury are at a significantly greater risk to suffer ACL injury than those who have not,[85,116,117] with the likelihood of sustaining a second ACL injury ranging from 1 in 4 to 1 in 17.[116–118] The (Multicenter Orthopaedic Outcomes Network) MOON Group cohort had a high rate of subsequent ACL injury, particularly in females. The contralateral leg was more likely to sustain injury in this group,[119] which is consistent with general population data.[116,119,120] The risk of reinjury is influenced by the severity of the initial injury, as well as what course of treatment was followed, and the healing response of the patient.[41,115] In athletes returning to sport from ACL injury, Paterno et al found that second injury could be predicted based on a drop-landing task. The strongest predictor of second ACL injury in this group was hip net moment impulse in the first 10° of landing in the transverse plane on the uninvolved side.[117] Greater displacement of the knee joint in the frontal plane on the involved knee was also able to predict subsequent injury. ($P = .03$)[117] It is important that these risk factors be mitigated through proper rehabilitation and injury prevention programs to decrease the likelihood of sustaining further ACL injuries.

Anterior Cruciate Ligament Modifiable Risk Factors

Many identified risk factors are modifiable, which indicates that an individual can take proactive steps towards changing these risk factors to decrease the risk of ACL injury. Modifiable risk factors can be considered either intrinsic, that is within the body, or extrinsic, that is external to the body. The vast majority of modifiable risk factors are biomechanical, and therefore, can be considered intrinsic.

Intrinsic Risk Factors

Muscle Strength, Stiffness, and Dominance

The stiffness of the hamstrings has been studied and identified as an intrinsic risk factor for ACL injury. Decreased flexibility is correlated to decreased hamstrings stiffness, and individuals with greater hamstrings stiffness have been shown to demonstrate landing biomechanics which are favorable for the ACL.[50] Additionally, greater hamstrings stiffness is associated with decreased anterior tibial shear force, which loads the ACL less.[50] Significant hamstrings stiffness may limit the risk of injury to the ACL. It is important to emphasize that there may be negative consequences for musculotendinous injury to the hamstrings in the presence of increased stiffness, therefore, it is likely that an optimal level of hamstrings stiffness exists, where the risk of injury to both the musculotendinous unit of the hamstring as well as the ACL are minimized.[50]

When muscles do not adequately absorb the ground reaction forces, static stabilizers such as ligaments and joints must absorb high amounts of force.[44] This causes increased loads and potentially failure of the static structures,[50] and is termed ligament dominance. In the knee, the major muscles that commonly contribute to ligament dominance are the major muscles of the posterior leg: gluteus maximus, gluteus medius, hamstrings, soleus, and gastrocnemius.[121]

The tendency to stabilize the knee joint by using the quadriceps muscle is called quadriceps dominance. Females tend to exhibit quadriceps dominance, and therefore, tend to land from a jump with less knee flexion than males. Additionally, quadriceps dominance contributes to ACL injury risk by increasing the shear force on the ACL. When the quadriceps muscles contract, the tibiofemoral joint is compressed, and the tibia shifts slightly anteriorly.[69]

Knee Joint Angle

The angle of knee flexion has a significant influence on ACL loading. When knee flexion angles are less than 30°, quadriceps contractions can generate the significant anterior tibial shear forces that facilitate ACL loading.[30,104,122,123] Isolated knee valgus[52,67,68,123,124] and tibial rotation[27,42,62,67,84,124–126] have also been identified in ACL loading, however, the load of knee valgus and tibial rotation combined is less than that of isolated anterior tibial shear force.[30,67,86,122,127] A combination of knee valgus, tibial rotation, and anterior tibial shear force provide a much larger load on the ACL than these factors in isolation. It is important to note that isolated knee valgus does not provide enough load to injure the ACL without first causing injury to the Medial Collateral Ligament (MCL).[68,128–132]

Knee abduction angles were found to be 8° greater in ACL injured groups than uninjured groups in a study by Hewett *et al*. The same group found that knee abduction moments could predict ACL injury risk with 73% sensitivity and 78% specificity.[121] Multiple studies agree that an increased knee valgus motion or moment was present in females compared to males.[40,44,68,133]

Specific movements in each anatomical plane increase the risk of ACL injury. In the transverse plane, increased internal rotation angle of the hip[45,68] and increased knee internal rotation angle[68] during dynamic activities have been identified as risk factors for ACL injury.[68,134] In the frontal plane, when the knee is near full extension, forceful valgus collapse has been reported during noncontact ACL injuries[69,135]. Females have been identified as having a significantly greater knee valgus at baseline than males.[136–142] Decreased sagittal plane joint flexion has been identified as a risk factor for noncontact ACL injury. In combination with increased knee valgus and leg rotation, decreased knee, hip, and trunk flexion are common movement patterns in individuals predisposed to noncontact ACL injury.[68]

Other biomechanical patterns identified in noncontact ACL injuries are a heel-to-toe landing motion, lateral trunk flexion, and increased stance width during jump-landing.[136] Tibial internal rotation, which can be identified by foot position, has been identified as generating a greater tensile load on the ACL, whereas tibial external rotation causes the ACL to impinge on the lateral wall of the femoral intercondylar notch.[136]

Extrinsic Risk Factors

Several risk factors for ACL injury originating outside the individual have been identified. Cleats that feature high torsional resistance, such as those with long, irregular cleats on the periphery of the sole of the shoe, smaller, pointed cleats which are centrally positioned, and edge cleats have all been linked with an increased risk of sustaining an ACL injury.[41]

A higher risk of ACL injury is also associated with participating in sport in northern venues, as well as in games that occur earlier in the competition season. Bermuda grass turf and synthetic turf have also been identified as a higher risk environment for ACL injury.[41]

Risk Factors by Sex

As previously identified and widely discussed in the literature, females are at an increased risk of sustaining an ACL injury.[30,51,52,94,143,14423,35,36,93,133,145,44,48] High school aged female athletes are significantly more likely to undergo ACL reconstruction versus their male counterparts[37], ACL injuries in females tend to occur when the knee is flexed to a range between 15°-27°.[22] At this point in the range of motion, the center of the tibiofemoral contact region in the lateral compartment is in the center of the cartilage surface in the mediolateral direction, which is the same location as the slope measurements previously discussed. When the mechanism of injury involves external rotation and abduction of the tibia relative to the femur, and the knee is flexed beyond 30°, the ACL can become impinged against the femoral intercondylar notch. Correlations between ACL notch size and risk of ACL injury may support the aforementioned mechanism of injury.[22]

Male athletes are most likely to sustain a non-contact ACL injury when the knee is flexed between 9°-19°.[22] In this position, the menisci are better able to transmit loads, particularly when transitioning from non-weight bearing to weight bearing, such as in a landing or cutting task. The geometry of the posterior aspect of the menisci could have an influence on the magnitude of the anterior shear force on the tibia, and therefore, the load placed on the ACL.[22]

Several anatomical differences exist between females and males. Even after body weight is standardized, females have smaller ACLs than men.[48] The midsubtance of the ACL may also be thinner, although the literature on this is conflicting.[48] There is a variance in knee geometry among females, however, one study found that the posterior tibial slope of the medial plateau was higher in ACL injured females than in both the uninjured female control group as well as the ACL injured males studied.[48] Female athletes have been identified as having less medial tibial plateau depth with regard to concavity, as well as decreased femoral intercondylar notch size.[48] The width of the anterior outlet of the femoral notch was the most predictive risk factor for ACL injury in one study;[146] however, when considering the slope of the lateral tibial plateau and volume of the ACL, the prediction was not significantly stronger.[31,146]

Females at an increased risk of ACL injury have been shown to demonstrate biomechanical tendencies that may predispose them to injury. During a drop-landing task, females demonstrated increased knee valgus angle as well as increased external valgus movements.[68] Females also tend to have a larger quadriceps angle (Q-angle), narrower intercondylar notch, and increased medial posterior tibial slope.[48] A higher body mass index (BMI) has been identified as a predictor of future ACL injury in females, particularly in combination with greater knee-joint laxity.[37,106]

Risk Assessment Tools

A variety of tools have been developed to attempt to assess the risk of lower extremity injury, including ACL injury, based on movement strategy and biomechanics.

Functional Movement Screen

The Functional Movement Screen (FMS) is a screening tool that is comprised of 7 fundamental movements that assess stability and mobility: overhead squat, hurdle step, in-line lunge, active hamstrings, shoulder mobility, trunk stability, and rotary stability.[147] the FMS has been identified as having good intrarater reliability, but poor interrater reliability.[147] FMS scores have been associated with an increased risk of time-loss injury in professional football players.[148]

Drop Vertical Jump Test

The Drop Vertical Jump Test (DVJ) uses a 12-inch high box. Subjects are instructed to jump off the box, landing directly in front of it, then immediately complete a maximum vertical jump. Scores are divided into three groups: Low Risk, Medium Risk, and High Risk. A Low Risk jump requires the subject to land evenly on the balls of their feet with feet shoulder width apart, neutral alignment of the knees, good separation of the kneecaps, and knees and hips flexed. A High Risk jump is one that has off balance or heel landing, a narrow landing stance, valgus knee alignment, poor kneecap separation distance, and knees and hips not flexed enough. A Medium Risk jump is one that does not neatly fit into one of the aforementioned categories.[149] The DVJ has good inter- and intra- rater reliability and high sensitivity.[150] The DVJ has been reported to identify individuals with greater ACL injury risk.[44,148]

Standing Long Jump

The Standing Long Jump (SLJ) consists of the subject completing three submaximal jumps for distance, followed by three maximal effort jumps for distance. In both jumps, the subject must hold the landing for 5 seconds, and the distance is measured.[148] The SLJ mimics functional aspect of jumping and landing and assesses the athlete’s lower extremity strength and neuromuscular control. In a study on male and female Division III college athletes, no significant risk associations were found between SLJ sores and injury.[148]

Single Leg Hop for Distance

The Single Leg Hop for Distance (SLH) test requires the subject to perform 6 single leg jumps for distance, three on each leg, holding the landing for 5 seconds each.[148] It also mimics the functional aspect of jumping and landing and assesses the athlete’s lower extremity strength and neuromuscular control. It is frequently utilized to assess lower extremity function in athletes following ACL reconstruction. In the same study on male and female Division III athletes, it was discovered that preseason scores on the SLH could predict lower extremity and back injuries in Divison III athletes. [148]

Lower Extremity Functional Test

The Lower Extremity Functional Test (LEFT) is designed to assess the ability of injured athletes with regard to sport-specific movement patterns, measured through eight agility drills repeated for two trials each: forward run, backward run, side shuffle, carioca, figure-8 run, 45° cuts, and 90°cuts.[148] Slower scores were associated with an increase in thigh or knee injuries in female Division III athletes, and faster scores were associated with low back and lower extremity, particularly foot and ankle injuries, in male Division III athletes.[148]

Landing Error Scoring System

The Landing Error Scoring System (LESS) is a clinical assessment tool that has demonstrated preliminary predictive evidence for identifying individuals at high risk of lower extremity injury.[136] The LESS has demonstrated effectiveness in identifying elite youth soccer athletes who have a greater risk of suffering an ACL injury.[52,77] There are no current studies that support the LESS as a predictive tool for adults with regard to ACL injury.[52]

In the LESS, participants jump from 30-cm high box to a distance 50% of height away from the box, onto a force platform and immediately rebound to maximal vertical jump. Successful jump criteria are:

1. Jumping off box with both feet

2. Jump forward but not vertically to force plate
3. Land with entire foot of dominant LE on force plate
4. Land with entire foot of non-dominant LE off force plate
5. Complete task in fluid motion

The individual components that make up the LESS are: stance width, maximum foot-rotation position, initial foot-contract symmetry, maximum knee-valgus angle, amount of lateral trunk flexion, initial landing of feet, amount of knee-flexion displacement, amount of trunk-flexion displacement, total joint displacement in the sagittal plane, and overall impression.[68] In youth soccer players, a cutoff score of greater than 5 has been suggested to identify athletes at high risk of ACL injury.[77]

The LESS has good inter-rater and intra-rater reliability,[68,136] and includes a more comprehensive assessment of multi-planar biomechanics than previous clinical assessments of poor jump-landing biomechanics.[136,151] It distinguishes jump-landing biomechanics that have been previously shown to be related to ACL loading and injury mechanisms,[68] and is a valid and reliable tool to identify subjects with landing areas in multiple planes.[68] The LESS may be able to predict lower extremity stress fracture risk, [152] and can identify lower extremity biomechanics that are known risk factors for PFPS.[6]

No significant relationship between LESS score and risk of ACL injury was identified in a study using 28 ACL-injured high school and collegiate athletes, matched with controls, there were an average of 224 days between screening and injury.[62] Collegiate soccer players with a previous lower extremity injury history, defined as an injury that caused the individual to miss at least one practice or game, did not have LESS scores that were statistically significant compared to athletes who did not have a history of lower extremity injury.[153] In the same study, the LESS did not predict which participants would go on to sustain a lower extremity injury during the season.[153] More research is needed to determine the predictive ability of the LESS for noncontact ACL injury.[68]

Additional Considerations

Sport Specific Considerations: Soccer

Lower extremity injury accounts for 50%-85% of all time-loss injuries in senior female soccer players.[43] The majority of injuries occur during training, and the knee is the most frequently injured body part.[2,43] The dominant leg is also more likely to sustain injury.[43] NCAA women's soccer and women's basketball athletes demonstrated a significantly higher injury rate compared to men's soccer and men's basketball[57]; similar findings exist in subjects at the secondary school level.[49] ACL injury rates for female athletes is 2-8 times greater than for male athletes playing the same sport at the same level of competition.[37,38,53,154,155]

Timing of Injury and Fatigue

There is a paucity of information regarding the timing of ACL injuries. It has been identified that injuries are more common earlier in the athletic season and during practices.[2] It could be inferred that due to the effects of fatigue, injury is more likely when the athlete is fatigued, most reasonably in the later portions of a practice or game.

Fatigue affects the central and peripheral processing systems, and critically contributes to degradation of neuromuscular control of fatigued athletes by affecting concentration. Perceptual-cognitive skills are affected as the central control mechanism and it's effects on proprioception are overloaded. Furthermore, fatigue inhibits the ability to dynamically stabilize the knee joint effectively during side-stepping, and increases the load on the knee joint. Fatigue also induces degradation in muscle strength, and causes delays in neuromuscular responses. Because of this, knee joint proprioception is affected. Males tend to recruit significantly higher sagittal knee joint loading when fatigued in order to stabilize the knee joints, however, no clear connections in this area have been found in women. One study reported that the lower extremity was found to be at a higher risk for injury when unanticipated movement and fatigue are combined as participants tended to land with less hip and knee flexion after completing the fatigue protocol.[156]

Post-Injury Interventions

ACL injuries can be treated non-surgically, that is only with rehabilitation, or surgically reconstructing the ligament. The number of ACL reconstructions in individuals under 20 years old increased from 12.22 to 17.97 per 100,000 person years from 1994-2006.[35] No cause for this jump has been identified.[35] Reconstruction rates have cited success rate ranging from 60%-100% and are dependent on the patient’s activity level before reconstruction. A successful return to preinjury activity levels was most commonly reported in bicycling, jogging versus cutting/pivoting sports.[157]

There are two major categories of graft choices: autograft, and allograft. The two most common sites for autograft harvest are the hamstring tendons and patellar tendon, often using bone plugs from the tibia and patella. Higher rates of reinjury and ACL graft failure have been reported in younger patients,[157] and in patients with a high level of athletic participation.[157] Contralateral injuries have been found to be more common in patients who undergo ACL reconstruction prior to college.[157] Elite professional athletes may return to their sport successfully, but may fail to return to their prior level of play. Elite college athletes have been found to be very likely to return to play after ACL reconstruction.[157]

Conclusion

Lower extremity injury can have major impacts on the athletic future of affected individuals. Time loss, increased risk of future injury, and comorbidities such as osteoarthritis can have devastating impacts on the affected individuals. 25% of athletes who sustain ACL injury do not return to the same levels of sport participation after injury.[77,158] In order to prevent these injuries, it is essential to identify the factors that can be changed in order to prevent injury from occurring. A great deal of research has contributed to an ever-growing base of knowledge about the risk factors for lower extremity injuries in athletes, however, it is essential to also address the notion that these risk factors may change over the course of an athletic season. This study aims to identify the changes in risk factors, as well as athletic power in over one NCAA Division 1 Women's Soccer team's season.

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INTRODUCTION

Female collegiate soccer athletes sustain the highest number of injuries per year as compared to female athletes competing in other sports.[1] Approximately half of these injuries are categorized as sprains or strains,[1] and half of the injuries that required surgical intervention were sprains or strains.[1] Many of these injuries are associated with a long term sequelae. For example, anterior cruciate ligament (ACL) sprains have a high re-injury rate[2–4] and are widely associated with the early onset of osteoarthritis (OA).[5–13] Up to 73% of individuals who sustain a lateral ankle sprain develop chronic ankle instability (CAI),[14] which is a condition characterized by recurrent ankle sprains and may or may not also include functional impairment and functional instability.[15] These injuries have a high likelihood of affecting an athlete's life long after their competitive sport participation is over. Therefore, primary prevention of lower extremity musculoskeletal injuries in female collegiate soccer is critical.

Injuries occur with varying frequency during an athletic season. The majority of the literature indicate that the highest frequency of injuries occurs during preseason,[1,16–18] with the risk of injury significantly increasing when excessive training loads occur.[19] There is also an increased likelihood of injury later in the season, which may also be associated with greater training loads and consequently, fatigue.[19] Fatigue has been shown to increase the risk of injury,[20–23] as it affects the central and peripheral processing systems, and impairs neuromuscular control.[21,22,24,25] Declines in neuromuscular control due to fatigue may be specifically due to degradation in muscle strength and delays in neuromuscular responses, and can cause subsequent changes in knee joint proprioception.[24]

Altered neuromuscular control is a primary risk factor for non-contact lower extremity injuries, such as ACL injuries,[26–29] patellofemoral pain syndrome,[30] and lower extremity stress fracture.[31,32] While fatigue has been shown to acutely impair neuromuscular control, it is unknown how fatigue during a competitive sport season affects neuromuscular control. Monitoring changes in neuromuscular control and sport performance during a season may help identify times when the risk of injury is higher, and may also provide insight into when and how to implement procedures to decrease injury risk.

The primary purpose of this study was to evaluate changes in neuromuscular control, as measured by movement control during a jump landing task, and vertical jump performance over the course of one competitive collegiate soccer season. A secondary purpose was to investigate if there was an association between the incidence of non-contact lower extremity injuries and movement control. A final purpose was to evaluate the relationship between neuromuscular control and vertical jump performance. We hypothesized that neuromuscular control and vertical jump performance would be related to one another and would both be impaired during various points of the soccer season. We also hypothesized that athletes would be more likely to sustain an injury when their neuromuscular control was impaired. This study will aid in understanding the impact of a soccer season on neuromuscular control and injury risk.

METHODS

Experimental Design

We used a repeated measures study design to evaluate changes in neuromuscular control and power over the course of one competitive athletic season in NCAA Division I women's soccer athletes. Participants completed five identical test sessions over the course of the season, beginning with the start of pre-season and concluding with the end of post-season. Information regarding injury incidence, including mechanism of injury, was also collected during the season.

Participants

We recruited members of an NCAA Division I women's soccer team (n=29) for participation in this study. Twenty-five (86%) athletes volunteered to participate and provided informed consent prior to data collection according to guidelines approved by the university's institutional review board. All participants were free from injury or illness that prohibited participation in soccer at the time of all test sessions. Athletes were not excluded based on the history of injury as a goal of this study was to evaluate potential factors related to training and injury risk in this athletic population, which includes an athlete's injury history.

Procedures

Participants completed up to five test sessions during the 2015 fall collegiate soccer season. Test sessions were approximately 2-4 weeks apart beginning with the start of pre-season (Time 1), end of pre-season (Time 2), mid-season (Time 3), end of regular season (Time 4), end of post-season (Time 5). Each test session required approximately 15-30 minutes to complete. All test sessions occurred between 11:00am and 4:00 pm and prior to physical activity or on off-days so as to take place in a non-fatigued state. All testing sessions were conducted at indoor athletic facilities. Participants' height and mass were measured using a wall measuring unit and digital scale, respectively. Participants then completed a countermovement vertical jump test and standardized jump landing test in a random order.

Vertical Jump

Participants performed three trials of a countermovement vertical jump task. Vertical jump height was assessed with a Vertec (*Sports Imports, Columbus, OH, USA)*. Participants' standing overhead reach height was first measured to calculate baseline reach height. Participants were instructed to jump as high as possible, reaching overhead to displace the plastic flags on the measuring device. Participants did not receive feedback or coaching on jumping technique. The mean vertical jump height from three trials was calculated, and normalized by subtracting the standing reach height from the calculated mean vertical jump height.

Jump Landing Task

Participants performed three trials of a standardized jump-landing task. Participants jumped forward to a distance of 50% of their body height from a 30-cm high box, and immediately jumped vertically for maximal height upon landing. Participants were given the opportunity to perform practice trials as needed to feel comfortable with the task and perform it correctly. A successful jump required participants to: jump (1) forward off of the box (2) with both feet simultaneously, (3) land with both feet in a specified area approximately 50% of their body height from the leading edge of the box (4) in a fluid motion. The jump landing task was evaluated and scored using PhysiMax™ Athletic Movement Assessment Software (*PhysiMax Technologies Ltd., Tel Aviv, Israel*), which is a valid[33]and reliable[33] objective measure to evaluate jump landing movement technique using the Landing Error Scoring System (LESS). The LESS is a valid and reliable clinical movement assessment[28] that has been shown to predict injury in youth soccer athletes.[34] The LESS accounts for the number of landing errors performed during the jump landing task, with a high score indicating a high number of errors, and thus poor landing technique.[28]

Injury Recording

We collected data on lower extremities sustained throughout the season. For the purposes of this study, we collected data only on lower extremity injuries that required modified or restricted participation in sport. The team's Certified Athletic Trainer reported these data to us. We utilized the date of injury, injury description, onset and mechanism of injury, and number of days both modified and fully restricted from participation.

Data Reduction and Analyses

Errors on the LESS were counted if they occurred at least one time during the three trials. A composite LESS Score was created based on the number of errors demonstrated by each participant and used for analyses. Vertical jump scores were calculated by subtracting the standing reach height from the average of three vertical jump trials. Participant's LESS score for each time point was dichotomized into a GOOD (LESS>5) or POOR (LESS≤5) movement category.[35] Each time point was coded as INJURY or NO INJURY based on whether or not the participant sustained a non-contact lower extremity injury that required at least one day missed from soccer activities.

Separate repeated-measures analyses of variance were utilized to evaluate differences between time points for the LESS score and vertical jump height. Ninety-five percent confidence interval of the mean difference between time points were used to determine if a main effect was observed. Pearson correlations were calculated for LESS score and vertical jump height. A chi-square analysis was used to evaluate the association between movement category (GOOD, POOR) and the incidence of a non-contact lower extremity injury following each test point for each participant.

RESULTS

Twenty-five participants consented to participation (age= 20±1 years, mass= 66.5 kg ±6.6 height= 1.7 m ± 0.1, BMI= 23.4 ± 1.83). Fifteen participants (age= 20±1 years, mass= 66.6 kg ±6.5, height= 1.7 m ± 0.1,) completed all five test sessions. Ten participants did not complete all five test sessions and were not included in the repeated measures analyses: two participants sustained season-ending injuries, one participant did not complete one data collection session due to injury, one participant became ineligible for participation after quitting the team, and six participants did not participate in all five data collection sessions due to other circumstances (e.g. class conflicts.) LESS scores were not significantly correlated to vertical jump performance (R^2=0.0003, P=0.87). We observed a significant main effect for time for both LESS scores (P = 0.046) and vertical jump (P < .001) *(Table 1)*. LESS scores were significantly different from pre-season (Time 1) to end of pre-season (Time 2)(P = 0.005) as well as pre-season (Time 1) to mid-season (Time 3)(P=0.009). All other time points were not significantly different from each other (P > 0.05). Vertical jump performance significantly differed between the end of pre-season (Time 2) and all other time points (P < 0.001)*(Table 2).*

Participants in our study sustained a total of 26 injuries. Nine injuries (35%) occurred in preseason. Six injuries (23%) occurred between Time 2 and Time 3, six injuries (23%) between Time 3 and Time 4, and two injuries (7%) between Time 4 and Time 5.

LESS Scores			
Time Point 1 vs.	**Mean Less Score**	**Mean Difference ± SD**	**95% CI**
Time point 1	6.067	-	-
Time Point 2	4.2	1.73±2.02	[.617, 2.85]
Time Point 3	3.4	1.73±2.22	[.505, 2.96]
Time Point 4	5.067	0.80±2.98	[-.851, 2.45]
Time Point 5	3.8	1.27±2.34	[-.032, 2.57]

Vertical Jump			
Time Point 2 vs.	**Mean VJ Performance**	**Mean Difference ± SD**	**95% CI**
Time point 2	18.73cm	-	-
Time Point 1	38.95cm	-20.17±5.36	(-23.16, -17.20)
Time Point 3	39.77cm	-20.93±4.01	(-23.16, -18.69)
Time Point 4	39.82cm	-21.03±3.96	(-23.24, -18.85)
Time Point 5	39.21cm	-20.52±5.66	(-23.67, -17.40)

A significant association between movement category (GOOD, POOR) and incidence of non-contact lower-extremity injury (INJ, UNINJ) was observed ($\chi^2_{(1)} = 3.96$, p=0.047, Ö = 0.20, OR: 3.34, 95% CI [0.97, 11.49]

Movement Category	**Injured**	**Uninjured**
Good	5	62
Poor	7	26

DISCUSSION

The most important findings in this study are that neuromuscular control, as measured by the LESS, is not stable over the course of a competitive collegiate women's soccer season and is associated with injury risk. These results agree with our hypotheses and provide a novel contribution to the existing literature related to understanding injury risk during competitive sports seasons. Monitoring neuromuscular control during a sport season may provide critical insight into training load and fatigue levels of individual athletes, which based on the results of this study appear to directly influence their risk of injury. Coaches and clinicians can use this information to track training load and monitor neuromuscular control and biomechanics changes and then pre-emptively modify training and implement valid injury prevention strategies to decrease the risk of injury.

Preseason has been identified as a high risk time for injury[17], and results of our study are consistent with this finding. Multiple sources suggest that injuries occur more frequently when training loads are highest,[36] which is common in preseason. Gabbett[36] suggests that many non-contact, soft tissue injuries are likely secondary to excessive and rapid increases in training load, which is commensurate to our findings. Training loads are likely to sharply increase from the off season in preseason. Most injuries in this study were sustained between Times 1 and 2, which corresponds with the preseason. LESS scores were higher at Time 1 than Time 2, which is also consistent with our findings that higher LESS scores are indicative of likely injury in the short term. We speculate that many of our participants came into preseason with poor fitness levels. Proactive rehabilitation techniques are utilized by the team's Athletic Trainer to emphasize good movement techniques during preseason, and this may have also had a positive effect on LESS scores.

The role of neuromuscular control, as measured by movement technique during a jump landing task, on injury risk is inconclusive in the literature. Padua et al.[34] suggest that the LESS may be an appropriate screening tool for identifying youth soccer athletes at risk of sustaining ACL injury, as the LESS was able to differentiate injury risk in their study population. The neuromuscular characteristics of youth, which can be affected by factors such as decreased sport specialization and puberty, may play a role in the difference between these populations. A limitation of all previous prospective work is the use of a single baseline assessment of neuromuscular control. By monitoring neuromuscular control over time, the current study supports the findings of Padua et al[35] to demonstrate that athletes are more likely to sustain an injury when their neuromuscular control is impaired. Previous studies have demonstrated that the LESS is not able to differentiate injury risk in adult athletes;[11,37] however, these studies have utilized a single baseline LESS score to attempt to identify future injury, sometimes up to 2.6 years after the baseline assessment. Smith et al.[11] had an average of 224 days (SD 150 days, range 1-434 days) between baseline screening and ACL injury. Krosshaug et al.[37] evaluated female elite soccer and handball players and found that the Vertical Drop Jump Test, which utilizes the same jump-landing task as LESS scoring, is also not predictive of ACL injury. In their study, ACL injuries were sustained an average of 1.5±1.3 years after baseline screening. It is of interest to note that one participant in our study sustained a non-contact ACL injury within the study period, between Time 1 and 2. Therefore, this participant was only evaluated for pre-season injury risk; however, she had the highest single LESS score (10) recorded in the study. She also had a history of prior contralateral and ipsilateral ACL tear with surgical reconstruction.

Many of the injury risk factors cited in the aforementioned studies are modifiable.[28,38–41] Prevention Training Programs (PTPs), also known as Injury Prevention Programs (IPPs) that aim to improve neuromuscular control can effectively reduce the risk of injury. PTSs typically involve agility, balance, flexibility, plyometrics, and strengthening exercises.[42] Implementing Prevention Training Programs based on movement assessments conducted both at the beginning of the season and continuously throughout athletic participation may lead to improved neuromuscular control and subsequently a decrease in lower extremity injuries. As a result of a high frequency of injuries during preseason, many of the participants in our study were involved in rehabilitative processes with a strong emphasis on good biomechanics. We suspect that this could explain the improvement in LESS scores at Time 2. As participants were discharged from rehabilitation, their biomechanics and neuromuscular control may have reverted, demonstrating a learning effect that was not long lasting.

These findings also suggest that lower extremity power is relatively stable over time, with only one statistically and clinically significantly different Time (2) than the remaining four (1,3,4,5). We postulate that the significantly lower vertical jump height at Time 2 may be as a result of fatigue secondary to significantly increased training loads during preseason. LESS scores improved over the course of preseason, which aligns with our finding that the two are not correlated. Further research may be warranted to further investigate this interesting finding.

Limitations

Due to a small initial sample size and attrition, complete data were only collected on fifteen participants. Furthermore, the participants were all members of one NCAA Division 1 Women's Soccer team. Individuals from other populations, such as youth athletes, male athletes, and individuals competing at a different level of athletics and in different sports may not demonstrate the same findings. It is also possible that training regimens may differ by team, and similar results may or may not be found in comparable populations. Future research should evaluate changes in neuromuscular control along with objective measures of training load to further understand the impact of fatigue during a season on injury risk.

Conclusion

Results of this study would be bolstered if similar findings, particularly with regard to changes in LESS scores over time, were identified in a larger sample size, and in other populations. We believe this to be the first study of its kind, and feel that based on our findings, larger scale investigation is warranted. We have successfully demonstrated in our population that LESS score changes can occur in a short period of time, therefore, one single baseline cannot be expected to predict injury risk in the longer term. We have also demonstrated that injury risk for the short term can be predicted by LESS scores. We have found that LESS scores and vertical jump height are not correlated, and that power as measured by vertical jump is actually decreased after an increased training load, however, it stabilizes when training loads stabilize. This information can guide coaches and clinicians in making training decisions that will have a positive and evidence based impact on lower extremity injury reduction efforts.

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