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THE DEVELOPMENT OF THE SINGLE-LEG LANDING ERROR SCORING SYSTEM (SL-LESS) FOR LOWER EXTREMITY MOVEMENT SCREENING

by

Maegan L. O'Connor

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

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at

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December 2015

ABSTRACT

THE DEVELOPMENT OF THE SINGLE-LEG LANDING ERROR SCORING SYSTEM (SL-LESS) FOR LOWER EXTREMITY MOVEMENT SCREENING

by

Maegan L. O'Connor

The University of Wisconsin-Milwaukee, 2015
Under the Supervision of Professor Jennifer Earl-Boehm, PhD, LAT

Introduction: Musculoskeletal knee injuries are some of the most common sports-related injuries. Movement screening assessments are often implemented to identify high-risk individuals in order to prevent the injury and the negative long-term consequences related to sustaining these injuries. While there are numerous established field-based assessments none have shown a strong ability to predict future injury. Additionally, there is currently there is no two-dimensional (2D) screening measure to evaluate the movement of multiple body segments in more than one plane during a single-leg task. The purpose of this study was to investigate the validity and reliability of the Single-Leg Landing Error Scoring System (SL-LESS). Specifically, two aims were addressed: 1) to determine the concurrent validity of the SL-LESS in predicting external knee abduction moment (KAbM) at initial contact and at its peak and 2) to determine the interrater and test-retest reliability of the SL-LESS. **Methods:** Twenty-eight physically active females were evaluated for risky movement patterns using the SL-LESS during a single-leg drop vertical jump (SLDVJ). This study included two testing sessions that implemented a standardized warm-up and SLDVJ testing protocol. Two-dimensional videos of the frontal and sagittal planes were collected during session 1 while both 2D videos and three-dimensional (3D) kinematics and kinetics were collected during session 2. SL-LESS scores from session 2 were used to stratify participants into 3 groups (good, moderate, poor). Differences KAbM at initial contact and at its peak between the "good" and "poor" groups were investigated using an independent-samples t tests. Intraclass correlation coefficients ($ICC_{2,1}$) were used to determine the interrater reliability of session 1 total SL-LESS scores between two raters and test-retest reliability of total SL-LESS scores between sessions. To determine the agreement of the individual SL-LESS items, percent agreement and Cohen's kappa statistic were calculated to for each of the 11 items. **Results:** No statistical differences were found in KAbM at initial contact between groups or maximum KAbM between groups. The SL-LESS demonstrated fair interrater reliability and good test-retest reliability. Individual item percent agreement between raters ranged from 75.0–100% and kappa statistics indicated significant fair to perfect agreement. Between sessions percent agreement ranged from 78.6–100% and kappa statistics indicated significant moderate to perfect agreement. **Conclusions:** The results of this study indicate that this initial version of the SL-LESS does not predict KAbM. It does, however, provide the basis for a new single-leg, whole body movement analysis that future studies can build upon in order to develop a valid lower extremity injury screening assessment that can be easily implemented in a variety of field and clinical settings.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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CHAPTER 1: INTRODUCTION

Background

Musculoskeletal injuries are a common occurrence across all levels of athletic participation. Documentation of emergency room visits indicates sports related injuries account for over 3.7 million visits and the majority of these injuries occurred in people between the ages of 5 and 24 (Burt & Overpeck, 2001). It should be acknowledged, however, that these statistics may underestimate the actual number sports related injuries since many chronic and overuse injuries do not result in time lost from participation and may not be reported or treated. These statistics support an important area of research that aims to develop screening mechanisms to identify those individuals who may be at greater risk of injury.

Research suggests that over 50% of all sports related injuries occur in the lower extremities and that knee injuries, in particular, are extremely common (Agel et al., 2007; Hootman, Dick, & Agel, 2007; Powell & Barber-Foss, 2000). Two of the most prevalent lower extremity injuries are anterior cruciate ligament (ACL) injury and patellofemoral pain (PFP). The ACL is a ligament of the knee that provides stability and prevents abnormal movement of the joint (Butler, Noyes, & Grood, 1980). Injuries to this ligament are acute and are due to large loads produced through both contact and noncontact mechanisms (Agel et al., 2007; Arendt & Dick, 1995; Boden, Dean, Feagin, & Garrett, 2000; Boden, Torg, Knowles, & Hewett, 2009; Krosshaug et al., 2007; Myklebust, Maehlum, Holm, & Bahr, 1998; Olsen, Myklebust, Engebretsen, & Bahr, 2004). Annually, it is estimated that between 80,000-250,000 ACL injuries occur, costing over $2 billion (Gottlob, Baker, Pellissier, & Colvin, 1999; Griffin et al., 2006).

PFP is a chronic overuse injury that encompasses all anterior knee pain not associated with a specific anatomical pathology (Cowan, Bennell, Hodges, Crossley, & McConnell, 2001; McCarthy & Strickland, 2013; Thomeé, Augustsson, & Karlsson, 1999). PFP is believed to develop as a result of abnormal motion of the patella within the trochlear groove (Powers, Bolgla, Callaghan, Collins, & Sheehan, 2012). This condition accounts for a quarter of all injuries treated in sports medicine clinics and an estimated 2.5 million runners are diagnosed with PFP every year (Earl & Vetter, 2007; Taunton et al., 2002; Thomeé et al., 1999).

These two knee injuries stand out due to their high incidence, poor long-term prognosis, and risk of osteoarthritis development (Hinman, Lentzos, Vicenzino, & Crossley, 2014; Lohmander, Englund, Dahl, & Roos, 2007; Myklebust, Holm, Maehlum, Engebretsen, & Bahr, 2003; Utting, Davies, & Newman, 2005). In an attempt to identify individuals who are at a greater risk of developing these injuries and to establish effective preventative interventions, significant ongoing efforts are being made to better understand the mechanics of injury and the movement patterns that may increase an athlete's susceptibility (Griffin et al., 2006; Hewett, Myer, & Ford, 2006; H. C. Smith, Vacek, et al., 2012).

ACL injuries and PFP are believed to be associated with abnormal loading of the knee resulting from deficiencies in neuromuscular control that leads to unsuccessful postural adjustments during dynamic tasks (Dye, 2005; Griffin et al., 2006; Hewett, Myer, & Ford, 2006; Powers et al., 2012). Although the onset of PFP and ACL injuries are different, they have been found to have similar abnormal movement patterns associated with the development of the injury. Observational evaluations of injury videos have identified some of these movement patterns to include excessive contralateral pelvic drop, hip adduction, hip internal rotation, knee abduction, tibial rotation, and foot pronation (Ireland, Willson, Ballantyne, & Davis, 2003;

Powers, 2003). The combination of these, known as "dynamic malalignment", is thought to be a result of hip musculature weakness and produced increased lateral patellofemoral joint forces as well as imposes significant stress on the ACL that can lead to ligament failure (Ireland, 1999; Powers, 2010).

Three-dimensional (3D) analysis is considered the "gold-standard" approach to further investigate the kinematic and kinetic risk factors that may predispose an individual to serious knee injuries caused by insufficient neuromuscular control (McLean, Walker, et al., 2005). Studies have concluded that loading at the knee joint, specifically increased knee abduction moment, is related to injury (Hewett et al., 2005; Myer, Ford, Barber-Foss, et al., 2010). This moment results from proximal, local, and distal joint and segment movements, such as decreased trunk, hip and knee flexion and increased lateral trunk flexion, hip adduction, hip internal rotation, knee abduction, tibial rotation, and foot pronation (Boling et al., 2009; Dierks, Manal, Hamill, & Davis, 2008; Hewett & Myer, 2011; Hewett et al., 2005; Nakagawa, Moriya, Maciel, & Serrão, 2012a, 2012b; Powers, 2003, 2010; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007).

While 3D analyses yield precise information regarding the body's joint angles, movements, and loading conditions during functional tasks, it is not without limitations. The method requires expensive equipment and demands significant technical expertise and lengthy analysis, making it unusable in a field setting. In order to facilitate widespread implementation of lower extremity injury screening in a variety of field and clinical settings, two-dimensional (2D) screening measures have been developed.

Two-dimensional video analyses often incorporate measuring angles and distances using computer software or programs. The majority of 2D analyses focus on measuring knee movement in the frontal plane. The most common measurements are frontal plane projection angle (Jones et al., 2014; Mizner, Chmielewski, Toepke, & Tofte, 2012; Willson & Davis, 2008) and knee separation distances (Mizner et al., 2012; Sigward, Havens, & Powers, 2011), which are representations of medial knee position. Although this method is better suited for field settings when compared to 3D analysis, it still requires equipment and knowledgeable individuals to analyze the data.

A simpler and more easily implemented method of screening for knee injury involves observational analyses. These assessments often utilize some type of scoring rubric, produce results quickly, and are intended to be used in clinical or field settings where motion analysis systems and computer analysis software may not always be available. There are many types of observational movement screening tools available, with varying amounts of empirical evidence supporting their predictability of faulty biomechanics or injury risk. Many of these observational assessments evaluate a single criteria, often knee control or movement, in real-time (Ageberg et al., 2010; Chmielewski et al., 2007; Ekegren, Miller, Celebrini, Eng, & Macintyre, 2009; Harris-Hayes et al., 2014; Jones et al., 2014; Stensrud, Myklebust, Kristianslund, Bahr, & Krosshaug, 2011). While these assessments have been shown to be reliable and valid measures of injury risk level (Ageberg et al., 2010; Chmielewski et al., 2007; Crossley, Zhang, Schache, Bryant, & Cowan, 2011; Stensrud et al., 2011), they are often simplistic and tend to disregard the proximal and distal risk factors and the interactions between these factors, as well as assess motion in multiple planes.

Knee injuries do not occur as the result of a singular factor or even within a single plane of movement. For example, the valgus collapse commonly seen with ACL injuries is a combination of hip internal rotation, knee abduction, and tibial external rotation (Krosshaug et al., 2007). Similarly, it has been suggested that ACL impingement caused by anterior tibial translation, knee valgus, and tibial rotation may lead to injury (Ebstrup & Bojsen-Møller, 2000). Cadaver studies have also found that combined knee valgus and tibial internal rotation strains the ACL more than either movement alone, suggesting this combination may be what leads to injury (Kanamori et al., 2002; Shin, Chaudhari, & Andriacchi, 2011). Therefore, when screening for potential risk factors it is necessary to evaluate the person's movement in more than one joint and plane. One assessment that addresses this concept is the Landing Error Scoring System (LESS), which evaluates movements at multiple joints in both the frontal and sagittal planes during a drop vertical jump (Padua et al., 2009). Although the LESS utilizes two standard video cameras during the evaluation for the purpose of future playback, no joint angles or distances are measured. Instead, dichotomous ratings are given to indicate the presence of specific movement errors at different points during the drop vertical jump. The LESS has been shown to be a valid and reliable tool in identify individuals who demonstrate movement patterns and joint loading that is believed to be associated with increased risk of injury (Padua et al., 2009). While the LESS has been used in several studies to evaluate injury risk in the military and collegiate athletic populations (Beutler, de la Motte, Marshall, Padua, & Boden, 2009; Joyce, Boling, Buckley, Thigpen, & Padua, 2010; Onate, Cortes, Welch, & Van Lunen, 2010; Padua et al., 2015; Padua et al., 2009) there is conflicting evidence related to it's ability to predict future ACL injuries (Padua et al., 2015; Padua et al., 2010; H. C. Smith, Johnson, et al., 2012).

One potential limitation of the LESS that may contribute to the lack of injury predictability is that it evaluates a bilateral land-and-go maneuver (Ortiz et al., 2008; Renström et al., 2008). While these types of tasks are dynamic and incorporate rapid deceleration that eccentrically loads the lower extremities (Aerts, Cumps, Verhagen, Verschueren, & Meeusen, 2013; Ortiz et al., 2008; Walsh, Arampatzis, Schade, & Bruggemann, 2004), the vast majority of knee injuries occur during single-leg movements (Boden et al., 2000; Boden et al., 2009; Olsen et al., 2004). Forces and motion of the trunk and lower extremity are greater during single-leg tasks (Stensrud et al., 2011). Bilateral tasks may not reveal side-to-side differences between legs since they allow an individual to rely on one leg more while potentially hiding altered mechanics of the other (Olsen et al., 2004; Ortiz, Capo-Lugo, & Venegas-Rios, 2014; Stensrud et al., 2011). Removal of the contralateral leg may make certain known neuromuscular risk factors, such as trunk compensations and knee valgus, easier to identify (Dingenen, Malfait, Vanrenterghem, Verschueren, & Staes, 2014; Stensrud et al., 2011). For these reasons, screenings that evaluate a unilateral task may be more appropriate and may better predict future injury.

Single-leg tasks are implemented in an attempt to transcend the drawbacks of bilateral tasks, however, common single-leg tasks are often less dynamic and my not be representative of sports specific movements. For this reason they may not be suitable to incorporate in athletic populations. Another task that has become more popular in recent years that combines the benefits of each of these two types of tasks is the single-leg drop vertical jump (SLDVJ) (Dingenen et al., 2014; Ortiz, Olson, Libby, Kwon, & Trudelle-Jackson, 2007; Stalbom, Holm, Cronin, & Keogh, 2007; Wang & Peng, 2014). This task incorporates jumping of a box, landing, and immediately progressing into vertical jump, all performed on a single-leg. The SLDVJ demands high neuromuscular control and coordination especially at the knee and trunk and incorporates greater speeds and forces than lower-demand tasks like the single-leg squat (Ortiz et al., 2014). As emphasized in the LESS, assessing dynamic movement patterns in multiple planes across several joints is necessary to most accurately assess an individual's risk of knee injury.

Currently, there is no established scoring system for the SLDVJ; however, the development of one may lead to better screening outcomes.

Purpose

The purpose of this study is to investigate the validity and reliability of the Single-Leg Landing Error Scoring System (SL-LESS) to identify individuals who may be at a greater risk of knee injury.

Specific Aims

Aim 1: To determine the concurrent validity of the SL-LESS in predicting external knee abduction moment (KAbM) at initial contact and at its peak.

Hypothesis: Individuals with more observable movement errors will demonstrate larger KAbM at initial contact and at its peak.

Aim 2: To determine the interrater and test-retest reliability of the SL-LESS.

Hypothesis: The SL-LESS will demonstrate high interrater and test-retest reliability.

Delimitations

There are a few delimitations related to the sample chosen for this study:

- Subjects will only include females between the ages of 18 and 30 and who are recreationally active
- Individuals with any current pain in, recent injury to, or previous surgery to the back or lower extremities will not be represented in the sample
- Due to the specifics of the inclusion and exclusion criteria, results of this study will not be generalizable outside of the sample

Assumptions

The following assumptions were made when completing this study:

- Participants truthfully answered question regarding their physical activity and medical history
- Participants gave maximum effort during data collection
- All lower-extremity segments are rigid bodies
- All lower-extremity joints are frictionless

Limitations

There are also several limitations to this study:

- Subjects had different levels of activity/experience
- Lab environment does not replicate field testing or actual sports situations which may impact observed movement patterns
- Impact of menstrual cycle and hormonal changes between testing sessions

Significance

Currently there is no 2D screening measure to evaluate the movement of multiple body segments in more than one plane during a single-leg task. For this reason, the SL-LESS has been developed for this study to evaluate errors in movement patterns during a SLDVJ. Examining the validity and reliability of the SL-LESS may allow for more widespread injury screening. This could in turn facilitate the early identification of high-risk individuals and implementation of preventative training programs; potentially decreasing the high rate of knee injury.

CHAPTER 2: LITERATURE REVIEW

Background

The numerous benefits of engaging in regular physical activity and sports are well known; however, with this participation also comes an increased risk of injury. The National Hospital Ambulatory Medical Care Survey reports that sports related injuries account for over 3.7 million emergency room visits costing an estimated $680 million annually, with over 68% of those occurring in people ages 5-24 (Burt & Overpeck, 2001). Included within this age group are majority of collegiate athletes. Over a 16 year period, the National Collegiate Athletic Association's (NCAA) Injury Surveillance System reported a total of 181,476 injuries that resulted in at least one day of time loss (Hootman et al., 2007). It must be acknowledged, however, that these statistics may underestimate the actual number of sports related injuries since many chronic overuse injuries do not result in time lost from participation and may not have been reported or treated.

Research suggests that over 50% of all sports related injuries occur to the lower extremities and that knee injuries, in particular, are extremely common. A study of high school athletes found that 83.4% of all documented injuries were to the lower extremities (Powell & Barber-Foss, 2000). At the collegiate level, the NCAA reported that 53% of all injuries were related to the knee (Hootman et al., 2007). In NCAA women's basketball knee injuries accounted for 42% and 26% of all severe injuries (≥ 10 days of activity time loss) in games and practices, respectively (Agel et al., 2007).

Due to the high frequency of lower extremity injury and the potential long-term consequences, there are significant ongoing efforts being made to better understand the risk factors associated with injury. Modifiable risk factors such as neuromuscular and biomechanical functions are common focal points of injury prevention programs. Screening methods for these modifiable risk factors attempt to identify individuals who may be at a greater risk of injury and could benefit from preventative programs in hopes of decreasing injury rates. Unfortunately, many of these methods rely on expensive equipment that requires high technical expertise and lengthy analysis, making it unusable in a field setting. For this reason, there is a need for reliable and valid methods to screen individuals for such risk factors that can be easily performed in a field setting with minimal resources of time, personnel, and equipment.

To understand the application of injury screening tests in a field setting, one must have a firm understanding of the injuries that are being screened for. A vast body of literature exists regarding the pathoetiology of various sports, exercises, and activities related to lower extremity injuries. Within this literature, perhaps the most widely studied injuries are anterior cruciate ligament (ACL) injury and patellofemoral pain (PFP). The ACL is a ligament of the knee that provides stability and prevents abnormal movement of the joint (Butler et al., 1980). Injuries to this ligament are acute and are due to large loads produced through both contact and non-contact mechanisms (Agel et al., 2007; Arendt & Dick, 1995; Boden et al., 2000; Boden et al., 2009; Krosshaug et al., 2007; Myklebust et al., 1998; Olsen et al., 2004). PFP is a chronic overuse injury that encompasses all anterior knee pain not associated with a specific anatomical pathology (McCarthy & Strickland, 2013; Thomeé et al., 1999). These injuries stand out due to their high incidence, poor long-term prognosis, and risk of osteoarthritis development. Therefore, much of the injury screening literature is based around preventing these injuries.

Incidence

Annually, it is estimated that between 80,000-250,000 ACL injuries occur, costing over $2 billion (Gottlob et al., 1999; Griffin et al., 2006). A 16-year study of NCAA athletes between

1988 and 2004 reported 4,800 ACL injuries and revealed that yearly rates progressively increased each year (Hootman et al., 2007). A majority of these national estimates, however, were established over 20 years ago, which has led others to doubt their accuracy. In an effort to solve this problem, Mall et al. (2014) investigated the incidence over a 12-year period using information from insurance providers. It was concluded that the number of ACL reconstructions increased from 56,687 (32.94/100,000 person-years) in 1994 to 129,836 (43.48/100,000 person-years) in 2006. While this is a more accurate estimation it still only considers reconstruction and does not account for the injuries treated non-operatively, which can be difficult to estimate (Gottlob et al., 1999).

PFP is one of the most common lower extremity conditions across varying ages and levels of activity (Davis & Powers, 2010; Earl & Vetter, 2007; Powers et al., 2012; Wood, Muller, & Peat, 2011). This condition accounts for a quarter of all injuries treated in sports medicine clinics and an estimated 2.5 million runners are diagnosed with PFP every year (Earl & Vetter, 2007; Taunton et al., 2002). Athletes are not the only ones at risk of developing this condition, 37% of recruits at the United States Naval Academy are predicted to develop PFP symptoms during basic training (Boling et al., 2009; Powers et al., 2012).

Prognosis

For knee injuries in particular, long-term effects and re-injury are common (Rauh, Macera, Ji, & Wiksten, 2007). One example is the inability to successfully return to sport. Investigations of injuries experienced by female team handball players found that only 82% of operative and 58% of non-operative ACL injuries resulted in the athlete's returning to play at their pre-injury level (Myklebust et al., 2003). Additionally, it was also found that of those who returned, 22% re-injured their ACL. Another study that focused on male soccer players with previous ACL injuries found that only 30% of players were still playing soccer three years post-injury and none were still playing seven years post-injury, regardless of operative/non-operative treatment (Roos, Ornell, Gärdsell, Lohmander, & Lindstrand, 1995).

Studies on PFP outcomes have concluded that even with treatment and therapy 70-90% of individual still have recurrent or chronic pain (Powers et al., 2012; Stathopulu & Baildam, 2003). Reports of a 5.7-year follow-up of athletes with PFP showed that 73% were still suffering with pain (Blønd & Hansen, 1998). Of those, 74% said it negatively impacted their athletic activity and 6% said it affected their employment. Similarly, another follow-up study on individuals diagnosed in childhood found that 4-18 years later 91% still had pain, 45% had impacts on daily life, 36% required restricted physical activity, and 45% developed other diagnoses such as osteoarthritis (Stathopulu & Baildam, 2003). It is clear that ACL injury and PFP negatively impact the individual's ability to participate in sports or recreational activities following the injury.

Another potential long-term impact of sports related injury is associated with health-related quality of life. This concept takes into account physical, psychological, and social aspects of overall well-being. A recent study by Simon and Docherty (2014) surveyed 40-65 year old former NCAA Division I athletes and discovered these athletes had lower health-related quality of life compared to non-athletes/recreational athletes on scales of physical function, depression, fatigue, sleep disturbances, and pain interference. These individuals reported more limitations in daily life and exercise and almost half reported osteoarthritis. When reflecting on their time as collegiate athletes, 50% reported chronic injuries, 67% sustained major injury, and 70% practiced with an injury. This suggests that sustaining injuries during sport may result in negative long-term consequences on overall quality of life.

A final significant sequela of ACL injury and PFP is osteoarthritis (OA). OA is an age-related group of disorders associated with a loss of articular cartilage in the synovial joints that results in osteophyte formation, subchondral bone change, and synovitis (Lohmander et al., 2007). Documented rates of OA 10 to 20 years following an ACL injury vary between 10-90% (Lohmander et al., 2007). While this large range may reflect the influence of other factors, most researchers support the idea of a relationship between previous ACL injuries and the development of OA. In a study of ACL injuries sustained by female handball players, almost half had radiological signs of OA 6-8 years later (Myklebust et al., 2003). The fact that the majority of players returned to playing team handball after injury, further subjecting themselves to high loads and pivoting movements, may also contribute to these outcomes. Two other follow-up studies found similar results regarding the prevalence of OA, but also found that more than 30% of their athletes not diagnosed with OA still demonstrated some degree of radiographic changes of the cartilage (Lohmander, Östenberg, Englund, & Roos, 2004; von Porat, Roos, & Roos, 2004).

Unlike ACL injuries, there has been no specific mechanistic causative factor linking PFP and OA (Thomas, Wood, Selfe, & Peat, 2010; Utting et al., 2005), although some relationship between the two conditions has been observed. One study that investigated individuals undergoing surgery for isolated patellofemoral OA concluded that 22% reported anterior knee pain in adolescence or early adulthood, as compared to only 6% in the control group (Utting et al., 2005). A more recent study found that 55% of people under the age of 50 and 70% of those over 40 with patellofemoral joint pain had radiographic OA (Hinman et al., 2014). Results from these studies, in addition to the knowledge of the similar impairments and biomechanical risk factors between the PFP and OA, have lead to the idea that these two conditions potentially exist along a disease continuum (Crossley, 2014; Thomas et al., 2010).

In an effort to address the three significant public health issues related to knee injuries described above, much research has focused on modifiable risk factors, such as lower extremity biomechanics. Biomechanical factors including joint angles, moments, and overall alignment have been extensively studied in ACL injury and PFP. These factors have been examined while performing many functional tasks such as running, cutting, jumping, and squatting, and using various technologies (i.e., three-dimensional (3D) motion capture, two-dimensional (2D) video analysis, and observational analysis). To identify the gap in our knowledge of biomechanical screening for PFP or ACL injury risk, this review will first provide the context of both ACL injury and PFP so that the primary biomechanical risk factors can be understood. A comparison of laboratory and field based measures will follow, with the concluding section describing our knowledge of the demands of various tasks and how they relate to injury risk.

Anterior Cruciate Ligament Injury

Mechanism of Injury

Gross body movement. The ACL is one of the four major ligaments of the knee, originating from the posteromedial portion of the lateral femoral condyle and inserting at the anterolateral portion of the tibial plateau. The ACL prevents abnormal movement such as anterior tibial translation and knee hyperextension and stabilizes the knee against tibial rotation (Girgis, Marshall, & Al Monajem, 1975).

Injuries to the ACL can occur via direct contact of the knee from another player, although the majority are due to non-contact mechanisms (Agel et al., 2007; Arendt & Dick, 1995; Boden et al., 2000; Boden et al., 2009; Krosshaug et al., 2007; Myklebust, Maehlum, Engebretsen, Strand, & Solheim, 1997; Myklebust et al., 1998; Olsen et al., 2004). Questionnaires and analyses of video that captured the incident of injury have provided information about the characteristics and movement patterns that are typically associated with ACL injury. One key observation is that the injury often occurs at or near foot strike of deceleration tasks such as landing from a jump, often on a single leg, cutting before a change in direction (Boden et al., 2000; Boden et al., 2009; Krosshaug et al., 2007; Olsen et al., 2004). More comprehensive evaluations of ACL injuries have also established trends related to the mechanism of the injury. The body position at the time of injury usually features the knee near full extension, tibial rotation, a planted foot, and valgus collapse of the knee (Boden et al., 2000; Boden et al., 2009; Ireland, 1999; Krosshaug et al., 2007; Olsen et al., 2004).

The risk of experiencing an ACL injury can also be affected by an athlete's attentional focus and the presence of other players. Several observational studies have found that at the time of injury athletes often had possession of the ball, which may have diverted attentional focus and cause abnormal biomechanics due to additional stress imposed on the neuromuscular system (Boden et al., 2009; Krosshaug et al., 2007; Olsen et al., 2004). Another common characteristic of non-contact ACL injuries includes being in close proximity to opponents, potentially having a negative effect on coordination and body position (Boden et al., 2009; Krosshaug et al., 2007; Olsen et al., 2004). In support of these observations, McLean, Lipfert, and van den Bogert (2004) found that introducing a static obstacle representing a defensive opponent during sidestep cutting increased the loading of the knee joint through the increase in the medial ground reaction force as well as an increase in hip and knee abduction and flexion angles. Olsen et al. (2004) has also concluded that a majority of ACL injured athletes had experienced some form of perturbation from another player before the injury occurred and were described by their coaches to have been out of balance, both of which may have influenced the athlete's coordination and movements.

Tissue failure. The ACL is built to resist tensile forces; however, injury may occur if the forces applied to the ligament exceed the ultimate strength. When the knee is slightly flexed the ACL is the primary source of resistance to anterior translation (Butler et al., 1980). Additionally, in this position the force produced by the quadriceps greatly impacts the ACL, which also increases the strain of the ligament (Beynnon et al., 1995; Renström, Arms, Stanwyck, Johnson, & Pope, 1986). When performing tasks like the ones that facilitate ACL injuries, the quadriceps produce large eccentric forces in an attempt to decelerate the body (Colby et al., 2000). As a result, the tibia experiences an anterior shear force and the ACL must resist this translation of the tibia relative to the femur.

Slight knee flexion also results in frontal plane instability (Girgis et al., 1975; Olsen et al., 2004). During an ACL injury, large knee valgus range of motion is often seen, especially in women (Boden et al., 2000; Boden et al., 2009; Krosshaug et al., 2007). Knee valgus increases the axial force on the lateral side of the knee creating slack in the ACL (Matsumoto, 1990). This may permit internal rotation of the leg and anterior tibial translation due to forces from the quadriceps, which may increase the strain on the ACL bringing it closer to its ultimate strength.

Excessive tibial rotation may also facilitate ACL injuries. Olsen et al. (2004) described external tibial rotation as a mechanism of injuring during landing and either internal or external rotation during a planting/cutting maneuvers. Several other studies have also reported external rotation as a mechanism (Boden et al., 2000; Ireland, 1999). Cadaver studies have concluded that tibial internal rotation increases strain more than external rotation most likely due to the anterior translation that often accompanies it (Kanamori et al., 2002; Oh, Kreinbrink, Wojtys, &

Ashton-Miller, 2012). Koga et al. (2010) proposed that knee valgus and internal tibial rotation led to the ACL injury, which was then followed by observable external rotation. Due to the conflicting evidence, it is not clear whether it is internal or external tibial rotation that contributes to the injury.

The movements that occur at other joints have also been shown to have an impact on the loading of the knee. The evaluation of videos capturing ACL injuries occurring in both male and female professional basketball players indicated that all players demonstrated a flatfoot or hindfoot contact at initial contact with the ground (Boden et al., 2009). This landing pattern reduced the gastrocnemius-soleus complex's ability to absorb the ground reaction force, which increases forces on the knee. The injured players also showed little ankle flexion range of motion in addition to a shortened time period between initial contact and full contact of the foot. As a result, the gastrocnemius contraction that would normally cause to knee flexion does not occur and instead leads to knee abduction and internal rotation (Boden et al., 2009).

Ireland's description of body position during ACL injury included loss of hip and hip-trunk-pelvis control (Ireland, 1999). Conflicting evidence has been found related to sagittal plane hip and trunk movement. Hewett, Torg, and Boden (2009) and Boden et al. (2000) found that the hip was extended during injury, which may have placed the body inline and increased the axial force experienced at the knee. Others have found the hip to be more flexed (Boden et al., 2009; Ireland, 1999; Krosshaug et al., 2007). This position may reduced the hip muscles' ability to absorb the force from the upper body weight or stabilize the femur (Zazulak et al., 2005). The differences seen here may suggest that multiple combinations of body positions and movement patterns during landing may result in an increased force on the ACL leading to injury.

Hip adduction and lateral trunk movement are also recognized as important factors of knee loading and ACL strain. Ireland (1999) originally included hip movement, specifically adduction, as a component of the high-risk "position of no return" associated with ACL injuries; however, much of the research following this study focused only on the knee joint. Over time some of the focus has returned to considering proximal factors of knee injury. Hewett et al. (2009) determined that lateral trunk motion, especially during single-leg tasks, may play a significant role in the ACL injury mechanism. When the trunk leans towards the stance leg the ground reaction force vector is shifted to the lateral side of the knee joint creating in an external abduction moment at the knee and an adduction moment at the hip. If the internal moments created by the activation of lower extremity and trunk muscles are not able to counteract this increase, loading occurs at the knee.

ACL injuries do not occur as a result of a singular factor or even within a single plane. For example, the valgus collapse commonly seen with these injuries is a combination of hip internal rotation, knee abduction, and tibial external rotation (Krosshaug et al., 2007). Similarly, it has been suggested that ACL impingement caused by anterior tibial translation, knee valgus, and tibial rotation may lead to injury (Ebstrup & Bojsen-Møller, 2000). Cadaver studies have also found that combined knee valgus and tibial internal rotation strain the ACL more than either movement alone, suggesting these combinations are what lead to injury (Kanamori et al., 2002; Shin et al., 2011). Therefore, when screening for potential risk factors it is necessary to evaluate the person's movement of more than one joint and plane.

Gender Differences

There is evidence that females suffer from both ACL injuries (Agel, Arendt, & Bershadsky, 2005; Arendt & Dick, 1995; Powell & Barber-Foss, 2000) and PFP (Blønd &

Hansen, 1998; Boling et al., 2010; Taunton et al., 2002) at higher rates than males. The reasons for this are thought to be related to anatomical (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006; Chandrashekar, Slauterbeck, & Hashemi, 2005; Scerpella, Stayer, & Makhuli, 2005) and hormonal (Shultz et al., 2012; Shultz et al., 2011; Slauterbeck, Clevenger, Lundberg, & Burchfield, 1999) differences between genders. Furthermore, gender differences in movement patters have also been seen and are perhaps most modifiable (Ford, Myer, & Hewett, 2003; Hewett, Myer, & Ford, 2004; Huston, Vibert, Ashton-Miller, & Wojtys, 2001; Joseph et al., 2011; Kernozek, Torry, VanHoof, Cowley, & Tanner, 2005; Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007). Although not the focus of this review, one gender difference in mechanism of injury will be described as is may directly relate to injury screening. Boden et al. (2009) noted in their study that females were more likely to sustain an injury during a deceleration motion while injury during a landing was common in males. Females tend to land with more hip flexion and are more likely to experience valgus collapse during ACL injuries compared to males (Boden et al., 2000; Boden et al., 2009; Krosshaug et al., 2007). These gender differences have lead to the development of a theory that proposes men and women experience ACL injuries as a result of different mechanisms (Krosshaug et al., 2007). Regardless of the extent of this theory's validity it is important to note the diversity in mechanisms between genders.

ACL Injury Risk Factors

External Factors. External factors that impact the risk for ACL injury include playing surface and shoe-surface interaction. A common characteristic of ACL injuries is a flat foot firmly planted on the ground, so it is assumed that there is high friction between the ground and the shoe (Ebstrup & Bojsen-Møller, 2000). It is suggested that the risk of injury is significantly increased when playing on artificial floor compared to wooden floors, particularly in women

(Olsen et al., 2004; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2003). However, other studies have found that the majority of injuries occurred on natural or indoor had court surfaces (Boden et al., 2000). Mechanical testing of the shoe-surface interaction suggested that the differences in torques and rotational stiffness between varying cleat types and surface types was due to the surface, with artificial surfaces having higher levels of both compared to natural grass (Villwock, Meyer, Powell, Fouty, & Haut, 2009). Further research on shoe type has been conflicting as well; however, it is suggested that the high torques between the foot and the ground may be due to greater total effect area with is proportional to cleat number, length and size (Taylor, Fabricant, Khair, Haleem, & Drakos, 2012).

Anatomical Factors. Several anatomical factors may influence the risk of sustaining an ACL injury and while these are less modifiable than other factors their impacts are still important to understand. It was been suggested that there is a positive relationship between ACL size and risk of injury (Uhorchak et al., 2003). In general, a smaller ACL will experience larger stresses under a given load due to the smaller area (Griffin et al., 2006). Much of the research in this area is somewhat difficult to interpret and compare since there are no standardized methodology for data collection (Griffin et al., 2006).

Femoral intercondylar notch width and width index have been described as characteristics of ACL injured knees (Ireland, Ballantyne, Little, & McClay, 2001). It is suggested that a narrower notch may predispose females to a smaller and weaker ACL (Shelbourne, Davis, & Klootwyk, 1998; Uhorchak et al., 2003). However, the evidence supporting this theory is mixed (Griffin et al., 2006; Hewett, Myer, & Ford, 2006) and the relationship may be different for males and females (Chandrashekar et al., 2005; Uhorchak et al., 2003).

Greater lateral posterior-inferior tibial plateau slopes have been seen in injured individuals when compared to uninjured (Hashemi et al., 2010; Stijak, Herzog, & Schai, 2008). These larger slopes have been associated with greater peak ACL strain when combined with smaller ACL cross sectional area (Lipps, Oh, Ashton-Miller, & Wojtys, 2012), and greater anterior tibial translation relative to the femur (Giffin, Vogrin, Zantop, Woo, & Harner, 2004). A larger relative lateral slope as compared to the medial slope relates to greater peak knee abduction and internal rotation angles and greater anterior joint reaction forces (McLean, Lucey, Rohrer, & Brandon, 2010).

The influence of static malalignment on dynamic movement and subsequent injury risk is frequently debated. Mean Q angles has been found to be larger in injured individuals than in uninjured (Shambaugh, Klein, & Herbert, 1991; Zelisko, Noble, & Porter, 1982); however, there is conflicting evidence as to whether static alignment influences dynamic movement (Hewett, Myer, & Ford, 2006; Myer, Ford, & Hewett, 2005). Foot pronation may also increase tibial internal rotation (Allen & Glasoe, 2000; Loudon, Jenkins, & Loudon, 1996) and tibial translation (Loudon et al., 1996; Trimble, Bishop, Buckley, Fields, & Rozea, 2002), but like Q angle, not all studies have supported a relationship (Allen & Glasoe, 2000; Hewett, Myer, & Ford, 2006; J. Smith, Szczerba, Arnold, Perrin, & Martin, 1997).

Generalized joint laxity, knee hyperextension, and knee anterior-posterior and internal rotation laxity have been shown to be associated with non-contact ACL tears (Boden et al., 2000; Branch et al., 2010; Scerpella et al., 2005). Uhorchak et al. (2003) found that females with generalized joint laxity are 2.7 times more likely to sustain an ACL injury than those without laxity. These laxities affect movement in the sagittal and frontal planes potentially leading to increased ACL strain as it attempts to resist these movements and stabilize the knee (Boden et al., 2000; Hewett et al., 2005; Uhorchak et al., 2003). Interpreting the roles of these factors are important for both understanding the mechanisms of ACL injuries and identifying at risk individuals; however, intervention are not easily implemented to adjust them so future research should focus on more modifiable factors that can be altered to decrease risk of injury.

Hormonal Factors. Another commonly considered risk factor of ACL injury, particularly in females, is related to sex hormones. These hormones are known to affect the properties of ligament loading as well as impact knee joint laxity (Shultz et al., 2012; Shultz et al., 2011; Slauterbeck et al., 1999). While fluctuations in ligament laxity, ligament strength, and rate of ACL injury across the menstrual cycle have been seen in females there is still much conflicting evidence regarding the exact relationship (Hewett, Zazulak, & Myer, 2007). More research is needed to develop a better understanding of the interaction between hormonal fluctuations and ACL injury, as well as the influence they have on the significantly increased risk of injury in females.

Patellofemoral Pain

Etiology

Despite the commonness of PFP and the numerous studies that have been completed, there is still no clear understanding of the injury pathology at the tissue level. However, it is widely agreed upon that this condition has a multifactorial etiology (Davis & Powers, 2010; Thomeé et al., 1999). In general, PFP is believed to develop as a result of abnormal motion of the patella in the trochlear groove. This maltracking causes an increase in patellofemoral joint stress as a result of increased joint reaction force and/or decreased contact area. Over time the overloading of tissue causes microdamage and inflammation in the joint resulting in pain (Earl & Vetter, 2007; Powers et al., 2012).

The patella is a sesamoid bone that lies within the quadriceps tendon. Patellar tracking is dependent upon the balance of forces acting on it (Earl & Vetter, 2007; Powers et al., 2012). Laterally directed forces result from the lateral retinaculum, iliotibial band, and vastus lateralis while medial forces are produced primarily by vastus medialis obliquus through the medial retinaculum (Fulkerson & Buuck, 2004). Results of multiple studies have shown that individuals with PFP have greater lateral patellofemoral joint forces and lateral translation of the patella (Draper et al., 2009; Powers et al., 2012; Wilson, Press, Koh, Hendrix, & Zhang, 2009). When this occurs, the patella is forced against the lateral femoral condyle, increasing the pressure in that area (Huberti & Hayes, 1984; Lee, Morris, & Csintalan, 2003). This lateral patellar tracking is thought to be one potential mechanism of tissue damage.

Previously it was believed that the only cause of maltracking was an imbalance in forces acting on the patella, resulting in movement within the trochlear groove of a stable femur (Earl & Vetter, 2007). These conclusions were drawn from studies that implemented non-weight-bearing conditions, which are characterized by a fixed femur (Powers, 2003; Souza, Draper, Fredericson, & Powers, 2010). More recent research, however, has provided evidence that femoral rotation also contributes to patellar tracking (Powers, Ward, Fredericson, Guillet, & Shellock, 2003; Souza et al., 2010). Unlike non-weight-bearing activities, during weight-bearing the patella remains fairly stable and lateral maltracking is due to internal rotation of the femur (Powers et al., 2003; Souza et al., 2010). This internal rotation has been shown to not only increase the joint stress but also decrease the patellofemoral contact area (Lee, Anzel, Bennett, Pang, & Kim, 1994). Therefore, examining the movement of the femur and pelvis may be an important aspect of injury screening.

Anatomical Risk Factors

Though little can be done to alter anatomical alignment risk factors, acknowledging the impact they may have on lower extremity motion is important. Patellar movement is influenced by the iliotibial band, which acts through the lateral reticulum as a passive restraint to medial translation. It has been suggested that individuals with PFP may have a tighter iliotibial band on their injured side (Hudson & Darthuy, 2009). Additionally, loading of the iliotibial band has been shown to produced lateral translation, rotation, and tilt of the patella suggesting that iliotibial band length and tightness may lead to PFP (Merican & Amis, 2009).

Femur movement also influences patellar maltracking. Femoral head anteversion may lead to femoral internal rotation, which increases patellofemoral joint contact pressure (Lee et al., 1994). Femoral internal rotation may also be generated by tibial rotation and foot pronation. Tibial external rotation, potentially occurring as a compensation for femoral anteversion, increases the Q angle, and therefore joint stress, through the lateral displacement of the tibial tuberosity (Cooke, Price, Fisher, & Hedden, 1990; Tonnis & Heinecke, 1999). Internal rotation of the tibia may also lead to femoral rotation, as explained by the screw home mechanism. When the tibia internally rotates, potentially due to foot pronation, the femur must also internally rotate in order to lock into place (Tiberio, 1987). These alignments lead to increased knee valgus and patellofemoral joint stress (Powers et al., 2012).

The shape and size of the trochlear groove, specifically the trochlear inclination angle, can also affect the malalignment of the patella altering the joint stress and contact area. A low angle has been related to excessive lateral shift and patellar dislocation while a high angle is related to medial patellar translation and tilt (Harbaugh, Wilson, & Sheehan, 2010).

Neuromuscular Risk Factors

Many of the neuromuscular risk factors that have been investigated are common to both ACL injury and PFP. For this reason, this section will be presented together. Neuromuscular risk factors are the most modifiable and, therefore, it is suggested that the influences of such factors should be the focus of preventative and rehabilitative exercises.

Muscular Imbalances

Muscular imbalances between the quadriceps and the hamstrings may increase the risk of ACL injury. During landing, large demands on the quadriceps to decelerate the body results in an anterior shear force on the tibia, potentially causing anterior translation relative to the femur (DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004; Myers et al., 2012). This movement is a common mechanism of ACL injury due to the large amount of stress experienced by the ACL (Bates, Nesbitt, Shearn, Myer, & Hewett, 2015; Butler et al., 1980). Sufficient activation and strength of the hamstrings is needed to balance the extension moment produced by the quadriceps in order to compress the joint and resist knee abduction motion and anterior tibial translation (Griffin et al., 2006; Hewett et al., 2005; Hewett, Stroupe, Nance, & Noyes, 1996; Imran & O'Connor, 1997; Solomonow et al., 1987).

Females commonly demonstrate neuromuscular imbalances in activation patterns in which the quadriceps is increased relative to the hamstrings (Hewett et al., 1996; Sell et al., 2007). Hewett et al. (1996) concluded that males demonstrated a threefold greater internal flexion moment than females indicating a greater use of the hamstrings during landing. These results suggest that individuals, particularly females, with insufficient hamstring strength and activation are at a greater risk of anterior tibial translation that may result in injury.

Muscular imbalances between the vastus medialis obliquus and vastus lateralis may lead to lateral tracking of the patella in PFP. Several studies have indicated that a delayed onset of the vastus medialis obliquus relative to the vastus lateralis is present in PFP (Chen, Chien, Wu, Liau, & Jan, 2012; Cowan et al., 2001; Cowan, Hodges, Bennell, & Crossley, 2002; Voight & Wieder, 1991). This temporal imbalance may result in lateral tracking of the patella causing increased joint stress and decreased contact area. Pal et al. (2011) discovered a relationship between vastus medialis activation delay and patellar maltracking in participants who had PFP associated with abnormal tilt and abnormal bisect offset. Since vastus medialis activation delay is only one of many factors influencing maltracking this relationship is not expected to be seen in all cases of PFP. Instead, it was suggested that PFP with abnormal tilt and abnormal bisect offset may represent an extreme case of maltracking. There are, however, other studies that have found no difference in vastus medialis obliquus/vastus lateralis activation between healthy and PFP individuals (Cavazzuti, Merlo, Orlandi, & Campanini, 2010; Powers, Landel, & Perry, 1996).

Movement Patterns

Frontal and transverse plane movement of the lower extremities, potentially facilitated by weakness of the hip abductors and external rotators, is associated with both ACL injuries and PFP (Bell, Padua, & Clark, 2008; Hewett et al., 2009; Ireland et al., 2003; Powers, 2003; Prins & van der Wurff, 2009; Zeller, McCrory, Kibler, & Uhl, 2003). Individuals with PFP have shown decreased hip abduction and external rotation when compared to age-matched controls (Ireland et al., 2003). Prins and van der Wurff (2009) drew similar conclusions, in addition to decreased extension strength, when comparing affected and unaffected limbs.

Weakness of hip abductors results in the inability to resist frontal plane forces, causing a contralateral pelvic drop. This leads to increased femoral internal rotation and knee valgus, which increases the lateral patellofemoral joint force. Weak hip external rotators allow excessive hip internal rotation resulting in patellar maltracking and decreased contact area within the joint (Powers et al., 2012). The combination of these movement patterns, in addition to tibial rotation and foot pronation, is known as "dynamic malalignment" (Ireland et al., 2003; Powers, 2003). This position not only increases lateral patellofemoral joint forces but also has been described as a position that imposes large stress on the ACL, often prompting ligament failure (Ireland, 1999; Powers, 2010). Dynamic malalignment is observed more often in women than men and has been shown to be the most pronounced near full extension of the knee (Powers et al., 2003). Asymmetries in strength, flexibility, and coordination between dominant and nondominant limbs have also been established as a risk factor for knee injury (Ford et al., 2003; Hewett et al., 2005; Myer, Ford, Palumbo, & Hewett, 2005).

Understanding the influences of proximal strength on movement patterns and knee joint mechanics allows for the development of rehabilitative and preventative training programs to improve strength and neuromuscular control and potentially decrease risk of (re-)injury (Powers et al., 2012).

3D Biomechanics Related To Injury

Three-dimensional analysis is often used to assess kinematics and kinetics related to knee injury and is considered the gold-standard approach for laboratory analysis (McLean, Walker, et al., 2005). While this method yields precise joint angles and moments in 3D that describe the body's movement and loading conditions during functional tasks, it is not without limitations. Three-dimensional analysis requires expensive equipment demanding high technical expertise and lengthy analysis, making it unusable in a field setting.

A great deal of knowledge has been gained from prospective and cross-sectional studies on variables related to abnormal neuromuscular control and movement patters. Larger knee abduction angles during both single- and double-leg tasks have been found in individuals with PFP and ACL injuries when compared to non-injured (Hewett et al., 2005; Nakagawa et al., 2012a, 2012b). Injured populations have also shown greater external knee abduction moment (KAbM) (Hewett et al., 2005). Myer, Ford, Khoury, Succop, and Hewett (2010) concluded that subjects with PFP demonstrated greater KAbM at initial contact in their most-symptomatic limb as well as greater peak KAbM in their least-symptomatic limb. It is believed that these loading conditions at the knee are what ultimately result in tissue failure and injury; however, due to the kinetic chain relationships both proximal and distal movements will affect the kinematics and kinetics of the knee and therefore have also been considered.

Hip internal rotation and adduction angles are greater in individuals with PFP as compared to healthy individuals (Nakagawa et al., 2012a, 2012b). Increased hip internal rotation angle has been identified as a risk factor of developing PFP (Boling et al., 2009). Less external hip internal rotation moment was associated with PFP (Boling et al., 2009) and net hip rotation moment impulse alone was identified as a good predictor of a second ACL injury (Paterno et al., 2010). Large amounts of hip adduction in combination with contralateral pelvic drop during single-leg closed kinetic chain activities have been seen in individuals with PFP (Nakagawa et al., 2012a, 2012b). External hip adduction moment has been shown to positively related to KAbM in ACL injured people (Hewett et al., 2005).

Ipsilateral trunk lean may result as compensation for hip adduction and contralateral pelvic drop. This movement decreases the demand on the hip abductor muscles by shifting the ground reaction force vector closer to the hip joint center (Dierks et al., 2008; Souza & Powers, 2009). However, this lateral shift may also increase KAbM, increasing the stress on the patellofemoral joint and ACL (Hewett & Myer, 2011; Jamison, Pan, & Chaudhari, 2012; Powers, 2003, 2010). Lateral trunk lean has been found to be greater in individuals who went on to suffer an ACL injury or develop PFP (Nakagawa et al., 2012a, 2012b; Zazulak et al., 2007). Zazulak et al. (2007) concluded that lateral trunk displacement after a sudden force release was the strongest predictor of ligament injury.

Just as knee injury risk factors incorporate multiple joints they also are influenced by movement of these joints in multiple planes. Decreased knee and hip flexion during bilateral drop landings have been related to decreased energy absorption at the knee and hip, increased knee abduction angle, and increased KAbM (Pollard, Sigward, & Powers, 2010). During a bilateral drop vertical jump, Hewett et al. (2005) found decreased peak knee flexion angles in ACL injured individuals as compared to non-injured individuals and Boling et al. (2009) has identified it as a risk factor for PFP. These studies also concluded that external knee flexion moment was less in people who went on to develop PFP and greater peak external hip flexion moment was found in ACL injured individuals compared to uninjured individuals.

The specific positions and loading conditions that have been related to knee injury from 3D studies forms the basis for what movements can be strategically evaluated using systems that are less costly, resource intensive, and easier to apply in a field setting. Though joint moments cannot be evaluated, we rely on the known relationships between angles and moments that have been understood through 3D analysis.

2D Video Analysis

While 3D motion analysis is considered the "gold standard", the limitations related to cost, training, data collection, and time requirements do not allow this method to be utilized in varying situations. For this reason, 2D tests need to be developed in order to screen large numbers of people quickly in many different settings (Hewett et al., 2005). However, the challenge related to this is determining the 2D measures that are reliable and valid in relation to 3D measures. An obvious limitation is that transverse plane movement cannot be easily measured in 2D (Ageberg et al., 2010; Willson & Davis, 2008). In addition, combinations of 3D movements may create different observed 2D movements. As a result, much research has been and is currently being done to develop 2D video analysis methods.

Lower extremity movements and the forces they create at the knee joint have been a major area of research since knee injuries occur due to those forces exceeding the ultimate strength the tissue within the joint. In a study comparing individuals with significant medial knee movement to those with little medial knee movement it was found that more movement was related to greater 2D peak tibial and thigh angle and greater 2D knee valgus angle (Ageberg et al., 2010). When comparing the groups in 3D there was no difference in knee valgus angle. Instead the medial knee movement was related to greater peak hip internal rotation. While this indicates that greater medial movement is associated with a larger knee valgus angle and potential is due to hip rotation, it indicates that 2D and 3D measures of knee valgus may not be equivalent.

One of the most common 2D variables measured is the frontal plane projection angle (FPPA) (Willson & Davis, 2008). The FPPA is typically determined by finding the angle between a line from drawn from the ASIS to the midpoint of the knee joint and a line from the midpoint of the ankle joint to the midpoint of the knee joint. This can be found using the frontal plane coordinates of 3D data, or directly from 2D video analysis. When comparing 2D and 3D FPPA, McLean, Walker, et al. (2005) found that although 2D values were greater than 3D, they correlated well for side stepping and side jumping. Two-dimensional FPPA has also been shown to correlate with 3D hip adduction and knee external rotation angles during a single-leg squat, running, and jumping (Willson & Davis, 2008). Of all the 3D kinematics tested in this study, it was found that FPPA has the lowest correlation to the knee abduction angle. The explanation given for these results was that the FPPA in 2D is a combination of hip and knee rotations and that subjects may vary in their demonstration of these variables that lead to larger FPPA. Jones et al. (2014) also found that FPPA was not correlated to 3D knee abduction angles. Conversely, Mizner et al. (2012) found there was a correlation between FPPA and knee abduction angle although it better correlated to KAbM. This is possibly due to the fact that hip internal rotation may project knee flexion into the frontal plane. Although little knee abduction angle may be present the larger loading at the knee due to the hip motion is still represented by a larger FPPA (Nagano, Sakagami, Ida, Akai, & Fukubayashi, 2008). Differences in results may also be due to different protocols. For example, Olson, Chebny, Willson, Kernozek, and Straker (2011) concluded that low correlations between 2D and 3D knee abduction angle may have been due to recording FPPA at midpoint of the descent phase of a single-leg squat rather than at peak knee abduction angle. While FPPA may not be a direct measure of 3D knee abduction, these studies have provided good evidence to suggest that using 2D FPPA to examine dynamic malalignment is a reliable and valid method.

Measuring separation distances of the lower limbs are also used to represent position and medial movement of the knee. Minimum separation distance between the knee joint centers has been found to have a good correlation to 3D knee and hip abduction angles (Sigward et al., 2011). Stronger relationships between these were also found when normalizing knee separation distances to intertrochanteric distance (Sigward et al., 2011). While this suggests that normalized knee separation distance is a predictor of knee abduction angle, it was also highly related to frontal plane hip angle and stance width indicating that other factors may influence its values. A variation of this measure is the knee to ankle separation ratio. While 2D and 3D values were not the same, knee to ankle separation ratio was correlated to knee abduction angle and moment (Mizner et al., 2012). Although lower extremity separation distances are shown to be acceptable 2D measures, one major limitation is that they are restricted to bilateral tasks.

Three-dimensional analysis has demonstrated that lateral trunk movement influences the kinematics and kinetics of the knee; however, only recently has 2D measures of the motion been studied. Best assessed during single-limb tasks, lateral trunk lean angles may indicate a deficit in neuromuscular control and can result in increased knee joint loading. Dingenen et al. (2014) found that lateral trunk motion was greater during the faster and more demanding single-leg drop vertical jump as compared to the single-leg squat. They also found that although frontal plane trunk movement alone was not correlated to peak KAbM during landing the combination of knee valgus angle and lateral trunk angle was moderately correlated. There are many ways to represent lateral trunk angle and while different measures may best correlate to actual 3D measures at different points during a tasks DiCesare, Bates, Myer, and Hewett (2014) found that creating an angle between a line from the medial ASIS to the medial shoulder and a line from the medial ASIS vertical most closely represented 3D values when considering the task as a whole.

Numerous observational and 3D studies have concluded that knee injuries are related to multi-plane movement (Dingenen et al., 2015; McLean, Huang, & van den Bogert, 2005; Padua et al., 2009; Powers, 2010; Quatman, Quatman-Yates, & Hewett, 2010). Despite the support, 2D analyses seem to focus mainly on frontal plane motion. Only a few studies have considered 2D sagittal plane motion (Dingenen et al., 2015; Mann, Edwards, Drinkwater, & Bird, 2013; Myer, Ford, Khoury, et al., 2010). Dingenen et al. (2015) concluded that hip flexion was positively related to KAbM during peak joint motion of both double-leg and single-leg drop vertical jumps while Myer, Ford, Khoury, et al. (2010) determined that knee flexion range of motion was a predictive factors of high knee abduction motion. The results of these studies suggest that in order to better understand the mechanics of injury and more accurately predict risk of injury a multi-plane approach is necessary.

2D Observational Analysis

A simpler and more easily implemented method of screening for knee injury involves observational analyses. These assessments often utilize some type of scoring rubric, produce results quickly, and are intended to be used in clinical or field settings where motion analysis systems and computer analysis software may not always be available. Although this method is better suited for field settings when compared to 3D analysis, it still requires equipment and knowledgeable individuals to analyze the data.

Observational Assessments

Many observational assessments frequently used evaluate a single criteria, often knee control or movement, in real-time (Ageberg et al., 2010; Chmielewski et al., 2007; Ekegren et al., 2009; Harris-Hayes et al., 2014; Jones et al., 2014; Stensrud et al., 2011). Ageberg et al. (2010) investigated frontal plane knee control classifying an individual as either “knee-medial-to-foot” if the knee crossed over an imaginary vertical line extending up from the 2nd toe or “knee-over-foot” if it did not cross. It was concluded that the observational assessment was reliable and that the placement into either group was related to 2D kinematics. Stensrud et al. (2011) implemented similar criteria during different tasks and found that the validity of the assessment depends on the type of task as well as the appropriateness of the task related to the population being tested.

Chmielewski et al. (2007) compared an overall assessment of movement without specific scoring guidelines and a more specific method that assessed trunk, pelvis, and hip movement individually. Results indicated that both methods did not have high rater agreement. While the greater number of scoring options in the specific method increased the chance of disagreement, this method produced agreement among rater that is better than chance. This suggests that less ambiguity in scoring criteria may produce more reliable results. Other studies have built off of these results, further assessing ways to increase reliability (Crossley et al., 2011; Hollman, Galardi, Lin, Voth, & Whitmarsh, 2014; Whatman, Hing, & Hume, 2012). Whatman et al. (2012) concluded that a dichotomous scoring system produces better agreement than an ordinal scale.

Ultimately, the goal of these observational assessments is to identify individuals with movement patterns associate with an increased risk of injury. Studies have determined that with a clinical reasoning component for each of the criteria, reliability was high, and the assessment was able to identify hip muscle dysfunction (Crossley et al., 2011) and frontal plane knee kinematics (Hollman et al., 2014).

Functional Movement Screening

On the level of evaluating whole body movement and coordination, the Functional Movement Screen (FMS) is used to evaluate fundamental movement patters during performance of basic locomotor, manipulative, and stabilizing movements that require a certain level of neuromuscular and motor control (Cook, Burton, & Hoogenboom, 2006a, 2006b). These movements make compensatory movement patterns noticeable when inadequate stability and mobility is present. During the execution of these movements an examiner identifies potential dysfunctions and asymmetries due to weaknesses and imbalances. Numerous studies have found that lower FMS score are predictive of lower extremity injury (Chorba, Chorba, Bouillon, Overmyer, & Landis, 2010; Kiesel, Butler, & Plisky, 2014; Kiesel, Plisky, & Voight, 2007; Letafatkar, Hadadnezhad, Shojaedin, & Mohamadi, 2014; O'Connor, Deuster, Davis, Pappas, & Knapik, 2011); however, in depth biomechanical analysis of the FMS as it relates to knee injury is limited.

Landing Error Scoring System

The Landing Error Scoring System (LESS) is a clinical assessment tool used to evaluate movement patters/biomechanics during a jump-landing task that may be associated with a greater risk for lower extremity injury (Padua et al., 2009). In order to account for the multi-plane nature of knee injuries, the LESS incorporates the use of two standard video cameras to record movements in both the frontal and sagittal planes to be analyzed and evaluated at a later time.

During the LESS, the subject completes multiple trials of a double-leg drop vertical jump that incorporates both vertical (dropping from the 30 cm box) and horizontal movements (jumping out to a distance of 50% of height) (Padua et al., 2009). Immediately after landing the subject rebounds into a maximal vertical jump. The first landing after leaving the box is used for analysis, which includes counting the number of landing technique “errors” demonstrated during the task. LESS scoring incorporates the evaluation of 17 observable movements scored on a binary scale with “1” indicating an error was made and “0” indicating normal movements (Appendix F). The overall LESS score is the total sum of these errors; therefore, a high number suggests poor landing technique. Padua et al. (2009) implemented the LESS with 2,691 incoming freshmen at three U.S. military academies and from the results established four quartiles: “excellent” (LESS ≤4), “good” (4<LESS≤5), “moderate” (5<LESS≤6), and “poor” (LESS>6). These quartiles are specific to the population studied and although the authors stress that they should not be automatically applied to other populations, most studies still use these cutoff scores to interpret their data.

Moderate to excellent validity has been demonstrated related to the overall LESS scores as well as the individual items. In general, differences between groups were found in a variety of injury-related biomechanics including decreased knee and hip flexion angle, increased knee valgus and hip adduction angle and moment, increased knee and hip internal rotation moment, and increased knee and hip extension moment and anterior shear force (Padua et al., 2009). Gender differences were also observed. In male subjects, 30% were classified as “excellent” and only 23% were considered “poor” whereas in women only 14% were classified as “excellent” and 36% were considered “poor”. These results are supported by the trend that females have an increased risk of and experience more ACL injuries. When considering the validity between LESS scores and 3D kinematics, all items had moderate to excellent agreement except for lateral trunk flexion at initial contact, knee flexion at initial contact and symmetrical foot contact (Onate et al., 2010). The authors suggested that the time difference in contact time between feet may have been too fast for the human eye to see. In addition, knee valgus was significantly correlated to 3D values (Onate et al., 2010).

The LESS has been shown to have good interrater reliability (ICC = 0.84, SEM = 0.71) and excellent intrarater reliability (ICC = 0.91, SEM = 0.42) (Onate et al., 2010; Padua et al., 2009). An item specific analysis of the LESS concluded that all but the overall impression had significant or perfect agreement (80-100% agreement) when comparing scores between a novice and an expert rater (Onate et al., 2010). Therefore, this approach is easy to implement in for large-scale screenings where time for training raters may be minimal.

As with any pre-participation screening test, the goal of the LESS is to identify those individuals who demonstrate risky movement patters that may transfer over to their sports specific movements. The LESS suggests that more errors made during the jump-landing task, the more likely you are to sustain an injury. However, only two studies have been done on the ability of the LESS to predict lower extremity injury and have produced conflicting results. In adolescent soccer players, those that went on to have an noncontact ACL injury had a mean LESS score of 6.1 ± 1.7 at baseline testing while the uninjured players had a mean score of 4.5 ± 1.7 (Padua et al., 2010). ROC curve analyses also indicated that a LESS score greater than 5 indicated an increased risk of ACL injury with a sensitivity of 78% and specificity of 69%. Conversely, in a cohort of high school and college athletes, no relationship was found between less scores and incidence of injury (H. C. Smith, Johnson, et al., 2012). While these results may have been due to the lack of statistical power or specific population chosen it suggests that more research is still needed to determine the relationship between performance on the LESS test and its relationship to injury risk.

The inability of the LESS to predict future ACL injury may be due to the bilateral nature of the landing task. It is known that the majority of injuries occur during single-leg movements (Boden et al., 2000; Boden et al., 2009; Olsen et al., 2004) and that forces and motion of the trunk and lower extremity are greater during a single-leg task (Stensrud et al., 2011). Therefore, development of a scoring rubric similar to the LESS that assesses movement during a single-leg task may be an important next step in screening for knee injury risk.

Tasks

Drop Vertical Jump

The bilateral drop vertical jump (DVJ) is a task often utilized in both 3D and 2D analyses and is the recommended method used to identify individuals at risk of knee injury by the International Olympic Committee (Renström et al., 2008). Although protocols sometimes differ between studies, the DVJ generally consist of jumping off a platform, landing with both feet on the ground, and immediately rebounding up into a maximum vertical jump (Ford et al., 2003; Hewett, Myer, Ford, & Slauterbeck, 2006; Myer, Ford, & Hewett, 2002; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005). This task can be characterized as a land-and-go maneuver and incorporates a rapid deceleration that eccentrically loads the lower extremities, similar to ACL injury situations (Aerts et al., 2013; Ortiz et al., 2007; Ortiz et al., 2008; Walsh et al., 2004). It is thought that demonstrating altered movement patterns during the DVJ may increase the likelihood of utilizing them during athletic activities as well, potentially leading to injury.

While the DVJ is a recommended task and is often implemented, bilateral tasks also exhibit several limitations. Double-leg movements may not reveal side-to-side differences between legs and provide a situation where an individual can rely on one leg more while potentially hiding altered mechanics of the other (Olsen et al., 2004; Ortiz et al., 2014; Stensrud et al., 2011). Removal of the contralateral leg may make trunk compensations and knee valgus easier to identify (Dingenen et al., 2014; Stensrud et al., 2011). For these reasons, there may be differences in kinematics and demands of muscle forces and neuromuscular control between single-leg and double-leg tasks (Stensrud et al., 2011).

Single-Leg Squat

A commonly used unilateral task is the single-leg squat (SLS). This task is suggested to relate to components of athletic movements such as landing, running and cutting (Stensrud et al., 2011). Compared to the DVJ it often shows more knee flexion and has the ability to identify differences between legs (Stensrud et al., 2011). It requires strength and balance to maintain control of the body over the stance leg and is therefore often used as a method of assessing hip strength and trunk control (Zeller et al., 2003). Crossley et al. (2011) concluded that people who performed poorly on SLS had delayed onset of anterior gluteus medius EMG activity compared to people who were considered to have good performance. They also found that poor performers had lower hip abductors strength and lateral trunk strength and good performers. Willson, Ireland, and Davis (2006) found a relationship between hip external rotator strength and FPPA during a SLS, which suggested that individuals with stronger hip external rotators were able to resist hip internal rotation moments that relate to larger FPPA values. Therefore, the SLS seems to be a valid task to examine several components of lower extremity function.

SLS has excellent inter- and intratester reliability (Dingenen et al., 2014; Stensrud et al., 2011). In general, within-day and between-day test-retest reliability has also been good to excellent (Alenezi, Herrington, Jones, & Jones, 2014; Whatman, Hume, & Hing, 2013). Whatman et al. (2013) found that all lower extremity kinematics had excellent between-day reliability for the single-leg small knee bend (SLS with approximately 80º of knee flexion) except for the left pelvis lateral tilt, left ankle eversion and medial knee displacement. Stensrud et al. (2011) reported slightly different results. The within-day reliability for 2D frontal plane knee angle was ICC 0.57-0.84 and the kappa values for within-day subjective assessment was 0.32-0.43. These findings could potentially be the result of the experimental setup, which required athletes to complete multiple lower extremity maximal strength tests between the two sessions. Alenezi et al. (2014) also determined that results of vertical ground reaction force, joint angles, and joint moments had excellent test-retest reliability. While the SLS may be a good option to use in a less active population since it is a lower-demand task that more accurately resembles tasks of daily living, it may not be high-demand enough to identify risk factors in athletic populations.

Single-Leg Drop Vertical Jump

The single-leg drop vertical jump (SLDVJ) is another dynamic single-leg task used to assess for dangerous movement patterns. This task demands high neuromuscular control and coordination especially at the knee and trunk (Ortiz et al., 2014) and incorporates greater speeds and forces than lower-demand tasks such as the SLS. These unique characteristics may better resemble sport demands making the SLDVJ a more suitable option when testing an athletic population. Due to the nature of this task it is common to see lateral trunk motion, a predictor of knee injury, toward the stance limb to aid in balance and increase power production for the upcoming jump (Jamison et al., 2012). In a study comparing 3D frontal plane knee and trunk motion between SLS and SLDVJ it was found that knee valgus did not differ between tasks but that there was more lateral trunk motion in the SLDVJ (Dingenen et al., 2014). Tasks that challenge the control of the knee and trunk are important since lateral motion of the trunk moves the ground reaction force vector more laterally in the knee, resulting in a potentially dangerous external knee abduction moment even with little to no knee valgus present (Dingenen et al., 2014; Hewett & Myer, 2011; Jamison et al., 2012; Zazulak et al., 2007).

Examination of the SLDVJ is fairly new and no standard protocol has been developed. Utilized heights range from 10-50 cm (Dingenen et al., 2015; Dingenen et al., 2014; Ortiz et al., 2014; Ortiz et al., 2007; Pain, 2014; Stensrud et al., 2011; Wang & Peng, 2014). Stensrud et al. (2011) found that 10 cm may not have been high enough to reveal true knee control since landing would not require much knee flexion to absorb the impact. They cautioned, however, that if its too high insufficient strength may not allow for deceleration due to eccentric quadriceps activation and instead the individual will land stiff legged in order to remain standing (Lephart, Ferris, Riemann, Myers, & Fu, 2002; Stensrud et al., 2011). In support of this, Pain (2014) found that the endurance athletes involved in his study were not able to demonstrate control during the 30 cm height and that this height was considered the most strenuous activity, even compared to a 60 cm double-leg DVJ. Conversely, Wang and Peng (2014) determined that 30 cm plyometric jump training promotes improvements in transitioning from eccentric to concentric contractions and energy transfer. They also concluded that heights greater than 30 cm facilitate a protective mechanism that results in decreased performance. Ortiz et al. (2014) found that 40 cm was enough to show differences in knee valgus kinematics and neuromuscular recruitment strategies between individuals with a reconstructed ACL and healthy controls. A reliability study determined that five trials of SLDVJ separated by adequate rest to prevent fatigue were required to obtain reliable hip and knee joint kinematic (Ortiz et al., 2007). One study concluded that the sensitivity of the SLDVJ from 10 cm height may be too low to detect poor knee control; however, this study was based on one observer's subjective assessment of overall knee control and visual estimation of unmarked joint centers used to determine 2D frontal plane knee angles (Stensrud et al., 2011). The conditions under which visual assessments were made was not described and it could be possible that if done in real-time the task may have been too fast for the observer to accurate see flaws. Therefore, a SLDVJ from a height greater than 10 cm that challenges an individual while still remaining within their functional capacity as well as utilizing video cameras to allow for slower viewing may improve the utility of this tasks.

Conclusion

Despite prevalent research on the pathoetiology and predictive measures of sports related lower extremity injuries, the incidence, and therefore the negative short- and long-term outcomes, remains significant. PFP and ACL injuries are two of the most commonly studied injuries. Research has indicated that even though their injury onsets are different, both result from similar mechanisms. The biomechanical and neuromuscular risk factors associated with these injuries are frequently explored since they have the ability to be modified. Three-dimensional analyses have determined relationship between 3D variables and these injuries. Unfortunately, due the high cost, time, and knowledge required to use this method is not a realistic way to screen large populations for injury risks. As a result, many 2D screening methods have been developed. However, none have been universally accepted for reasons such as low levels of predictability.

In order to move forward with our understanding and application of field based injury screening it is necessary to develop valid and reliable 2D methods that are low-cost, time efficient, and easily implemented. Currently there is a large gap between the general simplicity of current field based measures that often look at one joint or in one plane and the comprehensive 3D analyses that are predicting lower extremity injury.

This study will have scientific and clinical impact because it will provide information regarding the relationship between 2D joint angles, which are easily measured in field settings, and 3D joint moments that are believed to be related to knee injury. In addition, the development of an observational movement assessment tool that takes into account the multi-joint, multi-plane nature of knee injuries is necessary to facilitate valid, widespread injury screening. As a result, this screening would allowing for early identification of high-risk individuals and implementation of preventative training programs with the overall goal of decreasing rates of injuries and the negative long-term outcomes associated with them.

CHAPTER 3: METHODS

Problem

Three-dimensional (3D) analyses are often used to assess the mechanics related to knee injury (i.e., patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury) and are considered the gold-standard approach for laboratory analysis (McLean, Walker, et al., 2005). While this method yields precise information regarding the body's movements and loading conditions during functional tasks, it requires expensive equipment and demands significant technical expertise and lengthy analysis, making it unusable in a field setting. In order to facilitate widespread implementation of lower extremity injury screening in a variety of field and clinical settings, time-efficient and cost-effective two-dimensional (2D) screening measures must be developed. Concurrently, there is not a 2D screening measure to evaluate the movement of multiple body segments in more than one plane during a single-leg task.

Purpose

The purpose of this study was to investigate the validity and reliability of the Single-Leg Landing Error Scoring System (SL-LESS). This tool could then be used in future studies to identify individuals who may be at a greater risk of knee. Specifically, two aims were addressed:

Aim 1: To determine the concurrent validity of the SL-LESS in predicting external knee abduction moment (KAbM) at initial contact and at its peak.

Aim 2: To determine the interrater and test-retest reliability of the SL-LESS.

Participants

Thirty female participants were recruited for this study from the University of Wisconsin-Milwaukee and the surrounding areas via flyers (Appendix B) posted around the campus. Inclusion criteria for participations required an individual to be between the ages of 18 and 30 as well as regularly partake in physical activity for at least 30 minutes a day, 3-4 days per week. These requirements were established to ensure that participants would be capable of successfully completing the tasks required with minimal risk of injury. Participants were excluded from the study if they had a history of back or lower extremity surgery, had experienced an injury to the back or lower extremities in the six months prior to data collection, were experiencing pain in the back or lower extremities at the time of data collection, or were pregnant.

To achieve Aim 1, we attempted to collect an equal distribution of participants with "good", "moderate", and "poor" landing mechanics, as defined by SL-LESS score. A power analysis indicated that at least 10 participants per group are necessary for adequate power.

Procedures

Session 1

Data collection took place over two testing sessions, at least 48 hours apart, in the Neuromechanics Lab at the University of Wisconsin-Milwaukee. An overview of the testing protocol can be found in Table 1.

Table 1. Generalized Testing Protocol

	Session 1	Session 2
Introduction	• Screening & medical history form • Consent form • Height measured	• Weight collected
Warm up	• Standardized warm up: 5-minute jog on treadmill at self-selected pace, 2x8 body weight squats, 2x5 maximum vertical jumps • Standardized verbal SLDVJ instructions • SLDVJ practice trials: 2-3 trials from the ground, 3-4 trials off the box	
Marker Placement	• 2D markers	• 2D and 3D markers • Standing calibration • Removal of calibration markers
Practice	• SLDVJ practice trials: 3-4 trials off the box (preferred leg only)	
Data Collection	• 5 trials • 2D frontal and sagittal plane video recordings	• 5 trials • 2D frontal and sagittal plane video recordings • 3D kinematic and kinetic data

During the initial session, all participants were informed about the intent of the study and provided written consent (Appendix A). A self-reported screening and medical history questionnaire (Appendix C) was completed and the individual's height and age were recorded on the data collection form (Appendix D). Participants were asked to change into clothes consisting of a T-shirt and tight fitting shorts that contoured to the skin. Standardized athletic shoes (Saucony Jazz, Lexington, MA) were used to prevent variance due to differences in the type of footwear from affecting the study results. Participants completed a warm up consisting of a five minute light jog on a treadmill at a self-selected pace followed by 2 sets of 8 repetitions of two-leg squat and 2 sets of 5 repetitions of two-leg maximum jumps (Stensrud et al., 2011).

Participants were provided with standardized verbal instructions on the single-leg drop vertical jump (SLDVJ) and the task was demonstrated. The SLDVJ consisted of the participant standing on a 20 cm box on a single leg and then jumping out a distance of 25% of their height and landing on a force plate with that same leg. Immediately following landing the participant progressed into a single-leg maximal vertical jump with arms moving freely. An emphasis was placed on the participants jumping as high as possible after landing from the box (Padua et al., 2009). A trial was considered invalid if the participant did not jump off one foot, jumped vertically off the box, did not land with entire foot on force plate, touched the ground with the non-supporting, lost balance/fell, or did not complete the task in a fluid motion (Dingenen et al., 2014; Padua et al., 2009; Stensrud et al., 2011). No feedback on jumping technique was given. Sufficient rest, as determined by the participant, but no less than 30 seconds, was provided between trials.

Participants then complete 2-3 practice trials on each leg from the ground and then from the box. During this time the participants choose the leg they felt most comfortable performing the task on during the data collection.

To allow for more accurate observational 2D kinematic analysis, participants had six adhesive markers which were placed on the acromioclavicular joint, greater trochanter, lateral femoral epicondyle, and lateral malleolus, estimated knee joint center (center of the patella, halfway between femoral epicondyles), and on the tip of the shoe in line with the great toe (Chmielewski et al., 2007; Ekegren et al., 2009; Harris-Hayes et al., 2014).

Participants were again instructed on the task to be performed and completed 3-4 more practice repetitions on their chosen leg to feel comfortable with the task and to reduce the impact of learning effects. Two-dimensional videos were collected using two standard video cameras (Canon VIXIA HF-R52, Sony Corp., San Diego, CA) on tripods placed 3.6 m anterior and 3.6 m lateral to the test limb at a height of 95 cm. Five valid trials of the SLDVJ were recorded and the first three valid trials were used for analysis.

Following the completion of data collection, participants were asked open-ended questions about their perceptions of the difficulty of the SLDVJ protocol and their comfort while performing the task (Appendix E). This information was evaluated in a descriptive way and used to support the interpretation of the study results.

Session 2

Participants returned no sooner than 48 hours after initial testing to complete the entire protocol a second time. During this session both 2D video and 3D kinematic and kinetic data were collected. After changing into the lab clothes the participant's weight was obtained followed by the standardized warm-up, verbal instructions, and SLDVJ practice trials from the ground and from the box. Jumps were performed on the same leg tested during the first session.

Participants had 32 reflective markers placed on their body for the collection of kinematic data. Four-marker clusters were placed on the upper back, lateral thigh, and lateral shank of the test leg using Velcro straps. A molded plastic four-marker calcaneal piece was taped to the heel of the participant's shoe. Individual markers were placed bilaterally on the acromioclavicular joint, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), iliac crest, and greater trochanter as well as on the medial and lateral epicondyle at the knee, medial and lateral malleolus, and first and fifth metatarsal heads of the test leg. A standing trial was collected, followed by the removal of the acromioclavicular joint, iliac crest, greater trochanter, medial and lateral knee, medial and lateral malleolus, and the first and fifth metatarsal head markers, leaving both ASIS and PSIS markers and all four clusters for segment identification. Adhesive markers used for 2D video analysis were placed in the same locations as the first session. Participants proceeded with the additional 3-4 practice trials and five valid trials of the SLDVJ for data collection. The first three valid trials with complete 3D data were used for analysis.

Data Reduction

Two-Dimensional Observational Assessment

To evaluate SLDVJ movement patterns an observational scoring tool developed for this study that identifies the presence of errors that may increase the risk of injury was utilized. This tool was adapted from the Landing Error Scoring System (LESS), originally developed by Padua et al. (2009).

The first step taken when adapting the LESS into the SL-LESS was to remove any criteria that did not apply to a single-leg task (i.e., symmetrical foot landing). The second step was to verify that the remaining criteria still had evidence supporting their relationship to increased injury risk. Additional criteria related to movement patterns not often observed during bilateral tasks but may become apparent during single-leg tasks were also added. In total, 11 items were included in the final revision of the SL-LESS (Table 2). Dichotomous ratings were given for each of the items with "1" indicating the error was present in two or more of the trials and "0" representing acceptable movement patterns in two or more of the trials. The total number of errors was added together to give a score ranging from 0-11.

Table 2. SL-LESS Itemized Description

		Item	Error (1)	Good (0)
SAGITTAL PLANE	1	Forward Trunk Flexion at IC	At IC the trunk is vertical or extended on the hips	The trunk is flexed on the hips
	2	Knee Flexion at IC	At IC the knee is flexed more than 30º	The knee is not flexed more than 30º
	3	Ankle Plantarflexion at IC	The foot lands heel to toe or with a flat foot	The foot of the test leg lands toe to heel
	4	Forward Trunk Flexion Displacement	Between IC and MKF there is no additional trunk flexion	There is additional trunk flexion
	5	Knee Flexion Displacement	Between IC to MKF the knee does not flex an additional 30º	The knee flexes an additional 30º
	6	Ankle Dorsiflexion Displacement	Between IC and MKF the heel does not touch the ground or the ankle does not move into a dorsiflexed position during landing	The heel touches the ground and the ankle becomes dorsiflexed during landing
FRONTAL PLANE	7	Knee Valgus at IC	At IC, a line drawn straight down from the center of the patella is medial to the midfoot	The line goes through the midfoot
	8	Lateral Trunk Flexion at IC	At IC, the midline of the trunk is flexed to the left or the right side of the body	The trunk is not flexed to the left or right side of the body
	9	Knee Valgus Displacement	At MKV a line drawn straight down from the center of the patella runs through the great toe or is medial to the great toe	The line is lateral to the great toe
	10	Pelvic Drop	During landing the contralateral pelvis positioned lower than the ipsilateral pelvis	Both sides of the pelvis remain level
	11	Tibial Rotation (toe pointed in/out)	Between IC and MKF the foot is internally/ externally rotated more than 30º	If the foot is not internally/ externally rotated more than 30º

IC, initial contact; ROM, range of motion; MKF, maximum knee flexion; MKV, maximum knee valgus

Frontal and sagittal plane videos were analyzed using Dartfish Connect, version 8 (Dartfish Inc., Fribourg, Switzerland). One rater (MO) time-synchronized both videos based on initial contact and scored the videos from both session 1 and session 2 of testing to determine the test-retest reliability of the tool (Appendix G). A second rater (JEB) independently viewed and scored the session 1 videos; this was used to determine the interrater agreement. Both raters viewed the trial videos at various speeds as many times as needed utilizing fast-forward, rewind, frame-by-frame, and measurement tools provided by the Dartfish software.

The session 2 scores were used to stratify the participants into three groups. Individuals with SL-LESS scores of one or two were categorized as "good", scores of three was categorized as "moderate", and scores of four or larger were categorized as "poor".

Three-Dimensional Analyses

Three-dimensional motion of the trunk and lower extremity of the preferred leg during a SLDVJ was collected via a ten-camera Eagle Digital Camera System (Motion Analysis Corp., Santa Rosa, CA). Data was collected using Cortex software, version 5.5 (Motion Analysis Corp., Santa Rosa, CA). Kinetic data was collected utilizing a Bertec force plate (Bertec Corp., FP4060-NC, Columbus, OH). Positional data was collected at 200 Hz, with force data collected synchronously at 1000 Hz in the Cortex software. Markers were identified and tracked throughout each trial. The first three valid trials of the SLDVJ were tracked and used in data analysis. If a marker was missing for an extended time or during a critical time period during the trials, that trial was eliminated and data analysis proceeded with the remaining good trials.

Tracked data was exported from Cortex and processed using Visual3D software, version 5 (C-Motion Inc., Rockville, MD). Kinematic data was filtered using a 4th order low pass Butterworth filter with a cutoff frequency of 12 Hz, and the kinetic data with a cutoff frequency of 50 Hz (Hamill, Bates, & Holt, 1992). Each segment was defined (trunk, pelvis, femur, shank, and foot) and its position and orientation within the global coordinate system were identified. Joint centers for the knee and ankle were defined as the midpoint between the medial and lateral joint markers (Ageberg et al., 2010). The hip joint center was estimated at 25 percent of the horizontal distance between the greater trochanters from the test side trochanter marker (Weinhandl & O'Connor, 2010).

An inverse dynamics approach as described by Kadaba et al. (1989) was used to derive the joint kinetic data from the ground reaction force and kinematic data. To be consistent with the existing literature on knee moments and injury risk, we chose to report external knee abduction moment (KAbM) normalized to body mass and height (N·m/kg·m) to represent loading on the knee (Dingenen et al., 2014; Hewett et al., 2005; Jamison et al., 2012; Padua et al., 2012). The values of this moment at initial ground contact and at its peak were used for analysis. KAbM represents frontal plane loading of the knee and has been found to predict ACL injury with a sensitivity of 78% and a specificity of 73% (Hewett et al., 2005). Peak KAbM during stance phase of a bilateral drop vertical jump has been found to be greater in female athletes who went on to experience an ACL injury when compared to non-injured females (Hewett et al., 2005). Similar trends have also been established related to PFP. Athletes who went on to develop PFP have demonstrated greater KAbM at initial contact of a bilateral drop vertical jump in their affected limb as well as greater peak KAbM in their unaffected limb (Myer, Ford, Barber-Foss, et al., 2010).

Statistical Analysis

Statistical analyses were performed in SPSS, version 22 (SPSS Inc., Chicago, IL).

Aim 1: To determine the concurrent validity of the SL-LESS in predicting KAbM.

To determine the validity of the SL-LESS an independent-samples t test was used to compare KAbM at initial contact between the "good" and "poor" SL-LESS groups. A second independent-samples t test was performed to compare maximum KAbM between the two groups. The alpha was set a priori at $p \leq .05$.

Aim 2: To determine the interrater and test-retest reliability of the SL-LESS.

Test-retest reliability of the SL-LESS was determined by the intraclass correlation coefficients (ICC, model 2,1) of the overall SL-LESS scores from session 1 and session 2. To determine the interrater reliability of the total SL-LESS score the ICC (model 2,1) was used. Paired-samples t tests were also completed to look for differences in scores between sessions and between raters. To determine the agreement of the individual items within the SL-LESS, percent agreement and Cohen's kappa statistic were calculated for each of the 11 items.

CHAPTER 4: RESULTS

A total of 30 participants (age 24.79 ± 2.36 years, height 1.70 ± 0.07 m, weight 62.14 ± 9.64 kg, BMI 21.54 ± 3.48 kg/m^2) were recruited for this study; however, two did not complete the testing sessions and were not included in the analyses. Additional information regarding factors that could potentially influence an individual's performance during this study was also collected using the data collection form; these results are presented in Table 3. Twenty-six of the participants classified themselves recreational athletes while two reported being part of an organized sports team.

Table 3. Participant Characteristics

	Yes	No
Ankles feel unstable during activity, particularly during cutting or landing?	6	22
Currently participate in activities that incorporate cutting/jumping/landing?	13	15
Previously competed jump/landing training?	10	18

The frequency of errors reported by both raters and both sessions can be found in Figure 1. The distribution of total Single-Leg Landing Error Scoring System (SL-LESS) scores from session 2 is illustrated in Figure 2. These scores were used to stratify participants into three groups. Participants with scores 1-2 were considered "good" (n = 8) while scores 4-6 were considered "poor" (n = 14). Participants with a score of 3 were not included in the final analysis to create more separation between the two groups.

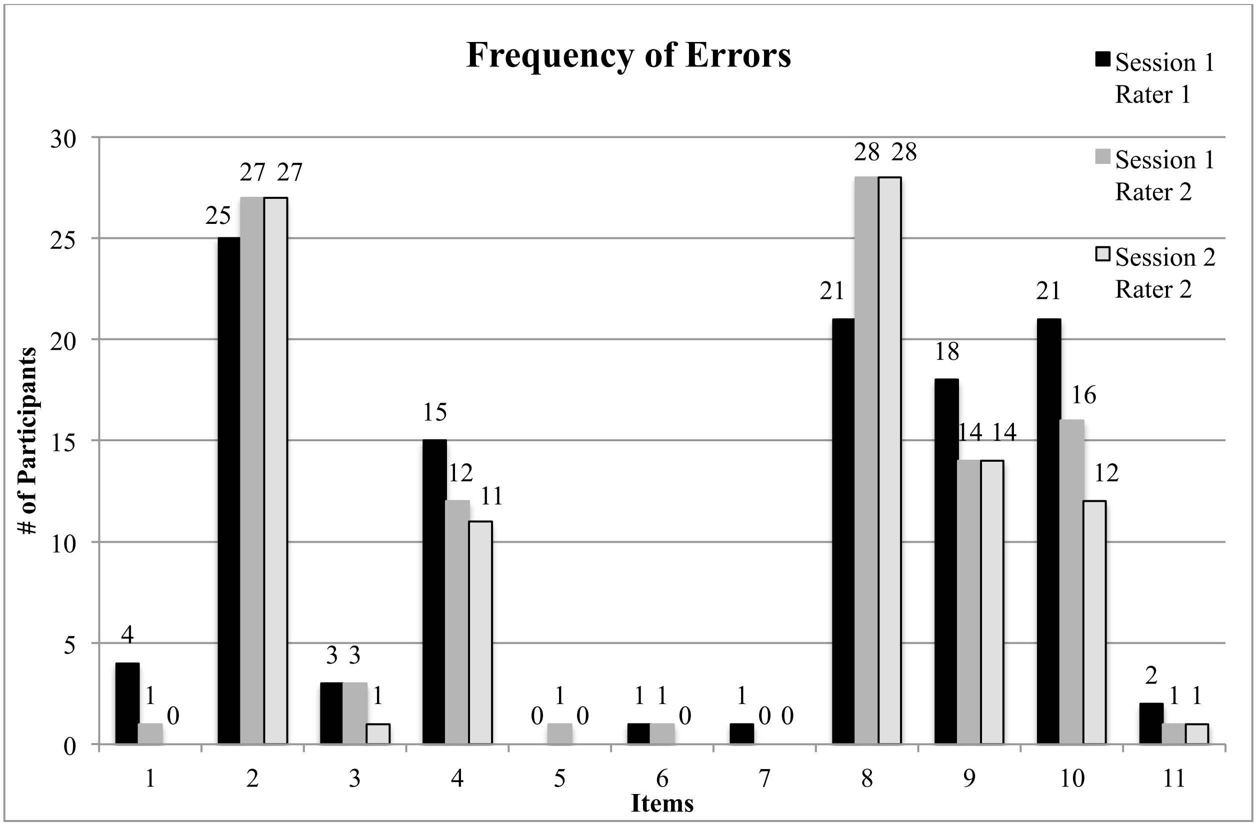

Figure 1. Frequency of errors present in each of the SL-LESS items

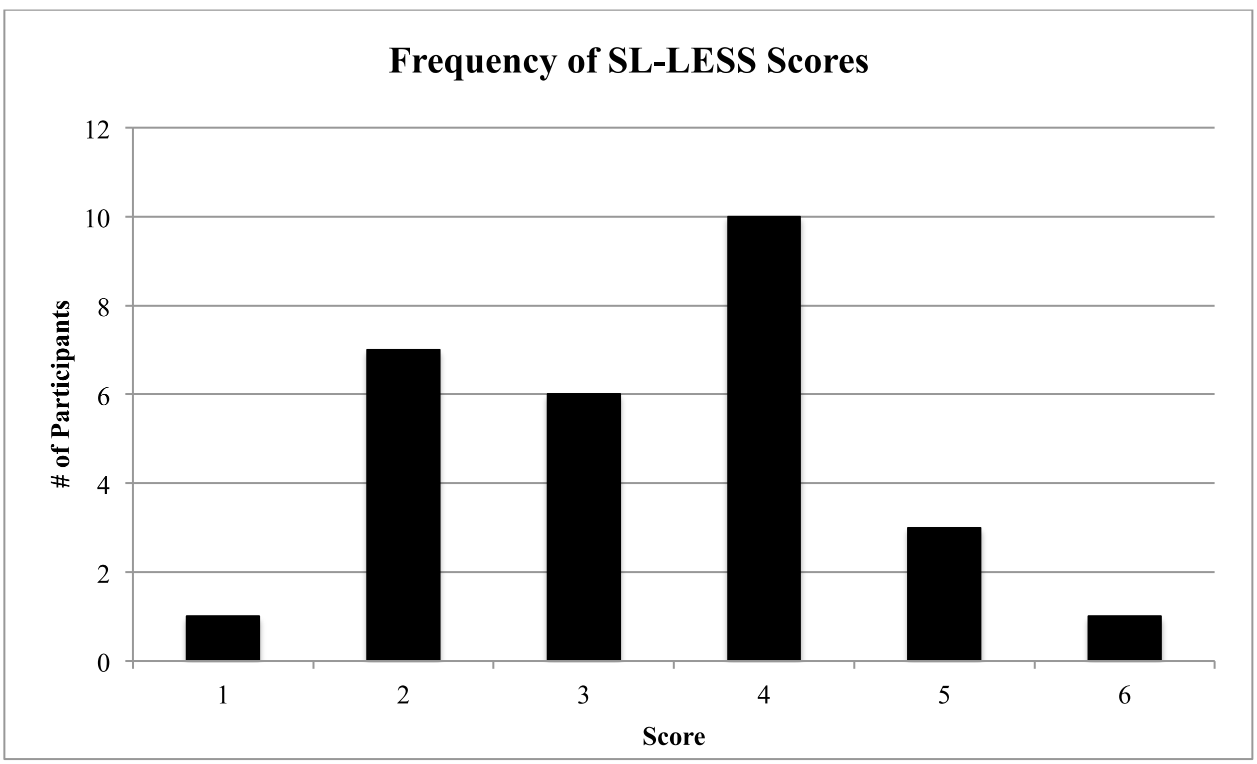

Figure 2. Frequency of session 2 SL-LESS scores

An independent-samples t test was performed to assess if external knee abduction moment (KAbM) differed between the "good" and "poor" SL-LESS groups (Table 4). There was no statistical difference in KAbM at initial contact (KAbMic) between groups (t_{20} = -1.58; p = 0.0645), although there was a trend toward the "good" group experiencing greater KAbM than the "poor" group (Figure 3). There was also no statistical difference in maximum KAbM (KAbMmax) between groups (t_{20} = -0.61; *p* = 0.274) (Figure 4).

Table 4. SLDVJ Knee Abduction Moments

	Good (n=8)	**Poor (n=14)**	**P value**
KAbMic (N·m/kg·m)	-0.0234 ± 0.0378	0.0030 ± 0.0377	0.065
KAbMmax (N·m/kg·m)	0.1334 ± 0.0802	0.1527 ± 0.0663	0.274

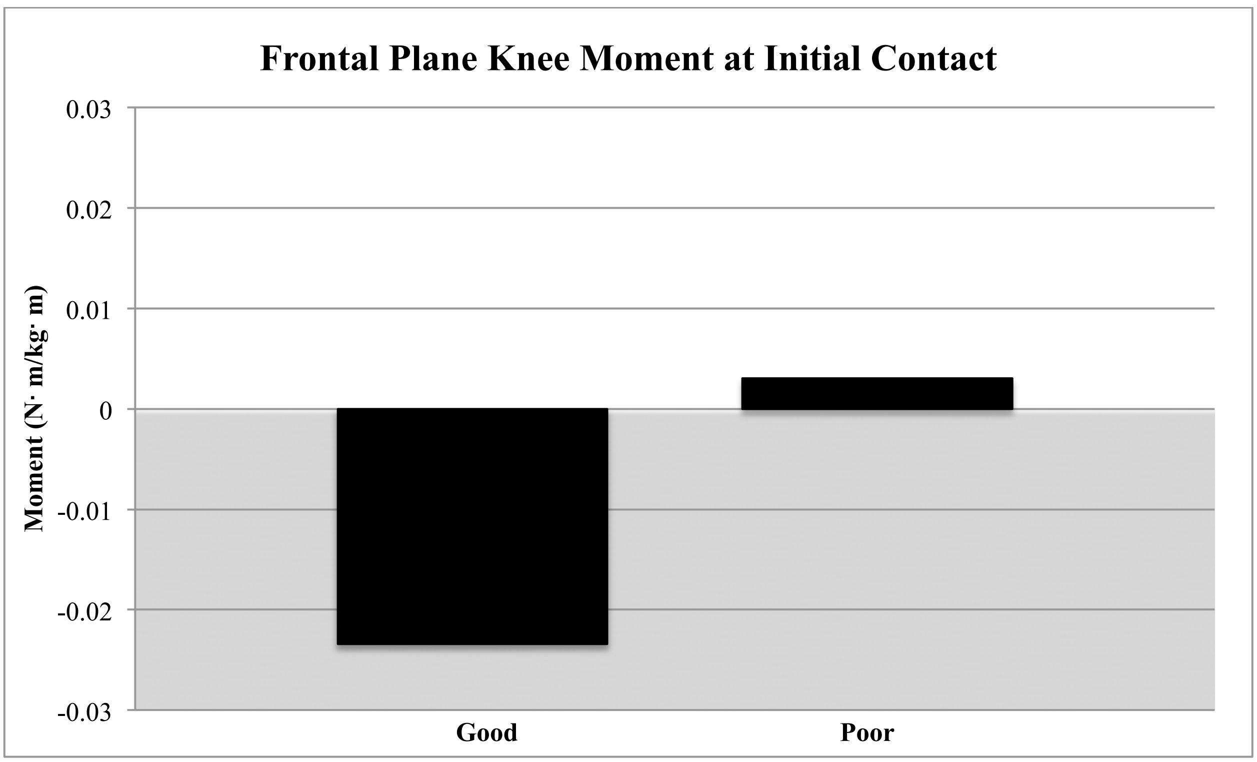

Figure 3. Comparison of mean frontal plane knee moment at initial contact between "good" and "poor" SL-LESS groups (white area indicates abduction moment, shaded area indicates adduction moment)

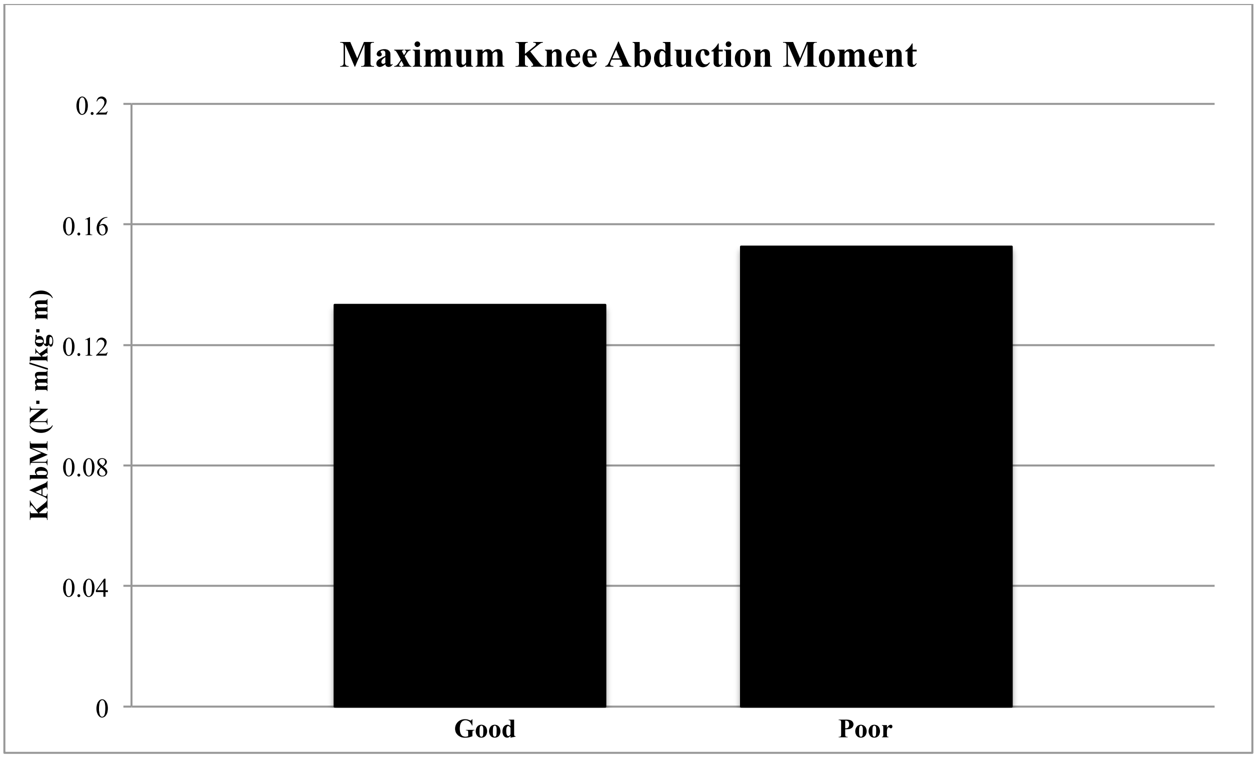

Figure 4. Comparison of mean maximum KAbM between "good" and "poor" SL-LESS groups

To determine the reliability of the SL-LESS, intraclass correlation coefficients (ICC) were used. The interrater reliability of the total SL-LESS scores was found to be fair ($ICC_{2,1}$ = 0.781; 95% CI: 0.581–0.892). A paired-samples t test, however, indicated that there was no statistical significant difference between the scores (p = 0.310). Percent agreement and Cohen's kappa statistic were used to assess the reliability of each of the 11 items included in the SL-LESS (Table 5). Percent agreement ranged from 75.0–100% and kappa statistics indicated significant fair to perfect agreement (κ = 0.364–1.00).

Table 5. Interrater Reliability

Item	% Agreement	Kappa	P	Level of Agreement
1	89.3	0.364	0.013	Fair
2	92.9	0.472	0.003	Moderate
3	100	1.000	<0.001	Perfect
4	89.3	0.788	<0.001	Substantial
5	96.4	---	---	---
6	100	1.000	<0.001	Perfect
7	96.4	---	---	---
8	75.0	---	---	---
9	85.7	0.714	<0.001	Substantial
10	82.1	0.615	<0.001	Substantial
11	96.4	0.650	<0.001	Substantial

The test-retest reliability of the total SL-LESS scores was found to be good ($ICC_{2,1}$ = 0.850; 95% CI: 0.596–0.938). However, a paired-samples t test found a significant difference between the scores of the sessions ($p = 0.005$). For the individual items, percent agreement ranged from 78.6–100% and kappa statistics indicated significant moderate to perfect agreement ($\kappa = 0.472–1.00$) (Table 6).

Table 6. Test-Retest Reliability

Item	% Agreement	Kappa	P	Level of Agreement
1	96.4	---	---	---
2	100	1.000	<0.001	Perfect
3	92.9	0.472	0.003	Moderate
4	82.1	0.632	0.001	Substantial
5	96.4	---	---	---
6	96.4	---	---	---
7	100	---	---	---
8	100	---	---	---
9	92.9	0.857	<0.001	Almost Perfect
10	78.6	0.580	0.001	Moderate
11	100	1.000	<0.001	Perfect

CHAPTER 5: DISCUSSION

The purpose of this study was to investigate the validity and reliability of the Single-Leg Landing Error Scoring System (SL-LESS) to identify individuals who may be at a greater risk of knee injury. The first aim of this study was to determine the concurrent validity of the SL-LESS in predicting initial contact and maximum external knee abduction moment (KAbM). It was hypothesized that individuals with more observable movement errors will demonstrate larger KAbM at both points in time. The second aim of this study was to determine the inter-rater and test-retest reliability of the SL-LESS. It was hypothesized that the SL-LESS will demonstrate high inter-rater and test-retest reliability.

Validity

The results of this study indicate there was no difference in KAbM at initial contact between "good" and "poor" SL-LESS groups. Although there was a trend toward greater moments experienced in the "poor" group it was not statistically significant. The "poor" group landed with a net KAbM; however, the average moment was small. Unexpectedly, the "good" group landed with a net knee adduction moment that was much greater in magnitude than the "poor" group's KAbM (Table 4, Figure 3). Only one study has considered KAbM at initial contact of a bilateral drop vertical jump and found values much greater than those experienced during the present study. Based on the differences between the current study and Myer, Ford, Barber-Foss, et al. (2010) it is possible that initial contact is not an appropriate time point. At initial contact, ground reaction force is relatively small which may lead to small KAbM values and a large variability within and between participants. Additionally, the body position and joint loading at initial contact may not relate well to those experienced at the time when ACL injuries are thought to occur (approximately 17-50 milliseconds after contact (Koga et al., 2010; Krosshaug et al., 2007)).

Results also suggest there was no difference in maximum KAbM between groups, in contrast to the hypothesis (Table 4, Figure 4). The values found are similar to those found by (Dingenen et al., 2014) in their evaluation of a 10 cm SLDVJ. Overall, the results of this study suggest that this initial version of the SL-LESS may not accurately predict external knee abduction moment during the landing of a single-leg drop vertical jump (SLDVJ).

Based on the relationship between high KAbM and knee injury (Hewett et al., 2005; Myer, Ford, Khoury, et al., 2010), several clinical evaluation tools have been developed with the purpose of identifying the presence of large moments. Previous research on the original Landing Error Scoring System (LESS) established that individuals who were classified as “poor” due to high scores on the LESS demonstrated larger KAbM than the other groups (Padua et al., 2009). Other studies have developed injury prediction algorithms that predict KAbM by evaluating variables such as knee flexion peak angle and range of motion (Myer et al., 2014; Myer, Ford, Khoury, et al., 2010). A major limitation of these evaluations is that they rely on a bilateral task while the vast majority of knee injuries occur during single-leg movements (Boden et al., 2000; Boden et al., 2009; Olsen et al., 2004). Bilateral tasks may not reveal side-to-side differences between legs since they allow an individual to rely on one leg more while potentially hiding risky mechanics of the other (Olsen et al., 2004; Ortiz et al., 2014; Stensrud et al., 2011). This may explain why there have been conflicting findings related to the ability of the LESS to predict future anterior cruciate ligament (ACL) injury (Padua et al., 2015; Padua et al., 2010; H. C. Smith, Johnson, et al., 2012).

The current study adds to the body of knowledge about injury screening tools by developing a new tool that may produce similar results utilizing a task that is more sport-specific and similar to movements associated with ACL injuries. The results of this study, however, did not find a difference in KAbM between people demonstrating "good" and "poor" landing mechanics.

The current study's results were most likely influenced by the low variability in SL-LESS scores. With the SL-LESS there is an opportunity for scores to range from 0 to 11; however, the range of scores for the participants in this study was 1 to 6 (Figure 2). Examination of participant characterizes identified the homogeneous nature of the sample population. Despite various physical activity levels qualifying for this study 26 of the 28 participants classified themselves as recreational active, often working out on their own or participating in group fitness classes. It is possible that the inclusion of more competitive athletes may have lead to different results, since this population is at a higher risk of knee injury. Furthermore, individuals who had experienced a recent injury or had ever undergone an injury-related surgery were excluded from this study. This may have limited participation to those individuals who were already at a low risk of injury, skewing the distribution of SL-LESS scores towards the lower end of the scale.

The SLDVJ was chosen for this study since it incorporates a single-leg land-and-go maneuver that is often associated with ACL injuries (Boden et al., 2000; Boden et al., 2009; Olsen et al., 2004; Ortiz et al., 2008). This task demands high neuromuscular control and coordination, especially at the knee and trunk (Ortiz et al., 2014). Early research by Stensrud et al. (2011) found that a SLDVJ from 10 cm was not sensitive enough to reveal poor knee control, most likely due to the low height. Stensrud et al. (2011) also suggested that individuals, females in particular, lacked the strength to perform a SLDVJ from 20 cm. However, follow up studies completed since then have determined that 20-30 cm provide similar level of intensity when compared to the commonly used 40 cm bilateral drop vertical jump and were able to facilitate the implementation of risky movements (Herrington, 2014; Ortiz et al., 2014; Wang & Peng, 2014). Other studies have also supported the appropriateness of utilizing drop heights larger than 10 cm (Ortiz et al., 2014; Pain, 2014; Stalbom et al., 2007; Wang & Peng, 2014). Feedback from the current study indicated that all participants felt comfortable performing the SLDVJ from 20 cm and most described it as challenging yet not too difficult.

Despite the commonality of single-leg land-and-go maneuvers in sport activities, participants described the SLDVJ itself as a novel task. The large number of practice trials, both from the ground and from the box, were implemented to familiarize the participants with the task. Although all participants reported feeling comfortable with the SLDVJ they may still have demonstrated cautiousness due to fear or uncertainty, influencing their performance.

Another factor that may have had a significant impact on performance is attentional focus. Previous research has acknowledged that ACL injuries often occur when an athlete is focused on something external, such as goal or an opponent. Taking this factor into account Dempsey, Elliott, Munro, Steele, and Lloyd (2012) implemented an overhead catch and landing task that required their participants to make adjustments to their body position and avert attention from the landing itself. In the current study a focus was placed on performing the highest vertical jump possible in a similar attempt to shift attention as well as produce maximum effort. Despite frequent reminders, it was noted that many of the participants still appeared to focus on the landing. For this reason, it is suggested that future studies include a type of overhead goal to reach for or provided participants with feedback on a performance variable, such as jump height or power produced.

One source of error associated with all two-dimensional (2D) movement assessments is that rotational movements in the transverse plane cannot be easily evaluated (Ageberg et al., 2010; Willson & Davis, 2008). Additionally, combinations of three-dimensional (3D) movements may create different observed 2D movements. For example, it has been shown that 2D and 3D measures of knee abduction may not be equivalent, possibly due to the fact that hip internal rotation may project knee flexion into the frontal plane (Ageberg et al., 2010). These factors may have influenced the evaluation of certain items of the SL-LESS scoring quite differently than how the 3D calculation of knee abduction moment was obtained.

A final point to make related to the validity of this study is the sensitivity of the evaluation tool. It is possible that the SL-LESS was not sensitive enough to identify differences in KAbM, though further investigation and comparison to previously established movement assessments is needed. Furthermore, it is important to address the idea that although the SL-LESS could not predict KAbM it still may predict injury. When prospective studies are not feasible, KAbM is used as a variable to represent risk of injury. This decision, however, is based on only two studies that found a relationship between KAbM and future injury (Hewett et al., 2005; Myer, Ford, Barber-Foss, et al., 2010). As mentioned previously, knee injuries are believed to occur as a result of multi-joint movement in all three planes. Therefore is it appropriate to hypothesize that KAbM is not the only variable that assessments should consider when attempting to represent injury risk.

Reliability

This study found that the SL-LESS demonstrated fair interrater reliability and good test-retest reliability (Onate et al., 2012). While this reliability is still considered acceptable, these results did not support our hypothesis that there would be high reliability (ICC > 0.9). Since the

SL-LESS is a new assessment tool that was developed for this study there have been no other reliability studies. However, the original LESS has been found to have good interrater reliability by both Onate et al. (2010) ($ICC_{2,1}$ = 0.835) and Padua et al. (2009) ($ICC_{2,k}$ = 0.84, SEM = .71), which are slightly higher than that of the current study.

Additionally, paired-samples t tests were completed to determine the differences between scores. Results indicated that scores between the two raters were not statistically significantly different while scores between sessions were.

There are several factors related to the methods implemented, the task performed, and the evaluation tool of the current study that may have influenced the level of SL-LESS reliability. Adhesive markers were used to assist with the evaluation of movement patterns using the 2D analysis method. Although they were only used as a visual reference point the accuracy of the placement could have lead to differences between raters. Additionally, different placement between testing sessions could have influenced the test-retest reliability.

Sufficient training of raters has also been cited as a critical component of observational movement assessments (Ageberg et al., 2010; Ekegren et al., 2009; Padua et al., 2009). Many of the commonly used assessments that have produced high levels of reliability incorporated more thorough training sessions for raters than was implemented in the current study. LESS training typically includes an educational session that provides background information specific to the tool and a detailed review of all items. This is typically followed by scoring several pilot subjects, comparing scores to an expert rater's, and discussing any discrepancies (Ekegren et al., 2009; Onate et al., 2010; Padua et al., 2009). The present study incorporated a review of all the items and two pilot scorings and while both raters expressed confident in utilizing the SL-LESS additional training may have improved reliability results.

An environmental factor that was not well controlled during data collection of this study was the lighting. Changes in natural light picked up by the video cameras resulted in some videos being extremely dark. While the videos were still able to be scored, this may have negatively impacted reliability.

A major trend noted during data collection and analysis related to the task implemented for evaluation was the variability in performance between trials, and even more so between sessions. The warm-up and practice sessions, which consisted of 10-12 practice SLDVJs, were developed in hopes of reducing the impact of a learning effect. However, it was not uncommon to see inconsistencies in the movement patterns chosen to complete the task during the trials. The procedures for this study were developed in accordance with Ortiz et al. (2007) who suggested that a familiarization process and warm-up be included and that data from five trials be collection in order to have acceptable reliability.

After completing the second data collection session, several participants expressed an increased comfort level with the task and therefore may have performed the task differently. This suggests that an additional practice session before data collection may improve the test-retest reliability. The results of the current study may suggest that even more practice should be incorporated.

During the development of the SL-LESS several factors previously investigated in observational assessments reliability studies were taken into consideration. First, the SL-LESS evaluates movement using a dichotomous scale. Previous studies have reported that dichotomous scales often result in greater reliability than scales with multiple levels (Chmielewski et al., 2007; Ekegren et al., 2009; Onate et al., 2010; Whatman et al., 2012).

Secondly, specific descriptions of what constituted an error for each item are also provided by the SL-LESS. In order to ensure the identification of movement errors, especially by those who may not have a substantial background in movement evaluation, providing clear criteria and instructions are necessary (Ageberg et al., 2010; Chmielewski et al., 2007).

Due to the multi-joint and multi-plane characteristics of knee injury the SL-LESS was developed to incorporate the evaluation of movement of several segments of the body. Some studies have found that an overall rating of movement quality produced higher reliability than looking at individual segments (Chmielewski et al., 2007; Ekegren et al., 2009; Whatman et al., 2012). Since the SL-LESS total score is the sum of 11 more specific items, the level of reliability may have reflected this. Chmielewski et al. (2007) explained, however, that although the greater number of scoring options in the specific method increased the chance of disagreement, this method produced agreement among raters that is better than chance suggesting that less ambiguity in scoring criteria may result in more reliable outcomes.

Individual SL-LESS Items

In addition to evaluating total SL-LESS scores, percent agreement and kappa values were determined to assess the reliability of the specific items included in the SL-LESS (Shrout & Fleiss, 1979). There were several items where all participants received the same score. In these cases kappa values could not be calculated so only percent agreement were recorded. Only one study has evaluated the interrater reliability of individual items of the LESS (Onate et al., 2010). When considering at the items that correspond to both the LESS and the SL-LESS results were similar to those found in this study (percent agreement range: 90-100%, κ range: 0.459-1.00).

Some of the lower kappa statistics seen in this study can be explained by the nature of the scoring method and a paradox associated with Cohen's kappa. Low kappa statistics can be the result of difference in the prevalence of given scores (Byrt, Bishop, & Carlin, 1993). For example, item 2 had a 92.9% agreement between raters; however, because only 1 participant from rater 1 and 3 from rater 2 did not receive an error score the kappa statistic was lower than expected.

Based on results of this study and the experiences of utilizing the SL-LESS several issues and suggestions can be addressed for many of the items. In situations where almost all participants received the same score for an item error score, it may suggest that the criteria for those items need to be adjusted to better stratify individuals. In situations where there were large differences between raters, more clear or precise criteria should be utilized. Several of these will be addressed in the following sections.

Initial contact forward trunk flexion and displacement demonstrated acceptable levels of agreement. Differences between raters may have been the results of difficulties seeing the reference point placed on the shoulder. Additionally, protraction and retraction of the scapula can shift the shoulder marker even when no actual trunk movement may be occurring. Using an angles created by the slope of the back may be a more accurate way to evaluate trunk flexion.

Knee flexion at initial contact and flexion displacement produced very high levels of both interrater and test-retest reliability. However, the frequency of errors given for insufficient knee flexion at initial contact indicated that this item did not aid in separating participant based on their jump performance. Despite this, it is suggested that less than 30º of knee flexion at initial contact should remain the error criteria due to the fact that an extended knee is one of the most characteristic body positions associated with ACL injuries (Boden et al., 2000; Krosshaug et al., 2007). Additionally it has been shown that when the knee is flexed at 30º the ACL provides around 85% of the total resistance to anterior tibial shift from the quadriceps (Beynnon et al., 1995; Butler et al., 1980).

Knee flexion displacement is a key factor associated with ACL injuries and patellofemoral pain (PFP) (Boden et al., 2009; Boling et al., 2009; Hewett et al., 2005). It is suggested that this decreased range of motion increases the loading of the passive structures of the knee (Aerts et al., 2013; Blackburn & Padua, 2008; Decker, Torry, Wyland, Sterett, & Steadman, 2003). The error criteria for this study were based on maximum knee flexion during a SLDVJ from several studies (Dingenen et al., 2015; McCurdy, Walker, Saxe, & Woods, 2012; Ortiz et al., 2008). Only one subject demonstrated the error suggesting that this cutoff may not be suitable for identifying individuals; however, until more prospective studies are done on the SLDVJ a more appropriate range of motion may not be able to be determined.

Ankle plantarflexion at initial contact showed perfect interrater agreement and moderate test-retest agreement. The differences between sessions seemed be the result of participants performing the task differently during session 2 rather than variations in error interpretation. Ankle dorsiflexion range of motion also produced high levels of reliability but it was another low frequency error. The error criteria for this item were chosen based on previous experience utilizing the original LESS. Stiff landings were frequently observed during the bilateral drop vertical jump and were often associated with individuals restricting their ankle dorsiflexion. In extreme cases there was no contact between the heel and the ground, which served for the basis of the current study's error criteria. Decreased ankle range of motion reduces the ability of the gastrocnemius to contract and absorb the ground reaction force and, as a result, the force is transmitted to the knee increasing the risk of ACL injury (Boden et al., 2009; Pflum, Shelburne, Torry, Decker, & Pandy, 2004). Rather than simply identifying the location of the heel during the landing, it may be necessary to measure the amount of dorsiflexion at maximum knee flexion to determine this error.

A valgus knee position at initial contact produced high levels of agreement although only one participant demonstrated this risky movement pattern. Knee valgus at this point is one of the key components of dynamic malalignment associated with PFP and the “position of no return” associated with ACL injuries (Ireland, 1999; Ireland et al., 2003; Powers, 2003). Since ACL injuries are believed to occur within 50 milliseconds after initial contact (Krosshaug et al., 2007) it is possible that assessing knee valgus at the first frame of ground contact is too early. A new LESS study has changed the definition of initial ground contact to “frame immediately before the foot was flat on the ground” (Padua et al., 2015). The implementation of this time frame may better represent the critical time period where excessive knee valgus may lead to ACL injuries.

The evaluation of lateral trunk flexion at initial contact resulted in almost all subjects receiving an error score (rater 1 = 21, rater 2 =28). This outcome is most likely due to the criteria, which was adopted from the original LESS to evaluate a bilateral task, stating that any deviation of the trunk past vertical constitutes an error. Lateral flexion of the trunk in the frontal plane is a component of dynamic malalignment and is often associated with noncontact ACL injuries and PFP (Boden et al., 2009; Hewett et al., 2009; Krosshaug et al., 2007; Nakagawa et al., 2012b; Whatman et al., 2012). Lateral flexion during a SLDVJ shifts the ground reaction force towards the landing leg within the base of support so slight lateral flexion is to be expected for the individual to remain balanced. Too much lateral ground reaction force shift past the knee joint center, however, leads to an increase the knee abduction moment (Chmielewski et al., 2007; Hewett & Myer, 2011; Hewett et al., 2009; Jamison et al., 2012; Nakagawa et al., 2012b). While the presence of any lateral flex is accepted during bilateral drop vertical jump, allowing up to 10º before classifying an error may be more appropriate during a SLDVJ (Hewett et al., 2009; Nakagawa et al., 2012a).

Contralateral pelvic drop provided substantial interrater reliability and moderate test-retest reliability. These levels of reliability can be attributed to both differences in task performance as well as difficulties with visual interpretation of pelvis movement by the raters. It is suggested that both sessions incorporate visible ASIS and PSIS markers to more accurately assess the presence of pelvic drop.

Tibial rotation is another important component of risky movement patterns since rotational movement of the lower leg coupled with KAbM increase the stress on the ACL and may also facilitate lateral displacement of the patella (Cooke et al., 1990; Kanamori et al., 2002; Olsen et al., 2004; Shin et al., 2011; Tiberio, 1987; Tonnis & Heinecke, 1999). While this SL-LESS item demonstrated good reliability, only one subject was scored with an error, most likely due to the requirement of 30º or either internal or external rotation. Similar to knee flexion displacement, this cutoff may not be suitable to identify individuals, but more research is needed to determine the magnitude of tibial rotation that increases ones risk of injury.

Limitations

There were several limitations to this study. As stated above, the presence of natural lighting during certain data collections resulted in darkness of several of the video, making it slightly more difficult to evaluate them. Future studies should focus on determining the appropriate exposure for each session or better control the presence of nature light.

A major limitation of this study was the sample size. Due to the time constrains of this study data on only 28 participants was obtained, which in conjunction with the homogeneity of the participants, made it unlikely to achieve a high statistical power.

A final limitation of this study is related to the environment of testing. While the tasks are chosen to reflect sport-specific movements the laboratory environment does not reflect the actual environments where injuries occur. It is known that the external environment is a major factor in lower extremity injuries; however difficultly replicating this situation is a common limitation of most laboratory studies and is difficult to control for.

Clinical Implications and Future Research

The development of the SL-LESS would lead to clinical use in screening for unilateral landing mechanics was well as side-to-side comparisons for injury risk, pre/post training, and return to play decisions.

Future research should perform further item analysis of the scoring tool in order to make adjustments and improve the validity and reliability of the tool in predicting KAbM. It is suggested that future research implement the use of an overhead goal, such as the Vertec, or provided participants with jump performance feedback to shift the attentional focus away from the landing. This could potential produce results that are more representative of the movement patterns demonstrated in real life sports activities.

More research is also suggested to evaluate the SL-LESS within the athletic population, since this a population that could benefit the most from the knowledge provided by the tool.

Conclusion

There was no difference in KAbM between the “good” and “poor” SL-LESS groups, although the “poor” group was trending towards larger moments. Additionally, the SL-LESS demonstrated fair interrater reliability and good test-retest reliably. The results of this study indicate that while this initial version of the SL-LESS may not predict KAbM, it provides the basis for a new single-leg, whole body analysis that future studies can build upon. The suggestions provided in this study to overcome several of its limitations and improve both the SLDVJ task and the SL-LESS may aid in developing a more sports specific 2D assessment tool that can facilitate widespread field screening of knee injury risk.

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Appendix A: Consent Form

UNIVERSITY OF WISCONSIN – MILWAUKEE
CONSENT TO PARTICIPATE IN RESEARCH

THIS CONSENT FORM HAS BEEN APPROVED BY THE IRB FOR A ONE YEAR PERIOD

1. General Information

Study Title:
The Development of the Single-Leg Landing Error Scoring System (SL-LESS) for Lower Extremity Movement Screening

Person in Charge of Study (Principal Investigator):
The Principal Investigator (PI) for this study is Jennifer Earl-Boehm, Ph.D., LAT. Dr. Earl-Boehm is a faculty member in the Department of Kinesiology and is the Director of the Athletic Training Education Program. The Co-PI on this study is Maegan O'Connor.

2. Study Description

You are being asked to participate in a research study. Your participation is completely voluntary. You do not have to participate if you do not want to.

Study description:
The purpose of this study is to test a new jumping evaluation test, the single-leg landing error scoring system (SL-LESS), and to identify how good it might be to evaluate individuals who may be at a greater risk of knee injury.

This study is being done to obtain information regarding the ability of the SL-LESS, an observational screening tool, to be used for widespread injury screening in hopes of identifying individuals who may benefit from preventative training programs to decrease their risk of injury. Data will be collected in order to study how performance during a single-leg task relates to loading at the knee joint during landing, a known risk factor of knee injury.

The study will take place in the Neuromechanics Laboratory (Enderis 132) at the University of Wisconsin-Milwaukee. Approximately 60 subjects will participate in the first session (~30 minutes) of this study. Of these, 30 will be chosen based on their SL-LESS score to return for a second session (~60 minutes). You will be informed via email within 48 hours if you need to return for a second testing session.

3. Study Procedures

What will I be asked to do if I participate in the study?
If you agree to participate you will be asked to report to the Neuromechanics Laboratory (Enderis 132) at the University of Wisconsin-Milwaukee for the initial testing session. A select number of participants, based on SL-LESS score, will be contacted by email within 48 hours after the initial testing session and asked to return to the laboratory to complete a second session.

Day 1 (~30 minutes)

- You will be asked several questions about your history of injury to the lower extremity, and if you are pregnant.
- Your name and preferred email will be recorded into the participant key and will be linked to your unique participant ID code under which all of your data will be saved.
- Data including your age, date of birth, and height will be collected.
- For the standardized warm-up you will:
    - Lightly jog on a treadmill at a self-selected pace for 5 minutes
    - Perform 2 sets of 8 repetitions of two-leg squat
    - Perform 2 sets of 5 repetitions of two-leg maximum jumps
- To practice the single-leg drop vertical jump (SLDVJ) you will:
    - Be given verbal instructions and a demonstration of the jump
    - The task will begin by standing on a 20 cm box on one leg. You will then jump out and off the box onto a force plate that is located a distance of 25% of your height. You will land on that same single leg and immediate progress into a maximal vertical jump with your arms moving freely. The final landing from the vertical jump will not be analyzed and you can land however you feel comfortable.
    - You will then complete 3-4 practice trials. You will choose the leg you feel most comfortable performing the task on during the data collection.
- Adhesive markers will be placed on your shoulder, hip, knee, shin, and toe to aid in data analysis
- Data collection
    - You may perform 2-3 additional practice trials if you would like to, then 3 SLDVJ trials will be completed and recorded to allow for two-dimensional (2D) analysis. A trial will have to be repeated if you lose your balance.
- Video recordings of the entire body, including the face, will be collected during the SLDVJs for data analysis purposes. For this reason if you refuse to be recorded you will not be able to participate in this study.

Day 2 (~60 minutes)

- If you are asked to return for a second session, it will be scheduled at your earliest convenience, but no sooner than 48 hours after initial session
- Your weight will be recorded and then you will perform the same warm-up as on Day 1
    - Reflective markers for three-dimensional (3D) motion capture in addition to the adhesive markers for 2D analysis will be placed on the body. Pads containing reflective markers will be attached to your foot, shin, thigh, and hip with adhesive tape, elastic wrap and sticky spray. These markers are used to record the movement of your joints.
- Data collection
    - 5 valid SLDVJ trials will be completed
- Video recordings of your entire body, including your face, will be collected during the SLDVJs for data analysis purposes. For this reason if you refuse to be recorded you will not be able to participate in this study.

4. Risks and Minimizing Risks

What risks will I face by participating in this study?

Physical Risks

- Muscle soreness as a result of testing (unlikely)
- Musculoskeletal injuries such as muscle strain as a result of testing (unlikely)
- Musculoskeletal injuries to the ankle of knee as a result of the SLDVJ (unlikely)
- Minor skin irritation due to spray tape adhesive or tape (unlikely)

Protection of Physical Risks

- The inclusion and exclusion criteria were established to help decrease the risk of these injuries

- To reduce the above risks, you will be allowed to practice all tests prior to data collection until you feel comfortable with the task. If you feel any soreness or strain while participating in this study, please tell the investigators as soon as possible. You will you initial be provided care by investigators, who are all certified in first aid and CPR, and will then be referred to the Norris Health Center (student) for follow-up care or your personal physician (non-students) for follow-up care.

Psychological or Social Risks

- None

Risk to Privacy and Confidentiality:

- Since your private information will be collected for this study, there is always a risk of breach of confidentiality (less than 1%).

Protection of Risk to Privacy and Confidentiality

- All data will be stored in a locked filing cabinet in a locked room. All data will be given a letter and number that is uniquely associated with you. This code will not contain any partial identifiers (i.e. last four digits of your SSN) and will be stored in a separate locked office in a locked filing cabinet. No identifiers will be stored with the research data. Only those individuals with an active role in this study will have access to the research data and only the PI and Co-PI will have access to identifying information. When all participants complete active participants in the study and data collection is completed, the code will be destroyed. All appropriate measures to protect your private information will be taken.

5. Benefits

Will I receive any benefit from my participation in this study?
Following data analysis, you will be provided with an individualized report that contains information regarding your performance on the SL-LESS as well as recommendations based on these results to reduce your risk of knee injury. You will be contacted by email when their reports are complete. You can choose to receive the report via email or standard mail.

6. Study Costs and Compensation

Will I be charged anything for participating in this study?
You will not be responsible for any of the costs from taking part in this research study.

Are subjects paid or given anything for being in the study?
You will receive a $10 gift card following the completion of each testing session.

7. Confidentiality

What happens to the information collected?
All information collected about you during the course of this study will be kept confidential to the extent permitted by law. We may decide to present what we find to others, or publish our results in scientific journals or at scientific conferences. Information that identifies you personally will not be released without your written permission. Only the PI and the Co-PI will have access to the information. However, the Institutional Review Board at UW-Milwaukee or appropriate federal agencies like the Office for Human Research Protections may review this study's records.

All information will be coded and stored in a locked file cabinet. The participant key that links the identifiable data (participant's name and email) and the participant code will be stored separately and will be destroyed when the study is complete. The data will be stored for 10 years for future use.

Video files will be coded and stored on a password protected computer. Video files will be retained in order to supplement data and results during presentations. Any video files used for this purpose will be completely de-identified by blocking or hiding the face prior to presentations. Only video files that can be completely de-identified will be used.

8. Alternatives

Are there alternatives to participating in the study?
There are no known alternatives available to you other than not taking part in this study.

9. Voluntary Participation and Withdrawal

What happens if I decide not to be in this study?
Your participation in this study is entirely voluntary. You may choose not to take part in this study. If you decide to take part, you can change your mind later and withdraw from the study. You are free to not answer any questions or withdraw at any time. Your decision will not change any present or future relationships with the University of Wisconsin Milwaukee. If you chose to withdraw, we will use the information collected to that point. If you are students, your refusal to take part in the study will not affect your grade or class standing.

10. Questions

Who do I contact for questions about this study?
For more information about the study or the study procedures or treatments, or to withdraw from the study, contact:

Jennifer Earl-Boehm, Ph.D, LAT
Department of Kinesiology
PO Box 413, Milwaukee, WI 53201
414-229-3227

Who do I contact for questions about my rights or complaints towards my treatment as a research subject?
The Institutional Review Board may ask your name, but all complaints are kept in confidence.

Institutional Review Board
Human Research Protection Program
Department of University Safety and Assurances
University of Wisconsin – Milwaukee
P.O. Box 413
Milwaukee, WI 53201
(414) 229-3173

11. Signatures

Research Subject's Consent to Participate in Research:
To voluntarily agree to take part in this study, you must sign on the line below. If you choose to take part in this study, you may withdraw at any time. You are not giving up any of your legal rights by signing this form. Your signature below indicates that you have read or had read to you this entire consent form, including the risks and benefits, and have had all of your questions answered, and that you are 18 years of age or older.

____
Printed Name of Subject/ Legally Authorized Representative

____ ____________________
Signature of Subject/Legally Authorized Representative Date

Research Subject's Consent to Audio/Video/Photo Recording:

It is okay to videotape me while I am in this study and use my videotaped data in the research.

Please initial: _____Yes _____No

Principal Investigator (or Designee)
I have given this research subject information on the study that is accurate and sufficient for the subject to fully understand the nature, risks and benefits of the study.

____ ____________________
Printed Name of Person Obtaining Consent Study Role

____ ____________________
Signature of Person Obtaining Consent Date

Appendix B: Recruitment Flyer

Evaluating leg biomechanics while jump-landing: A research study

University of Wisconsin – Milwaukee
Neuromechanics Laboratory, END 132

Title: The Development of the Single-Leg Landing Error Scoring System (SL-LESS) for Lower Extremity Movement Screening

Purpose: Leg biomechanics when landing from a jump are known to be related to knee injury. The purpose of this study is to investigate the validity and reliability of the single-leg landing error scoring system (SL-LESS). One day this may be helpful to identify people who are at risk for injury.

Participant requirements?

- Females, ages 18 to 30
- Participate in physical activity a minimum of 30 minutes, 3-4 times per week
- No history of injury to the back or lower extremities in the past six months
- No history of previous surgery to the back or lower extremities
- No current pain the back or lower extremities
- Not Pregnant

What will I do?

Day 1: Initial Screening (~30 minutes)	Day 2: Follow-up Session (~60 minutes)
• Complete questionnaires • Warm-up • 2D data collection of single-leg drop vertical jump trials	• A select number of participants from day 1 will be asked to return and complete the follow-up session • Warm-up • 2D and 3D data collection of single-leg drop vertical jump trials

Benefits to you?

Following each testing session you will receive a $10 gift card. Additionally, you will be provided a report containing your individual results and recommendations for reducing your risk of future knee injury.

Questions? Please contact **Maegan O'Connor** at **oconno64@uwm.edu**.

This research project has been approved by the University of Wisconsin-Milwaukee Institutional Review Board for the Protection of Human Subjects (IRB Protocol Number 15.310, approved on 05/01/2015)

Appendix C: Screening and Health History Questionnaire

SCREENING & HEALTH HISTORY

(To be read by research assistant) To make sure that you are eligible for this study, I need to ask you several questions about your legs and related medical history. Is this okay with you? Please listen carefully and answer to the best of your ability. If you don't understand a question please ask. This information will not be recorded or used for research purposes unless you are eligible, and consent to be in the study.

INCLUSION:

Y N Are you between the ages of 18 and 30?

Y N Are you physically active at least 30 minutes a day, 3-4 days per week?

EXCLUSION:

Y N Have you had any injury to the back or lower extremities in the past 6 months?

Y N Have you ever had surgery on the back or lower extremities?

Y N Do you currently have pain the back or lower extremities?

Y N Are you pregnant or do you have reason to believe that you may be pregnant?

OTHER:

Y N Do your ankles ever feel unstable when cutting or jumping?

Y N Do you participate in activities that involve jumping/cutting (i.e., basketball, volleyball, soccer, dance)?

Y N Have you ever participated in any formal jumping or landing training with a sport or other activity?

What is your level of activity participation?

Recreational Club/Organized Team Collegiate Team Other

Comments:

Appendix D: Data Collection Sheet

DATA COLLECTION FORM **ID Code:** _______________

Session 1 Date: __________/__________/__________
Month Day Year

Date of Birth: __________/__________/__________ **Age:** ____________
Month Day Year

Height (cm): ____________ **25% Height (cm):** ____________

Preferred Leg: R L

SL-LESS Scoring Day 1:

MO Score: __________ Good Moderate Poor

JEB Score: __________ Good Moderate Poor

Session 2 Date: __________/__________/__________
Month Day Year

Weight (N): __________

BMI (kg/m^2): __________

SL-LESS Scoring Day 2:

MO Score: __________ Good Moderate Poor

Appendix E: Post-Testing Questions

POST-TESTING QUESTIONS

How difficult did you find the SLDVJ task? What was difficult about it? Was it too easy?

Did you have any discomfort while performing the task?

Did you have any suggestions on improving the instructions that were given?

Appendix F: Landing Error Scoring System Items

LESS Item	Definition	Camera View	Error Condition	LESS Score
1. Knee flexion angle at initial contact	At the time point of initial contact, if the knee of the test leg is flexed more than 30º, score YES. If the knee is not flexed more than 30º, score NO.	Side	No	Y=0 N=1
2. Hip flexion angle at initial contact	At the time point of initial contact, if the thigh of the test leg is in line with the trunk then the hips are not flexed and score NO. If the thigh of the test leg is flexed on the trunk, score YES.	Side	No	Y=0 N=1
3. Trunk flexion angle at initial contact	At the time point of initial contact, if the trunk is vertical or extended on the hips, score NO. If the trunk is flexed on the hips, score YES.	Side	No	Y=0 N=1
4. Ankle plantar-flexion angle at initial contact	If the foot of the test leg lands toe to heel, score YES. If the foot of the test leg lands heel to toe or with a flat foot, score NO.	Side	No	Y=0 N=1
5. Knee valgus angle at initial contact	At the time point of initial contact, draw a line straight down from the center of the patella. If the line goes through the midfoot, score NO. If the line is medial to the midfoot, score YES.	Front	Yes	Y=1 N=0
6. Lateral trunk flexion angle at initial contact	At the time point of initial contact, if the midline of the trunk is flexed to the left or the right side of the body, score YES. If the trunk is not flexed to the left or right side of the body, score NO.	Front	Yes	Y=1 N=0
7. Stance width – Wide	Once the entire foot is in contact with the ground, draw a line down from the tip of the shoulders. If the line on the side of the test leg is inside the foot of the test leg then greater than shoulder width (wide), score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Yes	Y=1 N=0
8. Stance width – Narrow	Once the entire foot is in contact with the ground, draw a line down from the tip of the shoulders. If the line on the side of the test leg is outside of the foot then score less than shoulder width (narrow), score YES. If the test foot is internally or externally rotated, grade the stance width based on heel placement.	Front	Yes	Y=1 N=0
9. Foot position – Toe In	If the foot of the test leg is internally rotated more than 30º between the time period of initial contact and max knee flexion, then score YES. If the foot is not internally rotated more than 30º between the time period of initial contact to max knee flexion, score NO.	Front	Yes	Y=1 N=0
10. Foot position – Toe Out	If the foot of the test leg is externally rotated more than 30º between the time period of initial contact and max knee flexion, then score YES. If the foot is not externally rotated more than 30º between the time period of initial contact to max knee flexion, score NO.	Front	Yes	Y=1 N=0

11. Symmetric initial foot contact	If one foot lands before the other or if one foot lands heel to toe and the other lands toe to heel, score NO. If the feet land symmetrically, score YES.	Front	No	Y=0 N=1
12. Knee flexion displacement	If the knee of the test leg flexes more than 45º from initial contact to max knee flexion, score YES. If the knee of the test leg does not flex more than 45º, score NO.	Side	No	Y=0 N=1
13. Hip flexion at max knee flexion	If the thigh of the test leg flexes more on the trunk from initial contact to max knee flexion angle, score YES.	Side	No	Y=0 N=1
14. Trunk flexion at max knee flexion	If the trunk flexes more from the point of initial contact to max knee flexion, score YES. If the trunk does not flex more, score NO.	Side	No	Y=0 N=1
15 Knee valgus displacement	At the point of max knee valgus on the test leg, draw a line straight down from the center of the patella. If the line runs through the great toe or is medial to the great toe, score YES. If the line is lateral to the great toe, score NO.	Front	Yes	Y=1 N=0
16. Joint displacement	Watch the sagittal plane motion at the hips and knees from initial contact to max knee flexion angle. If the subject goes through large displacement of the trunk, hips, and knees then score SOFT. If the subject goes through some trunk, hip, and knee displacement but not a large amount, then AVERAGE. If the subject goes through very little, if any trunk, hip, and knee displacement, then STIFF.	Side	Average or Stiff (double penalty for Stiff)	Soft=0 Avg=1 Stiff=2
17. Overall impression	Score EXCELLENT if the subject displays a soft landing and no frontal plane motion at the knee. Score POOR if the subject displays a stiff landing and large frontal plane motion at the knee. All other landings, score AVERAGE.	Side, Front	Average or Poor (double penalty for Poor)	Ex=0 Avg=1 Poor=2

Appendix G: SL-LESS Scoring Sheet

	ID:	Trial 1	Trial 2	Trial 3	Score
Sagittal View	**1. Forward Trunk Flexion at IC** Trunk NOT flexed	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	2. Knee Flexion at IC < 30° flexion	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	3. Ankle Plantarflexion at IC Lands heel to toe or flat foot	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	4. Forward Trunk Flexion Displacement Trunk DOES NOT flex more than at IC	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	5. Knee Flexion Displacement < 30° more flexion after IC	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	6. Ankle Dorsiflexion Displacement Heel DOES NOT touch the ground	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
Frontal View	**7. Knee Valgus at IC** Knee medial to great toe	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	8. Lateral Trunk Flexion at IC Trunk NOT vertical	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	9. Knee Valgus Displacement Knee moves medial to great toe	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	10. Contralateral Pelvic Drop Contralateral drops below ipsilateral	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
	11. Tibial Rotation > 30°ER or IR	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	◯ **No Error** ◯ **Error**	
			OVERALL SCORE		