THE VALIDITY AND RELIABILITY OF THE VAIL SPORT TEST™ AS A MEASURE OF PERFORMANCE FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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BY

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DEDICATION

I dedicate this work to my family.

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ABSTRACT

JOSEPH HANNON

The VALIDITY AND RELIABILITY OF THE VAIL SPORT TEST™ AS A MEASURE OF PERFORMANCE FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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Background: The purposes of this study were to determine the convergent construct and external validity of the Vail Sport Test™. An additional purpose of this study was to determine the between-day test-retest reliability of the Vail Sport Test™.

Methods: Following clearance from their surgeon, forty-eight participants who previously underwent anterior cruciate ligament reconstruction (ACL-R) completed this study. All participants performed the Vail Sport Test™ in a clinical laboratory setting while being graded by an experience rater. Simultaneously, their performance was recorded by an 8-camera three-dimensional (3D) motion capture system time-synchronized with two force plates. A subset of participants returned between 2–7 days to repeat the Vail Sport Test™. Construct validity was assessed by comparing the scores collected visually to those obtained by analyzing post-capture 3D kinematic data. Additionally, the visual scores were compared to the scores on the International Knee Documentation Committee short form (IKDC). External validity was assessed by comparison of both the operated and uninvolved limb scores between those individuals who passed the Vail Sport Test™ and those who failed. A score of 46 out of 54 was used as the cutoff score for pass or fail. Five separate

Wilcoxon signed ranked tests ($\alpha = 0.01$) were used for comparisons and Pearson correlation coefficients were calculated to determine the relationships. Lastly, between-day test-retest reliability was assessed by comparing the visual scores of the operated and uninvolved limb collected on two separate sessions using intraclass correlation (ICC).

Results: There was no significant difference between the scores collected visually and those collected post capture for the operated limb ($p = 0.013$). There was a significant difference between scores for the uninvolved limb ($p = 0.006$). In addition, a moderate correlation was found between the scores collected visually and those determined post-capture on the operated limb ($r = 0.55$) and uninvolved limb ($r = 0.46$). Further, there was no significant difference between the scores collected visually and those of the IKDC ($p = 0.814$). However, a fair correlation was found between the two sets of the scores ($r = 0.20$). When comparing between limbs, there was no significant difference between the operated and uninvolved limb in the pass group ($p = 0.173$) or the fail group ($p = 0.465$). Lastly, good between-day test-retest reliability (ICC = 0.787) was found for the operated limb, but fair reliability (ICC = 0.485) for the uninvolved limb.

Conclusion: The Vail Sport Test™ demonstrated good convergent construct validity on the operated limb, good external validity on both the operated and uninvolved limb, and good between-day reliability on the operated limb. From a clinical perspective, the results of this study partially support the validity and reliability of the Vail Sport Test as a measure of readiness to return to play following ACL-R when used to assess the operated limb.

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CHAPTER I

INTRODUCTION

Anterior cruciate ligament (ACL) disruption is a common cause of knee instability and dysfunction, with a reported incidence of 81 cases per 100,000 (Frobell, Lohmander, & Roos, 2007). In addition, it is reported that up to 250,000 ACL reconstructions (ACL-Rs) are performed each year in the United States (Oro et al., 2011), with over 50% of cases involving patients between the ages of 15–25 who practice sports (Griffin et al., 2006). Given the high rate of injury and subsequent surgery, ACL injury, reconstruction and rehabilitation have been topics of interest amongst clinicians and researchers for years. Of current interest in the rehabilitation of individuals who sustain an ACL injury are the suspected neuromuscular control deficits seen both pre-injury and post-surgery in these individuals. Deficits in neuromuscular control and strength of stabilizing muscles around the knee have been shown to place an increased stress on the ACL and potentially predispose athletes to injuries (Griffin et al., 2000; Griffin et al., 2006).

Rehabilitation following ACL-R involves a lengthy process before a patient can return to his or her sport. Typical duration for rehabilitation and return-to-sport is approximately 6–9 months, but this may vary depending upon the patient's pain level and reported level of function (Van Grinsven, Van Cingel, Holla, & Van Loon, 2010). Although treatment for this injury places a heavy focus on strengthening, there is no gold standard for the types of exercises necessary for full restoration of function (Van Grinsven et al., 2010). Decreased strength and altered mechanics at the hip and knee are thought to predispose individuals to ACL re-injury by placing them in a position of risk (Alentorn-Geli et al., 2009b; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007a). Determination of a patient's readiness to return to sport following ACL-R is somewhat vague and often difficult to assess. If the patient has regained full range of motion (ROM), improved strength in their operated limb, and reports favorable outcome scores and no pain, the surgeon may give a release for return-to-sport. Although this may seem like a logical progression following this type of surgery, the patient may have underlying functional deficits that have not been identified during the course of rehabilitation. Likewise, if a patient returns to sport too quickly, the risk of re-injury increases. Therefore, it is critical that there be reliable and valid measures in place for testing a patient's ability to return to sport and for identifying those patients who may not be fully recovered from their surgical procedure.

Currently, a number of return-to-sport tests can be found in the literature and are being implemented in the decision to return an athlete to sport. These include patient's self-reported outcomes (Kanakamedala, Anderson, & Irrgang, 2016; Logerstedt, Lynch, Axe, & Snyder-Mackler, 2013), isokinetic strength testing (Butler, Lehr, Fink, Kiesel, & Plisky, 2013; Garrison et al., 2012; Johnson & Smith, 2001), hop testing (e.g., single hop [Hamilton, Shultz, Schmitz, & Perrin, 2008; Myer, Ford, & Hewett, 2008; Narducci, Waltz, Gorski, Leppla, & Donaldson, 2011], triple hop [Noyes, Barber, & Mangine, 1991], cross-over hop [Hartigan, Axe, & Snyder-

Mackler, 2010], timed hop [Benjanuvatra, Lay, Alderson J, & B.A., 2013], tuck jump [Reid, Birmingham, Stratford, Alcock, & Giffin, 2007]), and balance testing (e.g., balance error scoring system [BESS; Noyes et al., 1991], the lower extremity Y-balance test [Gribble, Hertel, & Plisky, 2012]). Although the above list may seem all encompassing, many flaws continue to exist in the current return-to-sport testing regimen, such as lack of evidence supporting the use of these tests for safe return of injured athletes to sports and lack of test components that challenge functional ability in planes other than the sagittal plane. In a systemic review examining return-to-sport testing, Harris et al. (2014) found that 65% of the studies reviewed did not report the criteria used to determine when an athlete is ready to return to sport (Harris et al., 2014). In summary, the literature cited above shows a smattering of possible tests that are reported with no consistency on which tests are used.

In addition to a varied testing battery, no consensus can be reached on what the appropriate scores on any of these tests is needed to return to sport. For example, the current literature on hop testing symmetry (operated vs. uninvolved) suggests anywhere from 80% – 100% as an acceptable score to return to sport (Grindem et al., 2011; Myer et al., 2011; Noyes et al., 1991; Wilk, Romaniello, Soscia, Arrigo, & Andrews, 1994). Clinically, this difference is significant, especially when taking into account that asymmetries in hop testing have been shown to be an injury risk factor in patients who have undergone ACL-R (Fitzgerald, Lephart, Hwang, & Wainner, 2001). Although the evidence suggests the hop test should remain an important part of the return-to-sport testing protocol, there is still much variability with regard to what is considered an acceptable deficit. The same can be seen with the current literature on strength testing. Numerous studies demonstrate that athletes demonstrate a 20% difference (operated to uninvolved) in quadriceps strength at as far as eight months post-surgery (Xergia, Pappas, Zampeli, Georgiou, & Georgoulis, 2013). This again is significant because most return-to-sport testing is performed at six months after ACL-R. However, a few studies (Schmitt, Paterno, & Hewett, 2012; Xergia et al., 2013) concluded that at six months post-surgery, athletes were allowed to return to sport with a 20% deficit in quadriceps strength, whereas other researchers suggested that no more than a 10% deficit should be acceptable at time of return-to-sport (Wilk et al., 1994).

This variability in acceptable deficits is seen across many of the current return-to-sport tests. However, this does not necessarily mean that these tests are invalid tests. The current best practice approach for return-to-sport testing is to include a measure of ROM, balance, strength, and power. Although the above-mentioned tests are used in attempt to objectively measure an athlete's readiness to return, there is still a large subjective component in these tests. Further, lack of standardization across clinicians in implementing and interpreting the tests weaken their utility.

In addition to the issues associated with utilizing and interpreting the above-mentioned tests, these tests also lack a major component of returning to sport safely, namely neuromuscular control. Current literature suggests that rehabilitation following ACL-R shoulder not only include emphasis on ROM, strength, and power, but also should focus on neuromuscular control (Gribble et al., 2012). A phrase currently seen in the literature regarding neuromuscular control is *quality of movement*, describing how well an athlete moves within the context of a given task. For example, the landing error scoring system (LESS) is a test that considers the quality of movement (Padua et al., 2011; Padua et al., 2009). During this test, the athlete is judged as they perform a double-leg landing maneuver from a box. Although this test is a good screening tool to assess landing technique and to observe movement faults during a double-leg landing, it does not have great usefulness as a return-to-sport test, as the majority of ACL injuries occur when the athlete plants, cuts, decelerates, or lands on one leg. Recent literature suggests that during a double-leg landing task, the operated limb demonstrates different forces in regards to vertical ground reaction forces and ankle, knee, and hip moments (Benjanuvatra et al., 2013). The uninvolved limb can often compensate for potential deficits of the rehabilitated knee, suggesting that a more appropriate testing protocol would examine single limb landing technique.

In addition to all of the above flaws regarding return-to-sport testing, athletes often are non-fatigued during most of the above return-to-sport tests (Bien & Dubuque, 2015). Literature has demonstrated that as athletes fatigue, their neuromuscular control decreases and unsurprisingly, their injury risk increases (Borotikar, Newcomer, Koppes, & McLean, 2008). This seems to indicate that tests performed in a fatigued state or tests performed with the focus of fatiguing the athlete may be more appropriate for determining readiness to return-to-sport.

As a variety of protocols have been reported in the literature, it is likely that the current return-to-sport testing regimen may be inconsistent in both implementation and interpretation. Due to the inadequacy of available return-to-sports tests, the Vail Sport Test™ was developed to assess an athlete's ability to perform four major sport-specific functional activities (see Appendix A and B): (1) single leg squat, (2) lateral bounding, (3) forward running, and (4) backward running. For each of the test components, a clinician assesses the athlete's joint movements and subjectively judges how well the athlete will perform during these sport specific functional activities and, therefore, identifies points of weakness.

The Vail Sport Test™ is designed to fatigue the athlete by requiring a longer duration of testing as compared to other potential return-to-sport tests and by limiting the allowed rest time. This is done intentionally to fatigue the athlete to best mimic a real sports event. Unlike the LESS and the straight forward hop test, which are performed entirely in the sagittal plane, the Vail Sport Test™ assesses multiple dynamic movements in multiple planes. The Vail Sport Test™ requires the athlete to move through both the frontal and sagittal planes while continuing to go through vertical excursions. Lastly, the Vail Sport Test™ also incorporates external perturbation to the athlete during the testing procedure. Blue and black resistive bands used during the test act as resistance to further challenge the athlete to maintain appropriate trunk and lower extremity positioning (Garrison et al., 2012).

As outlined above, many flaws exist in the current return-to-sport testing batteries, with significant implications in regards to the safe and effective return to sport following ACL-R. The Vail Sport Test™ helps to fill that void by incorporating more of the necessary components for a return-to-sport test while also examining movement quality. The aim of the test is to ensure that the athlete not only can complete all four test components, but also can complete them with good neuromuscular control. The Vail Sport Test™ also incorporates fatigue into the context of the test, thus helping to assess this aspect of injury risk once the athlete returns to sport.

Statement of the Problem

Although a plethora of tests exist to determine when an athlete returns to sport, few are considered to be valid measures (Narducci et al., 2011). Additionally, no prior test examines at the quality of movement the athlete performs. Rather, they assess an objective cut-off score (i.e., distance hopped) and determine if an athlete is ready to return to sport. More recently, researchers and clinicians have begun recommending testing batteries as a means to better assess return-to-sport readiness. However, these multi-test batteries still lack an assessment of the athlete's quality of movement. In contrast, the Vail Sport Test™ does assess the athlete's quality of movement to determine readiness to return to sport; however, its validity in the ACL-R population is undetermined.

Purposes of the Study

The first purpose of this study was to assess the convergent construct validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. A secondary purpose of this study was to determine the external validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. Lastly, the tertiary purpose of this study was to determine the between-day test-retest reliability of the Vail Sport Test™.

Research Questions

The following research questions were addressed in this study:

1. Does the Vail Sport Test™ demonstrate acceptable convergent construct validity?
    a. The convergent construct validity was examined by comparing the scores determined visually in real-time during testing to the scores determined post-capture using a 3-dimensional (3D) motion analysis system. The 3D motion analysis system served as a reference standard. The association between these two sets of scores was examined.
    b. The convergent construct validity was further examined by comparing the scores determined visually in real-time during testing to the scores obtained by the other reference standard, the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC). The association between these two sets of scores also was examined.
2. Does the Vail Sport Test™ demonstrate acceptable external validity?

   To determine the external validity of the Vail Sport Test™, participants were grouped into either a pass or fail group and the scores between operated and uninvolved limbs were examined.

3. What is the between-day test-retest reliability of the Vail Sport Test™?
   To determine the between-day reliability of the Vail Sport Test, a subset of participants returned to repeat the Vail Sport Test™ within 2 to 7 days of the first testing and their scores on the two testing dates were examined.

Hypotheses

Null Hypotheses

1. There were two null hypotheses in regards to convergent construct validity:
   a. There would be no significant difference ($p \geq 0.01$) between the scores determined visually and those determined using a 3D motion system for the Vail Sport Test™ for the operated and uninvolved limbs. In addition, there would be a close association ($r \geq 0.80$) between those two sets of scores.
   b. There would be no significant difference ($p \geq 0.01$) between the Vail Sport Test™ scores determined visually for the operated limb and the IKDC scores. In addition, there would be a close association ($r \geq 0.80$) between those two sets of scores.

2. There would be no significant difference ($p \geq 0.01$) between the scores of the operated and uninvolved limbs in the group that fails the Vail Sport Test™ and there would be a significant difference ($p < 0.01$) between the scores of the operated and uninvolved limbs in the group that passes the Vail Sport Test™. In addition, there would be a close association ($r \geq 0.80$) between the two sets of scores for the "fail" group and there would not be a close association ($r \leq 0.40$) for the "pass" group.
3. The between-day test-retest reliability would not be acceptable with the intraclass correlation coefficient (ICC) < 0.40 (Cicchetti, 1994).

Research Hypotheses

1. There were two research hypotheses in regards to convergent construct validity:
   a. There would be a significant difference ($p < 0.01$) between the scores determined visually and those determined using a 3D motion system for the Vail Sport Test™ for the operated and uninvolved limbs. In addition, the association between those two sets of scores would not be close ($r < 0.40$).
   b. There would be a significant difference ($p < 0.01$) between the Vail Sport Test™ scores determined visually for the operated limb and the IKDC scores. In addition, the association between those two sets of scores would not be close ($r < 0.40$).

2. There would be a significant difference ($p < 0.01$) between the scores of the operated and uninvolved limbs for the group that failed the Vail Sport Test™ and there would not be a significant difference ($p \geq 0.01$) between the scores of the operated and uninvolved limbs for the group that passed Vail Sport Test™. In addition, the association between the two sets of scores would not be close ($r < 0.40$) for the "fail" group and there would be a close association ($r \geq 0.80$) between the two sets of scores for the "pass" group.
3. The between-day test-retest reliability would be good-to-excellent with ICC ≥ 0.75 (Portney & Watkins, 2015).

Operational Definitions

1. *3D motion analysis:* The use of specialized infrared cameras and reflective markers to segment the parts of the human body in an image, track the movement of joints over an image sequence, and recover the underlying 3D body structure to allow analysis of movement (Aggarwal & Cai, 1997).
2. *Resisted single leg squat:* A task in which the participant stood on a single limb and then squatted against the resistance of a resistance band.
3. *Lateral bounding:* A task in which the participant was secured to a stable structure and was required to jump laterally against the resistance of a resistance band. To successfully complete this task, the participant must jump 100% of their leg length, which was measured from the participant's

most prominent portion of the greater trochanter to the floor in a standing position.

4. *Forward running*: A task in which the participant was required to first perform a single leg squat on the operated limb, then jump vertically into the air, and land on the opposite limb with a single leg squat and repeat. Prior to the start of the task, a resistance band was attached to the posterior aspect of the participant's waist line in order to providing a posterior perturbation force.
5. *Backward running:* A task in which the participant was required to first perform a single leg squat on the operated limb, then jump vertically into the air, and land on the opposite limb with a single leg squat and then repeat. Prior to the start of the task, a resistance band was attached to the anterior aspect of the participant's waist line in order to provide an anterior perturbation force.
6. *Operated Limb:* For the purposes of this study, the operated limb referred to the limb in which the participants injured their ACL and subsequently underwent ACL-R.
7. *Excessive anterior tibial translation:* During scoring the post-capture kinematic data of single leg squat, a distance between the tuberosity and toe markers greater than or equal to -0.03 meters on the x-axis (i.e., sagittal plane) was considered excessive for anterior tibial translation. When

excessive anterior tibial translation occurred, a “0” was given for the test criterion of “avoid patella extending past the toe during knee flexion”.

8. *Level-1 or level-2 sports:* A level-1 sport requires jumping, pivoting, and hard cutting (e.g., basketball, football, or soccer). A level-2 sport is one that requires lateral movement but less jumping or hard cutting (e.g., baseball, racket sports, or skiing). Sport must have included activities such as jumping, pivoting, or hard cutting for greater than 50 hours a year (Daniel et al., 1994; Paterno et al., 2010).

Assumptions

1. Participants provided an honest assessment of their condition when completing the IKDC.
2. Participants gave the same effort on the Vail Sport Test™ throughout all required time periods.
3. Participants who were tested on two separate visits for between-day reliability testing gave the same effort on each day.
4. The capture volume and noise were similar for all recordings. To ensure consistent recording, the motion analysis system was calibrated daily following manufacturer’s guidelines. The clinician was able to give consistent instructions during each Vail Sport Test™ for all of the participants.

Limitations

1. There was a potential for inconsistency in marker placement and this may affect the results. To minimize any potential variation, marker placement was standardized and completed by one of the same three testers for each participant.
2. As the tester was assessing bilateral limb motions during tasks which require both limbs, there was a potential for erroneous scoring due to the complexity of monitoring both limbs simultaneously.
3. The patients included in this study were specifically post-ACL-R. Therefore, the results of the study may not be generalizable to other patient populations.
4. As only 10 seconds of data was collected every thirty seconds, there is the potential for missing errors during camera grading.
5. Eligible participants were referred for return-to-sport testing (i.e. Vail Sport Test™) when they were released by the surgeons. Some patients may be ready for the Vail Sport Test™, but were not released by the surgeon.
6. Only patients who were cleared for testing by their surgeon were recruited for this study. This could result in a skewed sample of participants who might have achieved adequate functional levels as assessed by other clinical measures, thus resulting in their release for return-to-sport.

Significance of the Study

The current return-to-sport criteria following ACL-R are inconsistent and varied across the literature. Current literature supports the notion that much improvement in return-to-sport testing is needed to ensure a safe return to sport without subsequent re-injury or injury on the opposite side. This study examined whether the Vail Sport Test™ is a valid tool which clinicians can use to assess readiness to return to sport. As one of the only available tests to examine quality of movement, the findings of this study could provide a more detailed and comprehensive assessment for clinicians who are determining an athletes' readiness to return to sport.

CHAPTER II

REVIEW OF THE LITERATURE

The purpose of this study was to assess the convergent construct validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. A secondary purpose of this study was to determine the external validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. Lastly, the tertiary purpose of this study was to demonstrate the between-day test-retest reliability of the Vail Sport Test™. This literature review explored the epidemiology of ACL injuries and return-to-sports rates, mechanism of injury, current return-to-sport tests and test batteries, and the use of 3D motion analysis systems capturing movement in relation to this study.

Epidemiology of ACL Injuries

The incidence of ACL injuries has risen dramatically over the past two decades, especially in the young active population (LaBella et al., 2014). The accurate tracking of ACL injuries and reconstructions can be difficult as some studies reported incidence rates per 1,000 athletic exposures, whereas others reported incidence rates per 100,000 persons/year (Gianotti, Marshall, Hume, & Bunt, 2009; Hootman, Dick, & Agel, 2007; Moses, Orchard, & Orchard, 2012; Orchard & Seward, 2002; Prodromos, Han, Rogowski, Joyce, & Shi, 2007; Waldén, Hägglund, Magnusson, & Ekstrand, 2011). Larger outcome studies tend to use incidence per 100,000 persons whereas smaller epidemiological studies examine exposures

(Moses et al., 2012). Although both are considered accurate measures, this makes combining data across studies difficult. A systematic review by Moses et al. (2012) combined incidence rates by exposures and by 100,000/persons by converting exposures to rates per 100,000/year in Australia. They reported that the annual ACL injury incidence rates for professional athletes (ranging from 0.15% to 3.67%) were substantially higher than the national population rates (median rate of 0.03%). These percentages are expressed as a percentage of 100,000 persons, and these results are consistent with other studies which reported a higher incidence of ACL injuries in the athletic population. In the United States, the current estimated number of ACL injuries is between 100,000 and 200,000 annually (Ahldén et al., 2012). With high incidence rates, medical expense for ACL injuries is also increasing, becoming a burden on the United States health care system, with annual costs exceeding $625 million dollars (Sadoghi, von Keudell, & Vavken, 2012).

Hootman et al. (2007) examined 16 years of collegiate injury data through the National Collegiate Athletic Association Injury Surveillance System and compiled data for 16 sports (8 men's and 8 women's) (Hootman et al., 2007). Hootman et al. found that injury rates were statistically significantly higher in games (13.8 injuries per 1000 exposures) than in practices (4.0 injuries per 1,000 exposures), and preseason practice injury rates (6.6 injuries per 1,000 exposures) were significantly higher than both in-season (2.3 injuries per 1,000 exposures) and post-season (1.4 injuries per 1,000 exposures) practice rates. No significant change in game or practice injury rates was noted over the 16 years. More than 50% of all injuries were to the lower extremity. Ankle ligament sprains were the most common injury of all sports, accounting for 15% of all reported injuries. Rates of concussions and anterior cruciate ligament injuries increased significantly (average annual increases of 7.0% and 1.3%, respectively) over the sample period. These results demonstrate that the lower extremity is an area of high injury risk in the athletic population and supports the notion that ACL injuries are rising in the athletic population.

In the study by Hootman et al. (2007), ACL injury rates were highest in men's spring football and women's gymnastics (33 per 100 000 athlete - exposures). In women's sports, ACL injury rates represented a larger proportion of total injuries than in men's sports (3.1% vs. 1.9%), with women's basketball and women's gymnastics topping the list at 4.9% of total injuries. These findings support other studies that consistently reported a higher incidence of ACL injuries in females than males per athletic exposures (Griffin et al., 2000; Hewett, Myer, & Ford, 2006). However, it is important to note that males sustain more overall absolute ACL injuries; although, females sustain a higher rate of ACL injuries per athletic exposures.

Similar work has been done in the high school population. The National High School Sports Related Injury Surveillance Study has compiled data on the incidence of ACL injuries in 18 sports over a 5 year period (Swenson, Yard, Collins, Fields, & Comstock, 2010). The studies reported that ACL injury rates were highest in girls' soccer and boys' football (11.7 and 11.4 per 100,000 athlete-exposures, respectively) (Hootman et al., 2007; Swenson et al., 2010). This finding is again consistent with other reported data, demonstrating increased ACL incidence in female athletes (Griffin et al., 2000; Hewett et al., 2006).

The above literature is specific to primary or first-time ACL injury. Unfortunately, continued research has begun to identify the high re-injury rate following primary ACL-R. A systematic review by Wiggins et al. (2016) reported on the risk of secondary injury following ACL injury in young athletes. Wiggins et al. included 19 studies in their review with a total number of 72,054 subjects pooled across the studies. Overall, the total second ACL re-injury rate was 15%, with an ipsilateral re-injury rate of 7% and contralateral injury rate of 8%. The secondary ACL injury rate (ipsilateral and contralateral) for patients younger than 25 years was 21%. The secondary ACL injury rate for athletes who returned to a sport was 20%. Combining these risk factors, athletes younger than 25 years who returned to sport had a secondary ACL injury rate of 23%. These high re-injury rates potentially indicate serious flaws in our return-to-sport criteria. In conclusion, Wiggins et al. (2016) suggested that modifications to return-to-sport guidelines may have great potential to reduce re-injury risk and improve performance after ACL-R.

To summarize the epidemiological findings of ACL injuries, it is clear that despite a plethora of research, these injuries continue to be prevalent in our society. Younger and more active individuals are clearly at a higher risk, and women are at a greater risk than men. The continued high rate of both primary and secondary ACL injuries and reconstructions warrant continued research to allow for better rehabilitation of these athletes.

Mechanism of Injury

To better appreciate the epidemiological injury data, a brief review of the mechanism of ACL injuries is necessary. ACL injuries occur most often when the athlete decelerates suddenly such as during cutting and landing maneuvers (Pappas, Shiyko, Ford, Myer, & Hewett, 2016). To better help explain ACL injury risk, four theories have been developed (Pappas et al., 2016). The ligament dominance theory suggests that female athletes at high risk perform athletic maneuvers with excessive knee valgus, hip adduction and hip internal rotation (Hewett, Ford, Hoogenboom, & Myer, 2010; Hewett et al., 2005). Trunk dominance theory suggests that poor trunk control during athletic maneuvers leads to increased risk for ACL injury (Zazulak et al., 2007a; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007b). Quadriceps dominance theory suggests that excessive relative quadriceps forces or reduced hamstring recruitment place the ACL at high risk for injury. Finally, leg dominance theory suggests that large leg-to-leg asymmetries predispose athletes to injury (Zebis, Andersen, Bencke, Kjær, & Aagaard, 2009). Taken together, these factors consistently have been shown to be prevalent in those individuals who have later sustained an ACL injury (Boden, Dean, Feagin, & Garrett, 2000; Hewett, Torg, & Boden, 2009; Krosshaug et al., 2007).

To expand upon the above theories, movements can be observed in the sagittal, coronal (or frontal), and transverse planes of motion. Many studies have examined the trunk, hip, knee, and ankle flexion angles in the sagittal plane, when performing different tasks (Hewett et al., 2005; Hewett et al., 2009; Pappas et al., 2016; Paterno et al., 2010; Renstrom et al., 2008). In general, increased flexion across the joints during landing allows for more energy absorption and less impact across the knee joint (Alentorn-Geli et al., 2009a). Decreased knee flexion angles during landing places the ACL at increased risk of injury (Renstrom et al., 2008). Whereas some suggest that this is the result of increase vertical ground reaction forces (GRFs) and higher knee extensor moments, others suggest that this has more to do with the anatomy of the ACL. In a knee extended position, the ligament is more perpendicular with the tibial plateau, whereas as with the knee flexed near 90°, the ACL is more parallel to the plateau. The structural makeup of the ACL allows it to withstand tensile loads much better then shear loads (Alentorn-Geli et al., 2009a). In addition, in a more extended position, the anterior tibial shear force during landing is increased (Alentorn-Geli et al., 2009a). The inefficacy of the hamstrings to withstand the anterior shear force in a more extended position is also decreased. All of the above-mentioned factors could help to explain why increased knee flexion during landing maneuvers is an important factor to consider when examining ACL injury risk.

Many studies have examined the knee abduction angle in the coronal plane during dynamic movements to assess for potential injury risk (Chappell, Yu, Kirkendall, & Garrett, 2002; Ford, Myer, Toms, & Hewett, 2005; Hewett et al., 2005; Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007). Faulty movements in this plane are consistently found in the ACL injured population. Hewett and colleagues (2005) found that in a prospective study of 205 female athletes, those who went on to tear their ACL had a higher knee abduction (i.e., valgus) angle during jump-landing. These individuals also had a 2.5 times greater knee abduction moment. Both of these findings indicate difficulty in controlling their lower extremity from collapsing into a valgus position results in increased risk of ACL injury. Additional research has demonstrated that females demonstrate increased knee abduction during stop jumps and cutting tasks more than their male counterparts, further contributing to the higher ACL injury rates in females. The above literature identifies the underlying faulty movements that place the ACL in a position which can result in injury. The above biomechanical findings certainly do not fully explain how or why someone injures their ACL; however, they provide insight into positions that place the ACL at risk and movements that contribute to ACL injury.

When discussing mechanisms of injury associated with ACL injury, the context surrounding the injury must be considered. Although the above literature helps to explain positions which place the ACL at risk for injury, it does not explain how the athlete ends up in that position. Typically, this type of information is referred to as *contact*, *non-contact*, or *indirect contact*. Contact injuries are the result of a direct contacting of the athlete's knee by another player or object. Indirect contact refers to the contacting of another player or object to another part of the athlete, but not to their knee itself. This contact results in positioning of the knee in an at-risk position secondary to the rest of athlete's body. Lastly, non-contact injuries refer to an athlete sustaining an injury free from perturbation or contact of another player or object.

In the context of sport, most non-contact ACL literature comes from research into ACL injuries in female soccer athletes. In this specific group of individuals, non-contact ACL injuries are typically the result of an athlete decelerating or changing directions, landing from a jump with their knee more extended, or pivoting over a fixed foot with their knee extended (Alentorn-Geli et al., 2009a; Boden et al., 2000; Faunø & Wulff, 2006). This typically is associated with challenging an offensive player or jumping in an attempt to head the ball. To further support the pathobiomechanics for ACL injury, Boden et al. (2000) retrospectively reviewed competition video of individuals tearing their ACLs. Boden et al. observed that a position of tibial external rotation near full knee extension, a fixed foot and valgus knee position, during a deceleration movement was common in individuals who injured their ACLs. Given what is known about ACL strain, it is clear that this knee position places large loads across the ACL. Teitz (2001) also used video analysis to study ACL injuries and reported results similar to those of Boden et al. (2000); however, they also reported that the center of mass tended to be away from the base of support when the athlete was decelerating (Boden et al., 2000; Teitz, 2001).

This finding is also supported by Hewett and colleagues (2009) who examined video of landing and cutting tasks in 10 female athletes who injured ACLs and compared them to uninjured female athletes. Hewett et al. (2009) found that female athletes landed with greater lateral trunk motion during ACL injury. This confirmed that the trunk position, at which the center of mass is away from base of support, is an important factor contributing to ACL injuries. Interestingly, Alentorn-Geli et al. (2009a) pointed out that these specific knee and trunk positions were also achieved by those individuals who did not tear their ACL. Therefore, other factors are likely present that place some individuals at risk more than others.

These factors are numerous and range from environmental to anatomical to hormonal to neuromuscular. To completely review all of them is beyond the scope of this dissertation. However, given that the rate for non-contact ACL injuries ranges from 70–84 % and the non-contact injury mechanism by far contributes to the majority of ACL injuries reported in the literature, exploring the pertinent factors related to this study is warranted (Boden et al., 2000; Faunø & Wulff, 2006; Noyes, Mooar, Matthews, & Butler, 1983a; Noyes, Matthews, Mooar, & Grood, 1983b).

Fatigue is another primary factor that would contribute to ACL injury. As the muscles that surround the joint are partly responsible for controlling the movements at that joint, and as these muscles fatigue, it is logical that the body's ability to control these movements will be decreased. Laboratory studies have demonstrated that as muscles fatigue, their ability to absorb energy decreases and their threshold before an injury could occur also decreases (Mair, Seaber, Glisson, & Garrett, 1996). This theory has been shown to hold true in motion analysis studies. Chappell et al. (2005) placed 20 athletes through a fatigue protocol and examined their kinematics during a stop-jump task. Chappell et al. (2005) found that when fatigued, these athletes had significantly increased anterior tibial shear force, increased knee valgus moments, and decreased knee flexion angles.

Nyland (1999) investigated the effects of hamstrings fatigue on transverse plane kinematics during a cutting task. Nyland et al. (1999) reported that those athletes who fatigued demonstrated increased internal rotation during absorption. These studies seem to indicate that an individual's ability to control their knee decreases in a fatigued state, thus potentially resulting in an increased injury risk. However, although the above-mentioned studies by Chappell et al. (2005) and Nyland et al. (1999) demonstrated this point succinctly, other studies that examined muscle activation and timing in fatigued states do not consistently support this point. Nyland (1997) reported that following an eccentric fatigue protocol of the quadriceps and hamstring muscles, female athletes demonstrated delayed quadriceps muscle and earlier gastrocnemius muscle activation during a stop-cut task (Nyland, Caborn, Shapiro, & Johnson, 1997). Nyland et al. (1997) concluded that the gastrocnemius muscle acts a compensatory knee stabilizer during closed-chained activity in a fatigued state.

In contrast, Fleming et al. (2001) reported that the gastrocnemius muscle acts as an antagonist to the ACL (Fleming et al., 2001). During co-contraction with the quadriceps muscle with the knee at 15° and 30° of flexion, greater ACL strain was produced than when either muscle contracts in isolation. These inconsistencies in our understanding of muscle timing and activation seem to indicate that our knowledge of what causes changes in movement during fatigue is incomplete and may indicate that fatigue alone is not responsible for these changes. However, fatigue and cognitive decision-making have been shown to directly impact ACL injury risk (Besier, Lloyd, Ackland, & Cochrane, 2001; Houck, Duncan, & Kenneth, 2006; Pollard, Sigward, Ota, Langford, & Powers, 2006). Borotikar et al. (2008) studied 25 female division one athletes' performance of anticipated and unanticipated cutting tasks in a fatigued and non-fatigued state. They reported that fatigue resulted in increased hip internal rotation at initial contact and increased peak knee abduction angle (Borotikar et al., 2008). These increases were significantly more pronounced in the fatigued-unanticipated condition. In a review paper on non-contact ACL injuries, Alentorn-Geli and colleagues (2008) concluded that fatigue may contribute to other risk factors, but may not be an isolated factor. This is in line with earlier conclusions that one factor alone may not predispose an individual to injury, but rather that a culmination of potential factors may likely contribute.

Rates of Return-to-Sport Following ACL Injury

Due to the large number of ACL injuries in the athletic population, there is an obvious interest in successfully returning these athletes to their competitive sport. However, similarly to the reporting of ACL injury, there are inherent issues with the reporting of return-to-sport rates following ACL injury. First, when examining the data for return-to-sport following ACL injury, it is important to clarify if these individuals have undergone ACL-R or if they sustained an ACL injury and elected not to undergo surgery. Individuals who opt out of surgery are often referred to as copers. Data examining the success of return-to-sport in these copers is limited and vastly differs from those who have undergone ACL-R (Hartigan et al., 2010;

Williams, Buchanan, Barrance, Axe, & Snyder-Mackler, 2005). Hartigan et al. (2010) examined the time line for individuals who underwent ACL-R to successfully return-to-sport and reported that 52% and 22 % were still unable to return to sport at six and 12 months after surgery, respectively. Furthermore, Fink (2001) reported that following ACL injury, those who elected to undergo surgery were able to maintain a higher level of involvement in their sport at five and 10 years following surgery than those who did not (Fink, Hoser, Hackl, Navarro, & Benedetto, 2001). Given the variability between these two groups, this proposed dissertation study elected to examine only those individuals who have undergone ACL-R.

The next issue with examining the return-to-sport data is the varying definitions of return-to-sport and what is considered successful. This is evident with varied phrases such as "return to previous level of competition," "return to pre-injury level," and simply "return-to-play." These variations help to explain the wide range of data reported in the literature which currently ranges from 33% to 92% of individuals returning to sport following ACL-R (Ardern, Taylor, Feller, & Webster, 2012; Ardern, Webster, Taylor, & Feller, 2011b; Colombet et al., 2002; Langford, Webster, & Feller, 2009; Nakayama, Shirai, Narita, Mori, & Kobayashi, 2000). In a study conducted by Shelbourne (2009) on return-to-basketball and return-to-soccer in male and female high school athletes, the authors reported that 87% of the 402 patients in their study returned to basketball and 93% of females and 80% of males returned to soccer after surgery. These results appear extremely promising, especially considering that their average time to return to sport was approximately

5 ± 2 months. However, their classification on return-to-sport was defined as "full participation at a low level in activities pertaining to their primary sport" as reported by the patient (Shelbourne, Sullivan, Bohard, Gray, & Urch, 2009).

In contrast, Ardern et al. (2012) reported different return-to-sport outcomes on 314 subjects between two and seven years following ACL-R. They reported that only 45% were participating in their sport at pre-injury level, 29% were playing competitive sports at all, although 93% had attempted to return to sport after surgery. This is in stark contrast to the results of Shelbourne et al. (2009). While the mean age of the subjects in the two studies varied greatly, with an average age of 15 in Selbourne's' study and 32 in Arden's' study, which could explain some of the differences in their results, the more telling variable is their definition of return-to-sport.

To better standardize terminology, it has been suggested that researchers use the pre-injury sports participation level as a baseline comparison for return-to-sport (Feller & Webster, 2003). This is because research by Corry, Webb, Clingeleffer, and Pinczewski (1999) has shown post-surgery sports participation levels to be lower than pre-injury levels (Corry, Webb, Clingeleffer, & Pinczewski, 1999). Therefore, Ardern et al. (2012) suggested that comparing post-operative sports participation to pre-injury levels may be a more valid method of evaluating the effectiveness of the ACL-R surgery.

In a systematic review and meta-analysis, Ardern (2011a) reviewed 48 studies with a total subject pool of 5,770 (Ardern, Webster, Taylor, & Feller, 2011a).

Ardern et al. (2011a) reported that at an average of 3.5 years following ACL-R, 82% of participants returned to some sports participation, 63% had returned to their pre-injury level of participation, and 44% had returned to competitive sport at final follow-up. The classification system used in the Ardern et al.'s review provides some insight into the actual number of athletes who return to sports.

Return-to-Sport Testing

In addition to the variability of defining return-to-sport, there is perhaps even more discrepancy in when an athlete is cleared to return to sport. In a review, Harris et al. (2014) examined return-to-sport after ACL-R and reported that 65% of the studies they reviewed did not describe which criteria were used in the return-to-sport decision-making process, and only 10% of the studies even indicated whether the subjects were able to return to sport. This lack of reporting makes drawing conclusions based on numerous studies difficult and makes standardizing return-to-sport decisions nearly impossible.

As expected, numerous tests and test batteries exist in the literature for determining an athlete's ability to return to sport. These include patient's self-reported outcomes, isokinetic strength testing (Butler et al., 2013; Garrison et al., 2012; Johnson & Smith, 2001), hop testing (e.g., single hop [Hamilton et al., 2008; Myer et al., 2008; Narducci et al., 2011], triple hop [Noyes et al., 1991], cross-over hop [Hartigan et al., 2010], time hop [Benjanuvatra et al., 2013], tuck jump [Reid et al., 2007]), and balance testing (e.g., balance error scoring system [BESS; Noyes et al., 1991], the Y-balance test [Gribble et al., 2012]).

Strength testing is typically included in the return-to-sport test batteries. When discussing strength testing, it is important to recognize that most literature reported strength measures as a measure of limb symmetry index (LSI), which is the uninvolved limb strength divided by the operated limb strength multiplied by 100, a percentage of the operated to uninvolved limb strength. Typically, it is thought that a LSI of greater than 90% is acceptable; however, much variability exists in what is considered acceptable.

It is thought that restored lower extremity muscle function, such as knee extensor and flexor muscle strength, is important after an ACL-R in order to successfully return to sports (Ageberg, Thomeé, Neeter, Silbernagel, & Roos, 2008; Augustsson, Roland, & Karlsson, 2004; Eitzen, Holm, & Risberg, 2009; Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998; Lee, Seong, Jo, Park, & Lee, 2004; Myklebust, Holm, Mæhlum, Engebretsen, & Bahr, 2003). Multiple studies have identified persistent knee extensor or quadriceps muscle weakness and/or activation deficits in early and late post-operative periods (Hart, Pietrosimone, Hertel, & Ingersoll, 2010; Lepley et al., 2015; Palmieri-Smith, Thomas, & Wojtys, 2008; Pietrosimone, Lepley, Ericksen, Gribble, & Levine, 2013; Snyder-Mackler, Delitto, Bailey, & Stralka, 1995). Specifically, quadriceps muscle strength has been studied extensively from the return-to-sport perspective, and it has been shown that those patients who regain their quadriceps strength have improved outcomes and a faster return-to-sport (Schmitt et al., 2012; Sousa et al., 2015). However, a meta-analysis by Xergia (2011) indicated that patients with bone-patellar tendon-bone autograft have greater deficits in extensor muscle strength and a lower deficit in flexor muscle strength as compared to those with hamstring autograft (Xergia, McClelland, Kvist, Vasiliadis, & Georgoulis, 2011). This is important as surgical literature consistently recommends bone-patellar tendon-bone grafts in the athletic population. This seems to indicate that although quadriceps strength symmetry is important, it also is known to be decreased following ACL surgery, especially following a bone-patellar-bone autograft. The next logical question must be "How much of a deficit is acceptable?"

A systematic review by Barber-Westin (2011) reported that only 25 of the 264 studies included in their review used quadriceps strength as a measure of return-to-sport, and the cut-off scores varied from anywhere between 80 – 90% LSI (Barber-Westin & Noyes, 2011). For a variety of reasons, such as insurance limitations, deconditioning, and continued pain, patients routinely are discharged and subsequently released to return-to-activity with an 80% quadriceps deficit (Hart et al., 2010; Snyder-Mackler et al., 1995), placing these individuals at risk for re-injury of the same or contralateral limb. This discrepancy between what is considered to be adequate to return to sport and when a patient is released raises further concern regarding not only the tests themselves, but also the implementation of them.

Hop testing is seen frequently reported in the literature as measure of readiness to return-to-sport. In the review by Barber-Westin et al. (2011), only 10 of the 264 studies included in their review used distance symmetry of single leg hop as a measure of return-to-sport (Barber-Westin & Noyes, 2011). However, six of these studies used a 90% LSI as a cut-off score. Although 90% is consistently seen in the literature, by no means is this considered the gold standard. Literature regarding hop tests is vast and numerous studies have shown the importance of symmetry on hop test performance. Hamilton et al. (2008) reported on the ability of the triple hop test as a predictor of power, strength, and balance in 40 collegiate male and female soccer players. Hamilton et al. (2008) reported that triple hop distance explained 69.5% of the variance in vertical jump height and 49% of the variance in quadriceps strength. Similarly, Xergia (2015) reported that in 22 male subjects following ACL-R, there was a significant positive correlation between the LSI of the single-limb hop distance and the LSI of the peak extension torque at 120°/s and at 180°/s (Xergia, Pappas, & Georgoulis, 2015). Both of these demonstrate the association of hop tests with other clinical measures used to determine readiness to return to sport.

The next progression of this line of reasoning would then be to determine if hop tests can predict successful return-to-sport. Müeller (2015) examined which factors predict return to pre-injury level following ACL-R (Müeller, Krüger, Franke, Schmidt, & Rosemeyer, 2015). Included in their measures were quadriceps and hamstrings muscle strength tests, hop tests, the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC), and two fear-avoidance questionnaires. Müeller et al. (2015) concluded that the LSI on the single hop for a distance test was the best predictor for successful return-to-sport. This study helps to demonstrate not only that hop testing is correlated with other clinical tests, but that it also may be one of the better predictors of successful return-to-sport. Interestingly, they found a cut-off score of 75.4%, which is well below other reported values. This further shows the variability in the LSI cut-off scores for return-to-sport.

Logerstedt et al. (2012) used logistical regression analysis to identify factors that predicted self-reported knee function at one year following ACL-R. Logerstedt et al. (2012) asked 120 patients to complete four single leg hop tests and the IKDC questionnaire at their six-month time point following ACL-R and then tracked these patients up to their one-year time point. function at one year following ACL-R (Logerstedt et al., 2012). Logerstedt et al. (2012) reported that those individuals who rated themselves as having normal knee function at one year were four times more likely to have a cross-over hop test of 95% LSI or higher than those who considered themselves having non-normal knee function. Likewise, those who rated themselves as having non-normal knee function were five times more likely to have a 6-meter timed hop test below 88% LSI than those who considered themselves as having normal knee function. These results indicate that hop testing has some influence not only on return-to-sport, but also on the athlete’s perception of normal knee function.

To date, literature of strength testing and hop testing has shown inconsistencies with accurate cut-off scores and what is deemed acceptable, resulting in numerous “clinical suggestions” and best practice publications from varied researchers. For example, Bizzini (2012) published a clinical commentary on returning-to-soccer after ACL-R (Bizzini, Hancock, & Impellizzeri, 2012). Bizzini et al. (2012) suggest a 90% LSI for hop tests and a 95% LSI for quadriceps and hamstrings strength. As the literature suggested (Barber-Westin & Noyes, 2011; Hart et al., 2010; Snyder-Mackler, De Luca, Williams, Eastlack, & Bartolozzi, 1994), 95% LSI for knee extension is rarely achieved, especially at six months following ACL-R. Schmitt et al. (2012) reported on 55 high school athletes at six months following ACL-R and classified them as high quadriceps strength (> 90%), and low quadriceps strength (< 85%). Twenty-three of their subjects classified as high quadriceps and 24 as low. The results demonstrated that those in the high quadriceps strength group performed more similar to a healthy control group on single-leg hop tests than the low quadriceps strength group. Additionally, only about half of their subjects classified as high quadriceps strength and their "high" strength group was still less than the cut-off score suggested by Bizzini et al. (2012). These inconsistencies between performance of single-leg hops and quadriceps strength go beyond these two studies and beyond hop testing, but they help to demonstrate that neither hop testing result nor quadriceps strength should be used as the sole criterion for a return-to-sport decision.

Although a plethora of research on return-to-sport testing exists, the implementation and translation of research to the clinic and the field is lacking. Additionally, what all of the above-mentioned tests (e.g., hop testing, strength testing) fail to address is the quality of movement of the athlete. None of the tests thus far have examined how an athlete moves, just simply assessed whether or not they are generating equal forces on both limbs. This is in contrast to the mechanisms of ACL injury reviewed earlier, which clearly identified the movements and positions that often strain the ACL and place an athlete at risk. There is limited research from a clinical standpoint which presents suggestions on examining how an athlete moves in relation to their readiness to sport. Again, there are numerous clinical commentaries and suggestions that state things such as “good neuromuscular control at knee, hip, trunk” as a criteria for progression or clearance, but this is open to interpretation (Bizzini et al., 2012). The only test that attempts to quantify this is the LESS (Padua et al., 2009). This test was developed by Dr. Padua and utilizes an ordinal grading scale to quantify the movement of the subject during a double leg jump-landing. The test requires subjects to jump forward 50% of their height from a 30 cm box. Upon landing, the subjects must complete a maximal vertical jump. They subject is then graded based on 17 readily observable movement errors of the subject’s feet, knee, hips, and trunk. Traditionally, grading is completed at a later time with the use of video-recorded trials. This test has been shown to have good inter-rater reliability and intra-rater reliability (Padua et al., 2009).

Padua et al. (2009) collected data on 2,691 subjects while they performed a jump-landing task. Subjects were scored based on a review of their videotaped performance, and this score was compared to concurrently collected data using 3D motion analysis. They reported that subjects with high LESS scores (> 6) displayed significantly different lower extremity kinematics and kinetics compared to those with low LESS scores (< 4). These identified kinematic and kinetic differences have been associated with ACL injury, including changes of movements in the frontal, sagittal, and transverse planes, and altered vertical GRFs.

One issue with the LESS is that test scores are determined at a later date after video review, making it appropriate as a screening tool, but limiting its clinical utility. To address this concern, Padua (2011) recently assessed the reliability of a modified LESS test, LESS-Real Time (LESS-RT) (Padua et al., 2011). For this modified version, healthy participants completed four trials of the task, allowing raters to grade different aspects of the jump during each trial. Padua et al. reported good inter-rater reliability with $ICC_{2,1} = 0.72 – 0.81$, standard error of measurement (SEM) = 0.69 – 0.79. Padua et al. (2011) concluded that the LESS-RT is a quick, easy, and reliable clinical assessment tool to identify lower extremity injury risk.

A limitation of the LESS and the LESS-RT is that both tests are based on a double leg landing movement. While the International Olympic Committee recently published updated current concepts on non-contact ACL injuries in female athletes and recommended the use of a jump-landing to identify at risk individuals, there is obviously some inherent flaws with this task (Renstrom et al., 2008). As previously discussed, ACL injuries tend to occur during rapid deceleration and change of direction on one limb and the double-leg jump-landing task may not be challenging enough to elicit poor movement patterns. Additionally, it has been shown previously that following an ACL-R, athletes adopt altered movement strategies when completing double leg tasks to compensate for their operated limb (Myer et al., 2011). Myer et al. (2011) reported on the results of 18 male athletes who returned to sport within one year following ACL-R. These athletes were put through a series of tests that included both double-leg and single-leg performance.

Myer et al. (2011) reported that there were not significant differences in those tests which required bipedal performance between the ACL group and age- and sport-matched healthy controls. However, there were significant between-group differences ($p < 0.05$) in tasks that required single limb performance. Myer et al. (2011) suggested that bipedal tests may not be sensitive enough and that single limb tests are recommended to better identify deficits in performance. In conclusion, although the LESS consists of testing components that could be used objectively to quantify poor movement patterns, it has some flaws, namely its reliance on a double-leg task. Therefore, the LESS may be adequate for use as a screening tool for non-injured subjects, though its use as a return-to-sport test for those recovering from an ACL injury should be cautioned.

With so much interest in return-to-sport testing following ACL-R, numerous systematic reviews exist on the topic. Narducci et al. (2011) reviewed 12 studies to examine the clinical utility of return-to-sport tests in participants less than one year following ACL-R. Narducci et al. (2011) concluded that none of the tests reviewed had construct or predictive validity as a return-to-sport test in an athletic population one-year post ACL-R. This finding strongly suggests that current return-to-sport testing may not be evidence-based. Additionally, Barber-Westin and Noyes

(2011) concluded that a lack of an objective assessment before release to unrestricted sports activities is also prevalent in the literature.

In summary, it appears that no single test is adequate to determine safe return to sports and that a test battery is likely the most comprehensive solution. However, it also must be noted that a lack of reporting on the requirements used to determine return-to-sport also hinders the ability to correctly identify the factors which are important.

Vail Sport Test™

To date, research on the Vail Sport Test™ is scarce (see Appendix A and B). The most relevant literature on this test battery comes from Garrison et al.(2012), in which the intra-rater and inter-rater reliability of the test was examined in 30 subjects following ACL-R (Garrison et al., 2012). All subjects were post-operative ACL-R (5.2 ±1.9 months). Each subject completed the Vail Sport Test™ once and was videotaped from the anterior and lateral views. The videotape was then viewed and graded at two different points in time (48 hours apart) by three graders. Intra-rater reliability was excellent with a range of 0.95 to 1.0. Reliability between graders also was excellent with $ICC_{(2,1)} = 0.97$ and SEM = 1.55 (Garrison et al., 2012). This is the only study that reported the psychometric properties of the Vail Sport Test™ as a measure of return-to-sport following ACL-R. However, the Vail Sport Test™ has been suggested previously as a return-to-sport test in alpine skiers following ACL-R (Kokmeyer, Wahoff, & Mymern, 2012). Kokmeyer recommended its use in a clinical commentary on return-to-sport in alpine skiers following ACL-R. It also has been used as a measure of return-to-sport in a case study which reported that a 15-year-old athlete successfully returned to alpine skiing from a combined ACL and posterior cruciate ligament injury using the Vail Sport Test™ as the return-to-sport criterion (Beecher, Garrison, & Wyland, 2010).

In addition to the limited use of the Vail Sport Test™ in the ACL-R population, there are few studies that report on its use following hip arthroscopy (Philippon, Christensen, & Wahoff, 2009; Pierce, LaPrade, Wahoff, O'Brien, & Philippon, 2013; Stalzer, Wahoff, & Scanlan, 2006; Wahoff & Ryan, 2011). However, its use in this population cannot be compared to its use in the ACL population as the version used for hip studies (the Vail Hip Sports Test™) has been modified from the original version. The Vail Hip Sports Test™ is composed of four testing components of functional tasks, with a 20-point scoring system. The last two testing components were modified from the original Vail Sport Test™ to incorporate a rotational and deep hip flexion and extension component (Pierce et al., 2013). Additionally, the total possible score was modified to be 0 – 20 points, with a passing score of 17 or higher, as compared to the original Vail Sport Test™, which has a total possible score of 0 – 54 points, with a passing score of 46 or greater.

Subjective Outcome Measures

In addition to objective outcome measures as reviewed above, there is a plethora of research examining subjective outcome measures in the ACL-R population. However, unlike the objective criteria, the subjective measures are more agreed upon in regards to their use. In a systematic review, Magnussen (2015) summarized the expected patients' self-reported outcomes at a minimum of 10 years following ACL-R (Magnussen, Verlage, Flanigan, Kaeding, & Spindler, 2015). Magnussen et al. (2015) found 13 studies with the Lysholm scores being reported in six studies, IKDC scores being reported in five studies, Cincinnati Knee scores reported in three studies, and the Knee Injury and Osteoarthritis Outcome Score (KOOS) reported in two studies. This study lays out the most commonly used patient self-reported outcome measures in the literature. These four outcome measures can be found throughout the ACL literature. In a long-term follow-up study, Fink et al. (2001) utilized the IKDC and Lysholm scores to identify the long term clinical outcomes of operative versus non-operative management of ACL injuries (Fink et al., 2001). Similarly, Lee et al. (2004) used the IKDC and Lysholm questionnaires to look at long-term follow-up following ACL-R (Lee et al., 2004).

The Lysholm score was first described in the literature in 1982 and was intended as an outcome measure following knee ligament surgery (Briggs et al., 2009). The scale was eventually modified and has been used extensively throughout the literature to measure outcomes following knee ligamentous injuries (Briggs et al., 2009). The measure consists of eight questions for a total of 100 points with a higher score being better. The test-retest reliability has previously been examined and the tool demonstrates acceptable values with an ICC > 0.70. Additionally, the minimum detectable change was found to be 8.9 (Briggs et al., 2009). The content validity of the Lysholm score was also examined, and adequate floor (< 30%) and ceiling effects were found (Briggs et al., 2009). In addition, the criterion validity was assessed against the SF-12 and IKDC measures and a significant correlation was found to between the Lysholm score and the physical component of the SF-12 and between the Lysholm and IKDC scores (Briggs et al., 2009). Based on the psychometric findings of the study by Briggs, it was concluded that the Lysholm score is an acceptable measure to be used following ACL-R. However, a more recent systematic review looking at outcome measures in musculoskeletal conditions concluded that it may not be an optimal tool for some conditions due to unacceptable floor effects for squatting and unacceptable ceiling effects for limping and instability, which limits its discriminative ability for these tasks (Howe, Dawson, Syme, Duncan, & Reid, 2012).

The KOOS scale was developed in 1998 to assess knee-related quality of life in young and middle-aged subjects with ACL injury, meniscus injury, or posttraumatic osteoarthritis (Roos, Roos, Lohmander, Ekdahl, & Beynnon, 1998). Roos, Roos, Lohmander, Ekdahl, and Beynnon (1998) felt that other available scales (e.g., the Hospital for Special Surgeries rating scale, the Cincinnati Knee Ligament rating system, and the Lysholm Scale) were not truly patient-reported and potentially had observer bias. The scale itself covers five dimensions that are reported separately: pain, symptoms, activities of daily living, sport and recreation function, and knee-related quality of life. This totals 37 questions in which each question can be answered on a five-point Likert scale. Initial psychometric property testing was completed on 21 subjects undergoing ACL-R. The KOOS demonstrates good test-retest reliability and good construct validity to the SF-36. Roos et al. (1998) concluded from this original study that the KOOS meets basic criteria of outcome measures and can be used to evaluate the course of knee injury and treatment outcome.

However, as indicated in its name the KOOS examines osteoarthritic changes in addition to knee ligamentous injuries, potentially limiting its applicability to ACL injuries specifically. A study by van Meer et al. (2013) looked specifically at comparing the KOOS to the IKDC scores to determine which measure was more useful following ACL-R. van Meer et al. (2013) reported that the IKDC questionnaire is more useful in the short term and up to one year following ACL-R than the KOOS scale. In available literature, the KOOS is widely used, but given the above findings, it is typically seen in long-term follow-up studies examining the incidence or arthritic changes following ACL injuries, and may not be the outcome of choice for more short-term outcome-based studies (Barenius et al., 2014; Risberg et al., 2016).

The Cincinnati Knee score is an eight-question measure that was developed to provide a comprehensive measure of knee condition and ranges from 0–100 points, with a higher score indicating better function. It has been shown to be reliable, valid, and responsive in an athletic population and has shown sensitivity to change over time following ACL-R (Barber-Westin, Noyes, & McCloskey, 1999; Marx et al., 2001; Risberg, Holm, Steen, & Beynnon, 1999).

The IKDC questionnaire was developed by Dr. Irrgang (1998) as a knee-specific, rather than a disease-specific measure of symptoms, function, and sports activity (Irrgang, Ho, Harner, & Fu, 1998). The possible score of the IKDC ranges from 0–100, with a higher score indicating higher level of functioning. In this seminal study, Irrgang et al. (1999) administered the IKDC and the 36-Item Short Form Health Survey (SF-36) to 533 patients with multiple knee conditions. Irrgang et al. (1998) reported that the internal consistency and test-retest reliability were 0.92 and 0.95, respectively. Based on the results of the test-retest reliability, the value for a true change in the score was reported to be 9.0 points (Irrgang et al., 1998).

Recently, Wera et al. (2014) published a systematic review on the use of IKDC questionnaire in the ACL-R population(Wera et al., 2014). A total of 421 studies from 2005-2012 were included in their review. The results of their review showed that the IKDC questionnaire used across the world with its most use in Europe (45.4%) followed by Asia (26.4%) and North America (19.5%). In addition, Wera et al. (2014) concluded that the IKDC questionnaire is comparable to that of the Lysholm scale and they continued to recommend its use. Additionally, Higgins et al. (2007) studied the concurrent validity of the IKDC questionnaire in patients with knee disorders (Higgins et al., 2007). The authors found significant, positive correlations between the IKDC scores and the SF-12 scores ($r = 0.45$, $p < 0.0001$), and concluded the IKDC to be valid and worthy of consideration for use in a broad patient population (Higgins et al., 2007). A limitation to the above study is that the authors did not specify the diagnosis of the participants included in the study; however, they provided examples of knee disorders, such as osteoarthritis, ligamentous tears, general knee pain (Higgins et al., 2007).

Further, a systematic review by Kanakamedala et al. (2016) supports the use and interpretation of the IKDC questionnaire in orthopedic research. Kanakamedala et al. (2016) reported that the test–retest reliability to be excellent for the IKDC questionnaire, with the ICCs ranging from 0.85 to 0.99. Additionally, Kanakamedala et al. (2016) reported effect sizes (ES) and standardized response means (SRM) ranging from 0.76 to 2.11. In this systematic review, the IKDC questionnaire was shown to have moderate-to-excellent correlations to the Marx Activity Rating Scale and poor-to-fair correlations to the mental health scale, thus demonstrating its convergent and divergent validity (Kanakamedala et al., 2016). Lastly, Kanakamedala et al. (2016) concluded that the IKDC questionnaire has acceptable psychometric properties to support its use and interpretation to assess the clinical response of patients with a variety of knee conditions in clinical practice and research settings. In summary, based on both the systematic review by Higgins (2007) and the review by Kanakamedala et al. (2016), the use of the IKDC questionnaire can be used for determing physical levels in patients with knee complaints.

Whereas the above two studies (Higgins et al., 2007; Kanakamedala et al., 2016) specficially examined the reliabilty and validty of the IKDC, a study by Hambly & Griva (2010) compared the IKDC score to KOOS score to determine if one outcome measures is more useful or meaningful than the other (Hambly & Griva, 2010). Data was collected on 58 participants who completed the IKDC, KOOS, and Tegner Activity Scale following a cartilage procedure of the knee. Hambly & Griva found that the majority of the IKDC items were both frequently experienced and perceived to be important by the subjects. Hambly & Griva (2010) also reported that despite similar results in terms of the psychometric properties of each outcome measure, further evaluation revealed that the IKDC questionnaire is a better choice in regards to relevance and importance for this knee patient population (Hambly & Griva, 2010). Although this specific patient population is not the population of interest for this dissertation study, because knee cartilage procedures are similar to ACL-R, the studies mentioned above imply that the IKDC questionnaire could be recommended for other knee conditions (Hambly & Griva, 2010; Higgins et al., 2007; Kanakamedala et al., 2016). To further support the use of the IKDC questionnaire, a study by Briggs et al. (Briggs et al., 2009) examined the reliability, validity, and responsiveness of the Lysholm and Tegner Activity Scales for ACL injuries. In this study they used the IKDC as the gold standard to assess criterion validity of the Lysholm scale (Briggs et al., 2009).

In addition to psychometric studies, the IKDC questionnaire has been used extensively in clinical studies as an outcome measure, and in these cases, has been shown to play an important role in successful outcomes. In a study by Lentz et al. (2012), researchers attempted to identify clinical variables for predicting return-to-pre-injury level of sports participation at one year following ACL-R (Lentz et al., 2012). They found that the patients who rated themselves at 93 or greater on the IKDC questionnaire were more likely to return to sport at pre-injury level than those who scored below 93. The authors concluded that the clinical variables most strongly associated with return-to-sport status included self-reported knee function, episodes of knee instability, and knee joint effusion (Lentz et al., 2012). These findings are not surprising, as the IKDC questionnaire specifically asks about knee effusion and knee instability.

To further demonstrate the relationship between the IKDC questionnaire and objective measures, a study by Reinke et al. (2011) examined the relationship between the IKDC and hop testing scores (Reinke et al., 2011). Reinke et al. (2011) asked 69 subjects to complete the IKDC questionnaire, KOOS, and a single, triple, and timed hop test. Reinke et al. (2011) reported that the triple hop test was moderately and significantly correlated with the IKDC score ($r_{s} = 0.4$, $p < 0.0001$). In summary, the results of the above studies (Lentz et al., 2012; Reinke et al., 2011) further support the use of the IKDC questionnaire in the ACL-R population by demonstrating its relationship with clinical outcomes. While the IKDC questionnaire demonstrates a relationship with clinical measures, it by no means should replace the actual testing of these measures, as the IKDC relies on patients' reporting and has the potential to be inaccurate.

Application of Motion Analysis System to ACL Injury

The use of motion analysis in the identification of at-risk individuals for either primary or secondary ACL injury and in the rehabilitation of individuals following ACL-R has grown tremendously over the past decade. The use of motion analysis has allowed a more detailed look into mechanisms of injury and injury risk screening. Some of this has been covered in other sections and thus will not be repeated; however, this section will cover a few studies that utilized motion analysis systems specifically aimed at examining ACL injury risk, changes following ACL injury, or ACL return to sport.

Pappas et al. (2016) examined 721 high school female basketball, volleyball, and soccer players with the use of motion analysis. Pappas et al. asked subjects to perform a 45 degree cutting task. In this 3D motion analysis study, 37 reflective markers and a 10-camera system with two force plates were used. This configuration was successful in capturing a dynamic cutting task including movement of the trunk. Given the population studied and the dynamic movement assessed, this study is extremely relevant to the proposed dissertation work and supports the use of motion analysis in the capturing of dynamic movement in a young active population. Additionally, the authors were able to classify the athletes into different ACL injury risk movement patterns based on their kinematics.

While the study by Pappas et al. (2016) examined healthy athletes, Paterno et al. (2010) used a 3D motion analysis system to examine the movement patterns of individuals returning to sport following an ACL-R. In the study by Paterno et al. (2010), 56 athletes with an average age of 16 completed a motion analysis assessment of a jump-landing prior to being released to return to sport. A 10- camera system capturing at 240 Hz and two force plates were used for data collection. Similarly to Pappas et al.'s study, 37 reflective markers were used to identify trunk and lower extremity segments. This configuration allowed adequate data collection of a dynamic task in an ACL-R population. This study is one of the foundational studies for the use of motion analysis in ACL rehabilitation and injury prevention as the researchers were able to track subjects for 12 months and reported on 13 second ACL injuries. Given these second ACL injuries, the researchers concluded that transverse plane hip kinetics, frontal plane knee kinematics, and sagittal plane knee moments during landing predicted second ACL injuries(Paterno et al., 2010).

Decker, Torry, Noonan, Riviere, and Sterett (2002) utilized 3D motion analysis to assess landing adaptions following ACL-R compared to healthy controls. In this study, 11 healthy controls and 11 subjects who were at least one year after ACL-R participated in the study. A 5-camera system and two force plates were used to capture movement during a jump-landing, the researchers captured hip, knee and ankle kinematics for both groups and found increased reliance on ankle plantar flexors in the ACL-R group.

The above studies by Pappas (2016), Paterno (2010), and Decker (2002) utilized motion analysis to capture dynamic movement. Both the Pappas (2016) and Paterno (2010) studies utilized similar marker placements and camera configurations to the proposed dissertation work.

The above studies looked at a primarily sagittal plane movement, and not a frontal plane movement. As the proposed dissertation work intends to look at both, examining a study that looked at frontal plane movement is warranted. Kristianslund and Krosshaug (2013) examined 120 elite female handball players while they performed both a jump-landing and side cut task (Kristianslund & Krosshaug, 2013). Eight Qualisys cameras, two ATMI force plates, and 35 reflective markers were used for data collection. This configuration is similar to the one used in this dissertation study. With this configuration, Kristianslund & Krosshaug (2013) were able to adequately capture both sagittal and frontal plane movement during dynamic tasks. Kristianslund & Krosshaug (2013) concluded that kinematics during a jump-landing task do not predict kinematics during a cutting tasks, further warranting this dissertation study, as we examined multi-planar movement, which has more applicability to ACL injury mechanisms.

Based on the above studies, the use of motion analysis in ACL research is supported in the literature. Studies examining both health and ACL-R subjects completing dynamic tasks can be found. Additionally, tasks that require movement in multi-planes can be successfully captured in the ACL-R population which helps to support the proposed dissertation work.

Configuration of Motion Analysis System for Dynamic Movement Testing

This section will review the configuration of 3D motion analysis systems in order to determine the optimal setting specifications for the proposed dissertation study (see Appendix C). After performing a literature search, a total of 16 articles were included in review. Of the 16 studies reviewed, three studies included participants either returning from ACL-R or those who had already sustained an

ACL injury (Paterno et al., 2010; Phillips & van Deursen, 2008; Pollard et al., 2006). The other 13 studies included healthy participants (Blackburn & Padua, 2008; Chappell et al., 2005; Chappell & Limpisvasti, 2008; Cortes et al., 2007; Ford, Myer, & Hewett, 2003; Ford et al., 2005; McLean, Huang, & van den Bogert, 2005; Phillips & van Deursen, 2008; Yu et al., 2005). As a 3D motion analysis system was used in all of these 13 studies, all studies were conducted in a laboratory setting, either fully or partly. From a study design perspective, two were cohort studies (Padua et al., 2009; Paterno et al., 2010), four were repeated-measure trials (Benjaminse et al., 2008; Decker, Torry, Wyland, Sterett, & Steadman, 2003; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Pollard et al., 2006), and the remaining 10 were observatory studies, testing participants at one point in time (Blackburn & Padua, 2008; Chappell et al., 2005; Chappell & Limpisvasti, 2008; Cortes et al., 2007; Ford et al., 2003; Ford et al., 2005; McLean et al., 2005; Phillips & van Deursen, 2008; Yu et al., 2005).

Four commercially available camera systems for 3D motion analysis were each utilized in three studies: Vicon camera system (Benjaminse et al., 2008; Phillips & van Deursen, 2008; Pollard et al., 2006), Motion Analysis camera system (Chappell & Limpisvasti, 2008; Decker et al., 2003; McLean et al., 2005), Flock of Birds camera system (Blackburn & Padua, 2008; Cortes et al., 2007; Padua et al., 2009) and Eagle camera system (Ford et al., 2003; Ford et al., 2005; Pappas et al., 2007). In addition, the Motus camera system was used in two studies (Chappell, Creighton, Giuliani, Yu, & Garrett, 2007; Chappell et al., 2005), and the EVaRT system was used in one study

(Paterno et al., 2010). One study did not indicate the manufacturer of the camera system (Yu et al., 2005).

Next, the number of cameras used for each study was examined. This ranged from two to 10 cameras, with three studies not describing the number of cameras were used in their study (Blackburn & Padua, 2008; Cortes et al., 2007; Padua et al., 2009; Paterno et al., 2010; Pollard et al., 2006). The number of markers used was also examined. This ranged from 12 (Cortes et al., 2007; Pollard et al., 2006; Yu et al., 2005) to 37 (Paterno et al., 2010) markers. The majority of studies utilized similar marker sets for the lower leg and thigh, with most differences being found at the hip and trunk. Most studies utilized bilateral anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS) and greater trochanter marker placements to identify the joint centers of the hip (Chappell et al., 2005; Ford et al., 2003; McLean et al., 2005; Pappas et al., 2007; Phillips & van Deursen, 2008; Pollard et al., 2006). Additionally, one study utilized a sacral marker to further identify the hip complex (Ford et al., 2003). Variability exists in the trunk markers, with some studies utilizing bilateral acromions (Chappell et al., 2007; Chappell et al., 2005; Chappell & Limpisvasti, 2008; Ford et al., 2005; Yu et al., 2005) in addition to cervical (Blackburn & Padua, 2008), thoracic (Blackburn & Padua, 2008), and lumbar (Blackburn & Padua, 2008; Chappell et al., 2007; Chappell et al., 2005; Chappell & Limpisvasti, 2008; Yu et al., 2005) markers.

The capture rate used in these 13 3D motion analysis studies was also examined. Capture rates ranged from 50Hz-240Hz, with five studies capturing at

240Hz (Ford et al., 2003; Ford et al., 2005; McLean et al., 2005; Pappas et al., 2007), five capturing at 120Hz (Benjaminse et al., 2008; Chappell et al., 2007; Decker et al., 2003; Pollard et al., 2006; Yu et al., 2005), two capturing at 100Hz (Blackburn & Padua, 2008; Cortes et al., 2007), and one each capturing at 50Hz (Phillips & van Deursen, 2008), and 144Hz (Padua et al., 2009). One study did not report the capture rate (Chappell & Limpisvasti, 2008). Next, processing/filter rate was examined. Most studies ran the data through a filter, with the cut-off frequency ranging from 6 Hz (Pappas et al., 2007) to 18 Hz (McLean et al., 2005). Interestingly, no two studies used the same cut-off frequency, and most studies simply reported an estimated optimal cut-off frequency used in their studies (Benjaminse et al., 2008; Chappell et al., 2007; Chappell et al., 2005; Chappell & Limpisvasti, 2008; Cortes et al., 2007; Yu et al., 2005).

In regards to camera utilization, numerous configurations are supported in the literature. In this review, as few as two cameras were successfully used to capture movement, with six (Chappell et al., 2007; Chappell & Limpisvasti, 2008; Ford et al., 2003; Ford et al., 2005; Pappas et al., 2007; Phillips & van Deursen, 2008) of the 16 studies utilizing an 8-camera configuration.

The literature has shown a great variety in marker sets, including both the number and location of markers (Benjaminse et al., 2008; Chappell et al., 2007; Chappell et al., 2005; Chappell & Limpisvasti, 2008; Cortes et al., 2007; Yu et al., 2005). Two studies included in this review captured trunk movement (Blackburn & Padua, 2008; Ford et al., 2003). First, Blackburn et al. (2008) reported that they used C7/T1 and T12/L1 in combination with hip, knee, and ankle joint centers for trunk motion capture (Blackburn & Padua, 2008). This description is vague and makes reproducing this marker configuration difficult. As such, the marker configuration described by Ford et al. (2003) provided a clear instruction for assessing trunk motion. In Ford et al's (2003), 23 markers were used and placed on the sacrum bilaterally shoulders, ASISs, greater trochanters, mid-thighs, medial and lateral knees, mid shanks, medial and lateral ankles, and heels and toes (between second and third metatarsals) (Ford et al., 2003). With 23 markers, Ford et al. (2003) was able to accurately track trunk and lower extremity kinematics during a jump-landing task.

The use of force plates in orthopedic research is a common practice. Force plate data can be used to quantify the force that is generated by the body and can give feedback on force production and balance in the context of jumping and landing (Kiefer et al., 2015). When combined with motion capture systems, torque, work and power at each joint can be quantified (Kiefer et al., 2015). Additionally, this force plate data can be used to interpret when the subject first contacts the ground to time and sequence the remainder of the movement, and to help quantify when during a movement a specific event occurs. Ford (2007) examined the reliability of force plate data during a jump-landing. Within- and between-session reliability was examined in 11 middle and high school subjects. They found good-to-excellent reliability for joint moment variables in the sagittal (ICC ≥ 0.925 for within-session reliability; ICC ≥ 0.800 for between-session reliability) and frontal planes (ICC ≥

0.778 for within-session reliability; ICC ≥ 0.748 for between-session reliability) (Ford, Myer, & Hewett, 2007).

A clinical commentary by Keifer (2015) discussed the role of force plates in the rehabilitation of ACL-R patients. Specifically, its use to identify GRF asymmetries before, during, and after training to quantify improvement or the need for further improvement (Kiefer et al., 2015). The use of force plates for plyometric training also helps the subject to modulate force during take-off and landing (Kiefer et al., 2015). In addition to its use for plyometric training, force plate data has been used for monitoring weight bearing during functional tasks in the early rehabilitation process. Labanca et al. (2016) examined lower limb loading one-month following ACL-R and used force plates to examine GRF during a squat task. Labanca et al. (2016) found that GRF asymmetry during a squat task at one month was a significant predictor of a GRF asymmetry during a counter movement jump at six months. These results are important, in that GRFs are difficult to quantify when simply observing movement without the use of a force plate. Chmielewski (2011), in an editorial report, discussed the difficulties of assessing kinetic data with visual observation and concluded that assessing for this asymmetry is imperative to help improve outcomes (Chmielewski, 2011). Padua et al. (2009) reviewed the literature to examine the role of ACL injury prevention programs on vertical GRF and concluded the programs that are aimed at modifying GRF should be used as part of a training program. This study further supports the statements by Chmielewski

(2011) who suggest that assessing GRF is an important part of the rehabilitation process.

Based on this review, the following conclusions can be made. First, it is important to note that all the studies listed above included some version of a jump-landing, jump task or cutting task. This information helps to plan for the configuration of the motion analysis system to be used for the proposed dissertation study because four dynamic tasks will be studied.

In summary, this literature review has identified that ACL injuries continue to occur regularly in active adolescents. The mechanism behind these injuries is multifactorial. However, the literature suggests that rapid change of direction or deceleration results in high stress across the ACL. Despite a large quantity of research, return-to-sport following ACL-R remains an area of concern due to the inconsistencies in reporting of return-to-sport rates and the inconsistencies in the return-to-sport tests. Based on the literature review, there is a clear gap between what we know about ACL injury and ACL injury risk and what is being implemented to determine readiness to return to sport.

CHAPTER III

METHODS

Rehabilitation following ACL-R involves a lengthy process that ideally culminates in an athlete passing a series of tests and being cleared to return to sport. Although a plethora of tests exist to determine when an athlete returns to sport, few are considered to be valid measures. Additionally, these tests do not assess the quality of movement the athlete performs. Rather, they assess an objective cut-off score (e.g., distance hopped) and determine if an athlete is ready to return to sport.

More recently, researchers and clinicians have begun recommending multi-test batteries as a mean to better assess return-to-sport readiness, but even these multi-test batteries lack an assessment of the athlete's quality of movement. In contrast, the Vail Sport Test™ was developed to assess this aspect of readiness; however, it has yet to be shown to be a valid measure of readiness to return to sports in the ACL-R population.

The first purpose of this study was to assess the convergent construct validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. A secondary purpose of this study was to determine the external validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. Lastly, the tertiary purpose of the study was to establish the between-day test-retest reliability of the Vail Sport Test™. This chapter describes the research design, participants, instrumentation, data collection, and data analyses used for the study.

Research Design

This study used an exploratory methodological research design to examine the validity and the reliability of the Vail Sport Test™. The study had three components:

1. Does the Vail Sport Test™ demonstrate acceptable convergent construct validity?
    a. The convergent construct validity was examined by comparing the scores determined visually in real-time during testing to the scores determined post-capture using a 3-dimensional (3D) motion analysis system. The 3D motion analysis system served as a reference standard. The association between these two sets of scores was also examined.
    b. The convergent construct validity was further examined by comparing the scores determined visually in real-time during testing to the scores obtained by the other reference standard, the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC). The association between these two sets of scores was also examined.
2. Does the Vail Sport Test™ demonstrate acceptable the external validity?

To determine the external validity of the Vail Sport Test™, the scores between operated and uninvolved limbs in both the fail and pass groups were examined separately.

3. What is the between-day test-retest reliability of the Vail Sport Test™?

   To determine the between-day reliability of the Vail Sport Test, a subset of participants returned to repeat the Vail Spot Test™ between 2 to 7 days of the first testing and the scores on the two testing dates were examined.

Participants

A power analysis using G*Power 3.1.3 (Faul, Erdfelder, Lang, & Buchner, 2007), with a medium effect size of 0.50 (Cohen, 1998) and an alpha level of 0.01, revealed that 43 participants were required to reach a power of 0.80 for the comparison between operated and uninvolved limbs. A medium effect size was chosen based on the previous study (Pauda et al., 2009). Considering a 10% attrition rate, 48 participants were recruited for this study. Injured participants were recruited primarily from the Texas Health Ben Hogan Sports Medicine center. Potential participants were seen at their return-to-sport assessment once they were released by their orthopedic surgeon (about 5–8 months post-surgery). Release by their surgeon was based on clinical examination including assessment of knee ROM, patellar and anterior interval mobility, an absence of swelling or pain, and progression through increasingly demanding activity with their physical therapist.

Injured athletes were considered for inclusion in this study if they: 1) were between 13 and 25 years of age, 2) had injured their ACL for the first time and underwent surgical reconstruction, 3) were involved in a level-1 sport (e.g., basketball, football, or soccer) or level-2 sport (e.g., baseball, racket sports, or skiing) which must include activities such as jumping, pivoting, or hard cutting for greater than 50 hours a week (Daniel et al., 1994), 4) were in the return-to-sport rehabilitation stage of their treatment, which is typically five to eight months post-surgery depending on whether other structures (e.g., meniscus, articular cartilage, collateral ligaments, etc.) were involved. Injured athletes were excluded from this study if they: 1) injured their ACL more than once, 2) had a full-thickness chondral defect of $1cm^2$ or greater, 3) had a grade II or III medial or lateral collateral ligament sprain, 4) had a grade III posterior cruciate ligament tear, 5) had a simultaneous bony fracture with ACL tear, 6) did not play level-1 or level-2 sports, or 7) were not planning to return to sport after their ACL-R. Individuals who had previously torn their ACL were excluded as they may exhibit numerous deficits that could have potentially contributed to their subsequent ACL injury. This population (repeated ACL-injured athletes) must be examined separately from first time injured athletes to allow a clearer understanding of their specific deficits. Those athletes with full-thickness chondral defects, medial or collateral ligament sprains, posterior collateral ligament sprains, and those with bony fractures with their ACL tear were all excluded, as these pathologies would complicate both the surgery and the subsequent rehabilitation and return-to-sport phase testing. These pathologies tend to lead to prolonged non-weight bearing statuses and/or staged surgeries which would put these athletes outside the typical return-to-sport time frame (i.e., 6–8 months).

Instrumentation

Three-Dimensional Motion Capture System

An 8-camera Qualisys Motion Capture System (Qualisys AB, Göteborg, Sweden) with a capture rate of 120Hz was used to capture joint motions in all three planes during the Vail Sport Test™. The Qualisys system has been used previously in studies examining lower extremity movement in an athletic population (Hamill, Heiderscheit, & Pollard, 2005; Joseph et al., 2011), and was readily available to the investigator. A capture rate of 120Hz was chosen, as a review of the literature demonstrated that an acceptable capture rate falls between 50Hz-240Hz, with several studies of stop jumping and jump-landing using 120Hz (Benjaminse et al., 2008; Chappell et al., 2007; Decker et al., 2003; Pollard et al., 2006; Yu et al., 2005). Thirty-three reflective markers were adhered to participants' skin/clothing with double-sided tape, allowing the joint angle measurements of each component to be recorded by the Qualisys Motion Capture System. The marker set used was a combination of two previously-established marker sets so that knee flexion/extension, knee valgus/varus and trunk motions could be analyzed (Ford et al., 2003; Leardini, Biagi, Belvedere, & Benedetti, 2009). This combination allowed the best capture of the participants' movements required for scoring the Vail Sport Test™.

Force Plates

Two ATMI force plates (Advanced Mechanical Technology, Inc., Watertown, MA) were used during data collection to allow accurate time sequencing during data collection and processing, thus enabling accurate identification of initial contact during the jumping tasks (see Appendix D). This specific brand of force plate has been used previously throughout the literature when examining lower extremity kinematics (Owens, Shim, Beebe, & Yom, 2013; Wang, Wang, & Wang, 2015).

International Knee Documentation Committee Subjective Knee Form

The IKDC was used to assess current knee function (see Appendix E). The IKDC is a patient-reported outcome measure with scores ranging from 0–100, with a higher score indicating higher level of functioning (Irrgang et al., 1998). The IKDC is a standard measure used for assessing outcomes of patients who are participating in physical therapy following ACL-R surgery and has been shown to have acceptable psychometric properties (Collins, Misra, Felson, Crossley, & Roos, 2011; Crawford, Briggs, Rodkey, & Steadman, 2007; Grevnerts, Terwee, & Kvist, 2015; Higgins et al., 2007; Kanakamedala et al., 2016). The IKDC has be shown to be reliable with its intraclass coefficient coefficients (ICCs) ranging from 0.90 to 0.95 and internally consistent with Cronbach's (α) values ranging from 0.77 - 0.91. The minimal detectable change of the IKDC has been reported to be 8.8 - 15.6 and the standard error of measurement to be 3.2 - 5.6 (Collins et al., 2011).

Investigators

The grading of the Vail Sport Test™ in real time was completed exclusively by the principal investigator (PI). The PI had over four years of experience using the Vail Sport Test™ as a measure of readiness to return to sports. Limiting the real-time grading to only the PI was an attempt to ensure proper grading and to improve consistency in grading. Data processing of the 3D motion analysis was completed primarily by the PI with the assistance of lab personnel. This is included marker identification, data processing, and data exporting. Additional lab assistants were used to assist with lab and participant setup.

Procedures

After giving consent to participate in the study, all of the participants completed the IKDC and an injury history report form (see Appendix F). The intake form included demographic information, injury history, pertinent medical history, and athletic history was used to collect each participant's characteristics. In addition, clinical measurements of ROM and strength of both the operated and uninvolved limbs were extracted from their charts. This clinical data was used to further describe the participants of this study. All eligible participants were asked to wear compression shorts and female participants were asked to also wear sports bras. Those participants who arrived without the appropriate attire were provided with appropriate clothing to ensure accurate marker placement.

Prior to participants' arrival, either the PI or one of the two lab assistants set up the motion capture system and force plates in a specific sequence. First, all camera views were assessed for noises and reflections. Noises and reflections that could not be removed from the capture area were masked within the system. Next, the cameras were calibrated for the capture area and then the origin was set to the global/laboratory coordinate system using a 4-maker L frame reference object and a two maker "T" wand. Lastly, the force plates were zeroed out prior to the start of data collection.

Once the participants completed the required forms and had undergone a self-selected warm up (Mandengue et al., 2005) of no more than 10 minutes which could include stationary biking, elliptical, and gluteus muscle activation exercises, 33 reflective markers were affixed to their skin with double-sided tape allowing the joint angle measurements of each component to be recorded by the Qualisys Motion Capture System. Markers were placed on bilateral acromions, sternum, C7, T12, L5, bilateral anterior superior iliac crests, bilateral posterior superior iliac crests, bilateral superior sacral poles, inferior sacrum, bilateral greater trochanters, bilateral mid-thighs, bilateral medial and lateral femoral condyles, bilateral mid tibias, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral calcanei (see Appendix G). These 33 reflective markers were used during a static trial for building the biomechanical model of the participant. However, the medial femoral condyle and medial malleolus markers were removed for dynamic trials. During the single leg squat task, four additional markers were used to allow tracking of excessive anterior tibial translation. Markers were placed on bilateral tibial tuberosities and bilaterally on the most distal aspect of the patient’s toes.

Following maker placements, each participant was asked to stand still with extremities in an anatomical position and their arms at 90 degrees of abduction (see Appendix G), and to hold the position for 10 seconds so that a static trial could be captured. Next, the investigators removed the medial femoral condyle and medial malleolus markers. Then, all participants were asked to complete each component of the Vail Sport Test™ in the following order: single leg squat, lateral bounding/agility, forward running and backward running.

Appendix A illustrates each component of the test. The participants first completed the single leg squat test. Through both verbal and visual cueing, participants were instructed in completing a single leg squat against resistance. Resistance was provided via a SportCord® resistance band (STI, Baton Rouge, LA). Participants stood with their arms resting at their side. In their testing hand, they held either a black (heavy resistance) or blue (medium resistance) band. Those participants who weighed greater than 72 kg used a black SportCord® resistance band and those who weighed less than 72 kg used a blue SportCord® resistance band. Participants held one end of the band and the other end wrapped around their foot to secure the band in a taut position. This starting position was standardized so that no slack was visibly seen in the resistance band. This setup ensured that the participants squatted against resistance. If necessary, participants were allowed to use two fingers of their hand on the uninvolved side to balance themselves. They performed three minutes of continuous squatting on their injured limb. Following a 2.5-minute rest period, they then completed the single leg squat test on their uninvolved limb (Garrison et al., 2012).

After the participant had completed single leg squats on both limbs, they were given another 2.5-minute rest period prior to completing the next testing component, lateral bounding or agility. The lateral bounding component involved the participant performing a lateral hopping motion against the resistance of a SportCord® resistance band attached to the participant's waist via a belt and on the other end to an immoveable object that was level with the waist (e.g., wall, door, etc.). The injured leg was positioned as the inside leg or the leg closest to the wall. The participant was instructed to hop from one leg to the other (leg length distance). Leg length was measured from the participant's most prominent aspect of the greater trochanter to the floor in a standing position. The landing boundaries (distance of the hop) was marked on the floor with two pieces of tape, one of which began at the point of resistance of the SportCord® resistance band as it was stretched away from the wall, and the other the measured distance of the participant's leg length from the first piece of tape. The participant performed this test for 90 seconds. Following a 2.5-minute rest period, they then completed the lateral bounding test on their uninvolved limb.

After the participant completed lateral bounding on both limbs, they were given another 2.5-minute rest period prior to completing the next testing component, forward running. As with the lateral bounding, a SportCord® resistance band was attached to an immoveable object at waist height to provide resistance by pulling the participant toward its attachment point. This attachment was the same for both the forward and backward running.

The participant was instructed to hop from one leg to the other in an up-and-down manner (similar to jogging in place) with the knees flexed between 30° - 60°. The participant performed this test for two minutes. Following a 2.5-minute rest period, they turned around and completed the final component of the test, backward running. Because both of the above tests required equal contribution from both limbs, the participant only completed each of these tests one time. In addition, all participants were asked to return for an additional day of testing for the between-day test-retest reliability part of the study. This second test date was more than 48 hours but less than 168 hours after the first test to allow for adequate rest time while still limiting the duration of time for changes between the two testing sessions.

The Vail Sport test™ was scored following the previously published criteria (Garrison et al., 2012). The grading criteria included assessment of technique for each component and was based on a binary scoring system (*yes* = 1, *no* = 0; see Appendix B). One point was given for each standard completed with proper form during the set time intervals of each of the four testing components. The total possible number of points for the Vail Sport Test™ ranges from 0 to 54. A patient post ACL-R was required to score at least 46 out of 54 points in order to receive a passing score (Garrison et al., 2012). For each testing component, the participants received no points if they continued to perform with an incorrect movement pattern despite having received verbal feedback on three consecutive repetitions within the testing time interval (Garrison et al., 2012).

Due to the length of the testing period, 3D motion data for the entire test would have been excessively large, and it would not have been feasible to store and process it. Therefore, 3D motion data for only the final 10 seconds of each 30 second interval was collected and used for data processing. This was chosen to provide a sample of the movement and allow enough repetitions of each movement to be graded via the 3D motion data.

Kinematic Data Processing and Statistical Analyses

Following data collection, the static and dynamic trials of each participant were processed using the Qualisys Track Manager software (Qualisys AB, Göteborg, Sweden). First, the markers were identified and labeled. Once all markers were labeled and the segments were created for the full duration of each movement, the file was exported to a c3d file format. Using the Visual3D version 5 software (C-Motion Inc., Germantown, MD), the segments of the trunk, pelvis, thigh, shank and foot segments were created and then the joint angle (kinematics) between each of the distal and proximal segments were generated for the captured time frame of each Vail Sport Test™ component. Lastly, the digital kinematic data for knee flexion and extension, knee valgus, and trunk flexion were processed and exported in an ASCII file from Visual3D to Microsoft Excel.

Grading of the kinematic data was based on the data exported to the Excel file and quantified as follows. For the kinematic data of each 10-second time period, the maximum value was the average of the peak value and the values extracted from two frames before and two frames after the peak value. Trunk flexion greater than 30 degrees from the participant's starting position was considered excessive. Greater than 10 degrees of maximum knee frontal plane projection angle was considered excessive knee valgus. Greater than 0 degrees of knee extension from the starting position was considered excessive for the knee extension grading component. Sagittal plane knee kinematics for knee flexion was used to grade knee flexion during each test component. A knee flexion angle of less than 30 degrees was considered a deduction for that test component. The tibial tuberosity marker was compared to the toe marker and this difference was used to assess for excessive anterior tibial translation. Any value in which the tibial tuberosity marker exceeded the toe marker coordinate by greater than 0.03 meters was considered a failed test and a score of zero was given. When a joint motion was graded excessive, a "0" was given for that test component

IBM SPSS statistics 19 (IBM Corp., Armonk, NY) was used for statistical analysis. Means and standard deviation were calculated for participants' characteristics (i.e., age, gender, limb dominance, operated limb, sport, and IKDC scores), and ROM and strength data. First, paired *t*-tests were used to assess the difference in the ROM and strength measurements between the operated and uninvolved limbs ($\alpha = 0.05$). Next, each participant was assigned into a fail group (< 46) or a pass group (≥ 46) based on his/her real-time Vail Sport Test™ score. To assess the differences, five separate paired *t*-tests were planned for the following five sets of data with a corrected alpha level of 0.01: 1) between the scores collected visually in real-time and those collected using the 3D motion analysis system for the operated limb, 2) between the scores collected visually in real-time and those collected using the 3D motion analysis system for the uninvolved limb, 3) between scores collected visually and the IKDC scores for the operated limb, 4) between operated and uninvolved limbs in the fail group, and 5) between operated and uninvolved limbs in the pass group. To determine the association between the five sets of data as mentioned above with $p < 0.01$, five separate Pearson correlation coefficients (r) were calculated. Lastly, the intraclass correlation coefficient ($ICC_{3,1}$) was used to determine the between-day test-rest reliability.

CHAPTER IV

RESULTS

The first purpose of this study was to assess the convergent construct validity of the Vail Sport Test™ as a measure of readiness to return to sports following anterior cruciate ligament reconstruction (ACL-R). A secondary purpose of this study was to determine the external validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. Lastly, the tertiary purpose of this study was to determine the between-day test-retest reliability of the Vail Sport Test™. This chapter reports participant characteristics and findings from the data collected.

Participants

Sixty-six patients who had ACL-R and were referred by their surgeons for a return-to-sport assessment were screened for eligibility for the study from October 2016 to December 2017. Ten patients were excluded from the study because they previously underwent ACL-R. Seven eligible patients declined to participate in the study. Consequently, 49 eligible participants were enrolled in the study. The 49 subjects were referred by 4 different orthopedic surgeons; with one surgeon referring 40 participants, one surgeon referring 7, and two additional surgeons each referring 1 participant. Of the 49 enrolled participants, 48 completed the study. One participant was asked to discontinue the study because of an inability to keep markers attached to the participant's skin due to excessive sweating. The characteristics of the participants are summarized in Table 1, including age, gender, limb dominance, operated limb, sport, and IKDC scores. Table 2. includes range of motion (ROM) and strength measurements of the lower extremities of the participants. Significant differences were found between the operated and uninvolved limbs in the ROMs of knee flexion and extension and strength of the quadriceps and hamstrings muscles.

Table 1

Participant Characteristics of the Study

	All (*n* = 48)	Pass Group (*n* = 44)	Fail Group (*n* = 4)
Age (years)	16.7 ± 1.5	16.9 ± 2.7	15.6 ± 0.8
Height (cm)	168.9 ± 10.4	168.8 ± 12.4	162.5 ± 7.8
Weight (kg)	68.0 ± 9.38	67.3 ± 12.8	68.1 ± 6.9
Sex	Women: 30 Men: 18	Women: 29 Men: 15	Women: 1 Men: 3
Months post-surgery	7.0 ± 1.2	7.1±1.8	7.0±1.0
Concomitant injury	Meniscus Repair: 13 Meniscectomy: 10 None: 25	Meniscus Repair: 11 Meniscectomy: 9 None: 24	Meniscus Repair: 2 Meniscectomy: 1 None: 1
Mechanism of Injury	Direct: 10 Indirect: 12 Non-Contact: 26	Direct: 9 Indirect: 11 Non-Contact: 24	Direct: 1 Indirect: 1 Non-Contact: 2
Limb Dominance	Right: 45 Left: 3	Right: 43 Left: 1	Right: 2 Left: 2
Injured Limb	Right: 21 Left: 27	Right: 21 Left: 23	Right: 0 Left: 4
Sport			
Basketball	15	14	1
Football	10	9	1
Soccer	18	16	2
Volleyball	3	3	0
Softball	1	1	0
Cheerleading	1	1	0
IKDC	91.8 ± 8.2	91.3 ± 7.4	88.5 ± 6.4

Note: IKDC = International Knee Documentation Committee Subjective Knee Evaluation Form

Table 2

Range of Motion and Strength Measurements of Lower Extremities of the Participants (n = 48)

	Operated	**Uninvolved**	***P* Value**
AROM (°)			
Knee Flexion	139.5 ± 8.4	141.1 ± 8.5	0.040*
Knee Extension	1.6 ± 2.6	2.7 ± 1.9	0.003*
PROM (°)			
Hip Internal Rotation	44.0 ± 9.5	41.2 ± 8.0	0.060
Hip External Rotation	41.9 ± 7.5	41.5 ± 6.8	0.700
Ankle Dorsiflexion	40.4 ± 7.4	40.3 ± 7.4	0.340
Strength (kg)			
Hip Abduction	25.9 ± 5.2	24.6± 5.9	0.160
Hip External Rotation	20.5 ± 4.6	21.2 ± 4.8	0.360
Quadriceps (peak torque at 60 °/sec)	72.7 ± 26.0	100.7 ± 34.9	< 0.001*
Hamstring (peak torque at 60 °/sec)	47.5 ± 18.1	49.8 ± 18.1	0.003*

Note: AROM = active range of motion; PROM = passive range of motion; * $p < 0.05$

Construct Validity

The first purpose of this study was to assess the convergent construct validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. This was completed by comparing the scores collected visually in real-time to those determined by analyzing the post-capture data collected using a 3-dimensional (3D) motion analysis system simultaneously in real-time. Table 3 lists the scores determined visually in real-time and obtained from post-capture 3D kinematic data. Because the normality assumption was not met for both sets of scores, two separate non-parametric Wilcoxon signed ranks tests, rather than paired *t*-tests were used to analyze the data. The result showed no significant difference between the scores on the operated limb collected visually and those collected via 3D motion analysis ($p = 0.013$). Additionally, there was a significant difference on the uninvolved limb between real-time visual scores and post-capture 3D kinematic analysis scores ($p = 0.006$) as the a priori alpha level was set at 0.01. Lastly, Pearson's correlation coefficients were calculated to assess for an association between the two sets of scores. A significant moderate correlation was found with $r = 0.55$ ($p < 0.001$). Similarly, a significant moderate correlation ($r = 0.46$, $p = 0.001$) was also found for the two sets of scores on the uninvolved limb.

To further assess the construct validity, the scores collected visually in real-time for the operated limb were compared to the IKDC scores, as the IKDC is considered a standard outcome measure for assessing treatment outcome following ACL-R. Because these two sets of scores were measured on different scales, Z-scores were computed from the raw scores. Non-parametric Wilcoxon signed ranks tests were used to analyze the data because the normality assumption was not met. The analysis showed no significant difference between IKDC scores and the scores collected visually in real-time ($p = 0.814$) for the operated limb, but a non-significant weak correlation ($r = 0.20$, $p = 0.174$) between the two sets of the scores.

Table 3

Means and Standard Deviations of the Vail Sport Test™ Scores Collected Visually in Real-time and Obtained by Analyzing Post-capture 3D Kinematic Data

	Visual Data	**Post-Capture kinematic data**	***p* value**
Operated Limb	49.3 ± 3.4	50.5 ± 2.8	0.013
Uninvolved Limb	48.2 ± 6.3	50.2 ± 3.3	0.006*

Note. 3D = 3-dimensional. *$p < 0.01$.

External Validity

A secondary purpose of this study was to determine the external validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. To assess the external validity of the test, two non-parametric Wilcoxon signed ranked tests were used to compare difference in scores between those who failed and those who passed the Vail Sport Test™ in real-time. Forty-four participants successfully passed the test (Vail Sport Test™ score ≥ 46/54) and four participants failed the test (Vail Sport Test™ score < 46/54). Table 1 lists the participants' characteristics of the pass and fail groups, and Table 4 lists the Vail Sport Test™ scores as well as the clinical ROM and strength data for the operated and uninvolved limbs of the pass and fail groups. For the pass group, there was no significant difference between the scores of the operated limb and those of the uninvolved limb (*p* = 0.173). Similarly for the “fail” group there was no significant difference between the scores of the operated limb and those of the uninvolved limb (*p* = 0.465). Lastly, Pearson’s correlation coefficients were calculated to assess for an association between the two sets of scores for both the pass and fail group. A significant moderate correlation was found with *r* = 0.478 (*p* < 0.001) for the pass group. However, a non-significant good correlation (*r* = 0.745, *p* = 0.255) was found for the fail group.

Table 4

The Vail Sport Test™ Scores Collected Visually from Each Limb, and Range of Motion and Strength Data of the Lower Extremities for the Pass and Fail Groups (Mean ± Standard Deviation)

	Pass (*n*=44)		**Fail (*n* = 4)**	
	Operated*	Uninvolved*	Operated†	Uninvolved†
Vail Sport Test Score	50.0 ± 2.4	49.1 ± 5.4	41.5 ± 3.6	39.2 ± 9.1
AROM (°)				
Knee Flexion	143.6 ± 8.2	145.6 ± 7.8	130.0 ± 4.0	133.0 ± 7.3
Knee Extension	1.76 ± 2.4	2.7 ± 2.0	1.0 ± 3.0	1.0 ± 1.2
PROM (°)				
Hip IR	42.6 ± 9.2	40.2 ± 8.1	60.0 ± 12.0	42.0 ± 4.3
Hip ER	42.1 ± 7.0	40.8 ± 6.8	28.0 ± 10.0	45.0 ± 1.4
Ankle Dorsiflexion	41.4 ± 7.5	41.9 ± 7.5	32.8 ± 5.2	33.4 ± 5.6
Strength (kg)				
Hip Abduction	26.7 ± 5.2	26.0 ± 6.0	25.0 ± 3.6	23.8 ± 3.8
Hip ER	21.4 ± 4.7	26.7 ± 5.2	18.5 ± 2.0	22.0 ± 1.3
Quadriceps	72.2 ± 24.2	102.4 ± 32.4	63.2 ±12.2	81.2 ± 26.4
Hamstring	48.4 ± 16.1	51.7 ± 16.9	32.9 ± 7.8	44.8 ± 11.5

Note. **p* = 0.173between the operated and uninvolved limbs. †*p* = 0.465 between the operated and uninvolved limbs. Test at peak torque at 60 °/sec. IR = internal rotation. ER = external rotation.

Reliability

The tertiary purpose of this study was to determine the between-day test-retest reliability of the Vail Sport Test™. Intraclass correlation coefficients ($ICC_{3,1}$) were calculated to determine the reliability of the Vail Sport Test™ scores collected visually in real-time in two separate testing sessions from each participant for each limb. All participants were asked and 14 participants returned for a second testing session between 2 to 7 days later. Their characteristics and Vail Sport Test™ scores are listed in Table 5 and Table 6 respectively. The results showed good between-day test-retest reliability for the operated limb with the $ICC_{3,1}$ being 0.787 and 95% CI (confidence level) ranging from 0.459 to 0.926 Similarly, the results showed fair between-day test-retest reliability for the uninvolved limb with $ICC_{3,1}$ being 0.485 and 95% CI ranging from -0.038 to 0.800. To further illustrate the reliability, a Bland-Altman plot was created to show the limits of agreement of the reliability data for both the operated limb (see Figure 1) and the uninvolved limb (see Figure 2).

Table 5

Characteristics of the Participants in the Reliability Part of the Study (n = 14)

Age (years)	15.8 ±1.1
Height (cm)	166.3 ± 8.1
Weight (Kg)	64.2 ± 8.9
Sex	Women: 11 Men: 3
Months post-surgery	7.1 ± 0.5
Days Between Testing Sessions	6.1 ± 0.5
Mechanism of Injury	Direct: 6 Indirect: 1 Non-Contact: 7
Limb Dominance	Right: 14 Left: 0
Injured Limb	Right: 4 Left: 10

Table 6

The Vail Sport Test™ Scores (Means and Standard Deviations) Collected Visually on Two Separate Sessions and Intraclass Coefficient Coefficients (ICC) for the Between-day Test-retest Reliability

	Session 1	**Session 2**	**ICC$_{(3,1)}$**
Operated Limb	50.7 ± 1.8	49.7 ± 2.3	0.787
Uninvolved Limb	50.5 ± 1.9	49.4 ± 2.8	0.489

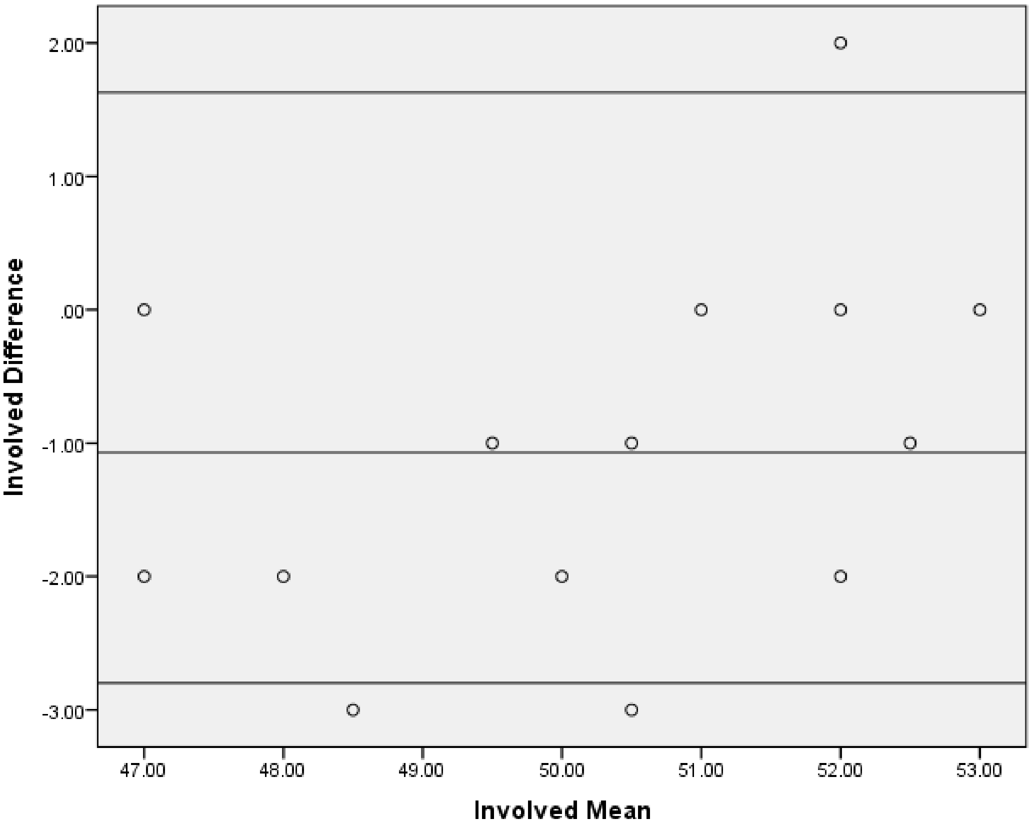


Figure 1. Bland-Altman plot for limits of agreement of the between-day test-retest reliability data for the operated limb

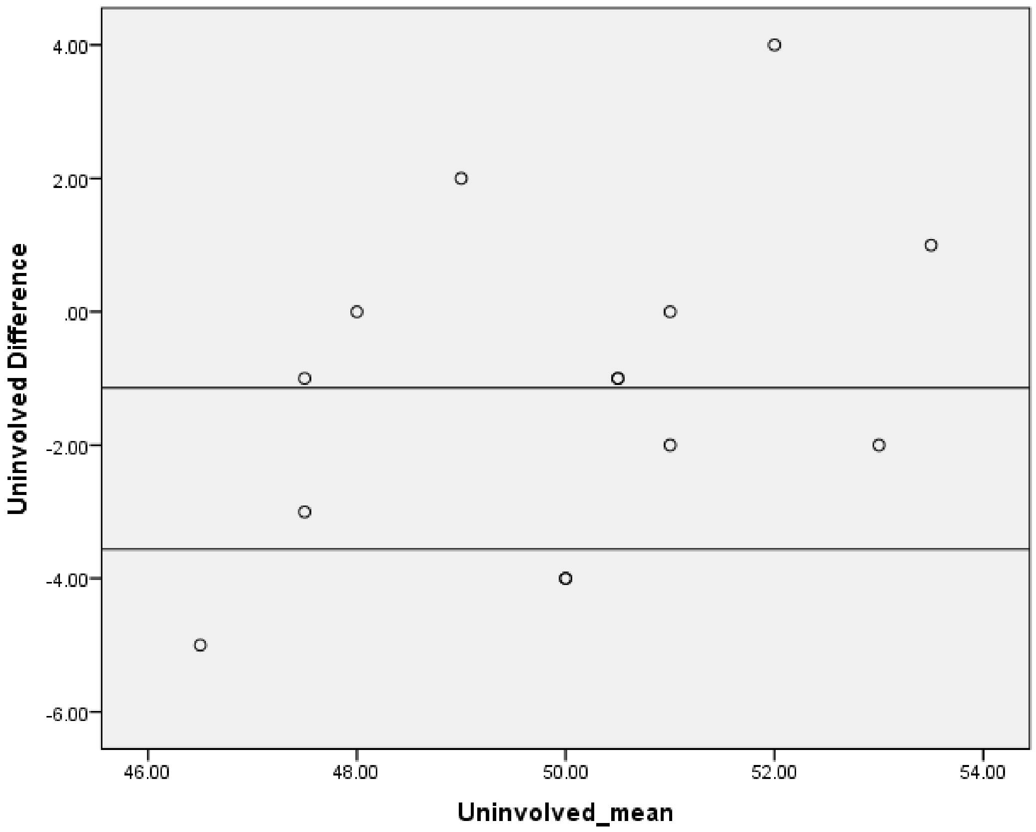


Figure 2. Bland-Altman plot for limits of agreement of the between-day test retest reliability data for the uninvolved limb

CHAPTER V

DISCUSSION

The primary and secondary purposes of this study were to assess both the convergent construct validity and external validity of the Vail Sport Test™ respectively, as measure of readiness to return to sports following ACL-R. The tertiary purpose of this study was to assess the between–day test-retest reliability of the Vail Sport Test™. This chapter provides a discussion of the results, highlights of the limitations, and provides a conclusion of the study.

Construct Validity

The first purpose of this study was to assess the convergent construct validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL-R. This was completed by comparing the scores collected visually in real-time to those determined by analyzing the post-capture data collected using a 3D motion analysis system simultaneously in real-time. The results of this analysis indicate that there was no significant difference between the scores collected visually and those collected post-capture for the operated limb. This finding supports the hypothesis that the Vail Sport Test™ is a valid measure. However, on the uninvolved limb there was a significant difference between scores with the post-capture scores being higher. In addition, a significant moderate correlation was found between both sets of scores for both the operated and uninvolved limbs. To further assess the construct validity, the calculated Z scores of the operated limbs

Vail Sport Test™ and the calculated Z scores of the participant's IKDC scores. This analysis showed no significant difference between IKDC scores and the scores collected visually in real-time ($p = 0.814$) for the operated limb.

The results of both of these analyses seem to support that the Vail Sport Test™ demonstrates good convergent construct validity when examining the operated limb of participants following ACL-R. Interestingly, given the significant difference between the scores collected visually and those collected post-capture, the convergent construct validity of the Vail Sport Test™ for the uninvolved limb is not supported. This discrepancy could be explained partially by inherent bias of the rater. The Vail Sport Test™ was designed to assess readiness to return to sports of the operated limbs (Garrison et al., 2012). However, the performance of both limbs was assessed in the present study while an assumption was made that the rater would grade both limbs at the same time equally in real-time. Therefore, the rater's past experiences of only grading the operated limb could have impacted the visually-collected scores of the study, specifically with regard to the results of the involved limb. It is arguable that the difference between the scores collected visually and those collected post-capture for the operated limb was near significant. Considering that the majority of the participants (44 out of 48) passed the Vail Sport Test™ and scored the test between 46 and 54, this narrow range of scores may have contributed to the near-significant difference and the moderate correlation between the two sets of the scores. However, despite the findings that do not support the validity of the Vail Sport Test™ on the uninvolved limb, this should not diminish the overall validity of the test, as the tests original intent was to assess the operated limbs readiness to return to sport.

3D motion analysis has been used previously as a reference standard to assess the validity of a visual movement screen (Padua et al., 2009). Padua et al. (2009) assessed the criterion validity of the LESS by comparing the scores graded by an expert to those obtained from 3D motion analysis. These authors found excellent agreements for the grading of ankle dorsiflexion at initial contact, knee flexion ROM, trunk flexion at maximum knee flexion and foot position at initial contact, as well as moderate agreements for trunk flexion at initial contact, knee valgus at initial contact, and knee valgus ROM (Padua et al., 2009). Padua et al. (2009) also found that participants with poor jumping techniques (i.e., high LESS scores) displayed different kinematics and kinetics of lower extremities from those with excellent jumping techniques. Similar to the Padua et al. study (2009), a 3D motion analysis system was used in this dissertation study to assess knee motions in the sagittal and frontal planes during jumping and landings tasks. The findings of this dissertation study were in agreement with those of the Padua et al. study, therefore further supporting the use of 3D motion analysis as a reference standard for validating visual assessment of dynamic movements.

The results of this dissertation study also showed no significant difference between the Z scores of the operated limbs Vail Sport Test™ scores and those of the IKDC scores. However, we found a fair correlation ($r = 0.20$) between the two sets of scores. The IKDC is a well-established outcome measure in this population and improved scores on the IKDC have been to be related to improved performance on clinical measures (Collins et al., 2011; Reinke et al., 2011). However, the IKDC is meant to assess the patients' perceived functional levels of both of the operated or involved limbs of participants with knee disorders, whereas the Vail Sport Test™ was scored for operated and uninvolved limbs separately. This discrepancy may have impacted the results. As discussed earlier, the majority of the participants had high passing scores on the Vail Sport Test indicating a high level of function. Therefore, the fair correlation between these scores was not surprising. Further, it is also speculated that the relationship may not be linear in the upper quartile of the Vail Sport Test™ scores.

External Validity

A secondary purpose of this study was to determine the external validity of the Vail Sport Test™ as a measure of readiness to return to sports following ACL reconstruction. To assess the external validity of the test, two non-parametric Wilcoxon signed ranked tests were used to compare difference in scores between those who failed and those who passed the Vail Sport Test™ in real-time. The results indicate that there was no significant difference in scores for those in the "pass" or "fail" group. It was hypothesized that those in the "pass" group would not demonstrate any significant difference between limbs as this would seem to indicate that their operated limb behaves similarly to their uninvolved limb. Similarly, it was hypothesized that there would be a significant difference between limbs in the "fail" group, indicating that their operated limb behaved differently (more poorly) than their uninvolved limb.

The results of this analysis must be interpreted carefully, as there was a marked difference in the number of participants who passed (*n* = 44) and those failed (*n* = 4). This discrepancy may be attributed to a number of reasons. Firstly, those participants who were eligible to participate in this study were cleared by their surgeon and physical therapist to do so. This increases the potential that a skewed sample was recruited to participate in the study. The surgeon and physical therapist must have felt confident that the patients were ready for jumping and cutting tasks which may partially explain their overall clinical presentation at the time of testing. A clearer understanding of this point can be achieved by examining the additional ROM and strength measures of the participants, as provided in Table 4.

The participants that completed the Vail Sport Test™ demonstrated noticeable differences between limbs for the ROM of knee flexion, knee extension and hip internal rotation, as well as the peak torque of the quadriceps and hamstring muscles. However, the values collected from the participants in this dissertation study would all be considered "good" by comparison to the normative values for participants following ACL-R reported in the published articles (Bien & Dubuque, 2015; Harris et al., 2014; Palmieri-Smith et al., 2008; Renstrom et al., 2008; Sousa et al., 2015; Wilk et al., 1994). This could explain why these participants performed so well on the Vail Sport Test™ and thus led to the unequal number of participants in the “pass” and “fail” groups. Due to the marked difference in participants in each group no statistical comparisons between groups could be made in regards to the descriptive data. However, the “fail” group had less knee flexion ROM, decreased quadriceps and hamstring peak torque, and lower IKDC scores than the “pass” group. Lastly, these additional clinical measures help describe the participants overall clinical presentation and may indicate why they were cleared by their surgeon and physical therapist for return-to-sports testing. However, it must be noted that the surgeon did not have these additional participant characteristics at the time of release for testing, but rather relied on their own clinical assessment and input from each participant’s rehabilitation team to determine readiness to test.

Additionally, there was no significant difference between scores in the “fail” group. This is opposite of the results that were hypothesized. Because a difference between limbs of participants in the “fail” group would hypothetically indicate that the operated limb was not able to perform as well as the uninvolved limb. However, not only was there no significant difference, there was actually a trend toward the operated limb outperforming the uninvolved limb. Therefore, the poor performance of the uninvolved limb may have contributed to the overall score of the participant, leading to them being classified into the “fail” group.

In other words, this finding indicates that these four participants may have failed the Vail Sport test™ specifically due to the poor performance of the uninvolved limb, and the emphasis on unilateral work of the operated limb during prolonged ACL-R rehabilitation. Although specific rehabilitation treatments were not controlled for this study, the participants' readiness to return to sports would certainly be influenced by their rehabilitation treatments. A plethora of research exists examining the role of continued asymmetries between limbs at the time of return-to-sport in participants following ACL-R (Benjanuvatra et al., 2013; Chmielewski, 2011; Labanca et al., 2016; Noyes et al., 1991; Schmitt et al., 2012; Xergia et al., 2013).

The asymmetry findings between limbs in the participants following ACL-R may warrant inclusion of the uninvolved limb training in the rehabilitation plan. Additionally, although it is beyond the scope of this study to sub-analyze each grading component of the Vail Sport Test™ for each group, two participants who failed the test were unable to complete the full test battery of the Vail Sport Test™ due to fatigue, thus resulting in a complete loss of points for the time segment in which they had to stop and any subsequent time remaining. The inability of these participants to complete the full test may have further skewed the results and subsequent group assignment.

In the only previously-published study on the use of the Vail Sport Test™ in participants following ACL-R, Garrison et al. (2012) reported on the performance of

30 subjects following ACL-R. In their study, the average age of participants was 18.1 ± 4.7, which is similar to the participants' age of 16.9 ± 1.2 in this dissertation study. The reported scores on the operated limb during the Vail Sport Test™ for the Garrison et al. study was 45.0 ± 10.2, which is lower than the reported average in this dissertation study (49.3 ± 3.4). However, this difference may be partially explained by the difference of the times at which the testing was completed in these two studies. In the Garrison et al. study (2012), the average time from surgery in months was 5.5 ± 1.5, whereas the average time from surgery to testing in months was 7.0 ± 1.2 in this dissertation study. These additional months of rehabilitation could have resulted in improved performance during functional tasks, it is not unreasonable to expect improved performance on outcome measures with increased rehabilitation time. This also indicates that sufficient time (approximately 7 months based on this dissertation study) may be a key factor for returning to sports at a competitive level following ACL-R.

Current literature suggests that the re-injury rate (ipsilateral and contralateral limb) of ACL is up to 30% in athletes who return to sport(Grindem, Snyder-Mackler, Moksnes, Engebretsen, & Risberg, 2016). In examining factors that directly affect re-injury rate, time-from-surgery and quadriceps strength have been found to be associated with decreased injury risk. Grindem et al. (2016) reported in their cohort of participants that those who delayed return to sports for nine months had a 51% decrease in re-injury (Grindem et al., 2016). Specifically, the time-from-surgery factor provided the most protective effect. In addition to time-from-surgery, Grindem et al. (2016) found that those participants who passed return-to-sport criteria and demonstrated more symmetrical quadriceps strength had lower re-injury rates. These findings support the notion that although objective criteria are important, time-from-surgery is also an important variable to consider when assessing readiness to return to sports.

Lastly, it is worth noting that the passing score of 46/54 established in the literature was done so based on clinician judgment. As this is a study to establish the validity of the Vail Sport Test, consideration of the tests parametric properties is warranted. Perhaps the previously recommended "passing" score needs to be reexamined using receiver operating curves (ROC) analysis to generate a new "passing" score. However, due to the small sample size (*n* =4) of the "fail" group, an ROC analysis was not performed in order to determine a cutoff score. Further, it is not clinically and ethically feasible to put those participants who were clinically not ready for return-to-sports testing at risk for re-injury. Based on the results of this analysis, the external validity of the Vail Sport Test™ is supported. However, for the reasons outlined above, the results should be interpreted with caution.

Reliability

The tertiary purpose of this study was to determine the between-day test-retest reliability of the Vail Sport Test™. Intraclass correlation coefficients ($ICC_{3,1}$) were calculated to determine the reliability of the Vail Sport Test™ scores collected visually in real-time in two separate testing sessions from each participant for each limb. The results showed good between-day reliability for the operated limb and fair between-day reliability for the uninvolved limb. These results are in agreement with those of previously published research examining both the inter-rater and intra-rater reliability of the Vail Sport Test™ (Garrison et al., 2012). In the Garrison et al. (2012) study, excellent inter-rater and intra-rater reliability was reported, with the ICCs being 0.95 and 0.97, respectively. The between-day test-retest reliability value (ICC = 0.787 for the operated limb) in this dissertation study was expected to be lower than the ICC values reported by Garrison et al. (2012) because the reliability was established by the graders watching a videotaped test in the Garrison et al. study. Where as in this dissertation study, participants performed the test twice within a short period of time. In addition, the participants scored lower on the second Vail Sport Test™ possibly because of a fatigue effect.

It is worth noting that the participants in the reliability part of this dissertation study were a sample of convenience and these participants self-selected to return for additional testing. This may have skewed the results because those participants who were not as challenged by the test may have been the participants who chose to return to test again. However, given the high overall pass rate in this study, it is likely that the reported ICC values in this dissertation study would remain high regardless of which participants returned to test. In summary, the results of this study, combined with the results of the Garrison study support the overall reliability of the Vail Sport Test™.

Interestingly, the ICC value for the uninvolved limb was only 0.48 with a confidence interval that crosses zero, which should indicate caution in the interpretation of these results. The poorer reliability on the uninvolved limb may be due to the grader's bias, as more detail is typically given to the operated limb during testing as discussed earlier. The grader was asked to assess bilateral movements at the same time in this study. However, only the operated limb is graded in the original application of the Vail Sport Test™. Again, this may be explained by the inherent rater bias previously discussed.

Limitations

The results of this study should be interpreted in light of several limitations. Firstly, the inclusion and exclusion criteria of participants, specifically, the criterion that the participants be cleared by the surgeon for return-to-sport testing, could have resulted in a non-normal (i.e., positively skewed) distribution of the Vail Sports Test™ scores, leading to notably unequal sizes of the "pass" and "fail" groups. Although the purpose of the Vail Sport Test™ is to determine readiness to return to sports, and as such highly functional individuals are expected to be the ones taking the test, the high proportion of those who passed the test limits the ability to interpret the external validity results. Additionally, it must be noted that the designation of passing or failing was originally based on clinical expertise and as such, future studies may need to further examine the psychometric properties of the test.

A second limitation, which relates strongly to the above limitation, is that the participants who were recruited for this study were cleared by their physician to complete return-to-sport testing. Therefore, there may have been additional patients who would have passed but were not tested and vice versa. In addition, it is uncertain whether or not those patients who were referred to the return-to-sport test but declined to participate in the study would pass the test.

A third limitation of this study is in regards to the rater. In this dissertation study, the rater was asked to grade both limbs simultaneously during the forward and backward jogging portion of the test. The Vail Sport Test™ was originally designed to grade only the operated limb. Grading of both limbs simultaneously is a challenging task for the rater. Given the good convergent validity that was found between the visual and post-capture grading and the good acceptable between-day test-retest reliability for each limb, it is likely that the rater was able to successfully complete this task. However, this might explain why between-day test-retest reliability for the uninvolved limb was poorer than that of the operated limbs. If the rater was unable to appropriately perform a dual task, they may have focused their efforts on grading the operated limb rather than the uninvolved limb, as this is typically the limb of interest. The other limitation regarding the rater is that the rater in this dissertation study was an expert rater. This may limit the generalizability of the results because the Vail Sport Test™ score may vary between an expert and a novice rater.

The last limitation of this study is that only a portion of the collected 3D data was used for the post-capture grading. In an ideal situation, the complete time of the testing would have been captured and graded. However, due to the large amount of data that is captured, it was not feasible to collect the entire testing session. As such, a 10-second window was chosen to allow both appropriate grading and feasible data management. In a previous study comparing visual grading to post-capture grading, although the entire test was captured, only three drop vertical jumps were analyzed and took much less time than the total of 13 minutes of capture time which would have been required for complete capturing of the Vail Sport Test™.

Conclusion

This is the first study to assess the convergent construct validity, external validity, and between-day test-retest reliability of the Vail Sport Test™. The results of this study supports the use of the Vail Sport Test™ as a measure of readiness to return to sports because the convergent construct validity and between-day test-retest reliability were found to be good for the operated limb. Although the external validity was also found to support the use of the Vail Sport test™, the results of this portion of the study should be interpreted with caution, given the non-normally distributed sample, large pass rate, and the lack of difference between limbs in the "fail" group.

Recommendation for Future Research

Given the results of the external validity portion of this study, future studies should explore the psychometric properties of the Vail Sport Test™ and re-evaluate appropriate cutoff scores. Additionally, it may be worth examining the difference between expert and novice rater as this may influence the results of the test. Lastly, evaluating test performance of non-injured participants and participants with other injuries may increase the generalizability of the use of the Vail Sport Test™.

REFERENCES

Ageberg, E., Thomeé, R., Neeter, C., Silbernagel, K. G., & Roos, E. M. (2008). Muscle strength and functional performance in patients with anterior cruciate ligament injury treated with training and surgical reconstruction or training only: a two to five-year followup. *Arthrit Care Res, 59*(12), 1773-1779.

Aggarwal, J. K., & Cai, Q. (1997). Human motion analysis: A review. Paper presented at the Nonrigid and Articulated Motion Workshop, 1997. Proceedings., IEEE.

Ahldén, M., Samuelsson, K., Sernert, N., Forssblad, M., Karlsson, J., & Kartus, J. (2012). The Swedish national anterior cruciate ligament register: A report on baseline variables and outcomes of surgery for almost 18,000 patients. *Am J Sports Med, 40*(10), 2230-2235.

Alentorn-Geli, E., Myer, G. D., Silvers, H. J., Samitier, G., Romero, D., Lázaro-Haro, C., & Cugat, R. (2009a). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc, 17*(7), 705-729.

Alentorn-Geli, E., Myer, G. D., Silvers, H. J., Samitier, G., Romero, D., Lázaro-Haro, C., & Cugat, R. (2009b). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. *Knee Surg Sports Traumatol Arthrosc, 17*(8), 859-879.

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2012). Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. *Am J Sports Med, 40*(1), 41-48.

Ardern, C. L., Webster, K. E., Taylor, N. F., & Feller, J. A. (2011a). Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*, 45(7), 596-606.

Ardern, C. L., Webster, K. E., Taylor, N. F., & Feller, J. A. (2011b). Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med, 39*(3), 538-543.

Augustsson, J., Roland, T., & Karlsson, J. (2004). Ability of a new hop test to determine functional deficits after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*, *12*(15), 350-356.

Barber-Westin, S. D., & Noyes, F. R. (2011). Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthroscopy, 27*(12), 1697-1705.

Barber-Westin, S. D., Noyes, F. R., & McCloskey, J. W. (1999). Rigorous statistical reliability, validity, and responsiveness testing of the Cincinnati knee rating system in 350 subjects with uninjured, injured, or anterior cruciate ligament-reconstructed knees. *Am J Sports Med, 27*(4), 402-416.

Barenius, B., Ponzer, S., Shalabi, A., Bujak, R., Norlén, L., & Eriksson, K. (2014). Increased risk of osteoarthritis after anterior cruciate ligament reconstruction a 14-

year follow-up study of a randomized controlled trial. *Am J Sports Med*, *42*(5), 1049-1057.

Beecher, M., Garrison, J. C., & Wyland, D. (2010). Rehabilitation following a minimally invasive procedure for the repair of a combined anterior cruciate and posterior cruciate ligament partial rupture in a 15-year-old athlete. *J Orthop Sports Phys Ther*, *40*(5), 297-309.

Benjaminse, A., Habu, A., Sell, T. C., Abt, J. P., Fu, F. H., Myers, J. B., & Lephart, S. M. (2008). Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc, 16*(4), 400-407.

Benjanuvatra, N., Lay, B. S., Alderson J, & B.A., B. (2013). Comparison of ground reaction force asymmetry of the one-legged and two-legged countermovement jumps. *J Strength and Cond Res, 10*, 2700-2707.

Besier, T. F., Lloyd, D. G., Ackland, T. R., & Cochrane, J. L. (2001). Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med. Sci. Sports Exerc., 33*(7), 1176-1181.

Bien, D. P., & Dubuque, T. J. (2015). Considerations For late stage ACL rehabilitation and return to sport to limit re-injury risk and maxamize athletic performance. *Int J Sports Phys Ther, 10*(2), 256.

Bizzini, M., Hancock, D., & Impellizzeri, F. (2012). Suggestions from the field for return to sports participation following anterior cruciate ligament reconstruction: soccer. *J Orthop Sports Phys Ther, 42*(4), 304-312.

Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech*, *23*(3), 313-319.

Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, *23*(6), 573-578.

Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G. (2008). Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech, 23*(1), 81-92.

Briggs, K. K., Lysholm, J., Tegner, Y., Rodkey, W. G., Kocher, M. S., & Steadman, J. R. (2009). The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee 25 years later. *Am J Sports Med*, *37*(5), 890-897.

Butler, R. J., Lehr, M. E., Fink, M. L., Kiesel, K. B., & Plisky, P. J. (2013). Dynamic balance performance and noncontact lower extremity injury in college football players an initial study. *Sports Health: A Multidisciplinary Approach*, *5*(5), 417-422.

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

Chappell, J. D., Herman, D. C., Knight, B. S., Kirkendall, D. T., Garrett, W. E., & Yu, B. (2005). Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *Am J Sports Med, 33*(7), 1022-1029.

Chappell, J. D., & Limpisvasti, O. (2008). Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med, 36*(6), 1081-1086.

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

Chmielewski, T. L. (2011). Asymmetrical lower extremity loading after ACL reconstruction: more than meets the eye. *J Orthop Sports Phys Ther, 41*(6), 374-376.

Cicchetti, D. V. (1994). Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychol. Assess., 6*(4), 284.

Cohen, J. (1998). *Statistical power analysis for the behavioral sciences* (Vol. 2nd ed.). Erlbaum: Hillsdale.

Collins, N. J., Misra, D., Felson, D. T., Crossley, K. M., & Roos, E. M. (2011). Measures of knee function: International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Knee Injury and Osteoarthritis Outcome Score (KOOS), Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), Lysholm Knee Scoring Scale, Oxford Knee Score (OKS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Activity Rating Scale (ARS), and Tegner Activity Score (TAS). *Arthritis Care Res, 63*(S11), S208-S228.

Colombet, P., Allard, M., Bousquet, V., de Lavigne, C., Flurin, P.-H., & Lachaud, C. (2002). Anterior cruciate ligament reconstruction using four-strand semitendinosus and gracilis tendon grafts and metal interference screw fixation. *Arthroscopy, 18*(3), 232-237.

Corry, I. S., Webb, J. M., Clingeleffer, A. J., & Pinczewski, L. A. (1999). Arthroscopic reconstruction of the anterior cruciate ligament A comparison of patellar tendon autograft and four-strand hamstring tendon autograft. *Am J Sports Med, 27*(4), 444-454.

Cortes, N., Onate, J., Abrantes, J., Gagen, L., Dowling, E., & Van Lunen, B. (2007). Effects of gender and foot-landing techniques on lower extremity kinematics during drop-jump landings. *J Appl Biomech*, *23*(4), 289.

Crawford, K., Briggs, K. K., Rodkey, W. G., & Steadman, J. R. (2007). Reliability, validity, and responsiveness of the IKDC score for meniscus injuries of the knee. *Arthroscopy, 23*(8), 839-844.

Daniel, D. M., Stone, M. L., Dobson, B. E., Fithian, D. C., Rossman, D. J., & Kaufman, K. R. (1994). Fate of the ACL-injured patient a prospective outcome study. *Am J Sports Med, 22*(5), 632-644.

Decker, M. J., Torry, M. R., Noonan, T. J., Riviere, A., & Sterett, W. I. (2002). Landing adaptations after ACL reconstruction. *Med. Sci. Sports Exerc, 34*(9), 1408-1413.

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech, 18*(7), 662-669.

Eitzen, I., Holm, I., & Risberg, M. (2009). Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. *Br J Sports Med, 43*(5), 371-376.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods, 39*(2), 175-191.

Faunø, P., & Wulff, J. B. (2006). Mechanism of anterior cruciate ligament injuries in soccer. *Int J Sports Phys Ther, 27*(1), 75-79.

Feller, J. A., & Webster, K. E. (2003). A randomized comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction. *Am J Sports Med, 31*(4), 564-573.

Fink, C., Hoser, C., Hackl, W., Navarro, R., & Benedetto, K. (2001). Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture-is sports activity a determining variable? *Int J Sports Phys Ther, 22*(04), 304-309.

Fitzgerald, G. K., Lephart, S. M., Hwang, J. H., & Wainner, M. R. S. (2001). Hop tests as predictors of dynamic knee stability. *J Orthop Sports Phys Ther, 31*(10), 588-597.

Fleming, B. C., Renstrom, P. A., Ohlen, G., Johnson, R. J., Peura, G. D., Beynnon, B. D., & Badger, G. J. (2001). The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J orthop res, 19*(6), 1178-1184.

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc, 35*(10), 1745-1750.

Ford, K. R., Myer, G. D., & Hewett, T. E. (2007). Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc, 39*(11), 2021.

Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc, 37*(1), 124-129.

Frobell, R. B., Lohmander, L. S., & Roos, E. M. (2007). The challenge of recruiting patients with anterior cruciate ligament injury of the knee into a randomized clinical trial comparing surgical and non-surgical treatment. *Contemp Clin Trials, 28*(3), 295-302.

Garrison, J. C., Shanley, E., Thigpen, C., Geary, R., Osler, M., & DelGiorno, J. (2012). The Reliability of the Vail Sport Test™ as a Measure of Physical Performance Following Anterior Cruciate Ligament Recosntruction *Int J Sports Phys Ther, 7*(1), 20.

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

Grevnerts, H. T., Terwee, C. B., & Kvist, J. (2015). The measurement properties of the IKDC-subjective knee form. *Knee Surg Sports Traumatol Arthrosc, 23*(12), 3698-3706.

Gribble, P. A., Hertel, J., & Plisky, P. (2012). Using the star excursion balance test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train, 47*(3), 339-357.

Griffin, L. Y., Agel, J., Albohm, M. J., Arendt, E. A., Dick, R. W., Garrett, W. E., Ireland, M. L. (2000). Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg, 8*(3), 141-150.

Griffin, L. Y., Albohm, M. J., Arendt, E. A., Bahr, R., Beynnon, B. D., DeMaio, M., Hannafin, J. A. (2006). Understanding and preventing noncontact anterior cruciate ligament injuries a review of the Hunt Valley II Meeting, January 2005. *Am J Sports Med, 34*(9), 1512-1532.

Grindem, H., Logerstedt, D., Eitzen, I., Moksnes, H., Axe, M. J., Snyder-Mackler, L., Risberg, M. A. (2011). Single-legged hop tests as predictors of self-reported knee function in nonoperatively treated individuals with anterior cruciate ligament injury. *Am J Sports Med, 39*(11), 2347-2354.

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med,* bjsports-2016-096031.

Hambly, K., & Griva, K. (2010). IKDC or KOOS which one captures symptoms and disabilities most important to patients who have undergone initial anterior cruciate ligament reconstruction? *Am J Sports Med, 38*(7), 1395-1404.

Hamill, J., Heiderscheit, B. C., & Pollard, C. D. (2005). Gender differences in lower extremity coupling variability during an unanticipated cutting maneuver. *J Appl Biomech, 21*(2), 143-152.

Hamilton, R. T., Shultz, S. J., Schmitz, R. J., & Perrin, D. H. (2008). Triple-hop distance as a valid predictor of lower limb strength and power. *J Athl Train, 43*(2), 144.

Harris, J. D., Abrams, G. D., Bach, B. R., Williams, D., Heidloff, D., Bush-Joseph, C. A., . . . Cole, B. J. (2014). Return to sport after ACL reconstruction. *Orthopedics, 37*(2), e103-108.

Hart, J. M., Pietrosimone, B., Hertel, J., & Ingersoll, C. D. (2010). Quadriceps activation following knee injuries: a systematic review. *J Athl Train, 45*(1), 87.

Hartigan, E. H., Axe, M. J., & Snyder-Mackler, L. (2010). Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther, 40*(3), 141-154.

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., & Myer, G. D. (2010). Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations-update 2010. *Int J Sports Phys Ther, 5*(4), 234.

Hewett, T. E., Myer, G. D., & Ford, K. R. (2006). Anterior cruciate ligament injuries in female athletes part 1, mechanisms and risk factors. *Am J Sports Med, 34*(2), 299-311.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes a prospective study. *Am J Sports Med, 33*(4), 492-501.

Hewett, T. E., Torg, J. S., & Boden, B. P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med, 43*(6), 417-422.

Higgins, L. D., Taylor, M. K., Park, D., Ghodadra, N., Marchant, M., Pietrobon, R., & Cook, C. (2007). Reliability and validity of the international knee documentation committee (IKDC) subjective knee form. *Joint Bone Spine, 74*(6), 594-599.

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

Houck, J. R., Duncan, A., & Kenneth, E. (2006). Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait & posture, 24*(3), 314-322.

Howe, T. E., Dawson, L. J., Syme, G., Duncan, L., & Reid, J. (2012). Evaluation of outcome measures for use in clinical practice for adults with musculoskeletal conditions of the knee: a systematic review. *Man Ther, 17*(2), 100-118.

Irrgang, J. J., Ho, H., Harner, C. D., & Fu, F. H. (1998). Use of the international knee documentation committee guidelines to assess outcome following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc, 6*(2), 107-114.

Itoh, H., Kurosaka, M., Yoshiya, S., Ichihashi, N., & Mizuno, K. (1998). Evaluation of functional deficits determined by four different hop tests in patients with anterior cruciate ligament deficiency. *Knee Surg Sports Traumatol Arthrosc, 6*(4), 241-245.

Johnson, D. S., & Smith, R. B. (2001). Outcome measurement in the ACL deficient knee—what's the score? *Knee, 8*(1), 51-57.

Joseph, M. F., Rahl, M., Sheehan, J., MacDougall, B., Horn, E., Denegar, C. R., . . . Kraemer, W. J. (2011). Timing of lower extremity frontal plane motion differs between female and male athletes during a landing task. *Am J Sports Med, 39*(7), 1517-1521.

Kanakamedala, A. C., Anderson, A. F., & Irrgang, J. J. (2016). IKDC subjective knee Form and marx activity rating scale are suitable to evaluate all orthopaedic sports medicine knee conditions: a systematic review. *Am J Sports Med*, jisakos-2015-000014.

Kiefer, A. W., Kushner, A. M., Groene, J., Williams, C., Riley, M. A., & Myer, G. D. (2015). A commentary on real-time biofeedback to augment neuromuscular training for ACL injury prevention in adolescent athletes. *J Sports Sci Med, 14*(1), 1.

Kokmeyer, D., Wahoff, M., & Mymern, M. (2012). Suggestions from the field for return-to-sport rehabilitation following anterior cruciate ligament reconstruction: alpine skiing. *J Orthop Sports Phys Ther, 42*(4), 313-325.

Kristianslund, E., & Krosshaug, T. (2013). Comparison of drop jumps and sport-specific sidestep cutting implications for anterior cruciate ligament injury risk screening. *Am J Sports Med*, 0363546512472043.

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball video analysis of 39 cases. *Am J Sports Med, 35*(3), 359-367.

Labanca, L., Laudani, L., Menotti, F., Rocchi, J., Mariani, P. P., Giombini, A., Macaluso, A. (2016). Asymmetrical lower extremity loading early after anterior cruciate ligament reconstruction is a significant predictor of asymmetrical loading at the time of return to sport. *Am J Phys Med Rehabil, 95*(4), 248-255.

LaBella, C. R., Hennrikus, W., Hewett, T. E., Brenner, J. S., Brookes, M. A., Demorest, R. A., LaBotz, M. (2014). Anterior cruciate ligament injuries: diagnosis, treatment, and prevention. *J. Pediatr, 133*(5), e1437-e1450.

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *Am J Sports Med, 35*(11), 1888-1900.

Langford, J. L., Webster, K. E., & Feller, J. A. (2009). A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. *Br J Sports Med, 43*(5), 377-378.

Leardini, A., Biagi, F., Belvedere, C., & Benedetti, M. G. (2009). Quantitative comparison of current models for trunk motion in human movement analysis. *Clin Biomech, 24*(7), 542-550.

Lee, S., Seong, S. C., Jo, H., Park, Y. K., & Lee, M. C. (2004). Outcome of anterior cruciate ligament reconstruction using quadriceps tendon autograft. *Arthroscopy, 20*(8), 795-802.

Lentz, T. A., Zeppieri Jr, G., Tillman, S. M., Indelicato, P. A., Moser, M. W., George, S. Z., & Chmielewski, T. L. (2012). Return to preinjury sports participation following anterior cruciate ligament reconstruction: contributions of demographic, knee impairment, and self-report measures. *J Orthop Sports Phys Ther, 42*(11), 893-901.

Lepley, A., Gribble, P., Thomas, A., Tevald, M., Sohn, D., & Pietrosimone, B. (2015). Quadriceps neural alterations in anterior cruciate ligament reconstructed patients: A 6-month longitudinal investigation. *Scand J Med Sci Sports*.

Logerstedt, D., Grindem, H., Lynch, A., Eitzen, I., Engebretsen, L., Risberg, M. A., Snyder-Mackler, L. (2012). Single-Legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction the Delaware-Oslo ACL cohort study. *Am J Sports Med*, 40(10), 2348-2356.

Logerstedt, D., Lynch, A., Axe, M. J., & Snyder-Mackler, L. (2013). Pre-operative quadriceps strength predicts IKDC2000 scores 6 months after anterior cruciate ligament reconstruction. *Knee, 20*(3), 208-212.

Magnussen, R. A., Verlage, M., Flanigan, D. C., Kaeding, C. C., & Spindler, K. P. (2015). Patient-reported outcomes and their predictors at minimum 10 years after anterior cruciate ligament reconstruction: a systematic review of prospectively collected data. *Orthop J Sports Med, 3*(3), 1-7.

Mair, S. D., Seaber, A. V., Glisson, R. R., & Garrett, W. E. (1996). The role of fatigue in susceptibility to acute muscle strain injury. *Am J Sports Med, 24*(2), 137-143.

Mandengue, S. H., Seck, D., Bishop, D., Cisse, F., Tsala-Mbala, P., & Ahmaidi, S. (2005). Are athletes able to self-select their optimal warm up? *J Sports Sci Med, 8*(1), 26-34.

Marx, R. G., Jones, E. C., Allen, A. A., Altchek, D. W., O'Brien, S. J., Rodeo, S. A., Wickiewicz, T. L. (2001). Reliability, validity, and responsiveness of four knee outcome scales for athletic patients. *J Bone Joint Surg Am, 83*(10), 1459-1469.

McLean, S. G., Huang, X., & van den Bogert, A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. *Clin Biomech, 20*(8), 863-870.

Moses, B., Orchard, J., & Orchard, J. (2012). Systematic review: annual incidence of ACL injury and surgery in various populations. *Res Sports Med, 20*(3-4), 157-179.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2008). Tuck jump assessment for reducing anterior cruciate ligament injury risk. *J Athl Train, 13*(5), 39.

Myer, G. D., Schmitt, L. C., Brent, J. L., Ford, K. R., Barber Foss, K. D., Scherer, B. J., Hewett, T. E. (2011). Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. *J Orthop Sports Phys Ther, 41*(6), 377-387.

Myklebust, G., Holm, I., Mæhlum, S., Engebretsen, L., & Bahr, R. (2003). Clinical, functional, and radiologic outcome in team handball players 6 to 11 years after anterior cruciate ligament injury a follow-up study. *Am J Sports Med, 31*(6), 981-989.

Nakayama, Y., Shirai, Y., Narita, T., Mori, A., & Kobayashi, K. (2000). Knee functions and a return to sports activity in competitive athletes following anterior cruciate ligament reconstruction. *J Nippon Med Sch, 67*(3), 172-176.

Narducci, E., Waltz, A., Gorski, K., Leppla, L., & Donaldson, M. (2011). The clinical utility of functional performance tests within one-year post-ACL reconstruction: a systematic review. *Int J Sports Phys Ther, 6*(4), 333.

Noyes, Barber, S. D., & Mangine, R. E. (1991). Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med, 19*(5), 513-518.

Noyes, F., Matthews, D., Mooar, P., & Grood, E. (1983a). The symptomatic anterior cruciate-deficient knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. *J Bone Joint Surg Am, 65*(2), 163-174.

Noyes, F. R., Mooar, P., Matthews, D., & Butler, D. (1983b). The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. *J Bone Joint Surg Am, 65*(2), 154-162.

Nyland, J., Caborn, D., Shapiro, R., & Johnson, D. (1997). Fatigue after eccentric quadriceps femoris work produces earlier gastrocnemius and delayed quadriceps femoris activation during crossover cutting among normal athletic women. *Knee Surg Sports Traumatol Arthrosc*, *5*(3), 162-167.

Orchard, J., & Seward, H. (2002). Epidemiology of injuries in the Australian football league, seasons 1997–2000. *Br J Sports Med*, *36*(1), 39-44.

Oro, F. B., Sikka, R. S., Wolters, B., Graver, R., Boyd, J. L., Nelson, B., & Swiontkowski, M. F. (2011). Autograft versus allograft: an economic cost comparison of anterior cruciate ligament reconstruction. *Arthroscopy, 27*(9), 1219-1225.

Owens, T., Shim, A., Beebe, J., & Yom, J. (2013). The biomechanical effects of cutting decision-making on the lower extremity during a drop-landing. *J Sports Sci Med, 16*, e74.

Padua, D. A., Boling, M. C., DiStefano, L. J., Onate, J. A., Beutler, A. I., & Marshall, S. W. (2011). Reliability of the landing error scoring system-real time, a clinical assessment tool of jump-landing biomechanics. *J Sport Rehabil*, 20(2), 146-156.

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics the JUMP-ACL Study. *Am J Sports Med*, *37*(10), 1996-2002.

Palmieri-Smith, R. M., Thomas, A. C., & Wojtys, E. M. (2008). Maximizing quadriceps strength after ACL reconstruction. *Clin Sports Med, 27*(3), 405-424.

Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. (2007). Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin Sports Med, 17*(4), 263-268.

Pappas, E., Shiyko, M. P., Ford, K. R., Myer, G. D., & Hewett, T. E. (2016). Biomechanical Deficit Profiles Associated with ACL Injury Risk in Female Athletes. *Med Sci Sports Exerc*, *48*(1), 107-113.

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med, 38*(10), 1968-1978.

Philippon, M. J., Christensen, J. C., & Wahoff, M. S. (2009). Rehabilitation after arthroscopic repair of intra-articular disorders of the hip in a professional football athlete. *J Sport Rehabil, 18*(1), 118-134.

Phillips, N., & van Deursen, R. (2008). Landing stability in anterior cruciate ligament deficient versus healthy individuals: A motor control approach. *Phys Ther Sport*, *9*(4), 193-201.

Pierce, C. M., LaPrade, R. F., Wahoff, M., O'Brien, L., & Philippon, M. J. (2013). Ice hockey goaltender rehabilitation, including on-ice progression, after arthroscopic hip surgery for femoroacetabular impingement. *J Orthop Sports Phys Ther*, *43*(3), 129-141.

Pietrosimone, B. G., Lepley, A. S., Ericksen, H. M., Gribble, P. A., & Levine, J. (2013). Quadriceps strength and corticospinal excitability as predictors of disability after anterior cruciate ligament reconstruction. *J Sport Rehabil, 22*(1), 1-6.

Pollard, C. D., Sigward, S. M., Ota, S., Langford, K., & Powers, C. M. (2006). The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clin Sports Med, 16*(3), 223-227.

Portney, L. G., & Watkins, M. P. (2015). *Foundations of clinical research: applications to practice*: FA Davis.

Prodromos, C. C., Han, Y., Rogowski, J., Joyce, B., & Shi, K. (2007). A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury–reduction regimen. *Arthroscopy, 23*(12), 1320-1325. e1326.

Reid, A., Birmingham, T. B., Stratford, P. W., Alcock, G. K., & Giffin, J. R. (2007). Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther, 87*(3), 337-349.

Reinke, E. K., Spindler, K. P., Lorring, D., Jones, M. H., Schmitz, L., Flanigan, D. C., Martin, M. (2011). Hop tests correlate with IKDC and KOOS at minimum of 2 years after primary ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc, 19*(11), 1806-1816.

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Krosshaug, T. (2008). Non-contact ACL injuries in female athletes: an international olympic committee current concepts statement. *Br J Sports Med, 42*(6), 394-412.

Risberg, M. A., Holm, I., Steen, H., & Beynnon, B. D. (1999). Sensitivity to changes over time for the IKDC form, the Lysholm score, and the Cincinnati knee score A prospective study of 120 ACL reconstructed patients with a 2-year follow-up. *Knee Surg Sports Traumatol Arthrosc, 7*(3), 152-159.

Risberg, M. A., Oiestad, B. E., Gunderson, R., Aune, A. K., Engebretsen, L., Culvenor, A., & Holm, I. (2016). Changes in knee osteoarthritis, symptoms, and function after anterior cruciate ligament reconstruction A 20-Year prospective follow-up Study. *Am J Sports Med, 44*(5), 1215-1224.

Roos, E. M., Roos, H. P., Lohmander, L. S., Ekdahl, C., & Beynnon, B. D. (1998). Knee injury and osteoarthritis outcome score (KOOS)—development of a self-administered outcome measure. *J Orthop Sports Phys Ther, 28*(2), 88-96.

Sadoghi, P., von Keudell, A., & Vavken, P. (2012). Effectiveness of anterior cruciate ligament injury prevention training programs. *J Bone Joint Surg Am, 94*(9), 769-776.

Schmitt, L. C., Paterno, M. V., & Hewett, T. E. (2012). The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther, 42*(9), 750-759.

Shelbourne, K. D., Sullivan, A. N., Bohard, K., Gray, T., & Urch, S. E. (2009). Return to basketball and soccer after anterior cruciate ligament reconstruction in competitive school-aged athletes. *Sports Health, 1*(3), 236-241.

Snyder-Mackler, L., De Luca, P. F., Williams, P. R., Eastlack, M. E., & Bartolozzi, A. (1994). Reflex inhibition of the quadriceps femoris muscle after injury or reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am, 76*(4), 555-560.

Snyder-Mackler, L., Delitto, A., Bailey, S., & Stralka, S. (1995). Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am, 77*(8), 1166-1173.

Sousa, P. L., Krych, A. J., Cates, R. A., Levy, B. A., Stuart, M. J., & Dahm, D. L. (2015). Return to sport: Does excellent 6-month strength and function following ACL reconstruction predict midterm outcomes? *Knee Surg Sports Traumatol Arthrosc*, 25(5), 1356-1363.

Stalzer, S., Wahoff, M., & Scanlan, M. (2006). Rehabilitation following hip arthroscopy. *Clin Sports Med, 25*(2), 337-357.

Swenson, D. M., Yard, E. E., Collins, C. L., Fields, S. K., & Comstock, R. D. (2010). Epidemiology of US high school sports-related fractures, 2005-2009. *Clin Sports Med, 20*(4), 293-299.

Teitz. (2001). *Video Analysis of ACL injuries. In: Griffin LY, ed Prevention of Noncontact ACL injuries.* Rosemont, IL: American Association of Orthopedic Surgeons.

Van Grinsven, S., Van Cingel, R., Holla, C., & Van Loon, C. (2010). Evidence-based rehabilitation following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc, 18*(8), 1128-1144.

Van Meer, B. L., Meuffels, D. E., Vissers, M. M., Bierma-Zeinstra, S. M., Verhaar, J. A., Terwee, C. B., & Reijman, M. (2013). Knee injury and osteoarthritis outcome score or international knee documentation committee subjective knee form: which questionnaire is most useful to monitor patients with an anterior cruciate ligament rupture in the short term? *Arthroscopy, 29*(4), 701-715.

Wahoff, M., & Ryan, M. (2011). Rehabilitation after hip femoroacetabular impingement arthroscopy. *Clin Sports Med, 30*(2), 463-482.

Waldén, M., Hägglund, M., Magnusson, H., & Ekstrand, J. (2011). Anterior cruciate ligament injury in elite football: a prospective three-cohort study. *Knee Surg Sports Traumatol Arthrosc*, *19*(1), 11-19.

Wang, I.-L., Wang, S.-Y., & Wang, L.-I. (2015). Sex differences in lower extremity stiffness and kinematics alterations during double-legged drop landings with changes in drop height. *Sports Biomech*, *14*(4), 404-412.

Wera, J. C., Nyland, J., Ghazi, C., MacKinlay, K. G., Henzman, R. C., Givens, J., & Brand, J. C. (2014). International Knee Documentation Committee knee survey use after anterior cruciate ligament reconstruction: a 2005-2012 systematic review and world region comparison. *Arthroscopy, 30*(11), 1505-1512.

Wilk, K. E., Romaniello, W. T., Soscia, S. M., Arrigo, C. A., & Andrews, J. R. (1994). The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-Reconstructed knee. *J Orthop Sports Phys Ther*, *20*(2), 60-73.

Williams, G. N., Buchanan, T. S., Barrance, P. J., Axe, M. J., & Snyder-Mackler, L. (2005). Quadriceps weakness, atrophy, and activation failure in predicted noncopers after anterior cruciate ligament injury. *Am J Sports Med, 33*(3), 402-407.

Xergia, S. A., McClelland, J. A., Kvist, J., Vasiliadis, H. S., & Georgoulis, A. D. (2011). The influence of graft choice on isokinetic muscle strength 4–24 months after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc, 19*(5), 768-780.

Xergia, S. A., Pappas, E., & Georgoulis, A. D. (2015). Association of the single-limb hop test with isokinetic, kinematic, and kinetic asymmetries in patients after anterior cruciate ligament reconstruction. *Sports Health, 7*(3), 217-223.

Xergia, S. A., Pappas, E., Zampeli, F., Georgiou, S., & Georgoulis, A. D. (2013). Asymmetries in functional hop tests, lower extremity kinematics, and isokinetic strength persist 6 to 9 months following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther, 43*(3), 154-162.

Yu, B., McClure, S. B., Onate, J. A., Guskiewicz, K. M., Kirkendall, D. T., & Garrett, W. E. (2005). Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *Am J Sports Med, 33*(9), 1356-1364.

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007a). Deficits in neuromuscular control of the trunk predict knee injury risk a prospective biomechanical-epidemiologic study. *Am J Sports Med, 35*(7), 1123-1130.

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007b). The effects of core proprioception on knee injury a prospective biomechanical-epidemiological study. *Am J Sports Med*, *35*(3), 368-373.

Zebis, M. K., Andersen, L. L., Bencke, J., Kjær, M., & Aagaard, P. (2009). Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am J Sports Med*, *37*(10), 1967-1973.

Appendix A

Vail Sport Test™

Single Leg Squat

Lateral Bounding

Forward Jogging

Backward Jogging

Appendix B
Grading Criteria for the Vail Sport Test™

Vail Sport Test™ Scored by:______________________________

SINGLE LEG SQUAT Goal: 3 Minutes	**Minute 1**		**Minute 2**		**Minute 3**	
	Yes (1)	**No (0)**	**Yes (1)**	**No (0)**	**Yes (1)**	**No (0)**
Knee flexion angle between 30° and 60°						
Performs repetitions without dynamic knee valgus (*knee valgus=patella falls medial to the great toe)						
Avoids locking knee during extension						
Avoids patella extending past the toe during knee flexion						
Maintains upright trunk during knee flexion						
Single Leg Squat Total Points:	/15					

*If patient repeats error on 3 consecutive repetitions after correction, they are not eligible to receive a point for that particular standard (within each 1 minute timeframe).

LATERAL AGILITY Goal: 90 Seconds	**1st 30 sec.**		**2nd 30 sec.**		**3rd 30 sec.**	
	Yes (1)	**No (0)**	**Yes (1)**	**No (0)**	**Yes (1)**	**No (0)**
Knee flexion angle between 30° and 60°						
Performs repetitions without dynamic knee valgus (*knee valgus=patella falls medial to the great toe)						
Performs repetitions within landing boundaries						
Landing phase does not exceed 1 second in duration						
Maintains upright trunk during knee flexion						
Lateral Agility Total Points:	/15					

*If patient repeats error on 3 consecutive repetitions after correction, they are not eligible to receive a point for that particular standard (within each 30 second timeframe).

FORWARD RUNNING Goal: 2 Minutes	**Minute 1**		**Minute 2**	
	Yes (1)	**No (0)**	**Yes (1)**	**No (0)**
Knee flexion angle between 30° and 60°				
Performs repetitions within landing boundaries				
Performs repetitions without dynamic knee valgus (*knee valgus=patella falls medial to the great toe)				
Avoids locking knee during extension				
Landing phase does not exceed 1 second in duration				
Maintains upright trunk during knee flexion				
Forward Running Total Points:	/12			

*If patient repeats error on 3 consecutive repetitions after correction, they are not eligible to receive a point for that particular standard (within each 1 minute timeframe).

BACKWARD RUNNING Goal: 2 Minutes	**Minute 1**		**Minute 2**	
	Yes (1)	**No (0)**	**Yes (1)**	**No (0)**
Knee flexion angle between 30° and 60°				
Performs repetitions within landing boundaries				
Performs repetitions without dynamic knee valgus (*knee valgus=patella falls medial to the great toe)				
Avoids locking knee during extension				
Landing phase does not exceed 1 second in duration				
Maintains upright trunk during knee flexion				
Backward Running Total Points:	/12			

Vail Sport Test **Scored By:**	
Single Leg Squat	/15
Lateral Agility	/15
Forward Running	/12
Backward Running	/12
Total Points	**/54**

Appendix C

Review Summary for Three-Dimensional (3D) Motion Analysis Studies

Pollard CD. The influence of In-Season Injury Prevention Training on Lower Extremity Kinematics During Landing in Female Soccer Players.2006	ACL	Pre-post intervention study	jump-landing-30cm	Vicon	Not stated	12-Anterior Superior Iliac Spine, Posterior Superior Iliac Spine, lateral epicondyles of knees, lateral malleolus, Calcaneus, 5th metatarsal	120Hz	Data normalized to 100% of drop jump cycle. Only reviewed early deceleration phase (1st 20% of land)	Peak: hip abduction angle, hip Internal rotation, knee valgus, knee flexion
Paterno MV. Biomechanical Measures During Landing and Postural Stability Predict Second ACL injury after ACL-R and RTS. 2010	ACL	Cohort	jump-landing-31cm	EVaRT	10	37-Not stated	240HZ	Filtered with a cut off frequency of 12Hz	Hip flexion, hip adduction, hip Internal rotation, knee extension, knee adduction, knee Internal rotation
Pappas E-Biomechanical Differences Between Unilateral and Bilateral Landings From a Jump: Gender Differences.2007	Healthies	Repeated measures-gender comparison	jump-landing-40cm	Eagle Camera System	8	20-Sacrum, L Posterior Superior Iliac Spine, Anterior Superior iliac Spine, bilateral 2nd Metatarsal, calcaneus, lateral malleolus, fibula, lateral epicondyle of knee, thigh, acromion, lateral humeral epicondyle, distal radioulnar.	240Hz	Filtered with a cut off frequency of 6HZ	Peak: Knee flexion, hip adduction, knee valgus
McLean SG. Association	Healthies	Laboratory study	Side step cut	Motion analysis	6	19-bilateral Anterior	240Hz	Filtered with a cut	Hip flexion, extension, hip abduction,

between LE posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury.2005						Superior Iliac Spine, Posterior Superior Iliac Spine, Greater Trochanter, thigh, medial/lateral femoral condyle, tibial tuberosity, fibula, tibia, medial and lateral malleolus, 2nd malleolus, calcaneus, 5th met, distal 5th malleolus		off frequency 18HZ	adduction, hip Internal rotation, hip external rotation, knee flexion, knee extension, knee varus and knee valgus, knee Internal rotation, knee external rotation, Ankle plantarflexion, Dorsiflexion, ankle inversion, ankle eversion
Ford KR. Valgus Knee Motion During Landing in High School Female and male Basketball Players.2003	Healthies	Laboratory study-gender comparison	jump-landing- -31cm	Eagle cameras -motion analysis	8	23- sacrum, bilateral shoulder, ASIS, GT, mid-thigh, medial and lateral knee, mid shank, medial and lateral ankle, heel, toe	240Hz	Filtered with a cut off frequency of 9Hz	Knee valgus
Decker MJ. Gender Differences in Lower Extremity Kinematics, Kinetics and Energy Absorption During Landing	Healthies	Repeated measures	jump-landing-60cm	Motion Analysis	5	13-not stated	120Hz	Filtered with a cut off frequency of 10Hz	Hip, knee, ankle flexion/extension

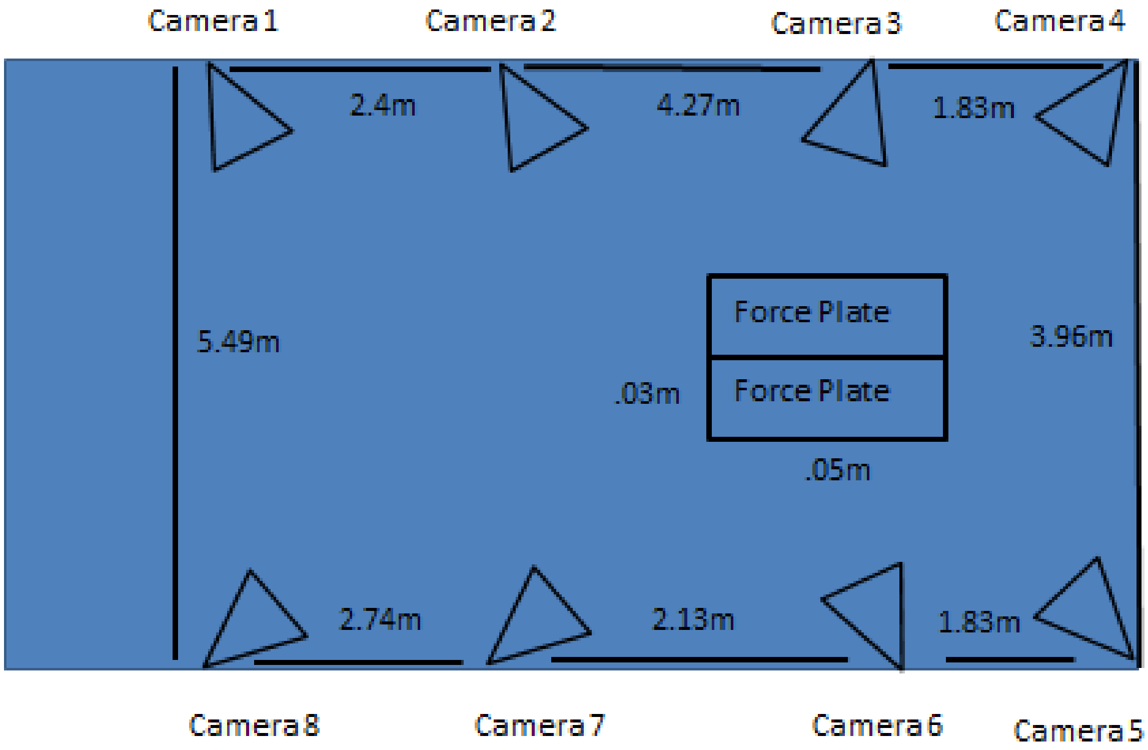
Chappell JD. Kinematics and EMG of landing preparation in vertical stop jump.2007	Healthies	Laboratory Study	Stop-jump task	Motus	8	L3-L4, Bilateral AC joint, Anterior Superior iliac Spine, lateral/medial knee joint line, lateral/medial malleolus, calcaneus, lateral thigh, lateral shank, heel, head of 1st Met, head of 5th	120Hz	Filtered with estimated optimal cut off frequency	Hip flexion, hip Internal, external rotation, hip abduction, hip adduction, knee flexion, knee internal rotation, knee external rotation, knee valgus/varus
Phillips N. Landing stability in ACL deficient vs healthy individuals: a motor control approach	ACL-D and Healthies	Laboratory study: case control	Running, deceleration , single leg hop	Vicon	8	19-Anterior Superior iliac Spine, Posterior Superior Iliac Spine, Greater Trochanter, lateral thigh(4), lateral/medial epicondyle, lateral shank (4), lateral/medial mal, 5th met, calcaneus(2).	50Hz	Not stated	Not stated
Chappell JD. Effect of fatigue on knee kinetics and kinematics in stop jump tasks.2005	Healthies	Laboratory study	Stop jump tasks	Motus	4	13-L4, Bilateral AC joints, Anterior Superior Iliac Spine, lateral/medial knee joint line, lateral/medial	180Hz	Filtered with estimated optimal cut off Frequency.	Knee flexion/extension, valgus-varus, internal-external rotation

						malleolus, calcaneus, lateral thigh, lateral shank, heel, head of 1st Metatarsal, head of 5th			
Padua-LESS is a valid and reliable clinical tool of jump landing biomechanics. 2009	Healthies	Cohort Study	jump-landing - 30cm	Flock of Birds Motion Monitor	2	15: Anterior Superior Iliac Spine, L5, lateral thigh, tibia, medial/lateral condyles, medial/lateral malleolus.	144Hz	filtered with a cut off Frequency of 14.5Hz	Hip and knee flexion, hip abduction/adduction, knee varus, valgus, internal rotation, external rotation
Chappell JD. Effect of NM training program on the kinetics and kinematics of jumping tasks.2008	Healthies	Laboratory study	Vertical jump, hop test, drop jump, stop jump	Real time motion analysis	8	18-Bilateral AC joints, Anterior Superior Iliac Spine, Posterior Superior Iliac Spine , lateral thigh, lateral condyle, lateral shank, lateral malleolus, heels, 1st met, L4.	Not stated	Not stated	Hip flexion, abduction, ER, knee flexion, valgus, IR, pelvic lateral tilt.
Ford KR. Gender differences in the kinematics of unanticipated cutting in youth athletes.2005	Healthies	Laboratory study	Jump stop, unanticipated cut move	Eagle Cameras	8	23-not stated	240Hz	Not stated	Knee flexion/extension, ankle inversion/eversion, knee abduction/adduction
Benjaminse A. Fatigue alters LE	Healthy	Repeated measure	Stop jump task	Vicon	6	Heel, lateral malleolus, 2nd	120HZ	Filtered with	Hip Internal rotation/external

kinematics during a SL stop jump task.		laboratory study				met head, lateral femoral condyle, Anterior Superior Iliac Spine, sacrum, mid thigh, mid calf		estimated optimal cut off Frequency.	rotation, adduction/abduction, varus/valgus, knee flexion/extension
Yu B. Age and gender effect on lower extremity kinematics of youth soccer players in a stop-jump task	Healthies	Laboratory Study	Stop jump task	Not stated	6	12- AC joint, Anterior Superior Iliac Spine, mid lateral thigh, lateral condyle, mid lateral shank, lateral malleolus. L4.	120Hz	Filtered with estimated optimal cut off Frequency.	Hip flexion/extension, abduction/adduction, Internal rotation/External rotation, knee flexion/extension, valgus/varus, Internal rotation/External rotation
Cortes N. Effects of Gender and Foot landing techniques on lower extremity kinematics during drop jump landings	Healthies	Study	jump-landing-30cm	Flock of Birds	Not stated	Medial/lateral malleolus, medial/lateral condyle, 2nd phalanx, Greater trochanter	100Hz	Filtered with estimated optimal cut off Frequency	Knee flexion, hip flexion, knee valgus, ankle flexion
Blackburn JT-influence of trunk flexion on hip and knee joint kinematics during a controlled	Healthies	Laboratory Study	jump-landing- -60cm	Flock of birds	Not stated	C7/T1, T12/L1, hip knee, ankle	100Hz	filtered with a cut off Frequency of 10Hz	Trunk flexion, knee valgus, hip flexion, adduction, Internal rotation

Appendix D

Motion Capture Area


Camera 1
Camera 2
Camera 3
Camera 4
2.4m
4.27m
1.83m
5.49m
Force Plate
Force Plate
3.96m
.03m
.05m
2.74m
2.13m
1.83m
Camera 8
Camera 7
Camera 6
Camera 5

Appendix E

2000 International Knee Documentation Committee (IKDC) Subjective Evaluation Form

2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name____

Today's Date: ______/_______/______ Date of Injury: ______/________/_____
Day Month Year Day Month Year

SYMPTOMS*:

*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?

$_4$☐Very strenuous activities like jumping or pivoting as in basketball or soccer
$_3$☐Strenuous activities like heavy physical work, skiing or tennis
$_2$☐Moderate activities like moderate physical work, running or jogging
$_1$☐Light activities like walking, housework or yard work
$_0$☐Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?

	0	1	2	3	4	5	6	7	8	9	10	
Never	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Constant

3. If you have pain, how severe is it?

	0	1	2	3	4	5	6	7	8	9	10	
No pain	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Worst pain imaginable

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

$_4$☐Not at all
$_3$☐Mildly
$_2$☐Moderately
$_1$☐Very
$_0$☐Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

$_4$☐Very strenuous activities like jumping or pivoting as in basketball or soccer
$_3$☐Strenuous activities like heavy physical work, skiing or tennis
$_2$☐Moderate activities like moderate physical work, running or jogging
$_1$☐Light activities like walking, housework, or yard work
$_0$☐Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?

$_0$☐Yes $_1$☐No

7. What is the highest level of activity you can perform without significant giving way in your knee?

$_4$☐Very strenuous activities like jumping or pivoting as in basketball or soccer
$_3$☐Strenuous activities like heavy physical work, skiing or tennis
$_2$☐Moderate activities like moderate physical work, running or jogging
$_1$☐Light activities like walking, housework or yard work
$_0$☐Unable to perform any of the above activities due to giving way of the knee

Page 2 – 2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?

4☐Very strenuous activities like jumping or pivoting as in basketball or soccer
3☐Strenuous activities like heavy physical work, skiing or tennis
2☐Moderate activities like moderate physical work, running or jogging
1☐Light activities like walking, housework or yard work
0☐Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:

		Not difficult at all	Minimally difficult	Moderately Difficult	Extremely difficult	Unable to do
a.	Go up stairs	4☐	3☐	2☐	1☐	0☐
b.	Go down stairs	4☐	3☐	2☐	1☐	0☐
c.	Kneel on the front of your knee	4☐	3☐	2☐	1☐	0☐
d.	Squat	4☐	3☐	2☐	1☐	0☐
e.	Sit with your knee bent	4☐	3☐	2☐	1☐	0☐
f.	Rise from a chair	4☐	3☐	2☐	1☐	0☐
g.	Run straight ahead	4☐	3☐	2☐	1☐	0☐
h.	Jump and land on your involved leg	4☐	3☐	2☐	1☐	0☐
i.	Stop and start quickly	4☐	3☐	2☐	1☐	0☐

FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

	0	1	2	3	4	5	6	7	8	9	10	
Couldn't perform daily activities	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	No limitation in daily activities

CURRENT FUNCTION OF YOUR KNEE:

	0	1	2	3	4	5	6	7	8	9	10	
Can't perform daily activities	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	No limitation in daily activities

Appendix F
Injury History Report

Injury History Report

Part 1: Demographics

Subject ID	**Initials** (First, Last)	**Age**	**Gender** (M, F)	**Height** (in.)	**Weight** (lbs)

Sport (circle when injury occurred) Basketball Football Soccer Volleyball Softball Cheerleading Rugby Flag Football Baseball Lacrosse Tennis Skiing	**Dominant Side** ☐Right ☐Left	***Level of Play*** *Commit to at least 1 hr/week (50+/yr)* *☐ Level-1 (jumping, pivoting, hard-cutting)* *☐ Level-2 (lateral motions, less jumping, pivoting, and hard-cutting)*	**Position**

Part 2: Injury Report

Injured Side ☐Right ☐Left	**Re-Injury** ☐Yes ☐ No	**Date of Injury** (mm/dd/yyyy)	**Date of Surgery** (mm/dd/yyyy)	

ACL Graft Type ☐Patella ☐Hamstring ☐Achilles ☐Allograft patellar ☐Allograft hamstring ☐Allograft Achilles ☐Other:______	**Mechanism of Injury** ☐Direct ☐Indirect ☐Non-Contact
Meniscal Involvement ☐ None ☐Meniscus repair ☐Meniscal debridement ☐No additional procedures	**Family History** ☐Yes ☐ No

Appendix G
Marker Placement