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COMPARISON OF CLINICAL VERSUS MECHANICAL MEASUREMENTS IN DETECTING LOWER LIMB ASYMMETRIES ASSOCIATED WITH A SECOND ACL INJURY

Alicia E. DenHerder
denhe1ae@cmich.edu

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By:

Alicia Eve DenHerder

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Comparison of clinical versus mechanical measurements in detecting lower limb asymmetries associated with a second ACL injury

This thesis by Alicia DenHerder________ is recommended for approval by the student's Thesis Committee and Department Head in the Department of
School of Health and Human Performance and by the Assistant Provost of Graduate Education and Research.

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Committee Chair: Dr. Sarah Clarke, PhD Date

____

First Reader: Dr. Erich Petushek, PhD Date

____

Second Reader: Dr. Marguerite Moore, PhD, AT Date

____

Third Reader: Dr. Kathryn Hosking, PT, DPT, OCS Date

____

Department Head: Dr. Elizabeth Wuorinen, PhD Date

____

Dr. Lisa S. Eckert Date
Interim Director of Graduate Education

ABSTRACT

COMPARISON OF CLINICAL VERSUS MECHANICAL MEASUREMENTS IN DETECTING LOWER LIMB ASYMMETRIES ASSOCIATED WITH A SECOND ACL INJURY

By

Alicia DenHerder

Study Design: Quasi-experimental. **Objectives:** To compare clinical and mechanical measures in detecting lower limb asymmetries associated with second anterior cruciate ligament (ACL) injuries. **Background:** Knee extension moment (KExtM) asymmetry is predictive of second ACL injury. Evaluation of clinical return to sport tests to assess and classify asymmetry is needed. **Methods:** While performing the drop vertical jump (DVJ), thirty healthy individuals underwent 3D motion analysis. Absolute difference in KExtM between limbs at initial contact of the DVJ (KExtM symmetry) was calculated separately for each trial and averaged. Subjects performed single leg hop (SLH) and Y-Balance tests (YBT). Limb symmetry index (LSI) and absolute difference in anterior reach distance (ANT RD) between limbs were used for SLH, and YBT symmetry measures; respectively. Pearson's correlation assessed the relationship between LSI, YBT, and KExtM symmetry. Confusion matrices were used to illustrate classification accuracy. **Results:** A moderate negative correlation (r = -0.418, p= 0.022; 95% CI = -0.68, -0.07) existed between LSI and KExtM symmetry. A weak negative correlation (r = -0.377, p = 0.040; 95% CI = -0.65, -0.02) existed between ANT RD and KExtM symmetries. LSI and ANT RD symmetry demonstrated no true positives in symmetry classification. **Conclusion:** Although LSI and ANT RD were related to KExtM symmetry, both tests failed to correctly classify asymmetries.

Key words: *classification, injury risk, moment, reach distance, return to sport*

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LIST OF SYMBOLS AND ABBREVIATIONS

Return to sport…………………………………………………………………………RTS

Drop Vertical Jump………………………………………………………………………DVJ

Single Leg Hop……………………………………………………………………...SLH

Y-Balance Test……………………………………………………………………...YBT

Anterior Cruciate Ligament………………………………………………………...ACL

Anterior Cruciate Ligament Reconstructive Surgery………………………………..ACLR

Range of Motion…………………………………………………………………...ROM

Ground Reaction Force……………………………………………………………..GRF

Anterior……………………………………………………………………………..ANT

Posterolateral…………………………………………………………………………PL

Posteromedial………………………………………………………………………...PM

Reach distance……………………………………………………………………..RD

Limb Symmetry Index……………………………………………………………….LSI

Three-dimensional……………………………………………………………………3D

Composite scores…………………………………………………………………..CS

Knee extension moment……………………………………………………………KExtM

CHAPTER 1: JOURNAL MANUSCRIPT

INTRODUCTION

An estimated 100,000 to 250,000 ACL injury incidents have been reported to occur annually in the United States.[23, 91] Young athletes in field sports and active individuals sustain the majority of these injuries with an epidemiological study reporting 120,000 ACL injuries occurring annually in athletes aged 15-25. [82] Other research studies have confirmed an estimated 38,000 ACL injury occurrences in women's and girl's athletics annually in the United States.[54, 139] Methods of knee arthroscopy and ACL reconstructive surgery (ACLR) have evolved and been refined substantially since the first reported ACL repair in 1900.[21, 25] ACLR is a typical recommendation for individuals who have experienced an ACL tear with the goal of restoration of normal anterior knee stability.[18, 21] Athletes commonly utilize ACLR as a method for facilitating return to sport.[74] National data stated approximately 125,000-200,000 ACLR surgeries were performed in the United States in 2006.[89]

Results of ACLR have been generally effective and patients can usually return to recreational activities and sports.[79,75,88,34] Despite the general effectiveness and high numbers of ACLR after ACL injuries, outcomes may not always be ideal. Adverse effects may include development of knee osteoarthritis and increased risk for subsequent injuries to the knee.[108] Wright et al.[146] reported that within 2 years after ACLR, 1 in 17 patients experienced a second ACL injury with equivalent occurrences of ipsilateral and contralateral tears. Many studies have found that the risk of experiencing a second ACL injury is at its peak during the first year in which athletes return to sport (RTS) after initial ACLR.[108, 144, 73] Paterno et al[107] reported the incidence rate of re-injury within 2 years after ACLR and RTS was 6 times greater when compared with a healthy control group. Part of the increased risk for ACL re-injury during the first two years when athletes RTS can also be due to lack of time or effective rehab to fully recover from injury and surgery before returning to rigorous play.[143] To reduce this risk, effective clinical methods need to be utilized when determining the proper time for an athlete to RTS after ACL injury and surgery.[144, 136]

There are several current clinical methods and criteria used regularly by physical therapists, athletic trainers and physicians to determine RTS readiness.[136] Timing of readiness for return to sport after ACL injury is largely dependent on symmetry between limbs.[62, 100] Increased bilateral limb asymmetry during lower body movements requiring multiple joints have shown to persist in individuals after ACL injury and surgery despite the rehabilitation methods utilized.[62, 27] Paterno et al[109] reported that athletes who have undergone ACLR and RTS may exhibit asymmetries in knee extension moment 2 years or more after ACLR as recognized during landing of a drop vertical jump task.[109] Paterno et al[109] also reported deficits in postural stability and altered neuromuscular control of the knee and hip during a vigorous landing task are predictors of second ACL injury after an athlete returns to sport.

The single leg hop (SLH) is commonly utilized by physical therapists for detecting asymmetries between limbs and determining RTS readiness in individuals after ACLR.[136, 48] SLH distance is the most common variable assessed within SLH test and used as a clinical RTS test.[124, 39, 45] The Y-Balance test (YBT) is one of the few field tests that has demonstrated predictive validity for lower extremity injury risk within an athletic population.[123] The YBT is a screen of dynamic balance which can determine asymmetries between limbs.[123]. The YBT, SLH, and DVJ tests all demonstrate significant evidence in determining asymmetries between limbs in individuals based on different performance variables.[109, 67, 77,123]

Although conducting a test such as the DVJ in the laboratory and determining knee extension moment asymmetry and hip rotation moment have shown predictive evidence in second

ACL injury; many clinical tests have been used such as the SLH and YBT to assess asymmetries and injury risk between limbs in individuals.[123, 109, 78] The ease of use of the SLH and YBT contribute to their dominance of usage in the clinic compared with testing several variables using the DVJ.[136, 78] As the SLH and YBT are preferred for clinical use due to accessibility, cost, and time; verification that these tests may assess the same asymmetries in individuals as a more costly and time consuming test such as the DVJ is necessary.[109, 50, 114, 100]

The purpose of this study was to compare clinical and mechanical measures in detecting lower limb asymmetries. The secondary purpose was to determine the ability of the SLH and the YB test to correctly classify asymmetries. The first experimental hypothesis was that there would be a significant correlation between the reach distances symmetries (ANT, PM, PL) and the knee extension moment (KExtM) symmetries at initial contact of the DVJ. The second hypothesis was that there would be a significant correlation between the SLH symmetry and KExtM symmetry at initial contact of the DVJ. The final experimental hypothesis was that performance variables from the YB test and the SLH test would classify individuals in the same symmetry category in which the DVJ categorized individuals.

METHODS

Participants

A quasi-experimental study design was utilized to assess the relationships between SLH, YBT, and DVJ symmetry measures and to test the ability of the SLH and YB tests in classifying healthy individuals in the same injury risk category in which the DVJ categorizes these individuals. Thirty healthy individuals (15 female, 15 males; 24 ± 6.2 y/o) participated in this study. Inclusion criteria required the participant to be between the ages of 18-55, have absence of pain or injury in the six months prior to involvement in the study, and have previously participated in any sport requiring jump-landing tasks (volleyball, basketball, soccer, football, rugby, lacrosse, etc.).

Procedures

The study was approved by the University's Institutional Review Board (HS17-819) and informed consent (Appendix A) was obtained from each participant prior to start of testing. To verify that each subject met the inclusion criteria to participate, both the Physical Activity Readiness Questionnaire (Appendix B) and the activity, injury, and, pain questionnaire (Appendix C) were completed prior to participation. Prior to completing any tests, the participants completed a dynamic warm-up consisting of 10 lunges, 10 reverse lunges, 10 straight leg kicks, and 10 repetitions of standing front leg swings on both legs.[57] Each subject then underwent a full 3-dimensional biomechanical motion analysis while performing the DVJ followed by completion of the YBT and SLH. The order in which the SLH and YB tests were performed was randomized for all subjects, whereas the DVJ was always performed first.

Drop vertical jump Maneuver Each participant underwent 3-dimensional motion analysis while completing the DVJ. Data from each trial were collected with EVaRT (Version 4 Motion Analysis Corporation, Santa Rosa, California) using a 9-camera motion analysis system (Raptor cameras, Motional Analysis Corporation) sampled at 240 Hz (Figure 1). Prior to testing, each participant was instrumented with 37 retroreflective markers (Figure 2). Standing in neutral position with arms across the chest, one static trial was utilized to align each participant with the laboratory coordinate system. This served as a reference point for subsequent kinematic analysis (Figure 3, Figure 4).

To perform the DVJ, the participant was positioned atop a 31-cm box. The subjects dropped off the box, landed with each foot onto separate force platforms, and then immediately executed a maximal effort vertical jump toward an overhead target. (Figure 5) The participant performed two practice trials for familiarization of the test and then three test trials which were used for data analysis. The data from both force platforms was sampled at 1000 Hz and synchronized with the motion analysis system. This methodology for the drop vertical jump have demonstrated high reliability in attaining the variables of interest and were replicated from Paterno et al.[109]

Kinematic Analysis Analysis of the drop vertical jump was assessed using Visual 3D software (Version 4.0, C-Motion, Inc, Germantown, Maryland). Inverse dynamics were used to calculate 3-dimensional lower limb joint mechanics, as previously described in Paterno et al[109]. A cutoff frequency of 12 Hz was used to filter marker trajectories through a low-pass Butterworth digital filter. Knee and ankle joint centers were identified as the midpoint between the lateral and medial ankle and knee joint retroreflective markers, respectively. Bell et al's[11] work was used to estimate the hip joint centers. Joint centers were used for 3-dimensional measures. Inverse dynamics were used to calculate knee extensor moments from the force plate and kinematic data. A low-pass Butterworth filter at a cutoff frequency of 12 Hz was used to filter vertical ground-reaction force data. The time at which the vertical ground-reaction force first exceeded 10 N was defined as initial contact of each limb. Knee extensor moments were described as positive values.

Single Leg Hop Test Each subject watched an instructional video and received detailed instructions on performing the SLH from the Doctor of Physical Therapy (DPT) prior to completing the SLH and YBT. The SLH required subjects to stand on each leg and hop as far as possible and land on the same leg (Figure 6). Participants were instructed to execute a balanced, controlled landing and to maintain foot placement of the landing foot until the physical therapist had recorded the landing position. The same procedures were completed on both legs. Jumps were completed on each limb until a total of three successful jumps were performed.

The limb symmetry index (LSI) was calculated for the SLH test. The LSI is calculated using an average of the three best trials performed by each participant on each limb (weak limb score divided by strong limb score × 100% for the distance measures). The limb which scored the highest hop distance was identified as the strong limb whereas the limb which scored the lowest hop distance was identified as the weakest limb. An LSI of less than 90% indicates asymmetries present between limbs. [31, 48] An LSI of 100% indicates that there are no asymmetries present between the limbs during the SLH test.[31 48]

Y Balance test. The YBT was assessed and rated by a DPT certified in the YBT (Move2Perform, Evansville, IN). Each participant watched an instructional video that demonstrated and explained the procedures of the YBT. The YB testing device is comprised of three PVC pipes attached in the anterior, posterolateral, and posteromedial directions. The pipes in the posterior direction are positioned 135° from the anterior pipe leaving 45° between the posterior pipes. Each of these pipes is marked for measurement in 5 mm increments (Figure 7).[113]

YBT comprises of a three-part test to assess neuromuscular control and lower extremity balance.[123] Barefoot participants stood on the center footplate, with the distal end of the right foot positioned at the starting line (Figure 8). While sustaining single leg stance on the right leg, with the free limb the subjects reached in the anterior (Figure 9), posterolateral (Figure 10), and posteromedial (Figure 11) directions based on the stance foot by pushing the indicator box the farthest possible distance. Subjects performed 3 practice trials in each direction on both the left and right limbs. After the practice trials, subjects completed three consecutive trials for each reach direction, and to decrease fatigue subjects altered limbs between each direction.[128, 123] The highest reach distance in each direction, on each limb were used for analysis. The methods utilized for the YBT were conducted based on a reliable protocol.[113] The physical therapist administered and measured all tests with the goal of maintaining consistency and avoiding inter-rater differences.

Statistical Analysis

Statistical analyses were performed with SPSS Version 24 (SPSS Inc, Chicago, IL). The alpha level was set at $p < 0.05$. All variables analyzed in SPSS were inspected for normal distribution using histograms, skewness, and kurtosis values. A test of correlation was performed for the LSI, YBT symmetry values, and DVJ symmetry values. The symmetry values for the YBT were the absolute difference in reach distance between right and left legs (ANT, PM, and PL symmetry values). The symmetry value for the DVJ was calculated as the absolute difference in the knee extension moment between right and left legs (KExtM symmetry).

A determination of classification accuracy assessed how many subjects were miss-classified in asymmetry by the SLH and ANT RD symmetry. Symmetry classifications for DVJ symmetry, LSI, and ANT RD symmetry were based on established cut-off values (Table 1). Several methods were employed to determine if participants were classified as asymmetrical by the DVJ. First, the absolute difference in knee extension moment between limbs at initial contact of the DVJ was calculated for each trial and averaged across three trials for each participant. The difference in the knee extension moment that classified individuals as at risk for second ACL injury by Paterno et al.[109], was calculated. This value, the difference in knee extension moment between limbs at initial contact of the DVJ, then classified individuals into symmetry categories (asymmetrical or symmetrical).

The symmetry classification of each individual by the DVJ was compared with the symmetry classification of the SLH and YBT by creating a confusion matrix. A true positive (TP) designates that the clinical test outcome and DVJ test outcome both classified these individuals as asymmetrical. A true negative (TN) specifies that the clinical test outcome and DVJ test outcome both classified individuals as symmetrical. A false positive (FP) designates that the clinical test outcome classified individuals as asymmetrical, but as symmetrical based on the DVJ test outcome. Lastly, a false negative (FN) indicates that the individuals were classified by the clinical test outcome as symmetrical but as asymmetrical determined by the DVJ test outcome.

RESULTS

Mean and standard deviation values for all participant demographics (Table 2) and performance variables (Table 3) were calculated. The Pearson correlation coefficient indicated a significant negative correlation (Figure 12, Table 4) between the LSI and the KExtM symmetry value (r = -0.418, p = 0.022; 95% CI = -0.68, -0.07). The Pearson correlation indicates that as the KExtM symmetry value increases, LSI decreases (more symmetrical). The symmetry values for the anterior reach distance and the knee extension moment were significantly negatively correlated (Figure 13, Table 4) according to the obtained Pearson correlation coefficient (r = -0.377, p = 0.040; 95% CI = -0.65, -0.02). The Pearson correlation coefficient indicates that as the KExtM symmetry value increased, the ANT RD symmetry value decreased. No correlations were present between the KExtM symmetry value and the PM and PL symmetry values. Therefore, only the ANT RD symmetry value was used for further analysis. The confusion matrices demonstrate that none of the participants were classified correctly in asymmetry by either the LSI or ANT RD symmetry (Table 5, Table 6; respectively).

DISCUSSION

This is the first study of its kind to assess the ability of several clinical tests to classify an individual's lower limb symmetry when compared to a biomechanical assessment of symmetry, which has demonstrated accuracy in injury risk prediction.[109] It was hypothesized that there would be a significant positive correlation between the ANT RD symmetry value and the KExtM symmetry value indicating that as ANT RD symmetry value increased, the KExtM symmetry value would also increase. Secondarily, the researchers hypothesized that there would be a significant negative correlation between the LSI and the KExtM symmetry value indicating that as the KExtM symmetry value increased, the LSI decreased. Lastly, the researchers hypothesized that the ANT RD symmetry value and LSI would independently classify individuals in the same symmetry category as the KExtM symmetry value.

There was a significant moderate negative correlation (Figure 12) between the LSI of the SLH and the difference in the knee extension moment demonstrated in the DVJ. Although LSI decreased as the KExtM symmetry increased, there were some differences in classification of the participants. There were no true positive classifications in the confusion matrix for LSI indicating that LSI did not correctly classify any individuals as asymmetric (Table 5, Figure 12). Of the participants that were classified as asymmetric or at high risk for second injury by the KExtM symmetry value, all scored an LSI in the range of 91-97%. Several studies have proposed that a value of 80-85% for the LSI measure is not high enough to detect asymmetries and therefore determine injury risk in individuals.[94] Recently Munro et al[94] has suggested an LSI of above 90% for determination of return to sport for an athlete after injury. Although an LSI of 90% may be high enough to indicate asymmetries between limbs, according to the findings in the present study it may not provide sufficient information to identify which previously injured individuals are ready to return to sport.[99]

Noyes et al[99] assessed ACL-deficient individuals on 4 hop tests and determined 52% were asymmetric, but concluded that these hop tests were unable to identify the source of the asymmetry or functional limitations. Although individuals may have been classified in the symmetric category by the LSI, they were not classified as symmetric by the DVJ test outcome. None of the participants were identified as asymmetric by the LSI. Based on the present findings, it could be suggested that KExtM symmetry may not be the source of any asymmetries that may be found when using the LSI for the SLH. Orishimo et al's[102] results seem to support this theory as he reported no differences in peak knee extensor moment between involved and uninvolved limbs at take-off and landing during single leg hop tests. Therefore, asymmetries in KExtM may not be as large in SLH testing when compared with DVJ testing.

One possible reason for the differences present in classification between the SLH and DVJ could be the altered demands placed on the individual in the two tasks. The SLH for hop distance is a dynamic test which evaluates sport specific movement by assessing unilateral strength symmetry and functional knee stability.[67] The lower extremity must absorb ground reaction forces placed on it as a result of landing from a jump.[102] Although both the DVJ and SLH are jump-landing tasks, the difference in a unilateral versus bilateral task could contribute to variances in lower extremity demands and therefore lead to alterations in kinematic and kinetic measures.[141]

For example, Wang[141] observed greater peak ground reaction, lateral shear and proximal tibia anterior forces during single leg stop-jump tasks compared with double-leg stop-jump tasks. Though, Wang[141] also observed smaller peak knee and hip flexion angles during the single leg stop-jump. Wang[141] concluded from these differences in kinematic and kinetic measures that landings from a single leg jump may have higher risk for ACL injury compared with double-leg landing in stop-jump tasks. Although these tasks may not replicate the SLH and DVJ, this study does emphasize differences in single and double leg jump-landing tasks.

There was a significant weak negative correlation between ANT RD symmetry and KExtM symmetry (Figure 13). This negative correlation demonstrated that as KExtM symmetry increased ANT RD symmetry decreased. The hypotheses was that as the KExtM symmetry increased, the ANT RD symmetry would also increase indicating asymmetry between the limbs. This relationship demonstrates the opposite of what was expected. Of all the participants classified as asymmetric by the ANT RD symmetry of the YBT, none were classified as asymmetric by the KExtM symmetry. The misclassification of the ANT RD symmetry is valuable information for evaluating the use of the YBT as a screening tool for injury risk.

To explain the differences in injury risk classification between the KExtM of the DVJ and the ANT RD of the YBT, the requirements and differences in demands of these two tasks, and differences in the population being studied, merit discussion. The ANT RD of the YBT is a single leg dynamic balance task which can indicate asymmetry between limbs and assess lower extremity strength.[28, 59 76] Although the YBT has been successful in assessing dynamic balance and muscle weakness, it does not test the neuromuscular control of an individual when landing during a dynamic functional movement such as a jump.[76] This neuromuscular control can be defined as the brains ability to unconsciously control muscle activation and dynamic joint stabilization during motion.[54] It could be said that the KExtM symmetry at initial contact of the DVJ may assess an individual's *preparation* for landing a jump, while the YBT is assessing the individual's ability to maintain *control* throughout a dynamic balance task.

ANT RD asymmetries greater than 4 cm have been associated with greater lower extremity injury risk.[127, 128] Interestingly the individuals in the current study who were classified as asymmetric or at high risk for second injury according to KExtM symmetry had ANT RD asymmetries less than 4 cm. Overmoyer et al[103] confirmed that while the YBT may have the ability to expose asymmetries and weaknesses present in ankle dorsiflexion via the differences between limbs in the ANT RD and PL RD, it is unclear how this has a role in second ACL injury risk. Though, it is clear that postural control is required and evaluated during performance of the YBT and deficits in postural control during the YBT have demonstrated risk for lower extremity injuries in sport.[17, 128]

Paterno et al[109] reported that individuals with deficits in single-leg, dynamic postural stability of the involved limb were two times more likely to suffer a second ACL injury as compared with individuals who did not display postural instabilities on the involved limb. This finding indicates that individuals who lack dynamic postural control may be at increased risk for second ACL injury. Though in the present study, there were no measurable differences in postural between individuals classified as at risk by KExtM symmetry and those who were not classified as at risk by KExtM. It is important to note that although participants with deficits in postural stability were twice as likely to have a second ACL injury, there was no significant difference in dynamic postural stability between these groups.[109] If postural stability and control are assessed using the ANT RD of the YBT, these differences may be too small to be identified. Smith et al[128] reported that the YBT cut-off point, an asymmetry value of greater than 4 cm in ANT RD demonstrated moderate sensitivity and specificity at 59% and 72%; respectively. Therefore ANT RD symmetry of the YBT may not be sensitive enough to identify these differences in postural stability and control.

Paterno et al[122] indicated several biomechanical factors related to neuromuscular control as predictors of second ACL injury risk. Participants with less hip external rotation moment during initial contact of the DVJ were over 8 times more likely to endure a second ACL injury when compared with individuals that displayed greater hip external rotation moment.[109] Individuals with increased frontal plane motion during the DVJ were also 3 times more likely to incur a second ACL injury compared with those who did not undergo second ACL injury.[109] Deficits in postural stability of the involved limb placed individuals at two times the risk of second injury.

Paterno et al[109] also demonstrated that a difference in internal knee extensor moment greater than 410% between limbs was predictive of second ACL injury. Individuals who demonstrated this asymmetry were over 3 times as likely to suffer an ACL injury then those who demonstrated symmetry in KExtM. The current study used this asymmetry value as a cut-off point and then used KExtM symmetry as the gold standard asymmetry measure. It is then important to consider what information the gold standard is reporting that these clinical test outcomes may not report.

A moment arm is the length between a joint axis and the line of force acting on the joint.[101] A joint moment is calculated as the product of the internal moment length and the perpendicular force.[101] Therefore, the knee extension moment is the product of the force the knee is absorbing and the length of the internal moment length.[101] Knee extension moment changes during movement and several studies have confirmed a peak knee extension moment as well as knee shear force during landing from a jump task. [138, 147] Assessing neuromuscular control when the ACL is loaded during landing tasks has been verified to be important when indicating an individual's risk for injury or return to sport after an injury or ACL surgery.[33, 42, 52, 109] Therefore, alterations in neuromuscular control patterns indicated by the asymmetry in the knee extensor moment should be assessed and tested for.[109]

The aforementioned information, and Paterno et al's[109] results were the rationale for using KExtM asymmetry. Although Paterno et al[109] confirmed that asymmetry in knee extensor moment at initial contact of a DVJ was one of the variables successful in prediction of second ACL injury risk, it was not an independent predictor. Though, less hip external rotator moment during initial contact was an independent predictor of ACL injury risk. Although hip rotation moment measure was not evaluated for this study due to the use of a healthy, uninjured population, it may serve as a better comparison in a study with injured or post-surgery patients. Although the present findings demonstrated many obstacles in producing a sound conclusion, alternative methods and future research study possibilities warrant discussion.

An alternative method that could be explored is the utilization of the landing error scoring system (LESS). The landing error scoring system is a reliable clinical screening tool which utilizes evaluation of biomechanics of landing in the DVJ test to identify individuals at increased risk for ACL injury.[105] Although Padau et al[104] used kinematic and kinetic measures as gold standard measures to compare the classification of individuals based on LESS scores, it is not clear what cut off value was used for these measures. Testing the ability of the landing error scoring system to classify individuals in the same risk category as the KExtM symmetry value or hip rotation moment which Paterno et al[109] identified as predictive of second ACL injury is something that should be considered and studied in the future.

Limitations

One major limitation of the current study is the use of a healthy population of individuals. The inclusion criteria of this study required the participants to have had no injury or surgery in 6 months prior to participation in the study. If a group of post-ACLR patients or previously injured individuals were utilized to assess the classification accuracy of these return to sport tests to identify asymmetries, the results may have yielded different conclusions. Also, if an injured population was used hip external rotation as an independent predictor of ACL injury risk during initial contact of the DVJ could have been assessed for classification of injury risk.

A secondary limitation of this study could be the sample size. Although this sample size may have been sufficient for correlation analysis, it was not large enough to calculate and report specificity and sensitivity values for classification accuracy. Confounding variables or factors may have played a role in the results of this study as well. A comparison of males and females or activity level have both demonstrated differing results in variables of interest.[13, 22, 30, 120] Therefore future research taking these variables into account and assessing their relationship would improve range and generalizability.

CONCLUSION AND PRACTICAL APPLICATIONS

Although both the SLH for distance and the YBT have demonstrated reliability in assessing asymmetry in individuals in other studies,[44, 99] these tests were unable to correctly classify asymmetries when compared with KExtM symmetry, a predictive measure of second ACL injury risk. Therefore, future research is warranted to identify classification accuracy with a larger sample size, and injured or post-surgery population. The SLH is suggested to be utilized with other tests such as the drop vertical jump as used in the LSSE. Perhaps, the YBT should not be used in combination with these tests as the relationship between the asymmetries was negative, and remains unclear. This would allow investigation of a battery of tests in which an individual must pass for clearance for return to sport.[9, 46, 67] The development of a checklist including several tests and injury risk components could greatly enhance clinical RTS practices for physical therapists.

KEY POINTS

Findings: Moderate and weak negative correlations exist between LSI and KExtM symmetry and ANT RD symmetry and KExtM symmetry; respectively. The LSI of the SLH and ANT RD symmetry value misclassified individuals which were classified as at high risk for injury by the KExtM symmetry value of the DVJ.

Implications: The LSI and ANT RD symmetry may indicate asymmetries but the source of these asymmetries is still somewhat unclear. Therefore, more research is needed to understand the relationships present between these measures.

Cautions: Symmetry classification accuracy of LSI and ANT RD symmetry could not be adequately determined with specificity and sensitivity as the sample size was not large enough to give power to these estimations.

TABLES

TABLE 1. Variables used for assessment of asymmetry and the cut off points for the Y-Balance test[128], single leg hop[95] and drop vertical jump[109].

TESTS	**VARIABLE**	**CUT OFF**
Y-BALANCE	REACH DISTANCE ASYMT	> 4 cm difference
SINGLE LEG HOP	HOP DISTANCE ASYMT	< 90% LSI
DROP VERTICAL JUMP	KNEE EXTENSION MOMENT ASYMT	410% greater difference between limbs

TABLE 2. Participant demographics. Values are displayed as mean ± standard deviation.

Participant demographics	Mean ± standard deviation
Age, y	24.0 ± 6.2
Height, m	1.72 ± 0.07
Weight, kg	71.7 ± 12.2
Sex, n	
Female	15
Male	15

TABLE 3. Performance variable for all participants on the YBT, SLH, and DVJ.

	Mean ± Standard deviation
LSI (%)	96.00 ± 2.79
ANT Symm (cm)	2.45 ± 1.65
PM Symm (cm)	4.65 ± 3.27
PL Symm (cm)	3.03 ± 2.02
KExtM (Nm/kg)	0.09± 0.05

Abbreviations: LSI, limb symmetry index; ANT, anterior reach distance; Symm, symmetry value; PM, posteromedial reach distance; PL, posterolateral reach distance; KExtM, knee abduction moment

TABLE 4. Pearson correlation coefficients and p-values.

Variables	Correlation coefficient	P-value
KExt symm & LSI	-0.418	0.022*
KExt symm & ANT symm	-0.377	0.040*

*Represents significant correlation at 0.05 level between variables listed.

TABLE 5. Confusion Matrix to illustrate the classification accuracy of the LSI of the SLH to classify individuals in the same injury risk category in which the KExtM symmetry value of the DVJ has classified these individuals.

KExtM symmetry value Cut-off	**High Risk Category (+)**	**Low Risk Category (-)**
≤ 4.1 times difference (+)	TP = 0	FN = 5
≥ 4.1 times difference (-)	FP = 0	TN = 25

TP = True Positive, FP = False Positive, TN = True Negative, FN = False Negative

TABLE 6. Confusion Matrix to illustrate the classification accuracy of the ANT RD symmetry value to classify individuals in the same injury risk category in which the KExtM symmetry value of the DVJ has classified these individuals.

KExtM symmetry value Cut-off	**High Risk Category (+)**	**Low Risk Category (-)**
≤ 4.1 times difference (+)	TP = 0	FN = 5
≥ 4.1 times difference (-)	FP = 5	TN = 20

TP = True Positive, FP = False Positive, TN = True Negative, FN = False Negative

FIGURES

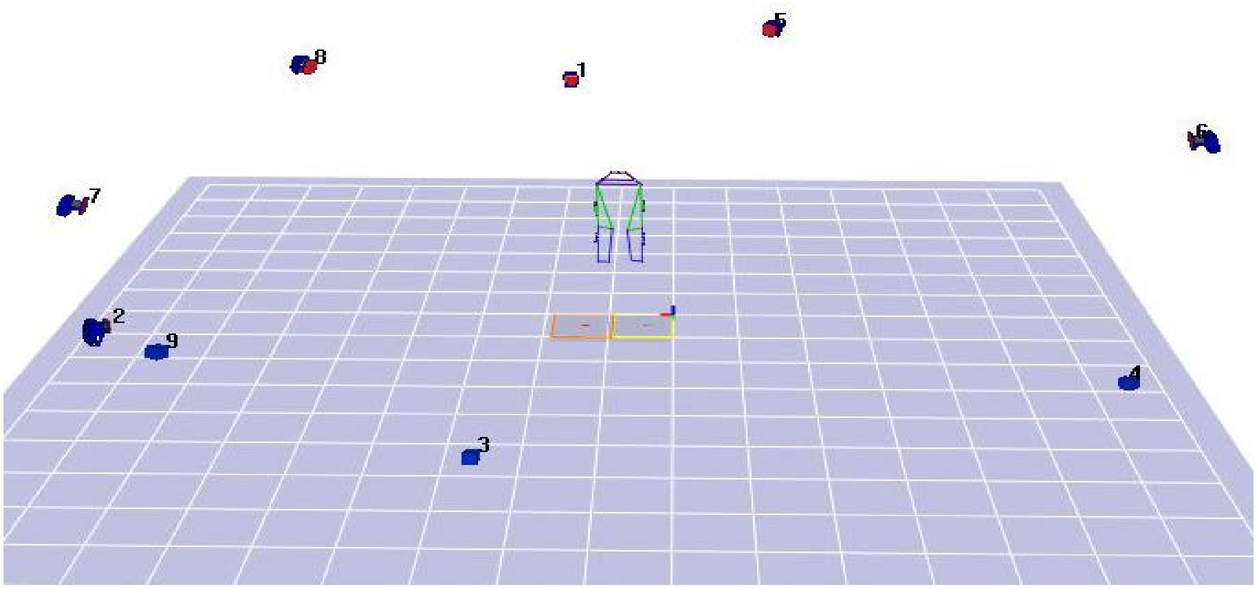

FIGURE 1. Video set-up for 3-dimensional motion analysis with 9 Raptor cameras arranged in a circular format.

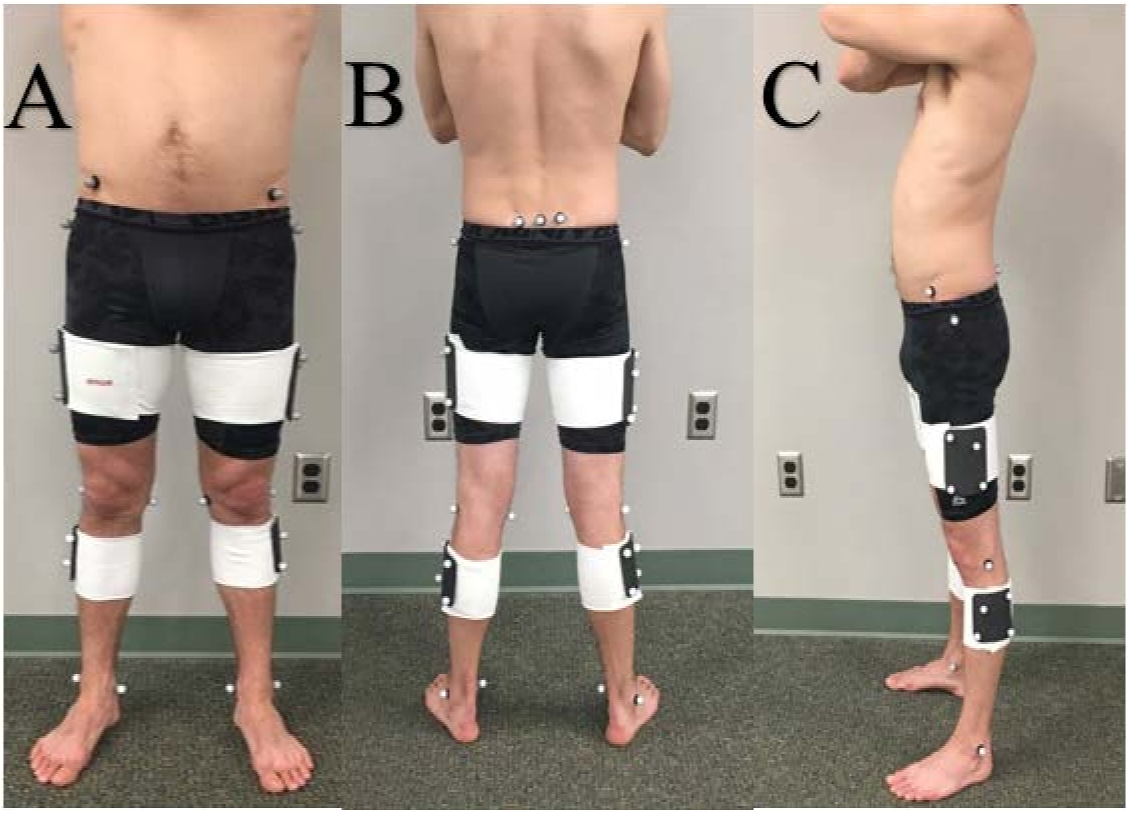

FIGURE 2. Anterior (A), posterior (B), and lateral (C) views of anatomical marker set used for 3-dimensional motion analysis and 3D visual processing.

FIGURE 3. To perform the drop vertical jump test, subjects started from this 31 cm tall box and landed with one foot on each of the force plates below, then immediately performed a maximal jump.

FIGURE 4. Subject position used to capture the static trial using 3-dimensional motion analysis.

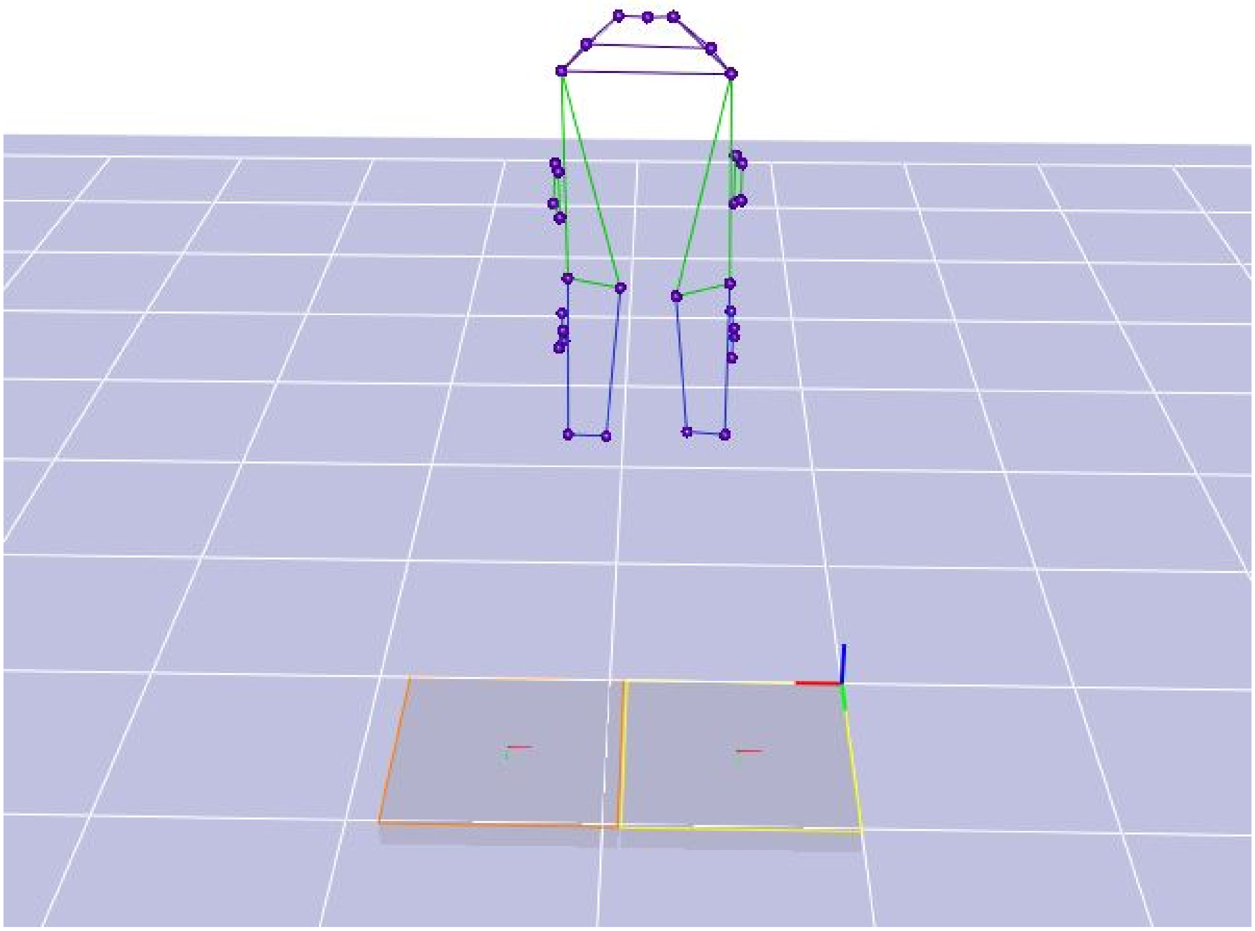

FIGURE 5. Three-dimensional motion analysis of static trial with identification of the marker set.

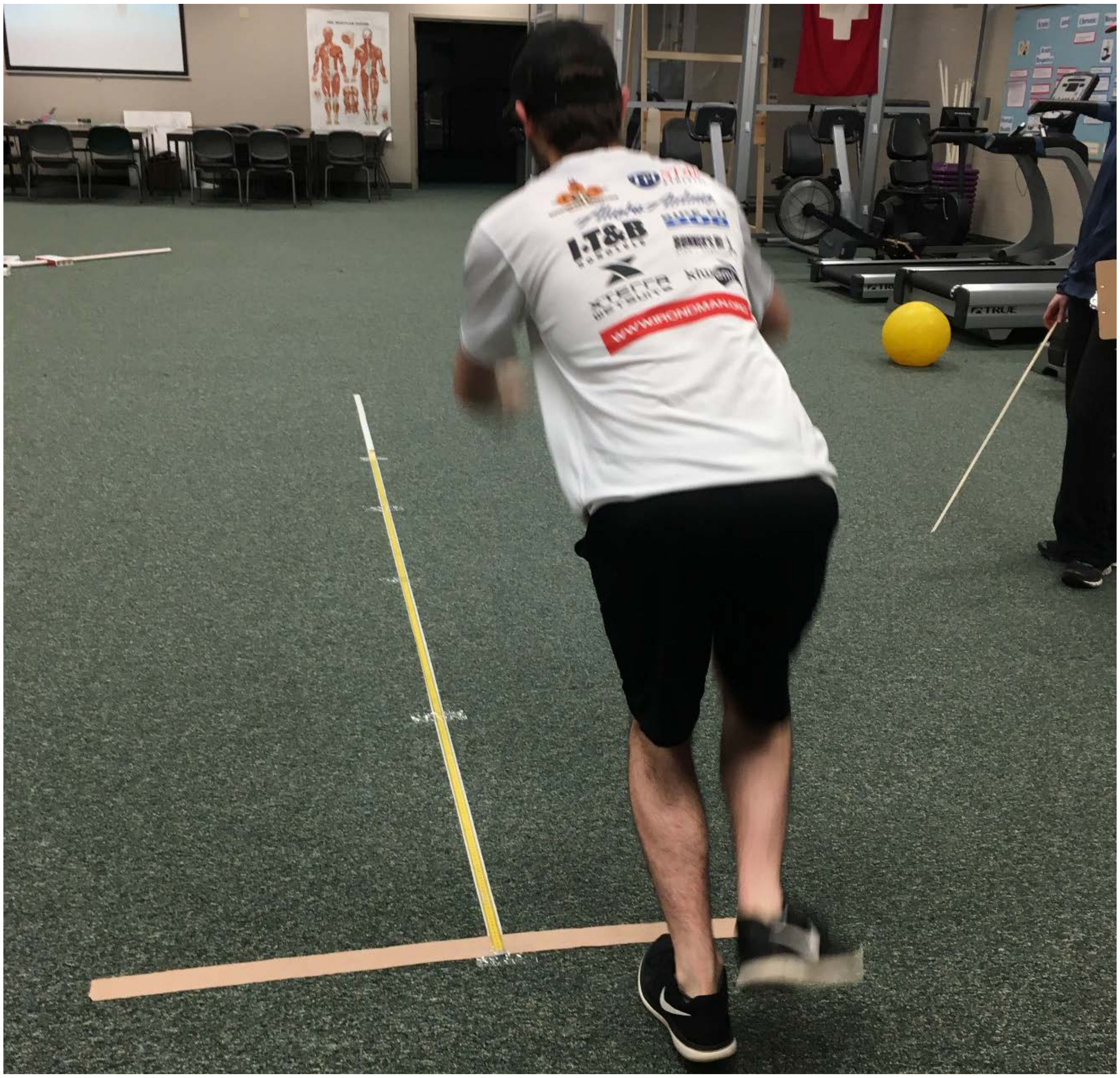

FIGURE 6. Set up and participants start position for the single leg hop for distance test.

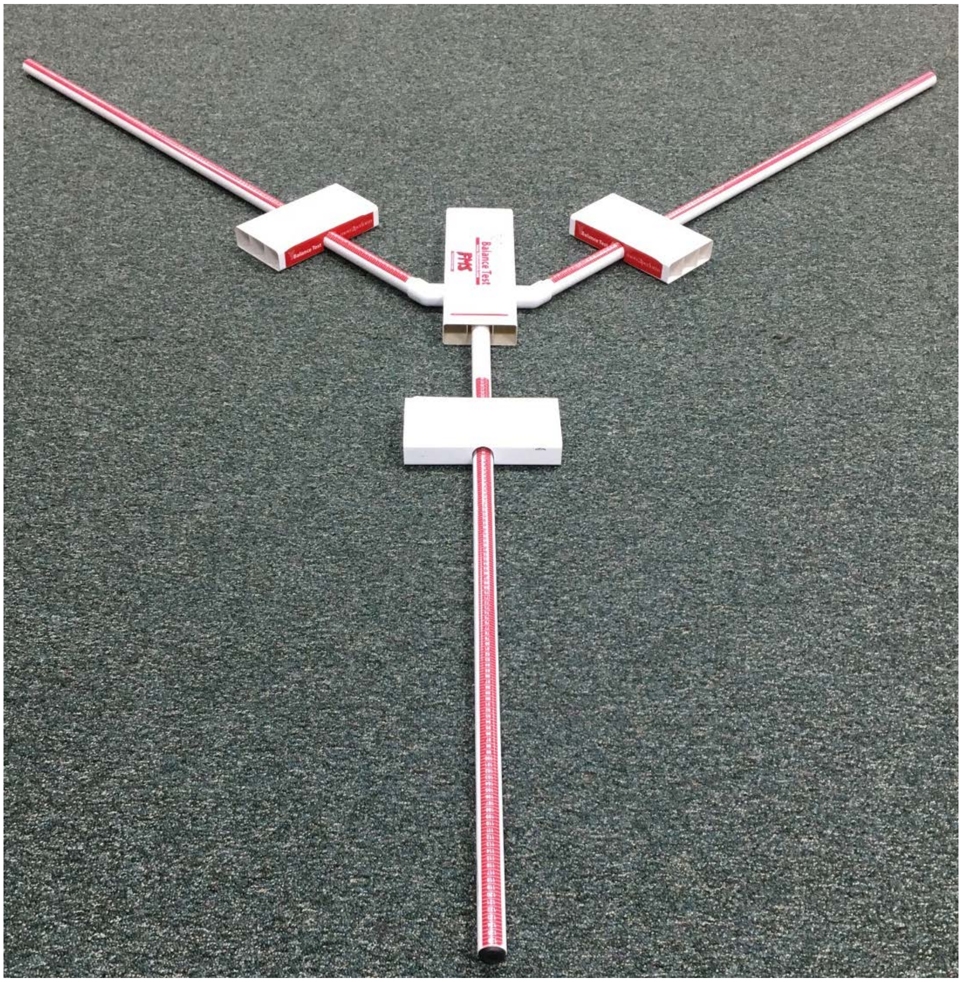

FIGURE 7. The Y-Balance testing device used to assess anterior, posteromedial, and posterolateral reach distance.

FIGURE 8. Starting position of the subject performing the YBT.

FIGURE 9. Lateral view of a subject performing the anterior reach distance assessment of the Y-Balance test (YBT) with the left limb.

FIGURE 10. Posterior view of a subject performing the posterolateral reach distance assessment of the YBT with the right limb.

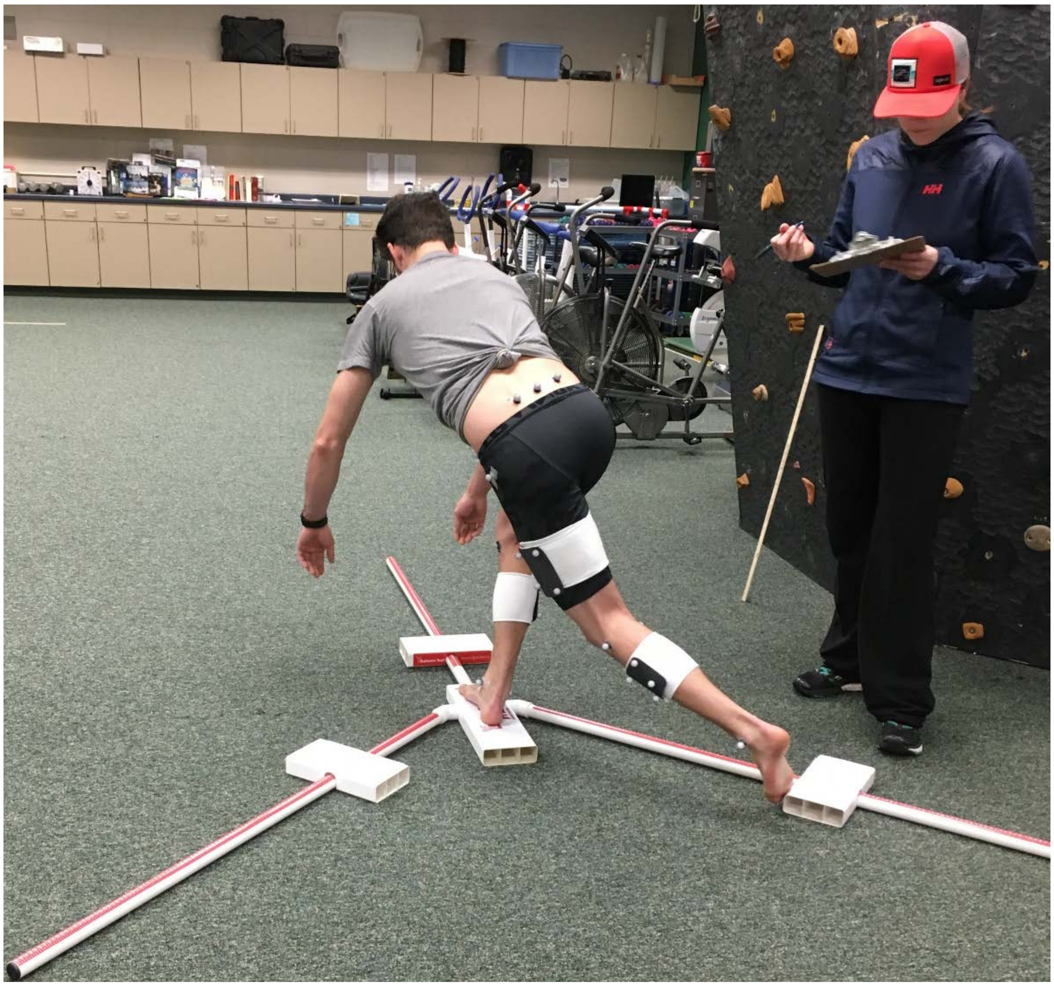

FIGURE 11. Posterior view of the subject performing the posteromedial reach distance assessment of the YBT with the left limb.

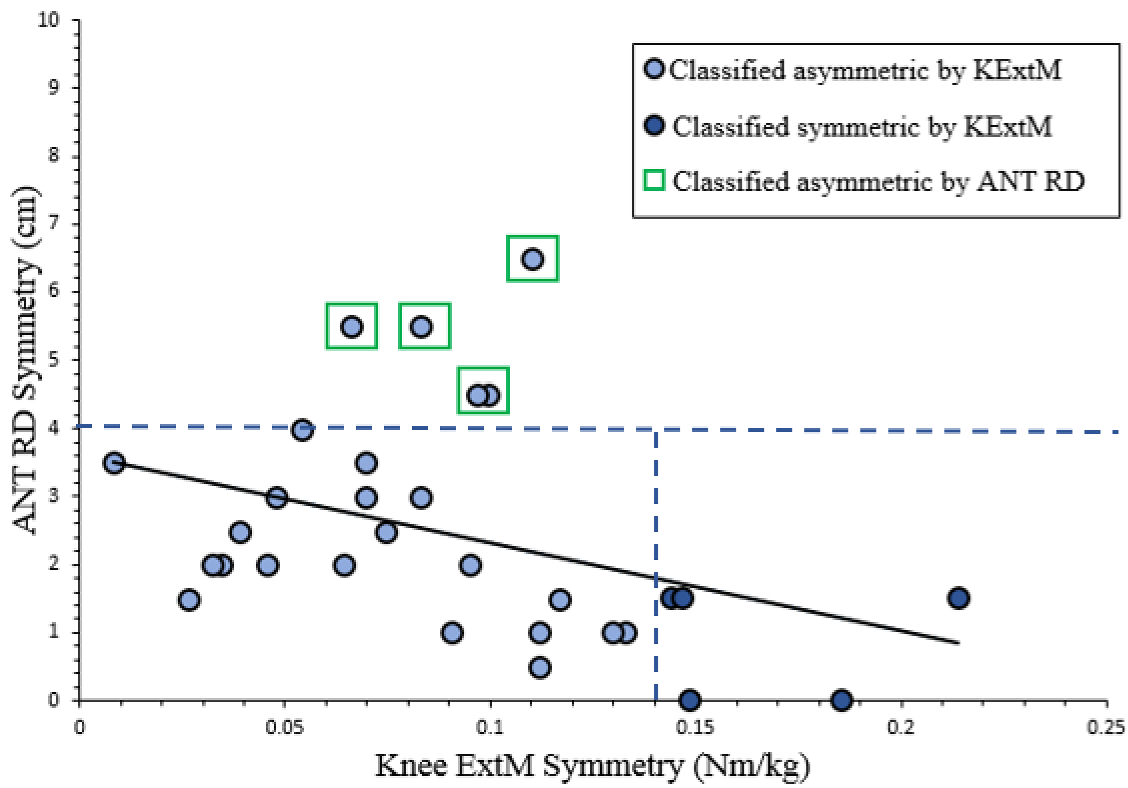

FIGURE 12. Scatterplot depicting the significant negative, weak correlation ($r = -0.418$, $p < 0.05$; 95% CI = -0.68, -0.07) between the difference in anterior reach distance in right and left limbs (Ant RD Symmetry) and the difference in the knee extension moment between limbs (KExtM symmetry). The dark blue markers indicate that these individuals have been classified as asymmetric by KExtM symmetry. The light blue markers indicate that these individuals have been classified as symmetric by KExtM symmetry. The green squares surrounding the markers indicate that these individuals have been classified as asymmetric based on ANT RD symmetry. The dotted lines indicate the cut off point for symmetry measures.

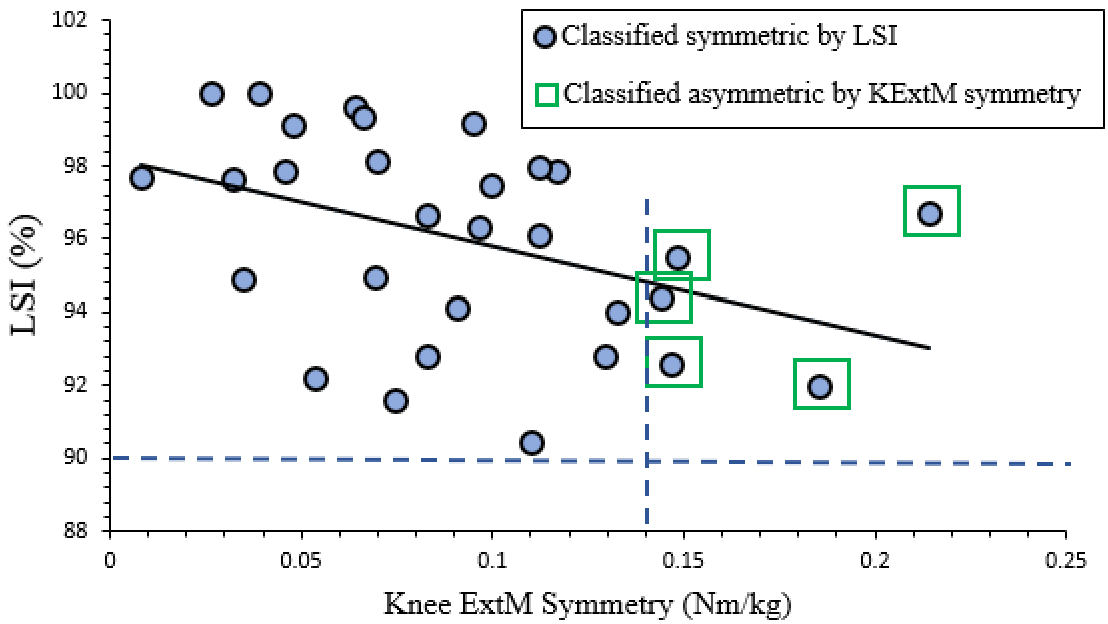

FIGURE 13. Scatterplot depicting the significant negative, moderate correlation ($r = -0.377$, $p < 0.05$; 95% CI = -0.65, -0.02) between the LSI of the SLH and the difference in knee extension moment between right and left legs. The blue circles indicate participants that have been classified as symmetric by the LSI while the green squares indicate participants that were classified as asymmetric by KExtM symmetry. The dotted lines indicate the cut off point for symmetry measures.

CHAPTER II: LITERATURE REVIEW

The purpose of this study was to assess the relationship between symmetry measures and to evaluate asymmetry classifications of clinical return to sport tests. The purpose of the literature review is to give insight into anterior cruciate ligament (ACL) injuries and to educate the reader on components related to initial and repeated ACL injury. This literature review is divided into separated into five sections: (a) Anatomy and physiology of the ACL (b) Injury to the ACL (c) Treatment for ACL injuries (d) Subsequent injury to the ACL and (e) Currently used clinical practices for return to sport following ACL reconstructive surgery.

Anatomy and Physiology of the Anterior Cruciate Ligament

The ACL of the knee originates from the medial and anterior intercondylar area of the tibia and twists on itself and expands out to insert at the lateral femoral condyle.[86] The ACL continues distally, medially and anteriorly toward the tibia. (Figure 14) Over the distance of its course, the fibers of the ACL undergo slight external rotation.[86] The ACL is the primary immobile stabilizer against anteroposterior displacement of the tibia and anterior translation on the femur.[86] More than 80% of the total force resisting anterior draw is accounted for by the ACL from 30-90° of flexion.[24] During many stages of knee movement, specific portions of the ACL appear to stabilize the knee joint.[86] (Figure 15)

The presence of multiple sensory endings also implies proprioceptive functioning of the ligament.[86] Three types of proprioceptive receptors account for 1% of the surface area of the ACL; ruffini nerve endings, Pacinian capsules, and Golgi tendon organs. The Pacinian capsules, classified as dynamic receptors, are sensitive to quick changes in acceleration, and adjust rapidly to low degrees of stress to the knee joint.[60] Golgi tendon organs and ruffini nerve endings adapt slowly, withstand a high degree of joint stress, and are thought to contribute information on knee joint position.[60] These components verify the vitality of the ACL to the mechanics of the knee joint and its function to protect the knee joint from injury.

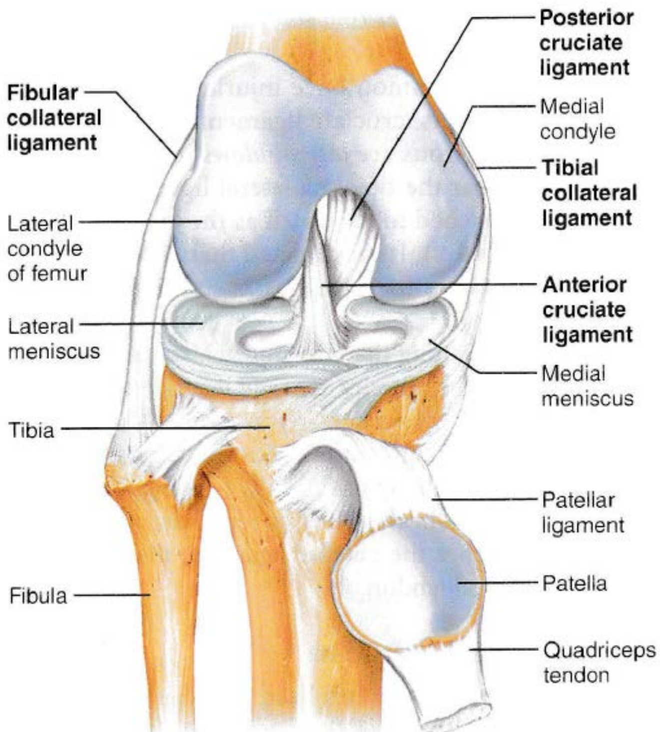

FIGURE 14. Displays an anterior view of the anatomical location of the ACL of the knee joint. The ACL of the knee connects the femur to the tibia in the center of the knee and limits forward motion and rotation of the tibia. [126]

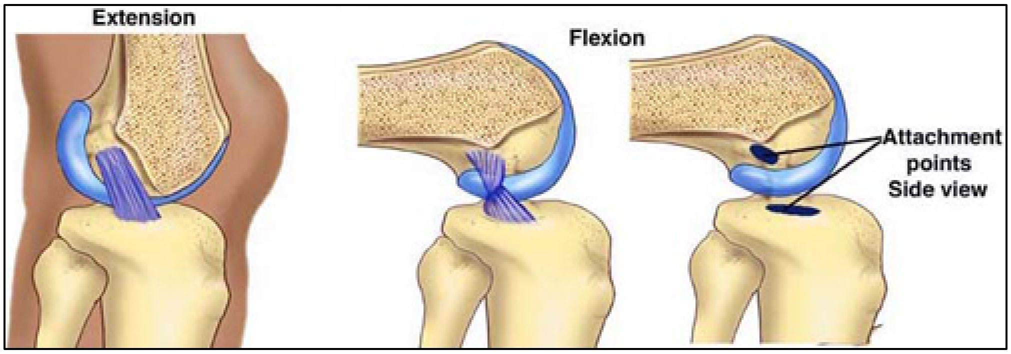

FIGURE 15. Normal movement and attachment points of the ACL during flexion and extension of the knee joint. As the knee joint moves into extension, the ACL becomes taut. During flexion of the knee, the ACL functions in stabilization of anteroposterior translation.[6]

Injury to the ACL

ACL Injury Prevalence Although the knee joint has several structures which function to protect it from injury, knee joint injuries have an incidence rate of 2.29 per a 1,000 persons population.[32 60, 82] Participation in sports increases the risk of encountering a knee injury which studies have reported account for up to 40% of the injuries which occur during sports.[71, 82] The most frequent and common diagnoses of knee joint injuries in sports are injuries to the ACL.[71] Majewski et al[82] completed a 10-year epidemiological study of injuries to the knee within sports and demonstrated that 20.3% of the knee injuries were diagnosed as ACL tears. Most epidemiological studies demonstrating the incidence rate of ACL injuries focus on occurrence in either all sports or specific sports such as soccer, lacrosse, rugby, cross country ski, basketball, and football.[37, 47, 93]

An estimated 100,000 to 250,000 ACL injury incidents have been reported to occur annually in the United States.[23, 91] Several studies have also calculated and demonstrated the incidence rate of ACL injuries in two manners: 1) dividing injuries by athletic exposures and reporting the incidence rate per 1000 athletic exposures or 2) dividing injuries by number of athlete hours and reporting the rate per 1000 athlete hours.[18, 36] A recent systematic review and meta-analysis demonstrated a total of 700 ACL injuries in 11,239,029 exposures which is equivalent to an incidence rate of 0.062 injuries per 1000 exposures.[36] Although many previous studies have reported incidence rates for a group of individuals or athletes, ACL injury rates also differ by sex, age, and frequency and intensity of activity level. To understand why ACL injury rates change with these variables, the mechanism of an ACL injury must be understood.

ACL Injury Mechanism The most common injury to the ACL is referred to as a tear or sprain of the ACL and are classified in severity by a grading system.[58] Typically, an individual with an injured ACL reports with feeling a sudden "pop" during landing from a jump, pivoting or side-cutting followed by excruciating pain, effusion, and an inability to fully extend the leg. [15, 42] Clinical tests can be performed to assess the ligament including Lachman's, anterior drawer, and the pivot shift test.[7, 72] An ACL injury is classified in one of four grades; intact, low-grade partial tear, high-grade partial tear, and complete tear.[58] A physician or surgeon can identify and diagnose the grade of an ACL injury by observing a magnetic resonance image (MRI) of the knee. [7, 58]

ACL injuries may also be classified as direct contact or non-contact injuries.[87] Approximately 30% of ACL injury incidents are a consequence of direct contact with an object or another player.[43] The primary mechanism of ACL sprains which compose 70% of ACL injuries are non-contact injuries.[43] Marshall[87] described the defining characteristics of a non-contact ACL injury as a result of the individual's own movements that are frequently influenced by a cognitive or physical perturbation immediately before or during the injury episode. Non-contact ACL injuries often occur when an individual is planting or cutting while running or landing after a jump.[87] ACL injuries most frequently occur in contact sports such as soccer, basketball, volleyball, and football which require these jump-landing, planting, cutting and pivoting movements, and rapid changes in direction.[15] The knee joints function in the movement of the limbs during several of these tasks during sport.[15, 145]

The knee joint moves in the sagittal, frontal, and transverse planes. Rotation in the knee joint can occur by flexion and extension in the sagittal plane, by adduction and abduction in the frontal plane, and by internal and external rotation in the transverse plane.[145] Anterior and posterior translation of the knee joint occur in the sagittal plane while medial and lateral translation occur in the frontal plane and compression and distraction occur in the transverse plane. (Figure 16) [116]

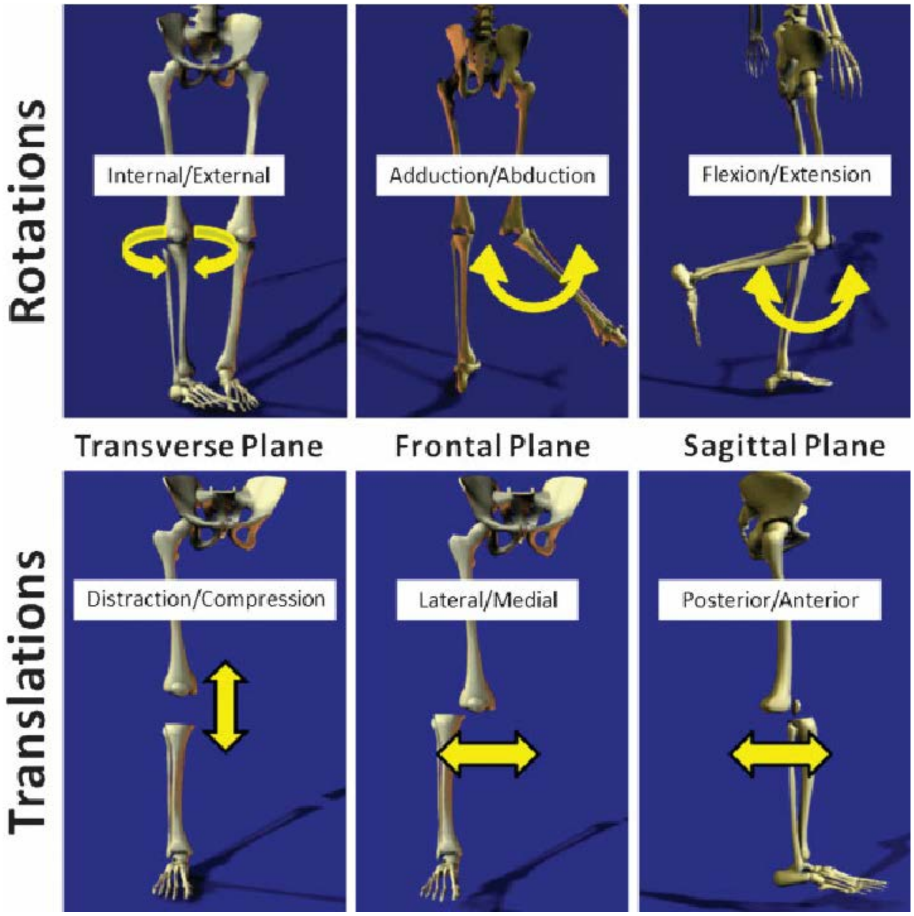

FIGURE 16. Classification of knee joint movements as rotations or translations.[116] Internal and External rotation, abduction and adduction, and flexion and extension are classified as rotations of the knee joint. Distraction and compression, lateral and medial movement of the knee joint, and posterior and anterior movement of the knee joint are classified as translations of the knee joint.[116]

As excessive loads are placed on the ACL, deficits in dynamic neuromuscular control manifest and are said to cause knee valgus and interior torque on the tibia which can lead to ACL injury. [15, 66] Kipour et al[66] utilized instrumented cadaveric legs to validate that regardless of loading mode, knee valgus has the primary effect on ACL strain. Several studies have utilized video footage, athlete interviews and experiences to demonstrate the afore-mentioned biomechanics, body position and movement that transpire prior to and during an ACL injury.[18, 55, 70]

During an ACL sprain the leg is usually near full extension and interaction with another player may cause interference in balance and the motor-control pattern.[15, 121] This disturbance is often referred to as physical perturbation.[87] As an individual's movement is blocked, a rapid adjustment must be made to change the planned course of movement, therefore this physical perturbation can also be cognitive or mental as well.[87] Neuromuscular control has been demonstrated as a strong predictor of ACL injury risk and thereby is also a primary component in the mechanism of ACL injuries.[54, 87] In addition to neuromuscular control, there are various different risk factors associated with ACL injuries.[14, 130, 131]

ACL Injury Risk Factors Griffin et al[43] and multiple different studies classified risk factors contributing to non-contact ACL injuries in four categories; biomechanical, anatomic, hormonal, and environmental.[4, 131] Biomechanical risk factor components include neuromuscular control and proprioception.[43] Anatomical risk factors also include differences between females and males, notch width index, and knee laxity. Hormonal risk factors primarily focus on the risk factors present in females due to differences in hormone distribution. Lastly, environmental risk factors include type and condition of playing surface, weather, and footwear.

Neuromuscular control can be explained as unconscious initiation of dynamic restrictions surrounding a joint in response to sensory stimuli.[43] Proprioception is a vital aspect of motor control which provides the information essential for facilitating neuromuscular control, and is best defined as sense of position, force and velocity.[56]Referring to the anatomy of the ACL, it has been noted that the ACL plays a major role in knee proprioception.[85, 86, 119] Proprioception thereby can enhance functional stability in the joint which is essential during sport activities.[43, 56, 60] There is lack of evidence of biomechanical risk factors for ACL injuries in male athletes, with most of the research focusing on the female athlete.[4] For example, Hewett et al[54] confirmed that female ACL injured athletes had significantly different posture and loading control during landing from a jump. The variable found by Hewett et al[54] to be most predictive of initial ACL injury risk was knee abduction moment at initial contact and of landing from a jump which were significantly different between female uninjured and ACL-injured groups. Significant correlations were also present between peak vertical ground reaction force (GRF) and knee abduction angles in ACL-injured athletes. Hewett et al[54] also demonstrated significant side-to-side differences in knee abduction moment as 6.4 times greater in ACL-injured compared to un-injured females. Hewett et al[54] concluded that female athletes with high abduction loads and increased dynamic valgus have an augmented risk for initial ACL injury. Sex is also a risk factor, as females are at a higher risk for ACL injury.[115]

Research studies have confirmed an estimation of 38,000 ACL injury occurrences in women’s and girl’s athletics annually in the United States.[54, 139] The probability for females participating in high-risk sports such as soccer and basketball to experience an ACL injury are 3 times greater than for men with the majority of these injuries classified as non-contact.[8, 115, 134] Possible influences for categorizing women at a higher risk for ACL injury are combined neural, hormonal, and anatomical or structural factors.[42, 54]

When transferring loads across the knee joint, the geometry of underlying and articular subchondral surfaces of bone are important and play a role in the knee's biomechanical response and concomitant risk for ACL injury.[13] The ACL is positioned in the intercondylar notch of the femur. Investigators have speculated that in certain positions of the knee and at the boundaries of joint motion, the ACL can become impinged against the notch.[130] Therefore the measure of notch width index (NWI) in females versus males has been used to determine sex differences in ACL injury risk. Several studies have demonstrated that females, on average, had a smaller NWI compared to males.[130, 133]

Another anatomical characteristic, knee joint laxity has also been identified as an ACL injury risk factor.[130] In comparison with males, females have greater knee joint laxity.[127] Myer et al[97] reported that there was an association between ACL injury in females and side-to side differences in anterior-posterior knee laxity and increased knee hyperextension. Studies have also reported that higher body mass index in females is an ACL injury risk factor for women.[140] Hormonal fluctuations due to the menstrual cycle have been identified as a reason for the increased risk women have for experiencing an ACL injury. Progesterone and estrogen receptors have been identified on the ACL. Reduced synthesis of collagen subsequently increasing susceptibility for ACL injury, have been associated with physiological levels of estrogen.[12] In conclusion, there are several anatomical sex differences which place women at a higher risk for ACL injury.[115, 130]

Risk factors for ACL injury that females and males may encounter are environmental risk factors. Environmental or extrinsic variables have been identified as risk factors for ACL injury including type and condition of playing surface, weather, and footwear.[4] Wet and rainy surfaces may reduce the friction between the shoe and the playing surface, therefore increasing risk for injury.[4] The grass type which athletes are playing on such as Bermuda grass turf have demonstrated an increase in ACL injury risk.[131] Warmer weather conditions, northern venues, and more evaporation have also been associated with an increase in ACL injuries.[131] Both intrinsic and extrinsic variables contribute to the rates of ACL injuries. Many individuals that succumb to these risk factors and experience an ACL injury receive ACL reconstructive surgeries (ACLR).[23]

Treatment for ACL Injuries

Reconstructive surgery of the ACL Authors have commonly reported an incidence of over 200,000 ACL reconstruction surgeries (ACLR) performed annually in the United States.[63] Buller et al[20] used the National Survey of Ambulatory Surgery and the National Hospital Discharge Survey to identify numbers of cases of ACLR performed in the United States in 1994, 1996, and 2006. Buller et al[20] found the number of ACLR increased from 86,837 in 1994 to 134,421 in 2006. These findings are similar to another study by Lyman et al[81] which found that there were 62,637 ACLR performed in 1997 and 105,118 in 2006. These statistics show an increase in ACLR performed annually, but Collins et al[23] revealed that less than a quarter of patients with ACL injury had ACLR in the three years after injury diagnosis which demonstrates that not all people who suffer an injury will receive ACLR. Collins et al[23] also revealed that female patients under the age of 29 with an ACL injury are more likely to undergo ACLR when compared to male patients. Although ACLR is a common treatment for ACL injury and the results have generally been successful, there are some negative outcomes and risks associated with ACLR. [29, 63, 83, 137]

One of the negative outcomes associated with ACLR is an increased risk for development of osteoarthritis (OA) in the knee.[108, 112] Even individuals who have been successfully rehabilitated and returned to sport have demonstrated the presence of OA 10 years after surgery in either the ipsilateral or contralateral knee.[65, 63, 78, 122] Outcomes and the success of ACLR can be dependent on sex, age, and activity level prior to and after ACLR.[23, 64, 137] Many studies have indicated ACLR to be the primary practice to put athletes back to high-level activities.[143] Although, in many cases ACLR can be successful in restoring the functional stability of the knee, many subsequent injuries after ACLR on either the ipsilateral or contralateral knee have been reported.[63, 107, 144]

Although ACLR is the primarily used treatment for ACL injuries, some more conservative approaches to treat ACL injuries are utilized as well.[2, 65, 68] Conservative treatments implement a non-surgical, rehabilitation-focused treatment method for ACL injury. [1, 65] Ahn et al[2] demonstrated that a selective group of individuals that experienced ACL tears but chose conservative treatment still showed restoration of continuity and improved joint laxity.[2] In a study completed by Kostogiannis et al[68] 100 patients with acute total ACL injuries that did not receive ACLR were observed for 15 years. Kostogiannis et al[68] concluded that neuromuscular rehabilitation and early modification of activity resulted in acceptable activity level and good knee function in majority of the patients. Although many studies have reported positive outcomes with non-surgical, conservative treatments for ACL injury, Strehl and Eggli[135] found that nearly two-thirds of patients that underwent primary conservative treatment required surgical reconstruction in the long-term. Some authors have also reported that individuals who seek conservative treatment and return to a high activity level may suffer secondary damage.[5, 50, 84]

Subsequent Injury to the ACL

In a longitudinal study measuring outcomes 5 years after ACLR, Salmon et al.[122] reported 12% of 612 patients have sustained a second ACL injury. In a 10 year follow up of this population, 27% of these individuals had experienced a second ACL injury.[122] These studies reported estimates of incidence proportions instead of incidence rates. Incidence rates adjust for the extent of athletic participation which may differ due to age, fear of re-injury, confidence, residual impairments and other aspects.[108] Paterno et al[108] reported that the incidence rate 24 months after ACLR and RTS for experiencing a second ACL injury was approximately 6 times greater compared to healthy control subjects. Laboute et al[73] also reported the mean time for a repeated rupture following RTS as 22 months after ACLR.

Risk factors and predictors of subsequent ACL injury Specifically referring to short-term outcomes, the risk of subsequent ACL injury is significantly higher when compared with initial ACL injury risk.[81, 125] The occurrence of subsequent ACL injury to either knee is dependent on several factors.[54, 63, 109, 125] Shelbourne et al[125] revealed in a 5 year follow up with 1415 ACLR patients that women endured more subsequent injuries to the contralateral knee than male patients. Kaeding et al[63] identified differences in subsequent injury risk based on the type of ACLR patients received; patients who received allograft were 5.2 times more likely to suffer an ipsilateral tear after ACLR compared with patients that received bone-patellar tendon-bone grafts. Kaeding et al[63] also concluded that younger age and higher activity level were predictors of increased chances of graft failure on the ipsilateral limb and as risk factors for contralateral tears post-ACLR.

Although there are many studies that have identified predictors of second ACL injury risk such as age[23, 63], sex[23, 125], activity level[63], and graft type[63] only few researchers have identified biomechanical variables that may contribute to or predict second ACL injury risk.[109] Gomes et al[35] found that professional soccer players with noncontact ACL re-ruptures demonstrated significantly lower mean internal-external hip rotation when compared with healthy, professional soccer players. In a study conducted by Delahunt et al.[26] a group of post-ACLR patients displayed an internally rotated and increased adducted hip joint position at both peak and averaged time following landing when compared to a non-injured group matched by sex, age and activity level. Myer et al[98] compared performance of athletes with unilateral ACLR cleared for RTS with matched healthy teammates on a single-legged vertical hop test and demonstrated reduced single-limb vertical jump height limb symmetry index (LSI) measures in the ACLR group. Therefore, although these athletes were cleared for RTS after ACLR, deficits in unilateral force development persisted during single-leg performance.[98] The above discussed articles demonstrate biomechanical differences in ACLR patients compared to healthy individuals, but none of these alterations were identified as predictors of second ACL injury following initial injury and ACLR.

Paterno et al[109] assessed lower limb asymmetries and measures of neuromuscular control in athletes who had undergone ACLR during a drop vertical jump and postural stability task. Paterno et al[109] identified 4 variables which predicted second ACL injury in individuals had undergone ACLR and RTS including asymmetries in internal knee extensor moment, hip net moment impulse, and joint range of motion (ROM). This study also found that subjects generated less force in the limb which had undergone ACLR than the unaffected limb.[109]

Wiggins et al[144] highlighted both activity level and age as key risk factors in sustaining a second injury after ACLR. Numerous elite-level high school athletes who endure an ACL injury will continue on to play at the varsity collegiate level. Division I athletes who experience an ACL injury or surgery have been associated with a higher risk for reoccurring injury or reoperation.[63] There have been more successful return to preinjury activity levels with sports such as bicycling and light jogging rather than more sports that require laborious cutting and pivoting movements.[63] Overall, several studies have found that the risk of second ACL injury is heightened in athletes who RTS after ACLR.[109, 122] Therefore, the approach for reducing the occurrence of subsequent ACL injuries after ACLR is identifying which RTS protocols or tests are being used for post-ACL injured and post-surgery patients.

Currently used clinical practices for return to sport following ACL reconstructive surgery

A wide variety of tests are used for determining RTS readiness for individuals after ACLR.[1, 136, 143] The amount of time postoperatively that patients were cleared for RTS was listed as criteria in 158 of the 264 studies included in Barber-Westin and Noyes et al's[136] systematic review on RTS protocols. In 84 of the 158 studies, time post- ACLR was the only criteria used. Time post-ACLR may not be effective when used alone for assessing RTS readiness as Bonfim et al[16] reported motor and sensory deficits at 12 to 30 months in ACL-reconstructed knees when compared with matched controls. To identify motor deficits, muscular strength assessments are also commonly utilized as RTS criteria.[136]

Muscles of the lower extremity such as the quadriceps and hamstrings play a major role in knee joint function and stabilization.[110] Muscle weakness has been demonstrated to persist months to years after ACLR.[1, 61] A method used clinically for assessing strength after ACLR and before RTS is the quadriceps limb symmetry index (Q-LSI), a measure which compares involved or injured limb quadriceps strength relative to the uninvolved or uninjured limb quadriceps strength.[1] Recommendations for isokinetic testing of the hamstrings and quadriceps range from a quadriceps index greater than 80% or greater than 90%.[1, 132, 144] In a published survey among instructors of the Association for joint surgery (AGA), only 40.8% of the participants reported the use of a muscular strength assessment as criterion for RTS.[111] Other criterion have been more commonly reported for clinical use in determining return to sport readiness.[1]

Range of motion is assessed during rehabilitation of the knee after ACLR and full range of motion (ROM) is frequently used as a RTS criterion. The Lachman test is also a frequently used clinical test for assessing ACL injury and patient progression after ACLR.[1] A Lachman test is conducted with the patient in supine position with the involved knee flexed at 20-30 degrees.[72] The examiner then precedes through several motions with the knee to determine anterior laxity and anterior tibial translation of the knee. An instrument called a KT-1000 can also be used to measure this magnitude of movement in millimeters.[72] A positive Lachman test is confirmed by the difference in anterior translation present between the involved and un-involved limb. In combination with other tests discussed below a negative Lachman test is frequently used to determine that an individual is ready to RTS. [1, 72]In addition to the Lachman test, the pivot shift is clinically used to determine RTS readiness.[1]

The pivot shift test is used to assess the dynamic laxity of the knee and provides information regarding the laxity of the knee joint following ACLR.[96] During the pivot shift test the examiner puts a moderate valgus and internal rotation force on the proximal tibia while the patient is in a supine position.[80] A pivot shift test is considered positive when the proximal tibia subluxes anteriorly on the distal femur at about 30 degrees of flexion.[80, 96] A negative pivot shift test is utilized as a criterion for RTS. [80, 96] Different variabilities of this complex maneuver have been utilized in the clinical setting which may contribute to its variability.[80] Although quadriceps symmetry index[1], the Lachman test[72], and the pivot shift test[80] all contribute relative information needed for RTS determination, sport-specific, functional and dynamic movement patterns must be assessed additionally.

Single leg hop as a return to play protocol The single leg hop (SLH) test is a test that incorporates numerous muscles to complete a functional movement through the utilization of several joints.[38] Several varieties of the SLH test have been utilized for determination of RTS such as the SLH for distance, triple hop test, the triple crossover hop test, and timed hop.[48, 50] Although these varieties of the SLH have also shown reliable, the SLH for distance has been the most commonly used and verified as a reliable test for individuals with healthy knees and those who have had ACLR.[106]

The SLH for distance utilizes the difference in hop distance between limbs to indicate asymmetries present between limbs.[94] In the single leg hop for distance, the individual hops horizontally one-legged on each leg aiming to reach as far a distance as possible.[67] The limb symmetry index (LSI), represented as a percentage, is the most commonly used method for quantifying this difference and is calculated as the ratio of hop distance on the injured/involved limb and the hop distance on the uninvolved limb multiplied by 100.[94] Cut off values for LSI have been established for clinical return to sport criteria and guidelines.[10, 94] An LSI of 85% or above has been demonstrated to indicate 'normal' limb symmetry and that function of the injured limb is being restored.[10] Although, other researchers have identified LSI values above 90% in healthy individuals, and therefore have suggested that the cut off value for return to sport criteria be increased to an LSI above 90%.[94] Several studies have also verified the use of hop tests for indicating larger asymmetries present between injured and non-injured groups.[46, 99]

Gustavsson et al[46] constructed a battery test of 3 different functional hop tests including the single leg hop for distance, the vertical jump and the side hop. Gustavsson et al reported significant differences in SLH, vertical jump and side hop performance between the injured and non-injured limb in individuals 6 months after ACLR. Gustavsson et al[46] also reported significantly larger side-to-side differences in these tests in the post-ALCR group compared to the healthy control group. An LSI value of 90% or greater was indicated as normal in this study.

LSI values were abnormal in 19 of 35 post-ACLR patients. Gutavsson et al[46] reported the sensitivity of this battery in identifying a patient as abnormal based on LSI as 91% in the group that had ACLR. This indicates that this hop test battery test presented a high ability to distinguish between hop performance of the injured and uninjured side in patients 6 months following ACLR using limb symmetry index.[46] Results of other studies utilizing series of hop tests have also provided information regarding its reliability and validity as a performance-based outcome measure for post-ACLR patients.[118]

Reid et al[118] evaluated the performance of individuals with ACL-reconstructed limbs on the single hop for distance, a triple hop for distance, 6-m timed hop, and crossover hops for distance. The subjects performed this series of hop tests 3 separate times within the 16th week following ACLR and once 6 weeks later. The results of this study demonstrated that changes in hop test scores on the operative limb were statistically greater compared with changes on the uninvolved limb.[118] Reid et al[118] concluded that the series of hop tests provides valid and reliable performance based outcome measures that can be used for patients undergoing rehabilitation following ACLR. Test-retest reliability of hop tests have also been studied. [19, 106]

Paterno and Greenberger[106] investigated the test-retest reliability of the SLH for distance in individuals with and without ACLR. There was no significant difference demonstrated in pre-tests to post-tests in healthy individuals on either dominant or non-dominant limb. Interclass correlation coefficients for Paterno and Greenberger's[106] study revealed values of 0.96 and 0.92 for non-dominant and dominant legs; respectively indicating that the one-legged hop test is a reliable test for individuals with healthy knees and with ACLR. Bremander et al[19] also assessed test-retest reliability of the SLH for distance and determined that it met the cut-off suggested for acceptable reliability with an interclass correlation coefficient of 0.93. Bremander et al[19] reported learning effects within patient performance, but the commonly recommended SLH protocol accounts for these effects by utilizing practice trials before measurements are taken.[49] Although the several results may support the use of the single leg hop test for distance as a measure for distinguishing hop performance between limbs[19, 106, 118, 148], other studies have suggested flaws with using this test to determine abnormalities between limbs.[10, 102]

Orishimo et al[102] stated that it shouldn't be assumed that the biomechanics during a single leg hop test are similar between limbs. Orishimo et al[102] reported hop ratios in post-ACLR patients that were greater than 85% and therefore classified in the normal range. Although, Orishimo et al[102] reported differences between the involved and uninvolved limb on range of motion, knee flexion at takeoff, and peak knee and hip extension moments, despite achieving normal hop ratios. Orishimo et al[102] concluded that although the SLH may identify asymmetries between limbs, hop ratio alone may not identify compensations at the ankle and hip and deficits at the knee present in patients following ACLR.

In addition to Orishimo et al's[102] conclusions regarding the reliability of hop tests, Barber et al[10] also noted some limitations with the use of hop tests as functional performance assessments. Barber et al[10] evaluated the efficacy of jumping, cutting-type, and hopping tests in determining functional limitations in ACL deficient knees. According to hop distance in the SLH 50% of the patients in this study performed normally, however all patients reported giving-way episodes within sports.[10] Barber et al[10] established that there is a lack of sensitivity of the SLH for distance to define functional limitations. In conclusion, SLH distance between limbs has commonly been utilized to measure total leg function and is not meant to diagnose underlying sources such as neuromuscular control, lack of strength or confidence.[124] Therefore, other dynamic tests such as the Y-balance test (YBT) and the drop vertical jump test (DVJ) have been used in a battery of tests or in addition to hop tests to help indicate these functional limitations present in post-ACLR patients.

Y-Balance test The YBT is a screen of dynamic balance which requires the individual to balance one leg while the contralateral leg reaches in anterior (ANT), posterolateral (PL), and posteromedial (PM) directions.[114] The YBT was developed based on prior research that indicated the Star Excursion Balance Test (SEBT) which used 8 different reach distance (RD) directions was redundant. [113, 123] Researchers and clinicians have utilized different formulas and data analysis techniques for assessing the relationship between YBT performance and injury risk based on asymmetry.[22, 103, 128] Absolute difference in each RD between limbs has been used to identify limb asymmetries present in individuals. [51, 123] Composite score (CS) is also commonly used as a normalized value to indicate performance on the YBT.[123] CS is calculated as the sum of the reach distances in each direction divided by 3 times the limb length and multiplied by 100%.[123] CS has been demonstrated for individual limbs or both limbs combined.[113, 123] The composite score is used by researchers and clinicians as a measure of overall YBT performance and YBT performance or symmetry between limbs.[113 123]

Munro and Herrington[95] determined the test-retest reliability of the YBT and demonstrated interclass correlation coefficients of 0.84 to 0.92. Munro and Herrington[95] also assessed the learning effects of the YBT and reported that reach distances stabilized after 4 practice trials were performed by participants. The use of 6 practice trials has been suggested by several researchers and clinicians to reduce the learning effect. [40, 41]

The YBT requires stability, balance and other neuromuscular characteristics such as flexibility, strength, and lower extremity coordination.[114] Although few studies have examined the relationship, some studies have reported that poor balance in numerous sports is a risk factor for lower extremity injury.[90, 142] Although many of these studies are referring specifically to risk for ankle injuries[90, 142] some studies have also indicated deficits in dynamic balance in individuals after ACLR.[3, 148] For example, Zult et al[148] revealed significant bilateral impairments in the SEBT using the CS when compared to healthy controls. Herrington et al[51] demonstrated significant differences for anterior, posterior-medial, medial, and lateral directions of the SEBT between ACL deficient individuals and a healthy control group. Herrington confirmed that ACL deficient individuals seem to have deficiencies in dynamic postural control when compared to individuals without ACL deficiencies. Although Zult et al and Herrington et al have demonstrated differences in reach distances in the YBT and SEBT between ACL injured/deficient and control/healthy individuals, these studies did not provide cut-off values on the YBT for determining injury risk. Other studies have provided cut-off values that may indicate injury risk.[114, 128]

Smith et al[128] assessed the association of the YBT reach asymmetry and injury in division 1 athletes and determined that participants with ANT asymmetry greater than or equal to 4 cm had significantly greater odds of injury when compared with individuals with less than 4 cm ANT asymmetry. Plisky et al[114] reported that bilateral composite RD were significantly associated with lower extremity injury in a group of 235 high school basketball players. Players with an anterior reach distance difference greater than 4 cm between limbs were 2.5 times more likely to suffer a lower extremity injury. Plisky et al[114] also demonstrated that girl basketball players with a composite reach distance less than 94% of their limb length were 6.5 times more likely to sustain a lower extremity injury.

Although studies have determined cut-off values for predicting injury risk using the YBT[128] [114], other studies have suggested the limitations that these cut-off values have in indicating deficits.

For example, Lee et al [77] indicated a weak correlation between lower extremity muscular strength and YBT. Yet, identifying muscular weaknesses or deficits in the lower extremity is key in assessing injury risk.[1, 61] Overmoyer et al[103] confirmed that while the YBT may have the ability to expose asymmetries and weaknesses present in ankle dorsiflexion via the differences between limbs in the ANT RD and PL RD, it is unclear how this has a role in ACL injury risk. Overmoyer et al[103] also suggested that the YBT should be used in combination with other tests to understand a broader picture and relationship of functional movement and injury risk. A test which may fill this gap in assessing functional movement may be the drop vertical jump test.[18, 69]

Drop vertical jump test The drop vertical jump test (DVJ) is a bilateral jump test which has been widely used in research related to ACL injury.[92] In a drop vertical jump test, the individual starts on top of a box (usually 30-31 cm tall), drops off the box and immediately following landing performs a maximal effort vertical jump.[109] Possible factors for injury risk have been quantified using three-dimensional (3D) or marker-based motion analysis systems during performance of the DVJ or vertical drop jump tasks.[54, 109] Specifically, 3D kinematics and kinetics are quantified and used for ACL injury risk assessment.[92] Hewett et al[54] were the first researchers to suggest the use of the DVJ in screening for ACL injury risk.

Hewett et al[54] demonstrated significantly different knee abduction angles at initial contact in athletes who had ACL ruptures compared to uninjured athletes. Hewett et al[54] indicated significant correlations between ACL-injured individuals and knee abduction angle and peak vertical GRF which was increased 20% in the injured group. Injured athletes also presented significant side-to-side differences in knee load and 6.4 times greater side-to-side knee abduction moment differences compared with uninjured athletes.[54] In conclusion, Hewett et al[54] identified knee abduction moment and dynamic valgus measures at initial contact of the DVJ as predictive of initial ACL injury risk. Paterno et al[109] reported deficits in postural stability and altered neuromuscular control of the knee and hip during a vigorous landing task are predictors of second ACL injury after an athlete returns to sport. Paterno et al.[109] demonstrated that a difference in internal knee extensor moment during landing of a DVJ greater than 410% between limbs was predictive of second ACL injury.

Referring back to the mechanism of ACL injury will aid in discussing the relevance of the DVJ as a RTS test. An ACL injury occurs when substantial loads are placed on the knee, specifically within the first 10% or approximately 40 milliseconds after initial contact (IC) with the ground during landing.[55] When excessive loads are placed on the ACL, deficits in dynamic neuromuscular control manifest and are said to cause knee valgus and interior torque on the tibia which can lead to ACL injury.[15, 66] Ligament dominance is responsible for this biomechanical deficit and in this condition muscles do not adequately absorb ground reaction forces therefore the joint and ligament must absorb large quantities of force over a small period of time.[53] Extension of the knee joint has been indicated as a component of the injury mechanism and relates to the neuromuscular imbalance which typically occurs in females termed quadriceps dominance.[53] Quadriceps dominance denotes the inclination to use the quadriceps muscle to primarily stabilize the knee.

As noted above, Paterno et al[109] indicated asymmetry in knee extension moment as predictive of second ACL injury risk. It stands to reason that this knee extension moment measure is also exposing quadriceps dominance or weakness in individuals as well. If an individual is not absorbing force properly at IC of landing, the DVJ can portray this muscular weakness, and deficits in functional and dynamic stability as kinetic and kinematic measures.[53, 109, 129] Therefore, the DVJ is essentially incorporating aspects of several RTS tests such as the

SLH and YBT into one test. The ability of the DVJ to indicate characteristics that place individuals at risk for both initial and second ACL injury is due to several aspects of the test itself. The DVJ is a dynamic, functional, two-legged, maximal effort activity which aims to replicate sport-specific activities.[117] When assessing individuals for readiness to return to sport, it has been suggested and verified that part of the rehabilitation process should be dedicated to the introduction of sport-specific movements.[1] To truly evaluate an athlete's progress with these sport-specific movements a standardized test such as the DVJ that indicates movement deficits in a similar functional movement can be used.[109]

Although, because the SLH and YBT are preferred for clinical use due to accessibility, cost, and time; verification that these tests may predict the same asymmetries as a more costly and time consuming test such as the DVJ is necessary.[, 50, 114, 100] The purpose of this study was to compare clinical and mechanical measures in detecting lower limb asymmetries associated with second ACL injuries determine the ability of the SLH and the YB test to classify asymmetries. The first experimental hypothesis was that there would be a significant correlation between the reach distances (ANT, PM, PL) and the knee extension moment at initial contact of the DVJ. The secondary experimental hypothesis was that performance variables from the YB test and the SLH test would classify individuals in the same symmetry category in which the DVJ categorized individuals.

CHAPTER 3: CONCLUSIONS AND RECOMMENDATIONS

Although both the SLH for distance and the YBT have demonstrated reliability in assessing asymmetry in individuals in other studies[99 44], these tests were unable to classify individuals in the same way a predictive variable such as KExtM during the dynamic task of a DVJ has in the current study. Based on the present findings, the SLH for distance and the YBT did not correctly identify asymmetries. The current study supports an increase in the cut-off value of the LSI used for the SLH for distance to above 90%. The SLH is suggested to be utilized with other tests such as the drop vertical jump as used in the LSSE. Perhaps, the YBT should not be used in combination with these tests as the relationship between the asymmetries was negative, and remains unclear. This would allow investigation of a battery of tests in which an individual must pass for clearance for return to sport.[9, 46, 67] The development of a checklist including several tests and injury risk components could greatly enhance clinical RTS practices for physical therapists.

One major limitation of the current study is the use of a healthy population of individuals. The inclusion criteria of this study required the participants to have had no injury or surgery in 6 months prior to participation in the study. If a group of post-ACLR patients or previously injured individuals were utilized to assess the classification accuracy of these return to sport tests to identify asymmetries, the results may have yielded different conclusions. A secondary limitation of this study could be the sample size. If a larger sample size was used, the results may have more value. The calculation of specificity and sensitivity give more value when a larger sample size is utilized. Therefore, the current study did not have a large enough sample size to yield an accurate representation of sensitivity and specificity. Confounding variables or factors may have played a role in the results of this study as well, such as differences in sex or activity level. A comparison of males and females or activity level have both demonstrated differing results in variables of interest.[14, 22, 30, 120] Future research should control or assess the differences which confounding variables may cause in order to decrease generalizability.

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APPENDIX A

CONSENT TO ACT AS A HUMAN SUBJECT

Comparison of Clinical Versus Mechanical Measurements in Detecting Lower Limb Asymmetries Associated with a Second ACL Injury

Department of Health, Physical Education & Recreation
Northern Michigan University
Alicia DenHerder (graduate student investigator), Dr. Sarah Clarke (thesis director)
Email: adenherd@nmu.edu, sabreen@nmu.edu

We are writing to invite you to participate in this research study in Marquette, Michigan requiring one visit to Northern Michigan Universities Exercise Science lab for approximately 1-2 hours.

INTRODUCTION:

Definitions to know related to the study and consent form:

1. **SLH (single leg hop):** This acronym will be used to describe the single leg hop test which each subject will perform.
2. **YB (Y-Balance):** This acronym will be used to describe the y-balance test each subject will perform.
3. **DVJ (drop vertical jump):** This acronym will be used to describe the drop vertical jump test which each subject will perform from a box of 31 cm in height.
4. **AIPQ (activity, injury, and pain questionnaire):** This acronym will be used to describe the questionnaire developed for this study including questions regarding potential subjects' activity level, injury history, and pain assessment.
5. **PAR-Q (physical activity readiness Questionnaire):** This acronym will be used to describe the American college of sports medicine (ACSM) physical activity readiness questionnaire which every subject must fill out before participation in the study.
6. **Anterior:** in front of the body
7. **Posterolateral:** behind and to one side (outer side).
8. **Posteromedial:** behind and to one side (inner side).
9. **Asymmetry:** lack of equivalent performance between both sides of the body.

There are several protocols currently utilized by physicians and physical therapists to determine an individual's injury risk and readiness to return to sport or sport-specific activities after injury or surgery. The single leg hop (SLH) is one test used to assess an individual's functional movement abilities by measuring the hop distance achieved on both non-involved and involved limbs. The Y-Balance (YB) test also assess differences between limbs by measuring the distances reached in several directions with both limbs. The drop vertical jump (DVJ) is a dynamic test that has predictive value of determining second injury risk by measuring several variables throughout completion of the movement. The purpose of this research project is to compare clinical and mechanical measures in detecting lower limb asymmetries associated with second anterior cruciate ligament ACL injuries in healthy individuals. The secondary purpose is to determine the ability of the SLH and the YB test to classify healthy individuals as asymmetrical or symmetrical in the same manner that the DVJ test does. Approximately 30-40 individuals will take part in this study.

RESTRICTIONS:

- Individuals may be excluded from this study if they have had an injury or pain in any area from the hip down to the feet.
- Individuals will be excluded if they answer 'yes' on any questions of the PAR-Q unless they have been cleared by a physician to participate in the study.
- Individuals will be excluded from this study if they are below the age of 18 years old or above the age of 55 years old. Individuals above the age of 55 years old will be excluded to minimize risk for injury.
- Individuals who do not have prior experience on a competitive sports team in which jump-landing tasks were required or involved will be excluded from this study.

PROCEDURES:

Data collection will require one visit to the Exercise Science lab in the Physical Education Instructional Facility (PEIF) of NMU for approximately 1-2 hours.

Lab visit components:

1. All subjects will first fill out a physical activity readiness questionnaire (PAR-Q), an activity, injury, and pain questionnaire (AIPQ), and sign a consent form before participating in the study; see attached documents.
2. Your age, sex, and height will be measured and recorded.
3. Warm-up:
   a.) 10 lunges, 10 reverse lunges, 10 straight leg kicks, and 10 repetitions of standing front leg swings on both legs
4. Dominant leg assessment:
   a.) Soccer ball kick
   b.) Single leg jump-landing task
   c.) Balance test: subjects will be slightly pushed from behind with one hand of the test proprietor between the subjects shoulder blades
5. DVJ test:
   a.) Subjects will jump from a 31-cm box, and upon landing with both feet on a force plate immediately execute a maximal effort jump.
   b.) Subjects will perform 3 trials of the DVJ.
6. SLH test:
   a.) Perform a single leg hop for distance on each leg until 3 successful trials have been recorded.
   b.) Successful trials include hops in which subject's exhibit controlled landings and maintain foot placement of the landing foot until the administrator has recorded the hop distance.

7. YB test:
   a.) Stand on a footplate, sustain single leg stance, and push a sliding box in the anterior, posterolateral, and posteromedial directions with both legs.
   b.) Subjects will perform a maximum of three trials on each leg.

BENEFITS:

Individuals who decide and are eligible to participate in this study will receive a free injury risk assessment screened by a licensed doctor of physical therapy (DPT). Individuals will also receive education on their form during sport-specific movements, and advice for avoiding injury in the future. Individuals in the sports science and physical therapy fields will benefit as a result of this research by receiving more evidence-based research on injury-risk assessment. The results of this research will inform clinicians the ability of tests they may use to detect asymmetries between limbs.

COMPENSATION:

There will be no compensation for participation in this research study.

RISKS AND DISCOMFORTS:

Every effort will be made to conduct the testing procedures in such a way as to minimize your discomfort and risk. You will be performing sport-specific movements, which will have been verified to impose minimal risk by your responses on the PAR-Q. The movements performed may cause minor muscular soreness or discomfort during or after involvement in the study. Risks of bodily injury including, but not limited to, injuries to the muscles, ligaments, tendons, and joints of the shoulder, ankle, knee, hip or any lower extremity musculoskeletal injury are possible. You will also be required to fill out the AIPQ developed for this study. Inclusion criteria requires that the you will have participated in any sport involving jump-landing tasks at any point in your lives, and pain and injury free for the last six months. The likelihood of injury during these tests is low, as you will have already performed several similar exercise tasks during your sport(s) involvement. Minor psychological risks may exist such as distress due to any inabilities exposed while performing the involved tasks. Emergency medical procedures are in place for testing sessions and a physical therapist will be present during all testing sessions.

COST:

You will not have any costs for being in this research study and you will not be paid for being in this research study.

INQUIRIES:

If you agree to participate, please let us know by returning an email to the primary researcher of the study (email displayed below) by February 20, 2017. One attempt will be made to reach everyone by phone before February 20, 2017. At this time, we will schedule an appointment for the completion of questionnaires and lab measurements.

If you have any further questions regarding your rights as a participant in a research project you may contact Dr. Robert Winn of the Human Subjects Research Review Committee of Northern

Michigan University (906-227-2300) rwinn@nmu.edu. Any questions you have regarding the nature of this research project will be answered by the principal researchers who can be contacted as follows: Alicia DenHerder (616)-970-1764, adenherd@nmu.edu. or Dr. Sarah Clarke (906-227-1143), sabreen@nmu.edu

CONFIDENTIALITY:

We will keep the information you provide confidential; however, federal regulatory agencies and the Northern Michigan University Institutional Review Board (a committee that reviews and approves research studies) may inspect and copy records pertaining to this research. After collection of results, the data will be tabulated and given to one of the principal investigators to assign a numerical ID to your data. This will ensure the data analysis will serve to protect the confidentiality of the data collected. Any electronic files from this study will be stored on a password protected flash drive and in possession of the principal investigators for 7 years. Any hard copy files from this study will be secured in locked filing cabinets in the principal investigator's office. Only members of the thesis committee who have been written given consent by you will have access to any data from the study.

FREEDOM OF CONSENT:

Taking part in this research study is completely voluntary. If you decide not to be in this study, or if you stop participating at any time, you will not be penalized.

	Yes	No
• I give permission for any test I perform in this study to be video recorded.	☐	☐
• I give permission for the video recordings of my test performance to be used for future research purposes such as in scientific presentations or demonstration of the tests performed.	☐	☐
o with the video footage in their original form and with my identity easily identifiable;	☐	☐
<u>OR</u>		
o with the original video footage blurred to fully disguise my identify;	☐	☐
<u>OR</u>		
o I **<u>do not</u>** give permission for the video recordings of my testing to be used for future research purposes	☐	☐

PLEASE READ THE FOLLOWING STATEMENTS, AND SIGN IN THE SPACES PROVIDED TO INDICATE YOUR CONSENT:

I have read the above “Informed Consent Statement.” The nature, risks, demands, and benefits of the project have been explained to me. I understand that I may ask questions and that I am free to withdraw from the project at any time without incurring ill will or negative consequences. I also understand that this informed consent document will be kept separate from the data collected in this project to maintain anonymity (confidentiality). Access to this document is restricted to the principle investigators

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Name of Subject (printed)

-- --------------------------
Subject’s Signature Date

Witness Signature

Thank you very much for your consideration.
Sincerely,

Alicia DenHerder
Graduate Student
Northern Michigan University
School of Health & Human Performance
Exercise Science

APPENDIX B

Physical Activity Readiness Questionnaire (PAR-Q) and You

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly:

YES	NO		
☐	☐	1.	Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
☐	☐	2.	Do you feel pain in your chest when you do physical activity?
☐	☐	3.	In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4.	Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5.	Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	6.	Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
☐	☐	7.	Do you know of <u>any other reason</u> why you should not do physical activity?

If you answered:

YES to one or more questions

Talk to your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want – as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to <u>all</u> PAR-Q questions, you can be reasonably sure that you can:

- Start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

Delay becoming much more active:

- If you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- If you are or may be pregnant – talk to your doctor before you start becoming more active.

Please note: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed use of the PAR-Q: Reprinted from ACSM's Health/Fitness Facility Standards and Guidelines, 1997 by American College of Sports Medicine

APPENDIX C

Activity, Injury and Pain Questionnaire

Age: __________

Sex: __________

1. Have you ever participated on a competitive sport team which required or involved jump-landing tasks?
   Examples: basketball, football, volleyball, soccer, gymnastics, cheerleading, rugby, track & field, karate, dance etc.

2. Are you currently playing a competitive team sport? If so, what sport?

3. Do you play a sport recreationally? If so, what sport?

4. Have you had any injuries in the last 6 months? If so, what was the injury?

5. Have you ever had any type of surgery on your knees, hips, legs, or ankles? If so, when?

6. Are you currently experiencing any pain in your muscles or bones? If so, where?

7. Do you experience any pain while jumping up and down or jumping forward? If so, where?