Movement Variability During Single Leg Drop for Individuals after Anterior Cruciate Ligament Reconstruction

Undergraduate Honors Thesis

Presented in Partial Fulfillment of the Requirements for Graduation with Honors Research Distinction

Department of Mechanical and Aerospace Engineering at The Ohio State University

By

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Abstract

Individuals who undergo anterior cruciate ligament reconstruction (ACLR) often experience suboptimal post-operative outcomes such as high risk of reinjury, low levels of returning to former level of sport and increased risk of developing knee osteoarthritis. Abnormal knee motion and movement patterns have been observed following ACLR and rehabilitation, which may be the cause for these suboptimal results, and is not currently considered in return to sport criteria. The dynamic movement theory proposed that there is a preferred range for movement variability; variability that is too high can lead to instability and reduced adaptability to environmental demands while variability that is too low is accompanied by lower ranges of motion. This theory into dynamic movements has been used in gait studies post-ACLR but has not yet been used to analyze more demanding dynamic tasks, such as jumping and landing, that are commonly performed by the young, active cohort with ACL injuries. Further understanding of movement variability after ACLR during demanding tasks could provide additional insight into the suboptimal outcomes of this patient population. Therefore, the purpose of this study was to compare lower extremity movement variability during a single leg drop test between young individuals who have undergone ACLR and a control group, and secondly compare the movement variability of the injured leg to the uninjured leg for the ACLR population. Motion capture data was processed by utilizing Cortex and the exported data was analyzed in MATLAB using a vector coding technique to find the coordinative variability associated with each subject. Both the injured and uninjured leg for the ACL population showed increased movement variability several key hip, knee and ankle joint couplings when compared to controls. Our findings indicated that patients following ACLR exhibit compromised neuromuscular control during this demanding task. Comparison of the injured leg to the uninjured leg did not show significant difference which may be due to the changes to neuromuscular control in both limbs

following ACLR. Further research needs to be done to determine the impact that increased movement variability has on post-ACLR functional outcome and on whether it contributes to the suboptimal outcomes seen in the ACLR population.

Acknowledgments

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I'd like to thank Laura Schmitt who assisted on this project and pushed me to challenge the process of analysis to get understandable and meaningful results. Laura has provided me with a wealth of information and expertise and has been most influential in the successful completion of this work. I'd also like to thank Jennifer Perry for her assistance with developing the software that was used and ensuring its correct implementation.

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My whole heart goes to my family and friends. You are my rock, and I'd go the world and back for you as you have for me countless times.

Saving the best for last, I'd like to thank my boyfriend John for his unwavering belief in me and his kind heart. Accomplishing this means that much more seeing him proud of me.

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Chapter 1

1.1 Background

The anterior cruciate ligament (ACL) is one of four ligaments in the knee which are responsible for keeping the knee stable as well as holding the femur and tibia together [2]. ACL injuries account for more than 50% of all knee injuries and are one of the leading causes of sports-related surgeries [14]. It is estimated that in the United States there are 200,000 ACL injuries a year [10].

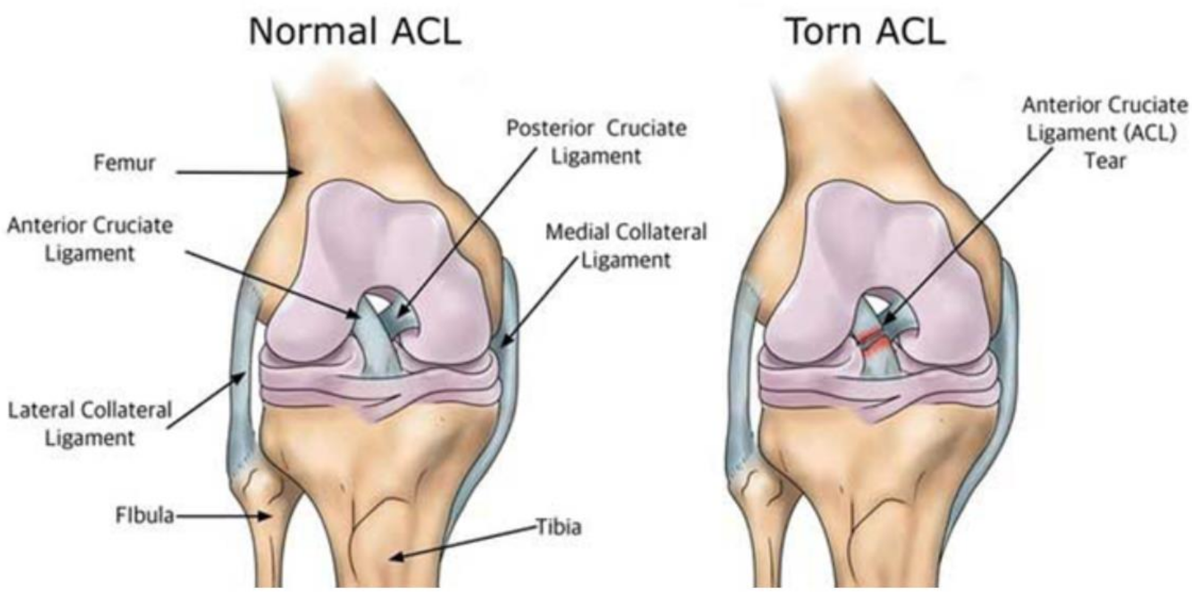

Figure 1: ACL Tear [20]

Nearly three quarters of ACL injuries are noncontact injuries, which is an injury that results without athlete-athlete contact [5]. Noncontact injuries usually occur during sharp dynamic movements such as sidestep cutting or rapidly stopping. As a result, the population that is mostly affected by ACL injuries are athletes who participate in sports that demand these dynamic movements such as soccer, basketball, or football [2]. On top of that, females have a two to eightfold higher rate of injuring their ACL more than men do [5]. Women are more susceptible to injuring their ACL than men because of differences in dynamic limb alignment and comparative deficits in strength in the hip and ankle [8].

Treatment

The challenge with ACL injuries is to return athletes to competitive sport in a timely and safe manner. ACL injuries are usually immediately followed by surgical reconstruction of the ligament [14]. During surgery, the torn ligament is replaced with a tissue graft from the hamstring tendon or the patellar tendon; in some cases, a cadaver tissue graft can be used [2]. The surgery utilizes an arthroscope that allows for internal visualization for the surgeon to make small incisions which is a less invasive technique than other surgeries and the benefits include less pain, less time spent in the hospital and quicker recovery time [2]. Reconstruction is followed by rehabilitation, and the goal is to recreate a stable knee that can adapt to a dynamic environment by improving neuromuscular and biomechanical control [24]. Rehabilitation attempts to achieve that goal by aiming to regain balance and stability in the knee, quadricep strength and full range of motion. Rehabilitation programs typically last between 6 to 9 months, but there is evidence that suggests that the body needs 2 years to fully recover following reconstructive surgery before returning to sport [7]. Quadricep strength deficits in the injured leg may be a risk factor for future injuries. Researchers suggest that the surgically repaired leg should have quadricep strength within at least 90% of the uninjured leg [3]. Muscles around the knee contribute to the protection of the joint structures as well as controlling the joint motion and reducing joint forces [22]. Weakened quadricep muscle strength may lead to altered movement patterns as well as excessive forces acting directly on the joint surfaces, which could promote cartilage damage [22].

Risks Associated with ACL Injury

Even with reconstruction and rehabilitation, individuals who have undergone an ACL injury often have suboptimal results. After an ACL injury, reportedly only 65% of people were able to return to their former level of sport and only 55% returned to competitive sport [4]. Incidences of ipsilateral or contralateral injury are six times greater in individuals who have had a surgically repaired ACL [16]. Female patients are less likely than male patients to be able to return to their former level of sport after an ACL surgery, and individuals who are under the age of 18 are unlikely to successfully able to return to sport [13]. On top of that, patients have an increased risk of developing degenerative osteoarthritis [11]. Reportedly, a third of those who have undergone ACL reconstruction will experience knee osteoarthritis (OA) within 10 years, and within 20 years nearly 50% will do so [15]. There is also a high risk of reinjury associated with ACL injuries. Up to 30% of individuals who have injured their ACL will suffer a second ACL rupture within a few years of the first one [12].

Current Return to Sport Guidelines

Movement pattern variability is not currently examined by the established guidelines for gauging the functional capacity of the individual in order to ensure their safe return to competitive sport. The current return to sport criteria tests strength, neuromuscular control, confidence in limbs and ability to withstand loads relevant to sports activities through a series of tests (Table 1). Patient reported outcomes are considered and give important information on the clinical picture of the knee and help indicate whether the patient is ready to return to sport [18].

Table 1: Factors Used to Return to Unconditional Sports Activities after ACL Reconstruction [17]

Return to Sport Criteria
Less than 10% deficit in strength of quadricep and hamstring
Less than 15% deficit in lower limb symmetry on single-leg hop test
Less than 3mm of increased anterior-posterior displacement on Lachman test
Greater than 60% normalized knee separation distance on a video drop-jump test
Absence of effusion
Full knee ROM
Normal patellar mobility
No or only slight patellar crepitus
Painless activity without swelling

Thigh muscle strength is an important predictor in functional outcomes following ACLR. Quadricep muscle strength in both the involved and uninvolved limb show weakness following an ACL injury, which can lead to asymmetrical limb loading and poor functional outcomes [22]. Side to side quadricep muscle symmetry is measured with isokinetic testing and should be within 90% strength to pass [1]. Quadricep to hamstring strength ratio of the injured leg is also considered and should fall in the range of 50-80% to be considered normal [8].

Another popular measure of strength and neuromuscular control is through using a dynamic test that mimics the demanding movements required in a sport in order to validate that the patient can complete the motion consistently and safely. One such test is called the single hop test and the test requires the individual to stand on one leg and hop as far as they can and stabilize themselves on the one leg [23]. From this, a limb symmetry index (LSI) can be calculated, which is the ratio of the jump distances from both legs and is used as a measure of how evenly the two legs are able to perform [23]. A similar test, called the single leg drop test, simulates landing by requiring an individual to stand on an elevated surface and jump and balance on the injured leg and is typically examined on a pass/fail basis. The hopping and landing tests are commonly used because they are not expensive and can highlight asymmetries in the leg and gives insight on functional performance. However, it is possible to achieve a passing score on these tests with very different jump strategies and, as a result, these tests do not currently give insight on how the individuals movement patterns have changed. On top of that, current return to sport criteria only considers one variable at a time and fails to consider how a movement is completed as a whole which means return to sport criteria fails to identify how coordinated movement patterns have changed. Movement patterns may be a key factor in predicting patient outcomes.

Abnormal Movement Patterns

Abnormal knee motion and movement patterns have been observed in the ACL population following surgery and rehabilitation which may be a cause for these suboptimal results [8]. It is known that the lower extremity acts as a linked system, meaning that the hip, knee and ankle move through various ranges of dynamic motion together. Instead of looking at the joints individually as has been done in the past, several studies are now investigating how they move in relation to one another [10,11,16]. This approach to studying the coordinated movement of joints, known as dynamic movement theory, states that the body will perform a task in the most efficient way when given a set of constraints [10]. This theory proposes that a healthy motor system has redundant degrees of freedom (DOF) that provide several pathways to perform a task, and the process of mastering these redundant DOF to produce a desired output is defined as coordination [10]. The variability within the amount of possible movement strategies for a desired motion is possibly an essential factor in stability and flexibility [10].

Unfortunately, individuals who have undergone ACL reconstruction (ACLR) do not display typical coordinated movement [10]. An injury can act as a constraint that demands the body to find new ways to perform a desired motion. It is suggested that there is a preferred range for movement variability; movement variability that is too high than that can lead to instability and reduced adaptability to environmental demands while a low amount of variability is accompanied by lower ranges of motion [16]. Compared to the healthy population, individuals following ACLR exhibited increased joint coordination variability in several hip-knee couplings during walking [16] and during performing dynamic tasks such as side-step cutting and landing [20]. Past studies have shown that the individuals following ACLR do not exhibit typical kinetic and kinematic characteristics which include decreased knee flexion and increased knee abduction, hip adduction, flexion and internal rotation and ankle eversion [9].

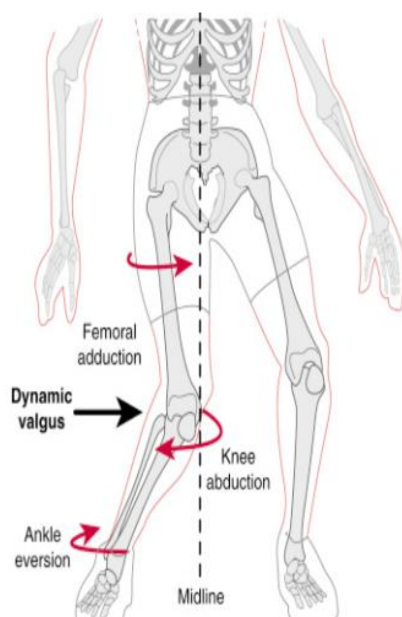

Figure 2: Medially Collapsed Limb [6]

Increased movement variability could possibly suggest that during demanding movements, people who have undergone ACLR are unable to adapt effectively to environmental demands, which could be a factor in the high risk for reinjury. Some of the risk factors for reinjury include biomechanical factors such as abnormal loading distribution on the knee and asymmetries in the kinetics and kinematics of both legs [1]. Quadricep weakness and asymmetry that is commonly seen in the individuals following ACLR is an important predictor of functional capacity and having deficits can lead to improper loading patterns on the knee [1]. Abnormal movement patterns seen in the individuals following ACLR may also put them at a higher risk of reinjury. Abnormal movement patterns are related to reinjury because reinjury typically happens when there is dynamic knee valgus, or the medially collapsed limb, which describes movement that has hip internal rotation, knee adduction and internal rotation and ankle eversion (Figure 2) [5]. Thus, it is important to understand how movement patterns have altered after an injury in order to better understand the low rates of returning to sport following ACLR as well as prevent a reinjury and lower the risk of developing knee OA.

1.2 Focus of Thesis

The focus of this study was to utilize dynamic movement theory to examine joint coordination and to quantify and compare joint coordination variability during the single leg drop test. Individuals that have undergone ACLR were compared to healthy controls to assess whether there is a difference in joint coordination variability in the involved and the uninvolved limb. We hypothesized that both limbs of the ACLR group would show increased movement variability compared to controls, and that within the ACLR group, the involved limb would have increased movement variability compared to the uninvolved limb.

1.3 Significance of Thesis

With current return to sport criteria following ACLR, it is possible that people are cleared to return to sport when their movement strategies could place them at risk of reinjury. People with ACLR are at a high risk for a noncontact reinjury [16]. By applying the dynamic movement theory to commonly used dynamic tests such as the single leg drop test, it is possible to develop new screening criteria for athletes returning to sport while decreasing the risk of reinjury and customizing rehabilitation strategies.

Chapter 2: Methodology

2.1 Participants

A total of 100 participants who have undergone ACLR (M/F 30/70; 17.65±2.7 y; 168.1±10.4 cm; 66.9±14.8 kg) were recruited local orthopedic practices, physical therapy clinics and the community from 2007 to 2015. All participants, or parents/guardians, provided written informed consent. Participants were included in this group if they had a primary, unilateral ACLR, had completed their rehabilitation program, were cleared for return to all high-level athletic activities by their surgeon and treating physical therapist, and intended return to cutting and pivoting sports on a regular basis (50 hours or more per year). Testing occurred within 6.98±2 months after return to sport. Individuals with bone-tendon-bone, hamstring tendon, or allograft tissue grafts and those with meniscus repair or partial meniscectomy at the time of ACLR were included in the study. Exclusion criteria were a history of low back injury or either lower extremity injury or surgery (beyond ACL injury) requiring the care of a physician in the past year, a concomitant ligament injury (beyond grade 1 medial collateral ligament injury) in the involved limb, or being skeletally immature as identified by an ACLR procedure that was modified due to open epiphyseal plates in the tibia or femur.

55 participants (M/F 15/40; 17.1±2.3 y; 166.4±8.9 cm; 61.5±12.1 kg) were recruited from the community to serve as the control group. Individuals were included in the control group if they reported no history of surgery in the low back or either lower extremity, no history of injury required the care of a physician in the past year in the low back or either lower extremity and regular participation (50 hours or more per year) in cutting and pivoting sports.

The involved, or test limb, was identified as the injured limb for the ACLR group. For the control group, the test limb was randomly assigned. The study protocol was approved by the Institutional Review Board of Cincinnati Children's Hospital Medical Center and all participants (or guardians, when required) provided written, informed consent and assent. Participants included in this analysis were part of an ongoing, prospective study of outcomes following ACLR.

2.2 Data Collection

Three-dimensional motion analysis was used to collect lower extremity kinematic data during the single leg drop test. A 10-camera motion analysis system (240 Hz cameras; Motion Analysis Corp., Santa Rosa, CA, USA) was used to track 37 retroreflective markers attached to specific locations and anatomical landmarks on the upper and lower extremities and trunk of each participant, as described by Paterno et al. [19] (Figure 3). These markers were utilized to determine joint centers and segment position, as well as track segment motion during SLL trials. During the SLL task, participants stood on one leg on top of a 31-cm box, and then were instructed to drop off of the box and land on a force plate (1200 Hz; AMTI, Watertown, MA, USA) on the same limb. The trial was considered successful if participants maintained a controlled landing for at least 3 seconds, and participants performed three trials on each limb. Kinematic data was filtered using a 12 Hz low-pass Butterworth filter.

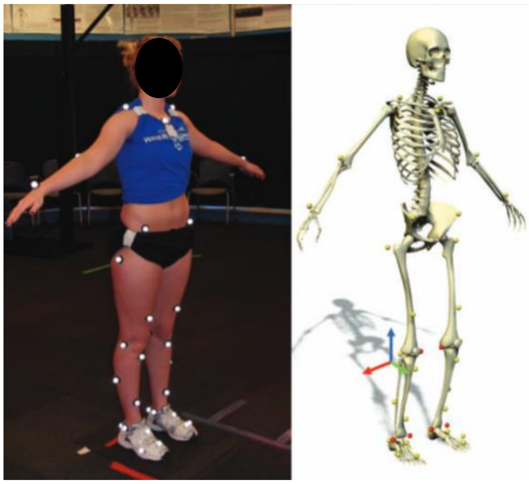

Figure 3: Marker Position [19]

2.3 Data Processing

Data was processed using Visual3D to get joint angles as a function of time. Hip, knee and ankle joint angles for flexion-extension, abduction-adduction and internal-external rotation were calculated according to the Cardan rotation sequence XYZ. The joint coupling angles observed in this study were chosen based on being associated with the medially collapsed limb which is associated with ACL injury as well as kinematic differences between ACLR population and uninjured population [9,10]. The joint couplings examined were hip abduction-adduction/knee abduction-adduction (HA/KA), hip rotation/knee abduction-adduction (HR/KA), hip flexion-extension/knee abduction-adduction (HF/KA), knee abduction-adduction/knee flexion/extension (KA/KF), hip rotation/knee rotation (HR/KR), hip abduction-adduction/knee rotation (HA/KR), knee abduction-adduction/knee rotation (KA/KR), hip flexion-extension/knee flexion-extension (HF/KF) and knee flexion-extension/ankle flexion-extension (KF/AF). The landing phase was examined for this study because ACL injuries typically happen during landing tasks [23]. The landing phase was defined from initial contact to the subject's lowest center of gravity of the body's mass.

A vector coding technique was used to quantify joint coordination variability [9, 10]. Using a custom script in MATLAB (MathWorks, Massachusetts, USA) an angle-angle curve was created such that the proximal and distal angular displacements were plotted on the x-axes and y-axes, respectively (Figure 4).

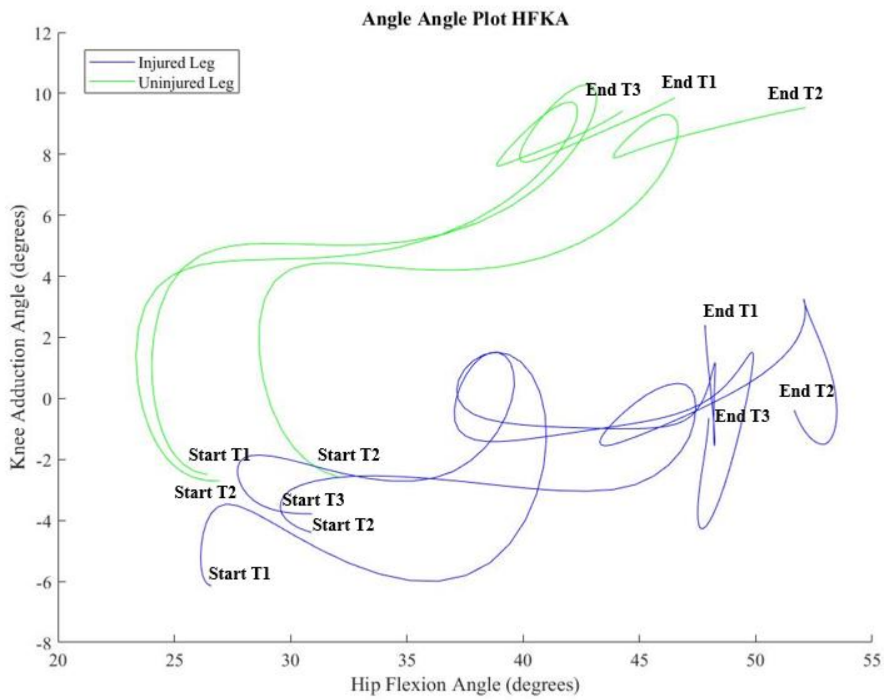

Figure 4: Injured and Uninjured Leg Angle-Angle Plot for Hip Flexion (+)/Knee Adduction (-) for one subject

From the angle-angle plot, a coupling angle (CA) was calculated as the angle between two adjacent points on the curve, expressed by Eq. (1).

$$CA = \tan^{-1}\left(\frac{y_{m,i+1} - y_{m,i}}{x_{m,i+1} - x_{m,i}}\right) \tag{1}$$

The CA was calculated at each percentage of the landing phase, for each trial, for each limb. The coupling angle ranged from 0˚ to 360˚ and was used to preserve the direction of joint movement that would be lost if the data were compressed to 0˚ to 180˚ (Figure 5).

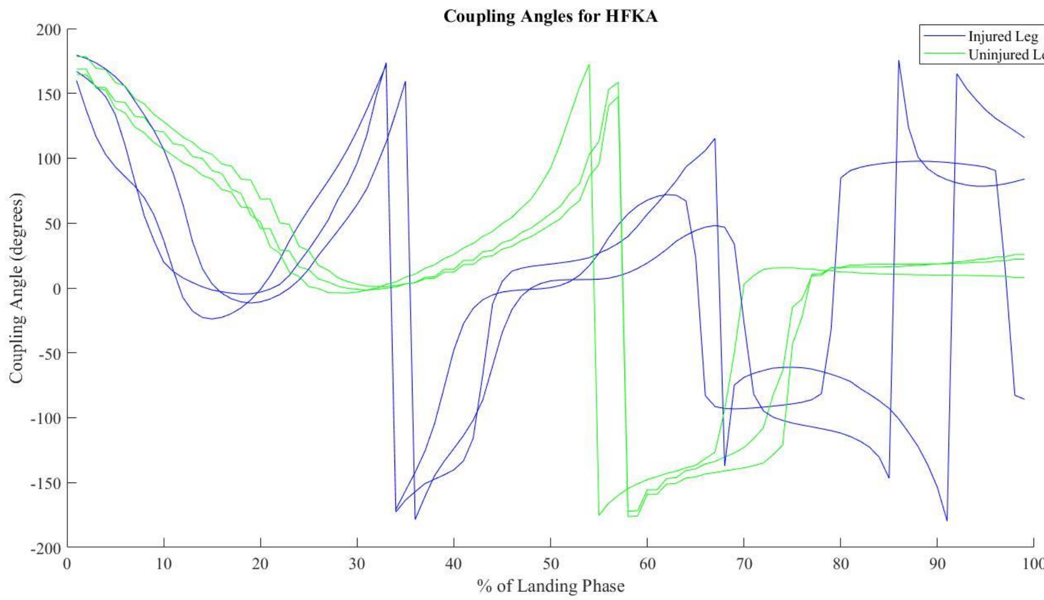

Figure 5: Coupling Angle for Hip Flexion (+)/Knee Adduction (-) for one subject across landing phase

Coupling angles were calculated per trial, and the circular standard deviation was taken at each time point across the three trials. The overall root mean square of the resulting circular standard deviation across the three trials was computed to represent the within-subject and within-limb variability. A paired Wilcoxon signed-rank test was used to compare the involved/uninvolved sides of the ACL group and a Mann-Whitney U test was used to compare both involved and uninvolved sides to the dominant side of Controls.

Chapter 3: Results

The injured leg for the ACL population showed increased movement variability for all nine of the examined joint couplings during the landing phase. This supports the first hypothesis that the involved limb will show an increase in joint coordination variability in the joint couplings examined. The contralateral limb also showed increased movement variability in all but one of the examined joint couplings, which also supports the first hypothesis. Contrary to the second hypothesis, there was not a significant difference between the injured limb when compared to the uninjured limb, which only showed an increase in variability in one joint coupling (Table 2).

Table 2: Joint Coordination Variability RMS Values and Significant Joint Couplings

Symbols indicate statistical difference in: IC – injured leg vs. control; UC – uninjured leg vs. control; IU – injured leg vs. uninjured leg

	Variability (Mean ± Standard Deviation of RMS)			**p-Value < 0.05**
Coupling	**Injured**	**Uninjured**	**Control**	
Hip Abduction-Adduction/Knee Abduction-Adduction (HA/KA)	0.835±0.252	0.823±0.273	0.691±0.234	IC, UC
Hip Abduction-Adduction/Knee Rotation (HA/KR)	0.855±0.247	0.835±0.26	0.69±0.248	IC, UC
Hip Flexion-Extension/Knee Abduction-Adduction (HF/KA)	0.821±0.237	0.749±0.251	0.739±0.222	IC, IU
Hip Flexion-Extension/Knee Flexion-Extension (HF/KF)	0.662±0.233	0.607±0.25	0.525±0.228	IC, UC
Hip Rotation/Knee Abduction-Adduction (HR/KA)	0.972±0.227	0.955±0.269	0.863±0.26	IC, UC
Hip Rotation/Knee Rotation (HR/KR)	0.928±0.234	0.918±0.25	0.782±0.262	IC, UC
Knee Abduction-Adduction/Knee Flexion/Extension (KA/KF),	0.704±0.234	0.652±0.222	0.575±0.207	IC, UC
Knee Abduction-Adduction/Knee Rotation (KA/KR)	0.947±0.23	0.913±0.256	0.831±0.247	IC, UC
Knee Flexion-Extension/Ankle Flexion-Extension (KF/AF)	0.598±0.239	0.558±0.246	0.437±0.189	IC, UC

The statistical analysis results from comparing the three populations, injured, uninjured and control, can be found in Table 3. Significant difference for specific joint couplings was determined for p-Values that are less than 0.05.

Table 3: Statistical Results from Comparing Variability

*Symbols indicate statistical difference

	p-Value		
Coupling	**Injured vs. Control**	**Uninjured vs. Control**	**Injured vs. Uninjured**
Hip Abduction-Adduction/Knee Abduction-Adduction (HA/KA)	0.00023*	0.00247*	0.95610
Hip Abduction-Adduction/Knee Rotation (HA/KR)	0.00006*	0.00039*	0.95610
Hip Flexion-Extension/Knee Abduction-Adduction (HF/KA)	0.03863*	0.66850	0.03627*
Hip Flexion-Extension/Knee Flexion-Extension (HF/KF)	0.00038*	0.03350*	0.10680
Hip Rotation/Knee Abduction-Adduction (HR/KA)	0.00521*	0.03350*	0.94520
Hip Rotation/Knee Rotation (HR/KR)	0.00028*	0.00138*	0.78060
Knee Abduction-Adduction/Knee Flexion/Extension (KA/KF),	0.00013*	0.02093*	0.09890
Knee Abduction-Adduction/Knee Rotation (KA/KR)	0.00281*	0.03541*	0.52020
Knee Flexion-Extension/Ankle Flexion-Extension (KF/AF)	0.00002*	0.00180*	0.17550

Additional angle-angle plots and coupling angle charts can be found in the appendix.

Chapter 4: Discussion

The purpose of this study was to quantify joint coordination variability individuals who have unilateral ACLR and uninjured controls while completing a single leg drop test. A vector coding technique was used to compare the joint coordination variability of the injured leg to the uninjured leg and then the injured and uninjured leg were compared to the dominant leg of controls during the landing phase.

4.1 Movement Variability

Our findings indicate that patients following ACLR display increased variability in both the injured and contralateral limb in several hip, knee and ankle couplings when compared to controls which supports our first hypothesis and previous studies [10,20]. Contrary to our second hypothesis, there was not a significant difference between the injured limb and uninjured limb when it was expected that the injured limb would comparatively show increased movement variability to the uninjured limb. The injured limb only showed increased variability one joint coupling of HF/KA when compared to the uninjured limb which is consistent with a previous study [23].

Both the injured and contralateral limb showed increased variability in HA/KA, HR/KA, KA/KF, HR/KR, HA/KR, KA/KR, HF/KF and KF/AF while the injured leg additionally showed increased variability in HF/KA when compared to healthy controls. Davis et al [10] examined lower extremity variability during gait and reported increased movement variability in HR/KR, HA/KR and HR/KA for the involved limb during walking and in HA/KR, HR/KR and HR/KA in the uninvolved limb when compared to healthy controls which is consistent with the findings in this study. Additionally, in a study by Pollard et al. [20] which examined joint coordination variability in female soccer players with ACLR during side-step cutting, found increased variability in the injured limb in HR/KA, HF/KA, KA/KF and KA/KR. A single leg hop study [23] which evaluated coordination variability in individuals with ACLR found an increase in variability in HA/KA, HR/KA, HR/KA, KF/KA and HF/KA in the injured leg 20 years following reconstruction. These studies examined different motion but reported similar findings to the present study. This suggests that individuals exhibit compromised neuromuscular control during a variety of tasks which include sport-specific ones.

This study is the first to examine joint coordination variability in patients following ACLR while completing a single leg drop which simulates some of the dynamic sport-specific tasks which have been showing to lead to reinjury [23]. Individuals who have undergone ACLR demonstrated greater movement variability during this demanding task which suggests a noisy or unstable system. It is suggested that there is a preferred range of optimal lower extremity variability which allows for a flexible system that is still able to reliably control movement [10,20]. This increased variability may interfere with the ability of these individuals to complete sport specific actions consistently and dependably and may be what is putting individuals at a high risk of reinjury and could be a cause for the suboptimal outcomes seen in the ACLR population [23].

4.2 Conclusions and Future Work

This study evaluated joint coordination in the ACLR population during a single leg drop test and it was found that individuals with ACLR do not display normal coordinative function in both the involved limb and the uninvolved limb. The increased bilateral movement variability observed may be an indicator for the risk of injury in more dynamic tasks and could contribute to the suboptimal outcomes seen in the ACLR population. Movement variability that is higher than the optimal range is associated with instability and reduced adaptability [10]. Coordinative function may not be fully restored in patients following ACLR and it remains unknown whether increased movement variability is a cause for ACL reinjury and other suboptimal outcomes. Additional analysis on the coordination patterns employed by the ACLR population in comparison to controls will give insight on the specifics of how the coordination patterns may have changed following ACLR. By considering the average coupling angle for a population, the primary coordination phase can be determined which described how the joints exerted themselves in reference to one another. Further research needs to be done on the processes leading to alterations in movement variability as well as the impact that changes in coordinative strategies play on ACLR patients' outcome, which may inform new rehabilitation practices as well be used in return to sport criteria.

Appendix

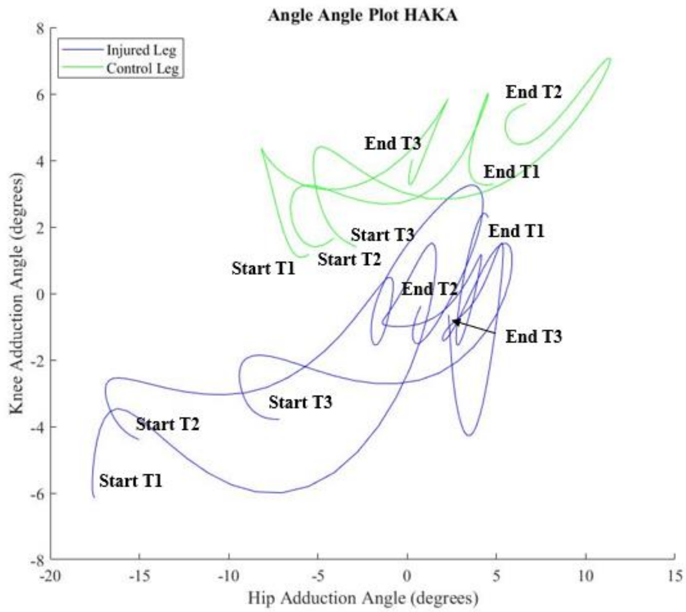

Figure 6: Injured Leg and Matched Control Angle-Angle Plot for Hip Adduction (-)/Knee Adduction (-) Across Three Trials

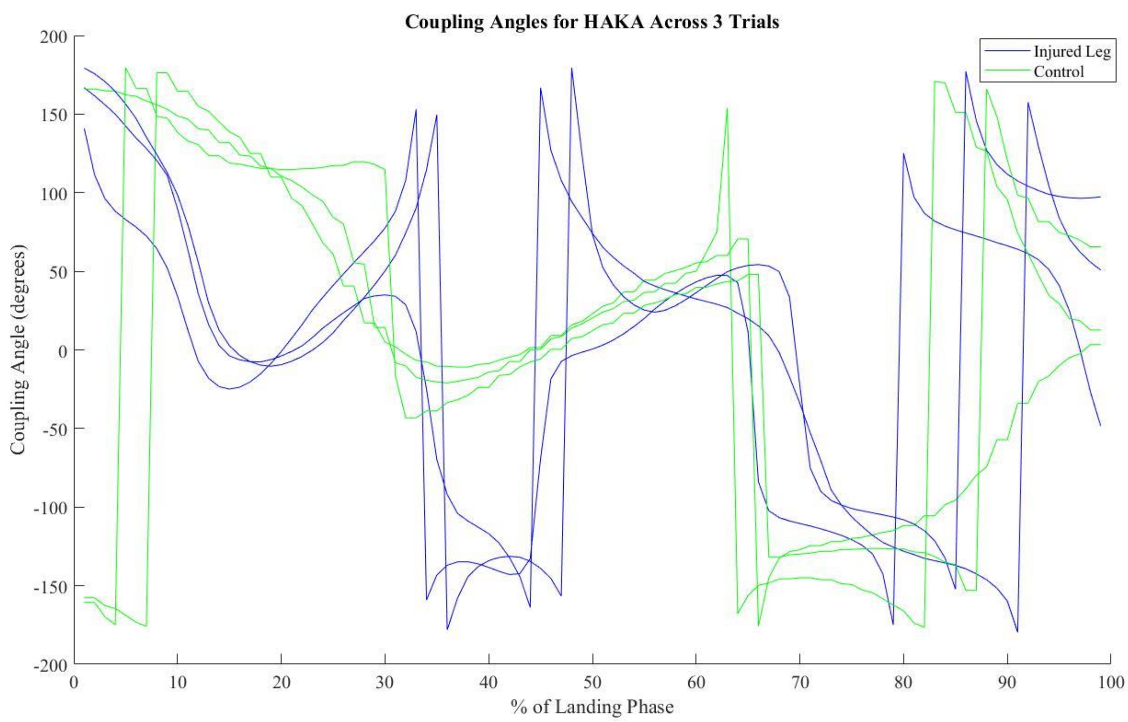

Figure 7: Coupling Angle for Hip Adduction (-)/Knee Adduction (-) for one matched pair across landing phase

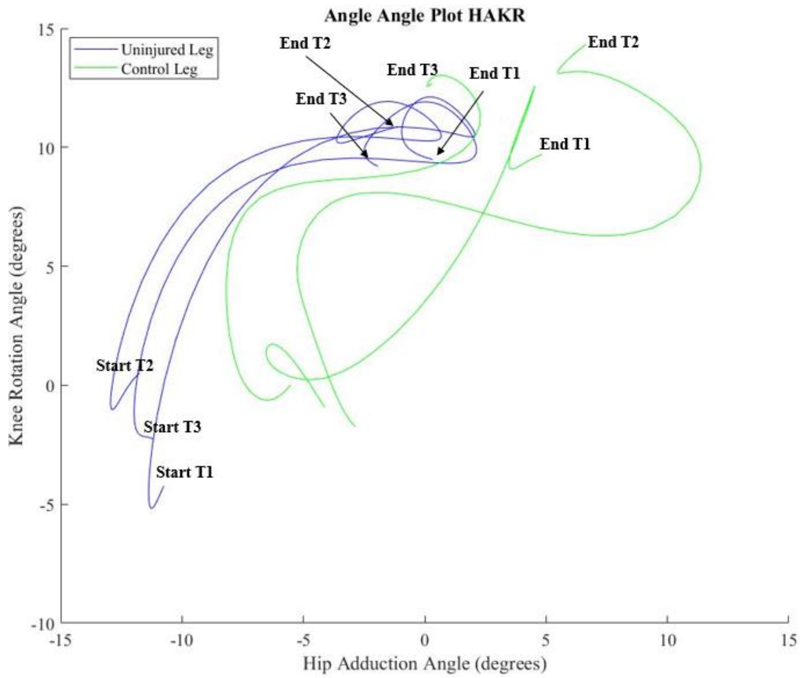

Figure 8: Uninjured Leg and Matched Control Angle-Angle Plot for Hip Adduction (-)/Knee Internal Rotation (+) Across Three Trial

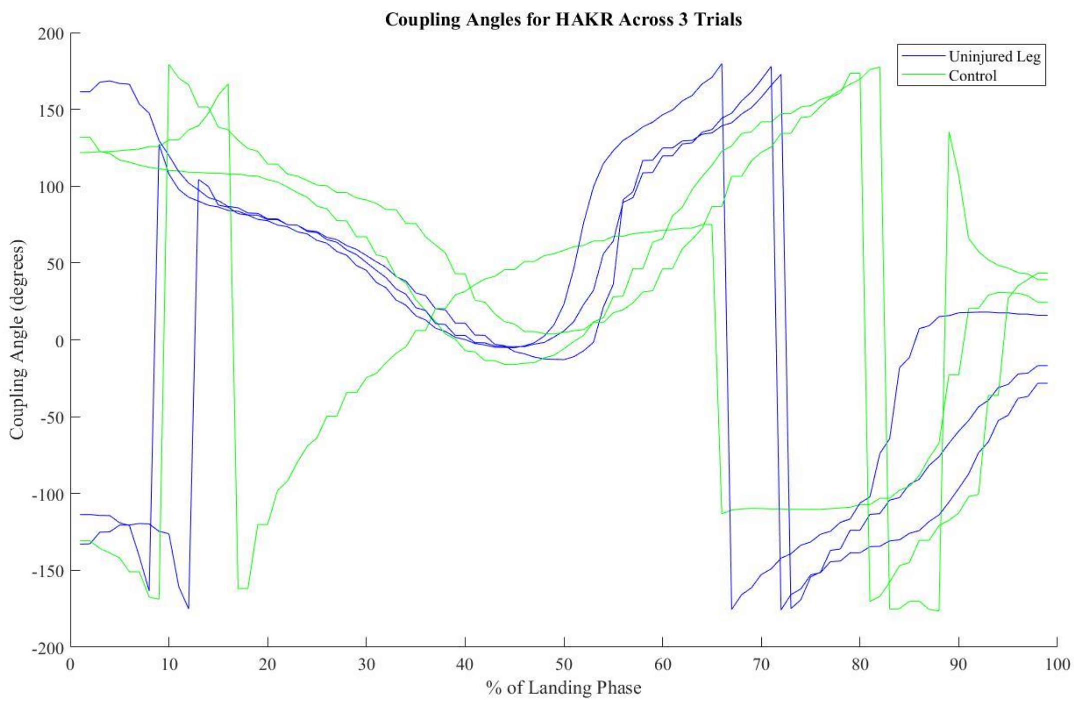

Figure 9: Coupling Angle for Hip Adduction (-)/Knee Internal Rotation (+) for one matched pair across landing phase

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