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Inter-Segment Coordination Variability Post Anterior Cruciate Ligament Reconstruction

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INTER-SEGMENT COORDINATION VARIABILITY POST ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

A Thesis Presented

by

DEVIN K. KELLY

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

September 2015

Department of Kinesiology
A Thesis Presented

by

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I would like to thank my advisor, Joseph Hamill for his invaluable guidance during both my undergraduate and graduate careers at UMass Amherst. I would also like to extend thanks to the members of my committee, Katherine Boyer and Richard Van Emmerik, for contributing their expertise and constructive suggestions during all stages of this project, as well as Susan Sigward for her insight and collaboration. I want to express my appreciation to Julia Freedman Silvernail for her additional mentorship over the past several years.

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ABSTRACT

INTER-SEGMENT COORDINATION VARIABILITY POST ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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There is an increased risk for ipsilateral graft rupture and contralateral ACL rupture following ACL reconstruction surgery (ACLR) despite return to sport clearance. The reason for this increased risk is not well understood. Previous literature has shown that decreased coordination variability is indicative of an injured system regardless of the absence of pain. PURPOSE: To quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes at three progressive time points post-surgery compared to the contralateral limb (NI) and healthy controls. METHODS: Three-dimensional kinematic and kinetic data were collected for 10 ACLR and 10 healthy athletes matched for age, gender, and activity level. The ACLR group was measured at 4 weeks, 12 weeks, and when cleared to run post-surgery. Kinematic data were used in a modified vector coding technique to determine inter-segment coordination variability of lower extremity couples of interest. Statistical significance was determined using two factor multivariate ANOVAs (limb x visit) for early (1-33%), mid (34-66%), and late (67-100%) stance with alpha level set at .05. Tukey post-hoc tests were
performed where appropriate. **RESULTS:** ACLR athletes have decreased inter-segment coordination variability of the involved lower extremity during the late stance phase of gait compared to both the contralateral limb and healthy controls at 4 weeks post-surgery. By 12 weeks post-surgery there were improvements in joint function as exemplified by inter-segment coordination variability of the ACLR involved limb becoming similar to the healthy control limb. **CONCLUSION:** Inter-segment coordination variability during late stance in the present study is not an indication for the increased risk for ipsilateral graft rupture and contralateral ACL rupture in ACLR athletes.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1-12</td>
</tr>
<tr>
<td>1.1</td>
<td>Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Statement of the Problem</td>
<td>7</td>
</tr>
<tr>
<td>1.3</td>
<td>Purpose of the Study</td>
<td>7</td>
</tr>
<tr>
<td>1.4</td>
<td>Significance of the Study</td>
<td>9</td>
</tr>
<tr>
<td>1.5</td>
<td>Summary</td>
<td>9</td>
</tr>
<tr>
<td>1.6</td>
<td>References</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>REVIEW OF THE LITERATURE</td>
<td>16-18</td>
</tr>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>ACL Reconstruction</td>
<td>17</td>
</tr>
<tr>
<td>2.2.1</td>
<td>ACL Injury Following Reconstruction</td>
<td>17</td>
</tr>
<tr>
<td>2.2.2</td>
<td>ACL Reconstruction Alters Gait- Traditional Measures</td>
<td>18</td>
</tr>
</tbody>
</table>
2.2.3 ACL Reconstruction Alters Gait - Traditional Measures

Summary...............................................................21

2.3 Dynamical Systems Approach to Coordination and Coordination

Variability...............................................................22

2.3.1 End-Point Variability versus Coordination Variability.............22

2.3.2 Coordination Variability and Loss of Complexity

Hypothesis...............................................................23

2.3.3 Dynamical Systems Approach Summary.................................26

2.4 Techniques for Quantifying Coordination and Coordination Variability......27

2.5 Joint Coordination and Coordination Variability Post ACL

Reconstruction.............................................................28

2.6 Chapter Summary...........................................................29

2.7 References..............................................................31

3: METHODS.................................................................39

3.1 Introduction.............................................................39

3.2 Participants..............................................................39

3.3 Experimental Set-up.....................................................40

3.4 Experimental Protocol....................................................41

3.5 Data Analysis............................................................42

3.6 Statistical Analysis.......................................................45

3.7 Summary.................................................................45

3.8 Reference...............................................................47
4: INTER-SEGMENT COORDINATION VARIABILITY POST ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

4.1 Introduction.................................................................................48

4.2 Methods.....................................................................................51
  4.2.1 Participants.................................................................51
  4.2.2 Experimental Setup......................................................52
  4.2.3 Experimental Protocol.....................................................52
  4.2.4 Data Analysis.................................................................53
  4.2.5 Statistical Analysis..........................................................55

4.3 Results.......................................................................................55
  4.3.1 Participant Characteristics.................................................55
  4.3.2 Walking Velocity..............................................................56
  4.3.3 Results-Hypothesis 1.........................................................56
  4.3.4 Results-Hypothesis 2.........................................................59
  4.3.5 Results-Hypothesis 3.........................................................62
  4.3.6 Results-Hypothesis 4.........................................................64
  4.3.7 Results-Coordination Variability Figures by Couple..........67
    4.3.7.1 Pelvis-Thigh Flexion/Extension.................................67
    4.3.7.2 Pelvis-Thigh Rotation...............................................70
    4.3.7.3 Thigh-Leg Flexion/Extension.......................................72
    4.3.7.4 Thigh Flexion-Leg Internal Rotation...........................75
    4.3.7.5 Thigh-Leg Rotation....................................................77
    4.3.7.6 Leg-Foot Flexion/Extension........................................80
4.3.1 Participant characteristics of the ACLR involved group (ACLR), ACLR noninvolved group (NI), and control group (CTRL) at 4 weeks (V1), 12 weeks (V2), and when cleared to run post-surgery (V3)………………………………………55

4.3.2 Group mean walking velocities and standard deviations at each visit………………56

4.3.3.1 Coordination variability of the ACLR involved limb compared to the healthy control limb during early stance at each visit .................................57

4.3.3.2 Coordination variability of the ACLR involved limb compared to the healthy control limb during mid-stance at each visit .................................58

4.3.3.3 Coordination variability of the ACLR involved limb compared to the healthy control limb during late stance at each visit .................................58

4.3.4.1 Coordination variability of the ACLR involved limb progressively over time during early stance……………………………………………………60

4.3.4.2 Coordination variability of the ACLR involved limb progressively over time during mid-stance ...........................................................................60

4.3.4.3 Coordination variability of the ACLR involved limb progressively over time during late stance .................................................................61
4.3.5.1 Coordination variability of the ACLR involved limb compared to the ACLR contralateral limb during early stance at each visit………………………………62

4.3.5.2 Coordination variability of the ACLR involved limb compared to the ACLR contralateral limb during mid-stance at each visit ..........................63

4.3.5.3 Coordination variability of the ACLR involved limb compared to the ACLR contralateral limb during late stance at each visit…………………………..64

4.3.6.1 Coordination variability of the ACLR contralateral limb compared to the healthy control limb during early stance at each visit……………………………..65

4.3.6.2 Coordination variability of the ACLR contralateral limb compared to the healthy control limb during early stance at each visit ………………………66

4.3.6.3 Coordination variability of the ACLR contralateral limb compared to the healthy control limb during early stance at each visit …………………………..66
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>43</td>
</tr>
<tr>
<td>3.2</td>
<td>44</td>
</tr>
<tr>
<td>4.3.7.1</td>
<td>67</td>
</tr>
<tr>
<td>4.3.7.2</td>
<td>70</td>
</tr>
<tr>
<td>4.3.7.3</td>
<td>72</td>
</tr>
<tr>
<td>4.3.7.4</td>
<td>75</td>
</tr>
<tr>
<td>4.3.7.5</td>
<td>77</td>
</tr>
<tr>
<td>4.3.7.6</td>
<td>80</td>
</tr>
</tbody>
</table>

3.1 Example of phase angle plot for rearfoot-forefoot coordination in the sagittal plane ........................................................................................................43

3.2 Polar plot providing reference for coordination patterns........................................44

4.3.7.1 Coordination variability of the pelvis-thigh flexion/extension couple during early, mid, and late stance........................................................................67

4.3.7.2 Coordination variability of the pelvis-thigh rotation couple during early, mid, and late stance........................................................................70

4.3.7.3 Coordination variability of the thigh-leg flexion/extension couple during early, mid, and late stance.................................................................72

4.3.7.4 Coordination variability of the thigh flexion-leg internal rotation couple during early, mid, and late stance.................................................................75

4.3.7.5 Coordination variability of the thigh-leg rotation couple during early, mid, and late stance......................................................................................77

4.3.7.6 Coordination variability of the leg-foot flexion/extension couple during early, mid, and late stance........................................................................80
4.3.7.7 Coordination variability of the leg rotation-foot eversion couple during early, mid, and late stance...........................................................................................................82
CHAPTER 1

INTRODUCTION

1.1 Background

The knee is one of the largest and most complex joints in the human body. Due to its complex structure, it is highly susceptible to injury. One prevalent injury to the knee is anterior cruciate ligament (ACL) rupture. The ACL acts to prevent anterior translation of the tibia and hyperextension of the knee. It is ruptured when, either an external force is applied to the knee and translated to the ACL (contact injury) which exceeds the breaking point of the stress-strain relationship of the tissue, or abnormal dynamic loading (noncontact injury) exceeds the breaking point. It is estimated that 80,000 to 250,000 ACL injuries occur every year (Flynn et al., 2005).

A common treatment for ACL rupture is reconstruction surgery. ACL reconstruction involves taking a graft of muscle or tendon tissue, often from the hamstrings or patellar tendon, and using it to replace the torn ligament. According to the Center for Disease Control, over 100,000 ACL reconstructions are performed each year. The goal of surgery is to restore stability to the joint and allow for return to play (Dye et al., 1999). Following surgery, the athlete may be determined healthy and cleared to return to activity by physicians, however less than half return to sport (Ardern et al., 2011). Regardless of this, athletes are at risk for ipsilateral graft rupture and contralateral ACL rupture (Hui et al., 2010). The likelihood of these injuries occurring has been within the ranges of 1.8-10.4% and 8.2-16% respectively (Wright et al., 2011). Therefore, surgery and rehabilitation may be considered unsuccessful and it is possible that these athletes are
returning to play too early. The literature has attempted to identify the etiology of injury following reconstruction by analyzing gait in ACL reconstructed athletes.

Many studies have measured kinematic and kinetic variables at the knee and hip in a post-ACL reconstructed (ACLR) population. In some instances the results have been consistent, while in others they have been contradictory. Consistent results for the knee include lesser external knee extension moments in the ACLR group compared to the healthy control group (Noehren et. al, 2013), as well as significantly lower knee external rotation moments during gait (Zabala et. al, 2013). At the hip, studies have shown greater external extension moments or a trend toward greater extension moments during gait in ACLR participants compared to healthy controls (Hall, Stevermer & Gillette, 2012; Noehren et. al, 2013).

Contradictory results have been reported for knee flexion angle. Some studies have reported decreased knee flexion angle post-surgery (Hall et al., 2012), while others have reported similar knee flexion angle between groups during the stance phase of gait (Noehren et.al, 2013; Patterson, Delahunt & Caulfield, 2014). Similarly, some studies have reported lower peak knee external adduction moments in the ACLR group compared to the healthy control group during walking (Patterson et al., 2014; Webster et al., 2011), while others have reported significantly greater peak knee external adduction moment post-surgery for the ACLR group compared to the healthy control group (Butler et. al, 2009), and some have reported no difference (Hall et al., 2012).

While the aforementioned results were based on comparisons between ACL reconstructed limbs and healthy control limbs, other studies have used contralateral limbs
as the controls. Contralateral limbs have been previously determined to be valid control limbs in the short term following unilateral ACL injury (Kozanek et al., 2008). Using this comparison between the ACLR limb and uninjured contralateral limb, Scanlan et al. (2010) reported no difference in varus-valgus rotation and knee flexion during the stance phase of gait. However, the ACLR limb had a smaller knee extension angle at heelstrike compared to the contralateral limb. Scanlan, Favre, and Andriachhi (2013) again reported that the ACLR limb had a reduction in knee extension compared to the contralateral limb at heelstrike during walking.

Further, some studies have compared the ACL reconstructed limb against both the uninjured contralateral limb and healthy control limb. Hall et al. (2012) reported increased hip extension moments in the ACLR limb and contralateral limb compared to the control limb, while there were no differences between ACLR and contralateral limbs for any kinematic or kinetic variables. Similarly, Noehren et al. (2013) found no between limb differences for the ACLR and contralateral limbs. Zabala et al. (2013) reported that ACLR limbs had lower peak external knee moments compared to healthy control limbs, while contralateral limbs had higher peak external knee moments compared to control limbs. The results of these studies suggest that there may be some compensatory changes to gait mechanics of the contralateral limb in an ACL reconstructed population. Therefore, the contralateral limb may not appropriately represent a healthy control limb.

It is evident that conclusions about the explicit mechanism of injury post reconstruction cannot be drawn from conflicting results presented in these traditional gait analysis studies. Additionally, there are two major limitations of this literature. First, it is difficult to compare results between studies as they differ in regards to factors such as the
use of the contralateral limb as a healthy control limb, sex of the participants, surgical type, exclusion criteria concerning concomitant injury at the time of ACL rupture, and the length of time from surgery when the data collection took place. Second, these studies report the net actions at joints and neglect the interaction between segments. In order to gain an improved understanding of the stages of recovery from ACL reconstruction surgery and the mechanism of injury following reconstruction, a non-traditional approach is necessary (Hamill et al., 2012).

A Dynamical Systems Approach, following the work of Bernstein (1967), examines the relationship between parts of a system to analyze a task. A healthy system uses the redundancy in available degrees of freedom to form multiple solutions through coordinative structures to optimize task performance. Interaction of coordinative structures such as adjacent segments is measured by the phase angle, or coupling angle, of a continuous relative angle-angle plot. Coordination of the relative movement of segments can be described as anti-phase (segments rotate in opposite directions), in-phase (segments rotate in the same direction), solely proximal segment rotation, and solely distal segment rotation. Coordination variability is the measure which represents the variation in use of these coordination patterns or the available degrees of freedom to perform a task. A healthy system will have a high coordinative variability, while an unhealthy system will freeze available degrees of freedom leading to frailty or a point of injury (Lipsitz, 2002). This equates to less coordination variability. Additionally, less than optimal coordination variability decreases the flexibility of the system and the ability to adapt to perturbations, potentially increasing the likelihood of injury (Hamill et al., 1999).
Decreased coordination variability in pathological populations has been reported in the literature. Van Emmerik et al. (1999) assessed the coordination variability in trunk-pelvis rotation in a population with Parkinson’s disease compared to healthy controls. The group with Parkinson’s disease had less coordination variability compared to controls suggesting that this group had a reduction in degrees of freedom in coordinating the trunk-pelvis coupling. Similarly, Seay, van Emmerik, and Hamill (2011) examined pelvis-trunk coordination variability in individuals with low back pain. The healthy control group had greater coordination variability in the transverse plane during running than individuals with current low back pain and individuals with history of low back pain. They suggested the reduction in coordination variability in the population with low back pain reflects reduced adaptability and that the absence of pain post injury does not necessarily equate to complete recovery in terms of coordination. Heiderscheit, Hamill, and Van Emmerik (2002) showed this relationship in individuals with patellofemoral pain (PFP). When averaged over the entire stride cycle, differences were masked; however, when the cycle was broken into parts, differences were apparent. At heel-strike during running at preferred velocity, there was less coordination variability in thigh rotation-leg rotation coupling in the PFP group compared to healthy control as well as the noninjured contralateral limb. Additionally, the noninjured contralateral limb had higher coordination variability at heel-strike compared to the healthy control limb. Hamill et al. (1999) again examined this relationship in individuals with PFP. They found those with PFP exhibited less coordination variability than those without, and suggested that this was due to participants’ avoidance of pain.
As evident from the results of these studies, the Dynamical Systems Approach is able to discern between healthy and pathological populations, and stages of recovery. Conclusions presented in the literature using this perspective state that despite resolution of pain, gait alterations in terms of coordination may still exist and that physicians should consider this when determining rehabilitation protocols. This translates directly to the present study. The Dynamical Systems Approach to coordination and coordination variability will contribute data on the progression of recovery from ACL reconstruction and may provide insight into the improvement of rehabilitation protocol to prevent injury following surgery.

Other nonlinear measures have been used to investigate joint coordination and coordination variability in a post ACL reconstruction population. Some of these studies have followed the idea that coordination variability lies on a spectrum. That is, a healthy system has an optimal high level of coordination variability. One that is too high is related to noise in the system; while one that is too low is too rigid (Lipsitz, 2002; Stergiou, Harbourne & Cavanaugh, 2006). Variability that is too high or too low is associated with an unhealthy system or injured state.

A study by Moraiti et al. (2010) reported a higher than optimal variability in an ACLR group, representing an unstable system compared to healthy controls. This analysis was done using the largest Lyapunov exponent which results do not easily translate to clinical interpretation. In another study, Kurz et al. (2005) examined thigh-shank and shank-foot coordination in an ACLR group compared to healthy controls. Differences were observed in knee joint coordination during walking, shank-foot coupling during stance while running, ankle joint coordination during running, and thigh-
shank coupling during running. However, this study did not report coordination variability and the authors cited limitations such as the inability to detect statistical significances due to the small number of subjects in the study which resulted in large within group variability and standard deviations.

1.2 Statement of the Problem

There is a high prevalence of ipsilateral graft rupture and contralateral ACL rupture following ACL reconstruction surgery. The mechanism for injury is not well understood. The literature has used traditional gait analyses post ACL reconstruction to identify possible etiology but the results are difficult to compare. This may be related to several factors which are unique to each study such as the use of contralateral limb as healthy control limb, sex of the participants, surgical type, exclusion criteria regarding additional injury at the time of ACL rupture, and the amount of time post-surgery that the data collection has taken place. These measures have not lead to a greater understanding of rehabilitation for recovery from ACL reconstruction or prevention of re-injury (Hamill, Palmer, & Van Emmerik, 2012). To gain a better understanding in this population, some studies have attempted to use additional non-linear measures to assess coordination and coordination variability (Moraiti et al., 2010; Kurz et al., 2005). However, these studies cited limitations in their ability to report statistical significance and used methods that are not easily interpreted in a clinical setting.

1.3 Purpose of the Study

Therefore, the purpose of this study was to quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes post anterior
cruciate ligament reconstruction surgery. This was done during walking for healthy age-matched control limbs at one time point and for the ipsilateral and contralateral limbs at three time points post-surgery: 4 weeks, 12 weeks, and when cleared to run. Analysis was done using a modified vector coding technique, which has been determined a valid method from a Dynamical Systems perspective and will lend itself to clinical interpretation as it includes only spatial information (Miller et al., 2010). We hypothesize that:

**Hypothesis 1:** The ACLR involved limb will have significantly less coordination variability during all three portions of stance at each of three time points compared to the healthy control limb measured at one time point.

**Hypothesis 2:** The ACLR involved limb will significantly increase coordination variability during all three portions of stance with each progressive time point post-surgery.

**Hypothesis 3:** The ACLR involved limb will have significantly less coordination variability during all three portions of stance at each progressive time point post-surgery compared to the ACLR contralateral limb.

**Hypothesis 4:** The coordination variability of the ACLR contralateral limb during all three portions of stance at each progressive time point will be similar to the healthy control limb at three portions of stance measured at one time point.
1.4 Significance of the Study

Much of the literature on gait post ACL reconstruction surgery is conflicting and conclusions about the explicit etiology of injury following reconstruction cannot be made. Results of these studies are not comparable due to a number of factors including use of the contralateral limb as a healthy control, sex of the participants, surgical type, inclusion/exclusion criteria regarding additional injury at the time of ACL rupture, and the amount of time post-surgery that the data collection has taken place. The few studies which have used nonlinear measures to address coordination and coordination variability were limited by small sample size and non-clinically interpretable techniques.

This study will use a modified vector coding technique based on the Dynamical Systems Approach to classify inter-segment coordination patterns and to quantify coordination variability in an ACL reconstructed population. It will control for age, sex, and pre-injury activity level of participants. Results will improve the understanding of the progression through stages of recovery from surgery including the contralateral limb, provide insight into the etiology of ipsilateral graft rupture and contralateral ACL rupture following reconstruction, and identify need for improvement of rehabilitation protocol and return to play clearance standards to prevent injury following surgery.

1.5 Summary

A common treatment for ACL rupture is reconstruction surgery. The surgery is performed with the goal of restoring stability to the joint and allowing for return to play (Dye et al., 1999). Despite clearance from physicians to return to activity, however, gait alterations in kinematic and kinetic variables have been reported. The literature on these
variables is often contradictory and it is difficult to make comparisons due to the use of contralateral limb as a control, differences in sex of the participants, surgical type, exclusion criteria regarding additional injury at the time of ACL rupture, and the amount of time post-surgery that the data collection has taken place. This literature has not lead to an improved understanding of rehabilitation for recovery from ACL reconstruction surgery (Hamill et al., 2012). This is problematic because there is a high incidence of ipsilateral ACL graft rupture and contralateral ACL graft rupture in the ACL reconstructed population. Therefore, a Dynamical Systems Approach may be useful in providing evidence for the etiology of injury occurrence. This approach focuses on the use of coordinative structures to complete goal directed movement. A healthy system utilizes all degrees of freedom in order to complete a task, while a pathological system operates within a constricted amount of degrees of freedom. Coordination variability is a measure of this variation in use of available degrees of freedom and is quantified using a modified vector coding technique. Coordination and coordination variability have been assessed in a post ACL reconstructed population before, however there were limitations to these studies including a small sample size possibly affecting observable differences. Therefore, the purpose of this study was to classify inter-segment coordination patterns and to quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes post anterior cruciate ligament reconstruction surgery. This was done during walking for healthy age-matched control limbs at one time point and for the ipsilateral and contralateral limbs at three time points post-surgery: 4 weeks, 12 weeks, and when cleared to run. Results may justify the use of contralateral limbs as healthy control limbs in this population. They will also improve the understanding of the
progression through stages of recovery from surgery, provide insight into the etiology of ipsilateral graft rupture and contralateral ACL rupture following reconstruction, and identify need for improvement of rehabilitation protocol and return to play clearance standards to prevent injury following surgery.
1.6 References


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CHAPTER 2

REVIEW OF THE LITERATURE

2.1 Introduction

ACL reconstruction corrects for rupture of the ligament with the intention of restoring stability to the joint. The goal of patients returning to play after surgery is not always met. This may be related to remaining gait alterations. Numerous studies have contributed to the literature on these alterations using traditional gait analyses, or examining kinematic and kinetic variables, but with conflicting results. It is difficult to make comparisons across these studies as they differ in relation to use of contralateral limb as healthy control, sex of the participants, surgical type, exclusion criteria regarding concomitant injury with ACL rupture, and the amount of time post-surgery that the data collection has taken place.

In order to gain understanding of gait changes following reconstruction which may contribute to the incidence of ipsilateral graft rupture and contralateral ACL rupture, as well as provide insight into the stages of rehabilitation for recovery from surgery and the recommendation for return to play, it is important to examine the variation in use of coordinative interactions of segments. Little research exists that attempts to do this in an ACL reconstructed population. That which does appear in the literature is limited and presents methods which have not been interpreted clinically. Therefore, the purpose of this study was to classify inter-segment coordination patterns using mean phase angle and to quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes post anterior cruciate ligament reconstruction surgery. This was
done during walking for healthy age-matched control limbs at one time point and for the ipsilateral and contralateral limbs at three time points post-surgery: 4 weeks, 12 weeks, and when cleared to run.

2.2 ACL Reconstruction

A common treatment for ACL rupture is reconstruction. The Center for Disease Control (CDC) reported in 1996 that 100,000 reconstructions were performed annually. In 2006 that number had increased to 129,836 (Mall et al., 2014). Reconstruction surgery involves taking a graft of muscle or tendon tissue, often the hamstrings or patellar tendon, and using it to replace the torn ACL. The goal of ACL reconstruction surgery is to restore stability to the joint and allow for return to play (Dye et al., 1999). Despite clearance from physicians to return to activity, however, many patients do not accomplish this or become reinjured.

2.2.1 ACL Injury Following Reconstruction

Ardern et al. (2011) reported that less than 50% of athletes actually return to sport after reconstruction surgery, thus the goal of surgery is not always achieved. There is a risk of ipsilateral graft rupture and contralateral ACL rupture in ACLR patients reported in the literature (Hui et al., 2010). Webster and colleagues (2014) sought to determine the rates of ipsilateral graft rupture and contralateral rupture in an ACLR population 3 or more years post-surgery in order to identify related patient characteristics. They found a 4.5% ipsilateral graft rupture rate and a 7.5% contralateral rupture rate in 561 patients who were a mean of 80 weeks post-surgery and ranged from 14-182 weeks post-surgery. Of the graft ruptures, half were reported to occur within the first year following
reconstruction. Results also showed that patients under 20 years old were 6 times more likely to rupture their graft and 3 times more likely to rupture their contralateral ACL than those older than 20. They suggested that this may be related to exposure, as 88% of the participants under age 20 return to sports with cutting maneuvers. Returning to a sport with cutting maneuvers independently increased the likelihood of graft rupture by 4 times and contralateral rupture by 5 times. Wright et al. (2011) conducted a systematic review of studies reporting graft rupture and contralateral rupture in a population at 5 or more years post reconstruction. Results showed a range of 1.8-10.4% and 8.2-16% respectively. The rate of return to play and incidence of ipsilateral graft rupture and contralateral ACL rupture may be related to gait alterations reported in the literature.

### 2.2.2 ACL Reconstruction Alters Gait – Traditional Measures

Many studies have used gait analysis to examine changes in kinematic and kinetic variables post ACL reconstruction surgery. Kinematic variables of interest at the knee have included flexion and adduction. Some studies have reported a decrease in knee flexion (Hall et al., 2012), while others have reported similar knee flexion angle between groups during the stance phase of gait (Noehren et al., 2013; Patterson et al., 2014). During the swing phase, decreased knee flexion angles as well as decreased knee adduction angles have been reported (Patterson et al., 2014). Kinematic variables at the hip have not been as widely studied, however, it has been reported that there is a reduced hip flexion angle in the ACL reconstructed group post-surgery as compared to the healthy controls (Noehren et al., 2013). These reductions in knee joint kinematic angles may be indicative of loss of muscular strength and proprioception post-surgery (Fremery et al.,
2000). It may also result in a change in loading pattern, which could lead to degeneration of articular cartilage (Andriacchi et al., 2004).

Kinetic variables of interest at the knee have included external knee extension moment, knee external rotation moment, and external knee adduction moment. Results for knee extension moments and knee external rotation moments have been consistent, while results for knee adduction moment have been contradictory. The literature shows smaller knee extension moments in ACL reconstructed (ACLR) group compared to healthy control groups (Noehren et al., 2013), as well as a significantly lower knee external rotation moments during gait (Zabala et al., 2013). For peak knee adduction moments, some studies have reported lower values for the ACLR group compared to control (Patterson et al., 2014; Webster et al., 2012), while others have reported significantly greater peak knee adduction moment post-surgery for the ACLR group compared to controls (Butler et al., 2009), and some have reported no difference (Hall et al., 2012). A study by Varma et al. (2014) further divided their ACLR group into those who did not suffer additional injury, and those who had sustained meniscal tear, cartilage damage, or MCL tear at the time of injury. They reported that those who had undergone ACL reconstruction and had not sustained concomitant injury at the time of rupture did not differ compared to the healthy control for peak knee adduction moment, but those who had undergone ACL reconstruction and suffered concomitant injury had a significantly larger peak knee adduction moment compared to controls. The main kinetic variable of interest at the hip has been external hip extension moment. Studies have shown greater hip extension moments, or a trend toward greater hip extension moments, in ACLR groups compared to healthy controls (Hall et al., 2012; Noehren et al., 2013).
Changes in kinetics at the knee may be related to decreased force production in the quadriceps post-surgery, while changes at the hip may be a compensatory mechanism.

While these studies compared the ACLR limb to a healthy age-matched control limb to determine differences in kinematic and kinetic variables following surgery, some studies use the contralateral limb as the control to make comparisons. A study by Kozanek et al. (2008) determined that the contralateral knee was a valid kinematic control following ACL injury. Three-dimensional kinematics of ACL deficient limbs, PCL deficient limbs, contralateral limbs, and healthy age matched control limbs were compared. Results showed no differences existed between the contralateral limbs of both deficient groups and uninjured control limbs for anterior-posterior translation, or internal-external and varus-valgus rotations at 0, 30, 60, and 90 degrees of flexion. Therefore, it was determined that ACL injury did not affect the knee joint kinematics of the contralateral limb in the short term following injury and could be used as a kinematic control.

Using the uninjured contralateral knee as a control, Scanlan et al. (2010) examined differences in tibiofemoral motion during the stance phase of walking at heelstrike, midstance, terminal extension, and toe-off. Results showed no differences in varus-valgus rotation and knee flexion during the stance phase of gait. However, there was a difference in knee extension at heelstrike. The ACLR limb had a smaller knee extension angle at heelstrike compared to the contralateral limb. Scanlan, Favre, and Andriachhi (2013) again reported that the ACLR limb had a reduction in knee extension compared to the contralateral limb at heelstrike during walking.
To further examine the relationship between ACL reconstructed limbs, contralateral limbs, and healthy control limbs, some studies have compared kinematic and kinetic data across all the three groups. Hall et al. reported increased hip extension moments in the ACLR limb and contralateral limb compared to the control limb, while there were no differences between ACLR and contralateral limbs for any kinematic or kinetic variables (2012). Similarly, Noehren et al. found no between limb differences for the ACLR and contralateral limbs (2013). Zabala et al. reported that ACLR limbs had lower peak external knee moments compared to healthy control limbs, while contralateral limbs had higher peak external knee moments compared to control limbs (2013). The results of these studies suggest that there may be some compensatory changes to gait mechanics of the contralateral limb in an ACL reconstructed population. Therefore, the contralateral limb may not appropriately represent a healthy control limb.

2.2.3 ACL Reconstruction Alters Gait – Traditional Measures Summary

ACL reconstruction surgery is a common treatment for ACL rupture. The goal of surgery is to restore stability to the knee joint so that the patient, when recovered, will regain healthy gait patterns and return to activity. Despite functional success of the surgery in terms of a reduction or elimination of pain, differences in gait characteristics, compared to an uninjured, healthy population, may exist post-surgery. However, the differences reported in the literature have been contradictory. This may be related to several factors which are unique to each study such as the use of the contralateral limb as a healthy control, sex of the participants, surgical type, inclusion/exclusion criteria regarding additional injury at the time of ACL rupture, and the amount of time post-surgery that the data collection has taken place. An additional limitation of these studies
is that they examine the action at only one joint and neglect the interaction of parts. Although traditional kinematic and kinetic analyses have provided some evidence that reconstruction does not restore normal joint mechanics, they have not lead to a complete understanding of rehabilitation for recovery from ACL reconstruction surgery or the explicit mechanism of ipsilateral graft rupture and contralateral ACL rupture following surgery (Hamill et al., 2012). Therefore, a non-traditional approach is necessary.

### 2.3 Dynamical Systems Approach to Coordination and Coordination Variability

According to Bernstein (1967), redundancy in available degrees of freedom allows for multiple solutions to a task and healthy systems utilize all degrees of freedom through coordinative structures in order to optimize task performance. Bernstein also suggests that examination of the relationships between parts of a system is essential to analyzing a task and is more useful than investigating the parts alone. The Dynamical Systems Approach is based on the idea that coordination of these redundant degrees of freedom is necessary to complete goal directed movements (Hamill et al., 2012). Coordination variability is the measure which represents the variation of use of available degrees of freedom to perform the task or goal directed movement.

#### 2.3.1 End-Point Variability versus Coordination Variability

Variability is necessary to accommodate the coordination patterns during locomotion (Hamill et al., 1999; Van Emmerik et al., 1999; Heiderscheit et al., 2002). Often, what is thought of as variability is in truth end-point variability. End-point variability is the variability in the product of a movement or a task outcome for example, stride length or stride time. An expert performing a task is less variable than a beginner
performing that same task, or, a healthy individual is less variable in performance than someone with pathology (Hamill et al., 2012). However, in order to achieve these consistent task outcomes, high variability of coordinative structures is necessary. In a study done by Arutyunyan (1968), a group of expert marksmen exhibited less end-point variability compared to novice marksmen. The expert group also had a high variety of joint motion coordination patterns between the shoulder, elbow, and wrist or greater joint coordination variability, compared to the novice group while completing the task of hitting a target. Similarly, in a study done by Morasso et al. (1981), participants completed a point-to-point reaching task with randomly sequenced visual targets. The results showed that although the path of the hand was consistent, the joint coordination variability between the shoulder and the elbow was high. These studies show that there is a distinction between end-point and coordination variability, and the two have opposite interpretations.

2.3.2 Coordination Variability and Loss of Complexity Hypothesis

It has been suggested that coordination variability, unlike end-point variability, lies on a spectrum. That is, a healthy system has an optimal high level of coordination variability. One that is too high is related to noise in the system; while one that is too low is too rigid (Lipsitz, 2002; Stergiou, Harbourne & Cavanaugh, 2006). Variability that is too high or too low is associated with an unhealthy system or injured state. This concept is further explained by Lipsitz (2002) as the loss of complexity hypothesis. The loss of complexity hypothesis links a loss of variability to a decrease in biological function leading to a point of injury, rather than increased variability reflecting decreased health.
This loss in complexity equates to a reduction in the redundancy of degrees of freedom of a system.

The loss of complexity hypothesis is supported by the literature. Studies show that a functional or healthy system is highly variable in order to accommodate potential perturbations to the system. However, a pathological system does not function in the same way, and shows reduced coordination variability resulting in less adaptability (Van Emmerik et al., 1999). This is evident in a study conducted by Van Emmerik and colleagues (1999), assessing coordination variability in a population with Parkinson’s disease. Rotations of the thorax and pelvis during treadmill walking at different velocities were calculated from kinematic data, and continuous relative phase analysis (CRP) was completed. Angular rotation and rotational velocity were combined in a phase-plane plot for all time points across the stride cycle. Variability was measured as the standard deviation between stride cycles of the CRP measure. Results showed significantly greater coordination variability between the thorax and the pelvis coupling patterns in the healthy control group compared to the Parkinson’s disease group. These results suggest that the Parkinson’s disease group was less adaptable in coordination of the thorax and pelvis.

Similar results were found in a study by Seay, Van Emmerik, and Hamill (2011), which sought to identify differences in pelvis-trunk coordination and coordination variability during running in individuals with low to moderate low back pain (LBP), individuals who had recovered from acute low back pain (RES), and healthy individuals who had never had low back pain (CTRL). Coordination variability was determined using a standard deviation of the CRP measure. Both the LBP group and the RES group had a more constricted coordination pattern, in this case more in-phase motion, than the
CTRL group. Additionally, results showed that the CTRL group had greater CRP variability in the transverse plane during running than the LBP group. They suggested the reduction in coordination variability in the population with low back pain reflects a reduced adaptability and that the absence of pain post injury does not necessarily equate to complete recovery in terms of coordination. The authors suggested that when clinicians make recommendations for rehabilitation for individuals with low back pain, they should not focus on diminished pain as an end goal.

Similarly, decreased coordination variability can be seen in populations with overuse injuries including patellofemoral pain (PFP). Hamill et al. (1999), investigated coordination variability in individuals with PFP. They used data from two studies comparing participants with a Q-angle larger than fifteen degrees, and a Q-angle less than fifteen degrees, as well as a study comparing a group experiencing PFP and a group without pain. Kinematic data were collected during overground and treadmill running. From these data, CRP calculations were used to create phase plots to show the coupling of segments. Mean CRP and CRP variability were determined for both the stance and swing phase of running. Results showed that participants without pain, despite Q-angle, had no differences in CRP or the variability of CRP. However, differences were seen in the variability of CRP comparing participants with and without PFP. Those with pain exhibited less variability than those without. The authors suggested that the coordination variability of the system was reduced due to the participants’ avoidance of pain.

Heiderscheit, Hamill, and Van Emmerik (2002) again sought to identify changes in coordination and coordination variability in a population with unilateral PFP. This was done using a vector coding technique modified from Sparrow et al. (1987). This
technique uses continuous relative motion angle-angle plots of joint couplings to quantify joint coordination. Circular statistics were used to determine inter-trial mean and standard deviations. Coordination variability was determined by the average standard deviation across the stride cycle. However, the authors suggested that averaging the variability separately during different portions of the stride cycle would be a more sensitive measure than averaging across the stride cycle. Therefore, the stride cycle was broken down into 5 parts: midstance, toe-off, swing acceleration, swing deceleration, and heel strike. The average coordination variability across the entire stride cycle was similar between the injured limb of the PFP group and the healthy group. However, when broken down, differences were found at heel-strike during running at preferred velocity. There was less coordination variability in thigh rotation-leg rotation coupling in the PFP group compared to healthy control as well as the noninjured contralateral limb. Additionally, the noninjured contralateral limb had higher coordination variability at heel-strike compared to the healthy control limb.

2.3.3 Dynamical Systems Approach Summary

The Dynamical Systems Approach focuses on the use of coordinative structures to complete goal directed movement. A healthy system utilizes all degrees of freedom in order to complete a task, while a pathological system operates within a constricted amount of degrees of freedom. This is referred to as the loss of complexity hypothesis. The loss of complexity hypothesis is related to the divergence of coordination variability from an optimal high level. The literature reflects this notion. Reduced coordination variability has been shown to occur in both diseased states such as Parkinson’s disease, and in overuse injuries such as low back pain and patellofemoral pain. Important
conclusions can be taken from the literature, which are relevant to the present study. This includes methodological considerations such as separating the stride cycle into parts and assessing coordination variability within each part to see between group differences which may be masked when variability is determined from the standard deviation across the entire gait cycle. Another conclusion is that although pain may be resolved, gait alterations in terms of coordination may still exist. Thus, physicians should consider this when determining rehabilitation protocols and return to play clearance. The Dynamical Systems Approach to coordination and coordination variability will contribute to the literature regarding progression of recovery from ACL reconstruction and health of the contralateral limb, and may provide insight into the improvement of rehabilitation protocol to prevent injury following surgery.

2.4 Techniques for Quantifying Coordination and Coordination Variability

Different techniques to quantify coordination and coordination variability are presented in the literature including continuous relative phase and modified vector coding. Continuous relative phase (Hamill et al., 1999; Irwin & Kerwin, 2007; Miller et al., 2008) and modified vector coding (Heiderscheit et al., 2002; Ferber, Davis, & Williams, 2005; Wilson et al., 2008) and are the two techniques most commonly used (Miller et al., 2010). CRP phase plots are spatio-temporal in nature, that is, position and velocity are included. On the other hand, modified vector coding includes only spatial information, or just the position of segments relative to one another. Miller et al. (2010) conducted a study comparing both methods quantifying variability. Results showed that the two methods yielded varying results, especially at transition points in the gait cycle such as heel-strike and toe-off. The authors suggest that both methods are valid from a
Dynamical Systems perspective but may not be perfect in all situations. The authors also suggest that vector coding has an advantage in that it lends itself more easily to clinical interpretations as it is related to positions, where CRP is a higher order mechanical analysis that has not been interpreted clinically. Therefore, this study will use the modified vector coding technique to quantify inter-segment coordination and coordination variability.

2.5 Joint Coordination and Coordination Variability Post ACL Reconstruction

Non-traditional measures of joint coordination and coordination variability have been reported previously in a post ACL reconstructed population. One study by Moraiti et al. (2010), reported alterations in gait variability following ACL reconstruction despite participants having returned to their activity levels from prior to injury. The largest Lyapunov Exponent (LyE) was used to quantify gait variability in knee flexion-extension across the gait cycle. Participants included two reconstruction groups separated by surgical type who were approximately two years post reconstruction surgery, and a healthy control group. Results showed no significant differences between surgical types in the reconstructed knee; however, both surgical groups had significantly larger LyE values in the reconstructed knee as compared to the healthy control group. This suggests that the reconstructed knee has a greater than optimal variability, or is representative of an unstable system (Stergiou et al., 2006). These results suggest that ACL reconstruction alters gait variability despite clinical assessment of the functional health. The largest LyE measure, however, is not one that translates easily to clinical interpretation.
In another study, Kurz et al. (2005) used relative phase dynamics to examine gait in individuals post ACL reconstruction surgery. Relative phase dynamics were calculated for the thigh-shank, and shank-foot couplings for an ACLR group and compared to those of a healthy control. The ACLR group differed from the control group in knee joint coordination during walking, shank-foot coupling during stance while running, ankle joint coordination during running, and thigh-shank coupling during running. There were additional differences in the mean absolute value of the ensemble continuous relative phase curves for the thigh-shank in walking and shank-foot in running. These results suggested that ACL reconstruction may alter relative phase dynamics. However, the authors of this study cited limitations including inability to detect statistical significances due to the small number of subjects in the study which resulted in large within group variability and large standard deviations. CRP standard deviations which would represent coordination variability were not reported.

2.6 Chapter Summary

Due to the complex structure of the knee, ACL injuries are prevalent. A common treatment for rupture is ACL reconstruction surgery. The surgery is performed with the goal of restoring stability to the joint and allowing for return to play (Dye et al., 1999). Despite clearance from physicians to return to activity, however, many patients do not return to play and they are at risk for ipsilateral graft rupture and contralateral ACL injury. This may be associated with gait alterations in kinematic and kinetic variables which have been reported. The literature is limited in that the measures of these variables are often contradictory and it is difficult to make comparisons due to the differences in use of the contralateral limb as a control, sex of the participants, surgical type, exclusion
criteria regarding additional injury at the time of ACL rupture, and the amount of time post-surgery that the data collection has taken place. Additionally, it reports the actions at only one joint and neglects the interaction of parts. This literature has not lead to an improved understanding of the stages of recovery from ACL reconstruction surgery and the mechanism of injury following reconstruction (Hamill et al., 2012). Therefore, a non-traditional approach is necessary. The Dynamical Systems Approach focuses on the use of coordinative structures to complete goal directed movement. A healthy system utilizes all degrees of freedom in order to complete a task, while a pathological system operates within a constricted amount of degrees of freedom. Coordination variability is a measure of this variation in use of available degrees of freedom. It can be quantified using a modified vector coding technique which lends itself easily to clinical interpretation, as it includes only spatial information and describes how the segments move relative to each other. Coordination and coordination variability have been assessed in a post ACL reconstructed population before, however there were limitations to these studies including a method that has not been interpreted clinically, and a small sample size possibly affecting observable differences. Therefore, the purpose of this study was to classify inter-segment coordination patterns and to quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes post anterior cruciate ligament reconstruction surgery. This was done during walking for healthy age-matched control limbs at one time point and for the ipsilateral and contralateral limbs at three time points post-surgery: 4 weeks, 12 weeks, and when cleared to run.
2.7 References


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CHAPTER 3

METHODS

3.1 Introduction

The purpose of this study was to classify inter-segment coordination patterns and to quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes post anterior cruciate ligament reconstruction surgery. This was done during walking for healthy age-matched control limbs at one time point and for the ipsilateral and contralateral limbs at three time points post-surgery: 4 weeks, 12 weeks, and when cleared to run.

3.2 Participants

A sample size of n=10 was determined to be large enough to detect significant differences between groups. This was based on previous literature which found statistically significant differences in coordination variability, calculated using a modified vector coding technique, between injured and noninjured limbs during the heelstrike portion of the stance phase of gait using a sample size of n=8 according to Cohen (1988) to estimate a minimum statistical power of 80% (Heiderscheit et al., 2002). Twenty athletes were separated into two groups: 10 ACL reconstructed (ACLR) and 10 healthy controls matched for age, gender, and activity level. Participants were included in the ACLR group if they were between the ages of 16-40, 4 weeks post-surgery and participating in physical therapy. Participants were excluded from the study if they had a current injury or history of injury to the contralateral lower extremity that would affect gait, their weight bearing status was affected by concurrent knee pathology, or they had a
medical condition that would interfere with their ability to complete experimental protocol.

Participants in the ACLR group were recruited from the same physical therapy clinic. Most participants attended physical therapy twice per week from 2 weeks through 6 months following surgery and all participants underwent rehabilitation with the goal of returning to their sport. Gait was assessed longitudinally at 3 time points: 4 weeks post-surgery (T1), 12 weeks post-surgery (T2), and during the month in which participants were cleared to begin running (T3). T3 was marked by clearance from a physician when participants could perform a single limb squat to 80 degrees of knee flexion, and when they had performed a series of single limb loading exercises without increasing pain or swelling. All participants signed an informed consent form in accordance with University policy.

3.3 Experimental Set-up

Three dimensional (3D) kinematic and kinetic data were collected at 250 and 1500 Hz respectively. This was done using 11 infrared cameras (Qualysis, Inc., Gothenberg, Sweden) set up around two 1.20 x 1.60 m strain gauge force platforms (Advanced Mechanical Technologies, Inc., Newton, Massachusetts, USA). The force data were collected using Qualysis Track Manager software (Qualysis, Inc., Gothenberg, Sweden) and thus was synchronized in time with the motion capture data collected using the same software.

A calibration of the collection space was completed prior to collection. Cameras were positioned around the walkway to capture participants’ gait such that each reflective marker could be seen by at least two cameras at any given time. Participants were fitted
with 43, 25 mm reflective spheres placed bilaterally on the lower extremity. They were placed bilaterally over the following anatomical landmarks: 1st and 5th metatarsal heads, distal 2nd toe, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, posterior superior iliac spine, and on the joint space between the fifth lumbar and the first sacral spinous processes. Reflective markers were also placed bilaterally on the lateral surfaces of the subject’s thigh, leg and heel counter of the shoe using clusters of at least three non-collinear markers attached to rigid plates. The rigid plates, distal toe, iliac crest, posterior superior iliac spine and lumbar marker remained on the subject during testing, while all other markers were removed after collection of a static calibration trial.

3.4 Experimental Protocol

ACLR group participants made three visits to the Human Performance Laboratory at CATZ in Pasadena, CA at 4 weeks post-surgery (T1), 12 weeks post-surgery (T2), and within the month they were cleared to run (T3) while control participants visited the laboratory only once. Upon arrival, the experimental procedures and protocol were explained to participants. They then read and signed an informed consent document approved by the Institutional Review Board. If the participants were under the age of 18, parental consent and youth assent were obtained. General anthropometric measurements were taken including height, body mass, and age. Then, 43, 25 mm retro-reflective markers were attached by adhesive tape and elastic wraps to specific anatomical landmarks to create 7 lower extremity segments.
Participants were allowed a five minute warm up period on a stationary bike prior to testing sessions. Then, they were asked to complete practice trials, walking along a 10m walkway at their preferred velocity. These trials were averaged to determine their preferred, or target, velocity. Participants were then asked to complete at least three successful walking trials. A successful trial was characterized by the foot striking the center of the force platform, and the velocity falling within +/- 5% of the target velocity. This was done for both limbs of the ACLR group and for one limb of the control group.

3.5 Data Analysis

Qualysis Track Manager (Qualysis, Inc., Gothenberg, Sweden) was used to track the positions of the markers and to process raw marker data. Kinematic data were then analyzed in Visual 3D (C-Motion Inc., Germantown, USA). A fourth order, zero lag Butterworth digital low-pass filter with a cutoff frequency of 8 Hz was used according to Winter (1990). The lower extremity was modeled as 7 rigid segments. Segment angles were calculated for the stance phase of gait referenced to a fixed laboratory coordinate system (X- medio-lateral; Y- line of walking progression; Z- vertical) using an XYZ Cardan rotation sequence.

The primary dependent measures to test our hypotheses include the coordination variability of the following segment coordination couplings of the lower extremity: pelvis-thigh flexion-extension, pelvis-thigh rotation, thigh leg flexion-extension, thigh flexion-leg internal rotation, thigh rotation-leg rotation, leg-foot flexion-extension, and leg rotation-foot dorsiflexion/eversion. These couplings were chosen to be the most relevant based on the function of the ACL to prevent anterior translation of the tibia and
hyperextension of the knee, and on the consistent findings in the traditional measures literature.

Relative segment angle-angle plots were used to determine inter-segment coordination by calculating coupling (phase) angles. Coupling angles were found by connecting two adjacent time points on the angle-angle plot (Chang et al., 2008; Sparrow et al., 1987; Heiderscheit et al., 2002). A custom MATLAB program was used to calculate coupling angles between segments. These were calculated by:

\[
\gamma_{ji} = tan^{-1}\left(\frac{(y_{j,i+1} - y_{j,i})}{(x_{j,i+1} - x_{j,i})}\right)
\]

where \(0^\circ \leq \gamma \leq 360^\circ\), and \(i\) is a percent of stance of the \(j\)th trial. An example is provided in Figure 3.1.

![Figure 3.1 Example of phase angle plot for rearfoot-forefoot coordination in the sagittal plane. Phase angles are presented in degrees.](image)

Adapted from Chang et al., 2008
Coordination of the relative movement can be described as anti-phase, in-phase, solely proximal segment rotation, and solely distal segment rotation (Figure 3.2). An anti-phase coordination pattern indicates that the segments are rotating in opposite directions and is categorized by $112.5^\circ \leq \gamma < 157.5^\circ$, and $292.5^\circ \leq \gamma < 337.5^\circ$ (negative diagonal). An in-phase coordination pattern indicates that the segments are rotating in the same direction and is categorized by $22.5^\circ \leq \gamma < 67.5^\circ$, and $202.5^\circ \leq \gamma < 247.5^\circ$ (positive diagonal). Solely proximal segment rotation is categorized by $0^\circ \leq \gamma < 22.5^\circ$, $157.5^\circ \leq \gamma < 202.5^\circ$, and $337.5^\circ \leq \gamma \leq 360^\circ$ (horizontal). Solely distal segment rotation is categorized by $67.5^\circ \leq \gamma < 112.5^\circ$, and $247.5^\circ \leq \gamma < 292.5^\circ$ (vertical).

Coupling angles are directional, thus, mean coupling angles and standard deviations were computed using circular statistics (Batschelet, 1981). Mean coupling
angles and standard deviations were calculated inter-trial within subject over three periods of the stance phase: early (1-33%), mid (34-66%) and late (67-99%). This was done to ensure that differences were not masked by group mean over the entire stance phase (Heiderscheit et al., 2002). Coordination variability was calculated as the inter-trial within subject variation of the coupling angle at each percent of stance using circular statistics. Group coordination variability was calculated by determining the standard deviation of the group mean coupling angles.

### 3.6 Statistical Analysis

Coordination variability for each coupling of the ACLR involved limb, the ACLR contralateral limb, and the healthy control limb was compared using two factor multivariate ANOVAs (limb x visit) for each portion of stance and with criterion alpha level set at .05. Tukey post-hoc tests were performed where appropriate.

### 3.7 Summary

The purpose of this study was to classify inter-segment coordination patterns and to quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes post anterior cruciate ligament reconstruction surgery. This was done during walking for healthy age-matched control limbs at one time point and for the ipsilateral and contralateral limbs at three time points post-surgery: 4 weeks, 12 weeks, and when cleared to run. Kinematic data were collected to complete coordination and coordination variability analysis. Results were compared between time points and between groups. This study used a modified vector coding technique based on the Dynamical Systems Approach to quantify coordination variability in an ACL.
reconstructed population. Results may justify the use of the contralateral limb as a healthy control limb in this population, improve the understanding of the progression through stages of recovery from surgery, provide insight into the etiology of ipsilateral graft rupture and contralateral ACL rupture following reconstruction, and identify need for improvement of rehabilitation protocol and return to play clearance standards to prevent injury following surgery.
3.8 References


CHAPTER 4

INTER-SEGMENT COORDINATION VARIABILITY POST ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

4.1 Introduction

There is a high incidence of anterior cruciate ligament (ACL) injuries amongst athletes. A common treatment for an ACL rupture is reconstruction of the ligament, with over 100,000 surgeries performed each year according to the Center for Disease Control (CDC, 2006). The goal of surgery is to restore stability to the knee joint and allow return to play. Following surgery, athletes are at increased risk for ipsilateral graft rupture and contralateral ACL rupture. This suggests athletes may not be fully recovered when deemed able to return to play. Therefore, it may be beneficial to examine gait in an ACL reconstructed (ACLR) population to determine the etiology of injury post-surgery.

Traditional kinematic and kinetic variables have been assessed in ACLR athletes. ACL reconstructed limbs have been compared to both uninjured contralateral limbs and healthy control limbs in the literature. Increased hip extension moments in the ACLR limb and contralateral limb compared to the control limb have been reported (Hall et al., 2012). No differences have been shown between ACLR and contralateral limbs for any kinematic or kinetic variables (Hall et al., 2012; Noehren et al., 2013). However, Zabala et al. (2013) reported that ACLR limbs had lower peak external knee moments compared to healthy control limbs, while contralateral limbs had higher peak external knee moments compared to control limbs. These data are inconsistent in determining whether
contralateral limb mechanics are comparable to healthy control limbs or are altered following reconstruction.

Compared to healthy control limbs, consistent results include lesser external knee extension moments, external knee rotation moments, and greater hip extension moments in the ACLR group (Noehren et al., 2013; Zabala et al., 2013), while inconsistent results have been reported for knee flexion angle and peak knee external adduction moment (Noehren et al., 2013; Patterson et al., 2014; Hall et al., 2012; Webster et al., 2011). As compared to a healthy contralateral limb, ACLR athletes have shown reduced knee extension moments of the involved limb at heel-strike during gait (Scanlan et al., 2013). Because the results of these studies show some differences between healthy controls and healthy contralateral limbs, there may be compensatory changes to gait mechanics in ACLR athletes. However, Kozanek et al. (2008) reported that the contralateral limb is a valid kinematic control following ACL injury. There are limitations to the aforementioned studies. First, comparisons between studies are difficult to interpret as they often differ in regards to sex of the participants, surgical type, exclusion criteria concerning concomitant injury at the time of ACL rupture, and length of time from surgery when data collection took place. Second, traditional kinematics and kinetics reported in these studies refer to net actions at joints and neglect the interaction between segments. In order to gain an improved understanding of the stages of recovery from ACL reconstruction surgery and the mechanism of injury following reconstruction, a non-traditional approach is necessary (Hamill et al., 2012).

A Dynamical Systems Approach, following the work of Bernstein (1967), examines the relationships between parts of a system to analyze a task. A healthy system
uses the redundancy in available degrees of freedom to form multiple solutions through coordinative structures to optimize task performance. Coordination variability is the measure which represents the variation in use of these coordination patterns or the available degrees of freedom to perform a task. A healthy system is considered to have a high coordinative variability, while an unhealthy system is considered to freeze available degrees of freedom leading to frailty or a point of injury (Lipsitz, 2002). This equates to less than optimal coordination variability which decreases the ability of the system to adapt to perturbations, potentially increasing the likelihood of injury (Hamill et al., 1999). This relationship has been demonstrated in populations with pathology and overuse injury (Hamill et al., 1999; Van Emmerik et al., 1999; Heiderscheit et al., 2002; Seay et al., 2011). Conclusions presented in the literature using this perspective state that despite resolution of pain, gait alterations in terms of coordination may still exist. Therefore, using dynamical systems measures to determine coordination and coordination variability in ACLR athletes could supplement traditional measures in describing the progression of recovery from ACL reconstruction and may provide novel insights and improvement of rehabilitation protocols to prevent injury following surgery.

Dynamical systems measures have been used to examine coordination variability in an ACLR population following the idea that an optimal level of variability exists and that which falls outside the range of optimality is unhealthy. A level of variability that is higher than optimal is related to noise in the system, while one that is lower than optimal is related to rigidity and freezing of degrees of freedom (Lipsitz, 2000; Stergiou et al., 2006). A Lyapunov Exponent analysis and a vector coding technique have been used to determine coordination variability during gait and during a side-step cutting task. Both
studies reported a higher than optimal variability in ACLR individuals compared to healthy controls (Moraiti et al., 2010; Pollard et al., 2015). However, these studies measured coordination variability at only one time point post-surgery which varied between participants at the time of data collection. Although this may identify long-term alterations to mechanics, it does not lend itself to the identification of the progression through stages of recovery from surgery which is essential for the improvement of rehabilitation techniques to reduce the risk of ipsilateral graft rupture and contralateral ACL rupture following reconstruction. Therefore, the purpose of this study was to quantify inter-segment coordination variability during three portions of the stance phase of gait in athletes at three progressive time points post anterior cruciate ligament reconstruction surgery compared to the contralateral limb and healthy controls. We hypothesized: 1) that the ACLR involved limb would have significantly reduced coordination variability during all three portions of stance at each of three time points compared to the healthy control limb measured at one time point; 2) that the ACLR involved limb would significantly increase coordination variability during all three portions of stance with each progressive time point post-surgery; 3) that the ACLR involved limb would have significantly reduced coordination variability during all three portions of stance at each progressive time point post-surgery compared to the ACLR contralateral limb; and 4) that the coordination variability of the ACLR contralateral limb during all three portions of stance at each progressive time point would be similar to the healthy control limb at three portions of stance measured at one time point.

4.2 Methods

4.2.1 Participants
Twenty athletes were separated into two groups: 10 ACLR individuals and 10 healthy control individuals matched for age, gender, and activity level. Participants were included in the ACLR group if they were between the ages of 16-40, approximately 4 weeks post-surgery and participating in physical therapy. Participants were excluded from the study if they had a current injury or history of injury to the contralateral lower extremity that would affect gait, their weight bearing status was affected by concurrent knee pathology, or they had a medical condition that would interfere with their ability to complete the experimental protocol. Participants in the ACLR group were recruited from the same physical therapy clinic. Most participants attended physical therapy twice per week from 2 weeks through 6 months following surgery and all participants underwent rehabilitation with the goal of returning to their sport.

4.2.2 Experimental Setup

Three dimensional (3D) kinematic and kinetic data were collected at 250 and 1500 Hz respectively with 11 infrared cameras (Qualysis, Inc., Gothenberg, Sweden) set up around two 1.20 x 1.60 m strain gauge force platforms (Advanced Mechanical Technologies, Inc., Newton, Massachusetts, USA). The force data were collected using Qualysis Track Manager software (Qualysis, Inc., Gothenberg, Sweden) synchronized in time with the motion capture data collected using the same software.

4.2.3 Experimental Protocol

ACLR group participants made three visits to the Human Performance Laboratory at CATZ in Pasadena, CA at 4 weeks post-surgery (T1), 12 weeks post-surgery (T2), and within the month they were cleared to run (T3), while control participants visited the laboratory only once. Upon arrival, the experimental procedures and protocol were
explained to all participants. Informed consent was obtained as approved by the University Institutional Review Board. If the participants were under the age of 18, parental consent and youth assent were obtained.

General anthropometric measurements were taken including height, body mass, and age. Participants were fitted with 43, 25 mm reflective markers placed bilaterally on the 1st and 5th metatarsal heads, distal 2nd toe, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, posterior superior iliac spine, the joint space between the fifth lumbar, the first sacral spinous processes, and rigid plates on the lateral surfaces of the participant’s thigh, leg and heel counter of the shoe. The rigid plates, distal toe, iliac crest, posterior superior iliac spine and lumbar marker remained on the participant during testing, while all other markers were removed after collection of a static calibration trial. Participants were allowed a five minute warm up period on a stationary bike prior to testing sessions. They were asked to complete practice trials, walking along a 10m walkway at their preferred velocity. Practice trials were averaged to determine target velocity. Participants were then asked to complete at least three successful walking trials characterized by the foot striking the center of the force platform, and the velocity falling within +/- 5% of the target velocity. This was done for both limbs of the ACLR group and for one limb of the control group.

4.2.4 Data Analysis

Qualysis Track Manager (Qualysis, Inc., Gothenberg, Sweden) was used to track the positions of the markers and to process raw marker data. Kinematic data were then analyzed in Visual 3D (C-Motion Inc., Germantown, USA). A fourth order, zero lag
Butterworth digital low-pass filter with a cutoff frequency of 8 Hz was used with the cutoff frequency determined according to Winter (1990). The lower extremity was modeled as 7 rigid segments. Segment angles were calculated for the stance phase of gait referenced to a fixed laboratory coordinate system (X- medio-lateral; Y- line of walking progression; Z- vertical) using an XYZ Cardan rotation sequence.

Coordination couplings of interest were selected based on the function of the ACL, to prevent anterior translation of the tibia and hyperextension of the knee, as well as to reflect the kinematic and kinetic variables of interest in the literature. Coordination variability of the following segment coordination couplings of the lower extremity were calculated: 1) pelvis-thigh flexion-extension; 2) pelvis-thigh rotation; 3) thigh leg flexion-extension; 4) thigh flexion-leg internal rotation; 5) thigh rotation-leg rotation; 6) leg-foot flexion-extension; and 7) leg rotation-foot eversion. Relative segment angle-angle plots were used to determine inter-segment coordination by calculating coupling (phase) angles. Coupling angles were found by connecting two adjacent time points on angle-angle plots (Chang et al., 2008; Sparrow et al., 1987; Heiderscheit et al., 2002). A custom MATLAB program was used to calculate coupling angles between segments. Mean coupling angles and standard deviations were computed using circular statistics (Batschelet, 1981). Mean coupling angles and standard deviations were calculated inter-trial, for n≥3 trials, within participants over three periods of the stance phase: early (1-33%), mid (34-66%) and late (67-99%). This was done to ensure that differences were not masked by group mean over the entire stance phase (Heiderscheit et al., 2002). Coordination variability was calculated as the inter-trial within participant variation of the coupling angle at each percent of stance using circular statistics. Group coordination
variability was calculated by averaging the within participant standard deviations from the mean coupling angle over the stance phase of gait.

### 4.2.5 Statistical Analysis

Coordination variability for each coupling of the ACLR involved limb, the ACLR contralateral limb, and the healthy control limb was compared using two factor multivariate ANOVAs (limb x visit) for each portion of stance and with criterion alpha level set at .05. Tukey post-hoc tests were performed where appropriate.

### 4.3 Results

Results are presented in the following sections according to the hypotheses in summary tables as well as graphically according to the coordination couples of interest.

#### 4.3.1 Participant Characteristics

Participants’ data were excluded from the dataset due to collection error resulting in insufficient number of trials to assess coordination variability. The participant characteristics are presented by group and visit in Table 4.3.1.

**Table 4.3.1** Participant characteristics of the ACLR involved group (ACLR), ACLR noninvolved group (NI), and control group (CTRL) at 4 weeks (V1), 12 weeks (V2), and when cleared to run post-surgery (V3).

<table>
<thead>
<tr>
<th>Group/Visit</th>
<th>N</th>
<th>Age Mean (SD)</th>
<th>Sex</th>
<th>Injured Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLR V1</td>
<td>10</td>
<td>23.4 (9.9)</td>
<td>7 F, 3 M</td>
<td>9 D, 1 ND</td>
</tr>
<tr>
<td>ACLR V2</td>
<td>9</td>
<td>22.7 (10.3)</td>
<td>7 F, 2 M</td>
<td>8 D, 1 ND</td>
</tr>
</tbody>
</table>
4.3.2 Walking Velocity

The group mean walking velocity was reduced at visit 1 for the ACLR group compared to visits 2 and 3, and compared to the healthy control group.

Table 4.3.2. Group mean walking velocities and standard deviations at each visit.

<table>
<thead>
<tr>
<th>Group</th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLR</td>
<td>1.26 (.24) m/s</td>
<td>1.45 (.14) m/s</td>
<td>1.48 (.13) m/s</td>
</tr>
<tr>
<td>Control</td>
<td>1.48 (.19) m/s</td>
<td>_</td>
<td>_</td>
</tr>
</tbody>
</table>

4.3.3 Results- Hypothesis 1

We hypothesized that the ACLR involved limb would have significantly reduced coordination variability during all three portions of stance at each of three time points.
compared to the healthy control limb measured at one time point. There was a limb x
time interaction difference observed (p < .05). However, during early stance the
interaction was not in the direction expected. None of the couples of interest had reduced
coordination variability and there was increased coordination variability in pelvis-thigh
rotation thigh-leg rotation and leg rotation-foot eversion during early stance at visit 1 (p
>.05). During mid-stance it was supported by the pelvis-thigh flexion/extension, leg-foot
flexion/extension, and leg rotation-foot eversion couples at visit 1, and the pelvis-thigh
rotation couple at visit 2 (p < .05). During late-stance the hypothesis was true for all
couples at visit 1 (p< .05), and for thigh flexion-leg internal rotation and leg rotation-foot
eversion at visits 2 and 3 (p < .05) (See Tables 4.3.3.1-4.3.3.3).

**Table 4.3.3.1** Coordination variability of the ACLR involved limb compared to the
healthy control limb during **early stance** at each visit. ↑ = significantly greater
coordination variability; ↓ = significantly reduced coordination variability; - = similar
coordination variability

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Pelvis-thigh rotation</td>
<td>↑</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Thigh-leg flexion/extension</td>
<td>-</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
<td>-</td>
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<tr>
<td>Thigh-leg rotation</td>
<td>↑</td>
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<tr>
<td>Leg-foot flexion/extension</td>
<td>-</td>
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</tbody>
</table>
Table 4.3.3.2 Coordination variability of the ACLR involved limb compared to the healthy control limb during **mid-stance** at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>↓</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Pelvis-thigh rotation</td>
<td>-</td>
<td>↓</td>
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<tr>
<td>Thigh-leg flexion/extension</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
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<tr>
<td>Thigh-leg rotation</td>
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<tr>
<td>Leg-foot flexion/extension</td>
<td>↓</td>
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<tr>
<td>Leg rotation-foot eversion</td>
<td>↓</td>
<td>-</td>
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</tr>
</tbody>
</table>

Table 4.3.3.3 Coordination variability of the ACLR involved limb compared to the healthy control limb during **late stance** at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>↓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pelvis-thigh rotation</td>
<td>↓</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4.3.4 Results- Hypothesis 2

We hypothesized that the ACLR involved limb would significantly increase coordination variability during all three portions of stance with each progressive time point post-surgery. There was an effect of time on the ACLR involved limb (p < .05). The hypothesis was not supported by any couples during early stance. During mid-stance, the hypothesis was supported by the thigh-leg flexion/extension, leg-foot flexion/extension, and leg rotation-foot eversion couples which all had reduced coordination variability at the first visit which increased at subsequent visits (p < .05). It was also supported during late stance by all couples which similarly had reduced coordination variability at visit 1, but increased in subsequent visits (p < .05). This occurred for almost all couples between the first and second visit, and then remained similar between the second and third visits (See Tables 4.3.4.1-4.3.4.3).
Table 4.3.4.1 Coordination variability of the ACLR involved limb progressively over time during **early stance**. $\uparrow$ = significantly increased coordination variability compared to the previous visit or higher coordination variability than the subsequent visits; $\downarrow$ = significantly reduced coordination variability compared to the previous visit; - = similar coordination variability to the previous visit; * significantly different from visit 1 only.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>-</td>
<td>$\downarrow^*$</td>
<td>-</td>
</tr>
<tr>
<td>Pelvis-thigh rotation</td>
<td>-</td>
<td>$\downarrow$</td>
<td>-</td>
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<tr>
<td>Thigh-leg flexion/extension</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thigh-leg rotation</td>
<td>-</td>
<td>$\downarrow^*$</td>
<td>-</td>
</tr>
<tr>
<td>Leg-foot flexion/extension</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Leg rotation-foot eversion</td>
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</table>

Table 4.3.4.2 Coordination variability of the ACLR involved limb progressively over time during **mid-stance**. $\uparrow$ = significantly increased coordination variability compared to the previous visit or higher coordination variability than the subsequent visits; $\downarrow$ = significantly reduced coordination variability compared to the previous visit; - = similar coordination variability to the previous visit; * = significantly different from visit 3 only.

<table>
<thead>
<tr>
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<th>Visit 1</th>
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</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pelvis-thigh rotation</td>
<td>$\uparrow$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thigh-leg flexion/extension</td>
<td>$\downarrow^*$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Visit 1</td>
<td>Visit 2</td>
<td>Visit 3</td>
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<tr>
<td>Pelvis-thigh flexion/extension</td>
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<tr>
<td>Pelvis-thigh rotation</td>
<td>↓</td>
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<tr>
<td>Thigh-leg flexion/extension</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
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<tr>
<td>Thigh-leg rotation</td>
<td>↓</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Leg-foot flexion/extension</td>
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</tr>
<tr>
<td>Leg rotation-foot eversion</td>
<td>↓</td>
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</table>

**Table 4.3.4.3** Coordination variability of the ACLR involved limb progressively over time (between visits) during **late stance**. **↑** = significantly increased coordination variability compared to the previous visit or higher coordination variability than the subsequent visits; **↓** = significantly reduced coordination variability; - = similar coordination variability.
4.3.5 Results- Hypothesis 3

We hypothesized that the ACLR involved limb would have significantly reduced coordination variability during all three portions of stance at each progressive time point post-surgery compared to the ACLR contralateral limb. There was a limb by time difference observed (p< .05). This hypothesis was supported by the leg rotation-foot eversion couple during early stance at visit 1 (p<.05). During mid-stance it was supported at the first visit for pelvis-thigh flexion/extension, thigh-leg flexion/extension, thigh flexion-leg internal rotation, leg-foot flexion/extension, and leg rotation-foot eversion (p< .05). During late stance coordination variability of ACLR involved limb compared to the ACLR contralateral limb was reduced at visit 1 for pelvis-thigh flexion/extension, pelvis-thigh rotation, thigh-leg flexion/extension, thigh-leg rotation, and leg-foot flexion/extension (p<.05). It was reduced at visit 2 during late stance for leg-foot flexion/extension and leg rotation-foot eversion (p<.05) (See Tables 4.3.5.1-4.3.5.3).

Table 4.3.5.1 Coordination variability of the ACLR involved limb compared to the ACLR contralateral limb during early stance at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
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<th>Visit 3</th>
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<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
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<tr>
<td>Pelvis-thigh rotation</td>
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<tr>
<td>Thigh-leg flexion/extension</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
<td>-</td>
<td>-</td>
<td>↑</td>
</tr>
</tbody>
</table>
Table 4.3.5.2 Coordination variability of the ACLR involved limb compared to the ACLR contralateral limb during mid-stance at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>↓</td>
<td>-</td>
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<tr>
<td>Pelvis-thigh rotation</td>
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<tr>
<td>Thigh-leg flexion/extension</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
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<tr>
<td>Thigh-leg rotation</td>
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</tr>
<tr>
<td>Leg-foot flexion/extension</td>
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<td>-</td>
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<tr>
<td>Leg rotation-foot eversion</td>
<td>↓</td>
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</table>
Table 4.3.5.3 Coordination variability of the ACLR involved limb compared to the ACLR contralateral limb during late stance at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>↓</td>
<td>-</td>
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<tr>
<td>Pelvis-thigh rotation</td>
<td>↓</td>
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<td>-</td>
</tr>
<tr>
<td>Thigh-leg flexion/extension</td>
<td>↓</td>
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<td>-</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
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<td>Thigh-leg rotation</td>
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</tr>
<tr>
<td>Leg-foot flexion/extension</td>
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</tr>
<tr>
<td>Leg rotation-foot eversion</td>
<td>-</td>
<td>↓</td>
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</tr>
</tbody>
</table>

4.3.6 Results- Hypothesis 4

We hypothesized that the coordination variability of the ACLR contralateral limb during all three portions of stance at each progressive time point would be similar to the healthy control limb at three portions of stance measured at one time point. However, there was a limb by time effect observed (p< .05). Differences were observed during early stance at visit 1 for pelvis-thigh flexion/extension, pelvis-thigh rotation, thigh-leg flexion/extension, thigh-leg rotation, leg-foot flexion/extension, and leg rotation-foot eversion (p< .05). During early stance differences were also observed for leg-rotation foot
eversion at visit 2 and thigh-leg flexion/extension at visit 3 (p< .05). During mid-stance differences were observed at visit 1 for thigh flexion-leg internal rotation and leg rotation-foot eversion; at visit 2 for pelvis-thigh flexion/extension, thigh flexion-leg internal rotation, and leg rotation-foot eversion; and at visit 3 for thigh flexion-leg internal rotation (p< .05). Differences were observed during late stance at visit 1 for thigh flexion-leg internal rotation and leg rotation-foot eversion; at visit 2 for pelvis-thigh flexion/extension, thigh flexion-leg internal rotation, and leg rotation-foot eversion; and at visit 3 for thigh flexion-leg internal rotation (p< .05) (Tables 4.3.6.1-4.3.6.3).

**Table 4.3.6.1** Coordination variability of the ACLR contralateral limb compared to the healthy control limb during early stance at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>↑</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pelvis-thigh rotation</td>
<td>↑</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thigh-leg flexion/extension</td>
<td>↑</td>
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<td>↑</td>
</tr>
<tr>
<td>Thigh flexion-leg internal rotation</td>
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<tr>
<td>Thigh-leg rotation</td>
<td>↑</td>
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<tr>
<td>Leg-foot flexion/extension</td>
<td>↑</td>
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<td>-</td>
</tr>
<tr>
<td>Leg rotation-foot eversion</td>
<td>↑</td>
<td>↑</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4.3.6.2 Coordination variability of the ACLR contralateral limb compared to the healthy control limb during **mid-stance** at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
<th>Visit 2</th>
<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
<td>-</td>
<td>↓</td>
<td>-</td>
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<tr>
<td>Pelvis-thigh rotation</td>
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<td>Thigh flexion-leg internal rotation</td>
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<td>Leg-foot flexion/extension</td>
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<tr>
<td>Leg rotation-foot eversion</td>
<td>↑</td>
<td>↑</td>
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</table>

Table 4.3.6.3 Coordination variability of the ACLR contralateral limb compared to the healthy control limb during **late stance** at each visit. ↑ = significantly greater coordination variability; ↓ = significantly reduced coordination variability; - = similar coordination variability.

<table>
<thead>
<tr>
<th></th>
<th>Visit 1</th>
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<th>Visit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis-thigh flexion/extension</td>
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<tr>
<td>Pelvis-thigh rotation</td>
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<td>Thigh-leg flexion/extension</td>
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<tr>
<td>Thigh flexion-leg internal rotation</td>
<td>↓</td>
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</tr>
</tbody>
</table>
4.3.7 Results- Coordination Variability Figures by Couple

4.3.7.1 Pelvis-Thigh Flexion/Extension

During early stance at visit 1 the control limb had significantly decreased coordination variability compared to the ACLR noninvolved limb (p=.03). There were no differences between limbs at visits 2 and 3 (p=.25; p=.44). Within group over time, the ACLR involved limb had significantly increased coordination variability at visit 1 compared to visit 2 (p=.001), and the ACLR noninvolved limb had significantly reduced coordination variability at visit 2 compared to the other visits (p=.0001) (Figure 4.3.7.1 A).

For mid-stance at visit 1, the ACLR involved limb had significantly reduced coordination variability compared to the other limbs (p=.005). At visit 2, the ACLR noninvolved limb had reduced coordination variability compared to the control limb (p=.004). There were no differences between groups at visit 3 (p=.786). Within group, the ACLR noninvolved limb had significantly reduced coordination variability at visit 2 compared to the other visits (p=.001). There were no differences between visit for the ACLR involved limb (p=.099) (Figure 4.3.7.1 B).
During late stance, the ACLR involved limb had significantly reduced coordination variability compared to the other limbs at visit 1, but there were no differences between limbs at the other visits (p<.0001; p=.05; p=.19). Within group, the ACLR involved limb had significantly reduced coordination variability at the first visit compared to the subsequent visits, as did the ACLR noninvolved limb (p<.0001; p=.0002) (Figure 4.3.7.1 C).
Figure 4.3.7: Coordination variability of the pelvis-thigh flexion extension couple during early (A), mid (B), and late (C) stance. * = p<.05 within group; ^ = p<.05 between groups
4.3.7.2 Pelvis-Thigh Rotation

During early stance, the control limb had significantly reduced coordination variability compared to the other limbs at visit 1 (p=.014). At visit 2, there were no significant differences between limbs (p=.1024). At visit 3, the ACLR involved limb had significantly increased coordination variability as compared to the ACLR noninvolved limb (p=.026). Within group, the ACLR noninvolved limb was significantly different at each visit (p=<.0001). Coordination variability was significantly higher at visit 1 than visit 3, which was significantly higher than visit 2. The ACLR involved limb had reduced coordination variability at visit 2 compared to the other visits (p=.006) (Figure 4.3.7.2 A).

During mid-stance at visit 2, the ACLR involved limb had significantly reduced coordination variability compared to the control limb (p=.0322). There were no differences between limbs at visits 1 and 3 (p=325; p=.077). Within group, the ACLR involved limb had significantly greater coordination variability at visit 1 compared to the following visits (p=.0013). The ACLR noninvolved limb had significantly greater coordination variability at visit 1 compared only to visit 2 (p=.0166) (Figure 4.3.7.2 B).

For late stance, the ACLR involved limb had significantly reduced coordination variability at visit 1 compared to the other limbs (p=.0023). At visit 2, the ACLR noninvolved limb had significantly reduced coordination variability compared to the control limb (p=.044). There were no differences between limbs at visit 3 (p=.673). Within group, the ACLR involved limb had significantly reduced coordination variability at visits 1 and 2 compared to visit 3 (p<.0001). The ACLR noninvolved limb had
significantly reduced coordination variability at visit 2 compared to visit 3 (p=.0194) (Figure 4.3.7.2 C).

A)

B)
Figure 4.3.7.2: Coordination variability of the pelvis-thigh rotation couple during early (A), mid (B), and late (C) stance. * = p<.05 within group; ^ = p<.05 between groups

4.3.7.3 Thigh-Leg Flexion/Extension

During early stance, the ACLR noninvolved limb has significantly greater coordination variability than the control limb at visits 1 and 3 (p=.002; p=.018). There were no differences between limbs at visit 2 (p=.418). Within group, the ACLR noninvolved limb had significantly reduced coordination variability at visit 2 compared to the other visits (p<.0001). There was no difference over time during early stance for the ACLR involved limb (p=.243) (Figure 4.3.7.3 A).
During mid-stance, the ACLR involved limb had significantly reduced coordination variability compared to the ACLR noninvolved limb at visit 1 and there were no differences between limbs at the other visits (p=.0029; p=.6295; p=.6713). Within group, the ACLR involved limb had significantly reduced coordination variability at visit 1 compared to visit 3, while the ACLR noninvolved limb had significantly increased coordination variability at visit 1 compared to visit 2 (p=.008; p=.031) (Figure 4.3.7.3 B).

During late stance, the ACLR involved limb had significantly reduced coordination variability at visit 1 compared to the other limbs, as well as subsequent visits (p=.0006; p<.0001). There were no other differences between limbs or visits (p=.486; p=.262; p=.262) (Figure 4.3.7.3 C).

A)
Figure 4.3.7.3: Coordination variability of the thigh-leg flexion/extension couple during early (A), mid (B), and late (C) stance. * = p<.05 within group; ^ = p<.05 between groups
4.3.7.4 Thigh Flexion-Leg Internal Rotation

During early stance, the ACLR involved limb had significantly increased coordination variability compared to the ACLR noninvolved limb at visit 3 (p=.034). There were no significant differences between limbs for visits 1 and 2 (p=.068; p=.714). Within group, the ACLR noninvolved limb had significantly increased coordination variability at visit 1 compared to visit 3 (p=.003). There were no differences over time for the ACLR involved limb (p=.117) (Figure 4.3.7.4 A).

During mid-stance, the ACLR noninvolved limb had significantly increased coordination variability compared to both limbs at visit 1 and compared to the control limb at visits 2 and 3 (p=.001; p=.011; p=.032). There were no differences within the ACLR involved limb or ACLR noninvolved limb over time (p=.968; p=.520) (Figure 4.3.7.4 B).

During late stance at visit 1 and 3, the ACLR involved limb and the ACLR noninvolved limb were significantly different from the control limb and each other, with the involved limb having reduced coordination variability compared to the noninvolved limb (p<.0001; p<.0001). At visit 2 the ACLR involved limb had significantly reduced coordination variability compared to the ACLR noninvolved limb (p=.002). Within group, the ACLR involved limb had significantly reduced coordination variability at visit 1 compared to subsequent visits while the ACLR noninvolved limb had significantly increased coordination variability at visit 1 compared to visits 2 and 3 (p=.001; p<.0001) (Figure 4.3.7.4 C).
4.3.7.5 Thigh-Leg Rotation

During early stance, the ACLR involved and noninvolved limbs had significantly increased coordination variability compared to the control limb at visit 1, but there were no differences between limbs at the other visits (p<.0001; p=.86; p=.70). Within group, the ACLR involved limb had significantly increased coordination variability at visit 1 compared to visit 2 (p=.001). The ACLR noninvolved limb had significantly increased coordination variability at visit 1 compared to visits 2 and 3 (p=.002) (Figure 4.3.7.5 A).

During mid-stance, there were no differences between limbs at visits 1, 2 and 3 (p=.780; p=.109; p=.788). There were also no differences over time within the ACLR limb or ACLR noninvolved limb (p=.087; p=.992) (Figure 4.3.7.5 B).
For late stance, the ACLR involved limb had reduced coordination variability, at visit 1, compared to the other limbs (p=.0001). There were no differences between limbs at visits 2 and 3 (p=.107; p=.510). The ACLR involved limb had reduced coordination variability at visit 1 compared to the other visits (p=.0001). There were no differences over time for the ACLR noninvolved limb (p=.119) (Figure 4.3.7.5 C).

A)
Figure 4.3.7.5  □CTRL ▲ACLR ▹NI Coordination variability of the thigh-leg rotation couple during early (A), mid (B), and late (C) stance. * = p<.05 within group; ^ = p<.05 between groups
4.3.7.6 Leg-foot Flexion/Extension

During early stance, the ACLR noninvolved limb had significantly increased coordination variability compared to the control limb at visit 1 (p=.002). There were no differences between limbs at the other visits (p=.86; p=.70). The ACLR noninvolved limb had significantly increased coordination variability at visit 1 compared to visits 2 and 3 (p=.005). There were no differences over time for the ACLR involved limb (p=.053) (Figure 4.3.7.6 A).

During mid-stance, the ACLR involved limb had significantly reduced coordination variability compared the other limbs at visit 1 (p<.0001). There were no differences between limbs at the other visits (p=.19; p=.81). The ACLR involved limb also had a significantly reduced coordination variability at visit 1 compared to visit 3 (p=.0025). The ACLR noninvolved limb was similar across visits (p=.17) (Figure 4.3.7.6 B).

During late stance, the ACLR involved limb had significantly reduced coordination variability compared to both limbs at visit 1 and compared to the ACLR noninvolved limb at visit 2 (p<.0001; p=.03). Within group, the ACLR involved limb had significantly reduced coordination variability at visit 1 compared to the other visits (p<.0001). For the ACLR noninvolved limb, coordination variability at visits 1 and 3 were different than at visit 2 and different from each other with visit 1 having increased variability compared to 3, but both are reduced compared to 2 (p=.002) (Figure 4.3.7.6 C).
4.3.7.6 Leg Rotation-Foot Eversion

During early stance, the ACLR noninvolved limb had significantly increased coordination variability compared to the other limbs at visit 1 and to the control limb at visit 2 (p=.0086; p=.036). At visit 3, the ACLR involved limb had increased coordination variability compared to the control limb (p=.032). Within group the ACLR noninvolved limb had significantly reduced coordination variability at visit 3 compared to visit 1 according to Tukey post-hoc tests (p=.057). There were no differences across time for the ACLR involved limb (p=.223) (Figure 4.3.7.6 A).

During mid-stance, all limbs were significantly different from each other at visit 1 with the ACLR involved limb having reduced coordination variability compared to the
control and the ACLR noninvolved limb having increased coordination variability compared to the control (p<.0001). At visit 2, the ACLR noninvolved limb still had significantly increased coordination variability compared to the control limb, and there were no differences between limbs at visit 3 (p=.044; p=.7209). Within group, the ACLR involved limb had significantly reduced coordination variability at visit 1 compared to visits 2 and 3, but there was no change over time for the ACLR noninvolved limb (p=.0016; p=.0799) (Figure 4.3.7.7 B).

During late stance, at visit 1 the ACLR involved and noninvolved limbs were significantly different from the control limb and from each other, with the involved limb having reduced coordination variability compared to the noninvolved limb, and both reduced compared to the control limb (p<.0001). At visit 2, the ACLR involved limb had reduced coordination variability compared to the other limbs, which were similar (p=.0004). At visit 3, the ACLR involved and noninvolved limbs were significantly different from the control limb and from each other, with the ACLR involved limb having increased coordination variability compared to the noninvolved limb, but both reduced compared to the control limb (p=.0023). Within group, the ACLR involved limb had significantly reduced coordination variability at visit 1 compared to the other visits (p<.0001). The ACLR noninvolved limb had significantly reduced coordination variability at visit 3 and even further reduced coordination variability at visit 1 compared to visit 2 (p<.0001) (Figure 4.3.7.7 C).
4.4 Discussion

The purpose of this study was to quantify inter-segment coordination variability during three portions of the stance phase of gait in individuals at three progressive time points post ACL reconstruction surgery compared to the contralateral limb of the ALCR group and healthy controls. Our hypotheses were partially supported during some portions of stance for certain couplings, but did not follow a distinctive pattern as expected. The first hypothesis was that the ACLR limb would have significantly reduced coordination variability during all three portions of stance at each of three time points compared to the healthy control limb measured. This was supported in the pelvis-thigh flexion-extension during mid-stance and late-stance at the first visit, pelvis-thigh rotation during late stance at the first visit, thigh-leg flexion-extension during late stance at the
first visit, thigh flexion-leg internal rotation during late stance at all visits, leg-foot
flexion-extension during mid and late stance at visit 1, and leg rotation-foot eversion
during mid-stance at visit one and late stance at all visits. These data suggest that for the
couples mentioned, the ACLR involved limb freezes available degrees of freedom
indicating that an injured system was expected usually during late stance at visit 1
(Lipsitz 2002).

The second hypothesis was that the ACLR involved limb would significantly
increase coordination variability for all three portions of stance with each progressive
time point post-surgery. The pelvis-thigh flexion-extension couple showed an increase in
coordination variability between visits 1 and 2 during late stance. Pelvis-thigh rotation
supported this hypothesis by exhibiting increased coordination variability in late stance at
visit 3 compared to previous visits, but contradicted expectations for early and mid-stance
showing increased variability in the first visit compared to the second visit. Thigh-leg
flexion-extension partially supported the hypothesis that over time the ACLR involved
limb would increase coordination variability for mid-stance with visit 3 significantly
greater than visit 1 and for late stance with visits 2 and 3 greater than visit 1. Thigh-
flexion-leg internal-rotation had increased coordination variability at visits 2 and 3
compared to visit 1 during late-stance. The hypothesis was supported during late stance
for the thigh-leg rotation couple with visit 1 having reduced coordination variability
compared to visits 2 and 3. This was also true of leg-foot flexion-extension and leg
rotation foot eversion for mid and late stance. Some of the data contradict this hypothesis
increasing between the first and second visit and decreasing from the second to third
visit. This may be contributed to a learning effect in which the athlete first freezes their
available degrees of freedom to protect the repaired knee, then unfreezes them to achieve closer to normal coordination before falling between the two at the third visit. However, most follow the trend that during late stance the ACLR involved limb increased their coordination variability compared to the first visit. This suggests that between four and twelve weeks following ACL reconstruction surgery with rehabilitation there was an improvement in joint function (Hamill et al., 1999).

The third hypothesis was that the ACLR involved limb would have significantly reduced coordination variability during all three portions of stance at each progressive time point post-surgery compared to the ACLR contralateral limb. This was partially supported in the pelvis-thigh flexion-extension coupling during mid and late stance with the ACLR involved limb significantly reduced at visit 1. Pelvis-thigh rotation during late stance had reduced coordination variability in the ACLR involved limb compared to the ACLR contralateral limb at visit 1 as well. Thigh-leg flexion-extension similarly had reduced coordination variability of the ACLR involved limb at visit 1 during mid and late stance. Thigh flexion-leg rotation partially supported this hypothesis during mid stance at visit 1. Thigh-leg rotation supported this hypothesis for late stance at visit 1. Leg-foot flexion-extension had reduced variability in the ACLR involved limb at visit 1 for midstance, and visits 1 and 2 for late stance. The leg rotation-foot eversion couple showed that the ACLR involved limb had reduced coordination variability compared to the ACLR contralateral limb during early stance at visits 1 and 2, but became similar at visit 3. During mid-stance this was shown at visit 1 but was similar for visits 2 and 3, while during late-stance this was shown for visit 2 only. These data suggest that there is a similar trend when comparing the ACLR involved limb to the healthy control limb as
there is when comparing the ACLR involved limb to the ACLR contralateral limb. That is, the ACLR involved limb showed reduced coordination variability in some couples during late stance at visit 1, but became similar at later visits. Although the results were not identical comparing the ACLR involved limb to the healthy control limb and the ACLR involved limb to the ACLR contralateral limb, these data similarly suggest that between four weeks and eight weeks post-surgery, there was an improvement in joint function indicated by the coordination variability of the ACLR involved limb changing from reduced, or having frozen degrees of freedom, to becoming similar to a healthy or ACLR contralateral limb.

The fourth and final hypothesis was that the coordination variability of the ACLR contralateral limb during all three portions of stance at each progressive time point would be similar to the healthy control limb measured. This was true for pelvis-thigh flexion-extension during late stance at all visits, but there were differences during early and mid-stance. These limbs were similar during mid-stance for the pelvis-thigh rotation couple at all visits, but differences existed in early and late stance. The thigh-leg flexion-extension refuted this hypothesis with the ACLR contralateral limb exhibiting greater coordination variability than the controls at visit 1 during all portions of stance and visit 3 during early stance. The thigh flexion-leg rotation couple showed no differences between limbs for any visit during early stance, but showed the ACLR contralateral limb had increased coordination variability compared to the healthy control limb at all visits during mid-stance. In contrast, the control limb had higher coordination variability during late stance at visits 1 and 3, but was similar at visit 2. The hypothesis was supported for the thigh-leg rotation couple for all visits during mid and late stance. For the leg-foot flexion-extension
couple the ACLR contralateral limb had increased coordination variability at visit 1 compared to the control during early stance, but was similar to control at subsequent visits and there were no other differences between limbs. This hypothesis was refuted by the leg rotation-foot eversion couple which showed differences in these limbs during all portions of stance at nearly every visit. These data suggest that the contralateral limb of an ACLR individual is significantly different from a healthy control limb in terms of coordination variability. These athletes may be using a compensatory gait strategy following surgery. This strategy was suggested by Noehren et al., 2013. Therefore, it may not be appropriate to use only the contralateral limb as a control limb when evaluating differences in ACLR individuals.

The results of the present study were in agreement with the literature regarding coordination variability with injury. That is, with injury, or in this case 4 weeks post-surgery, the body appears to adopt a guarded gait pattern, freezing available degrees of freedom in order to protect the repaired knee. Over time, as participants completed their physical therapy, they did not show this guarded pattern and their involved knee reacted similarly to the healthy control limb during late stance. This suggests an improvement to joint function and an overall healthy system (Hamill et al., 1999; Heiderscheit et al., 2002; Seay et al., 2011). These results, however, are not in line with the most recent work on coordination variability in an ACLR population. Moraiti et al. (2010) showed an increase in coordination variability during running in the knee flexion-extension couple, while Pollard et al. (2015) showed an increase in coordination variability for lower extremity joint couples in a side-step cutting task compared to healthy controls. Although during early stance there were some examples of increased coordination variability
following surgery in the present study compared to controls, the majority of the results
did not follow this pattern. This may be due to the type of variability being examined.
The prior studies used joint coordination variability while this study used inter-segment
coordination variability which may lend itself better to the assessment of improvement of
joint function as opposed to the temporal coordination between joints.

There are several limitations of this study that may have affected the results. First,
we assumed that the control group would not change between time points so the results
from this group come from just one time point. To our knowledge, change in
coordination variability of a healthy population over time has not been examined in the
literature; thus, it is possible that this assumption may have affected the results. The
walking velocity at each visit may have also affected the current study results. The
average walking velocity of the second and third visits for the ACLR individuals and the
healthy control group were within 5% of each other; however, the first visit of the ACLR
group was outside greater than -5% of the other groups (Table 4.3.6.1). It is possible that
this difference in velocity could affect results; however, we may expect that the slower
velocity would result in increased coordination variability. Chiu & Chou (2012)
investigated the effect of age and velocity on inter-joint coordination variability during
walking. They found that coordination variability was increased in both older and
younger adults when walking velocity was decreased and suggested that slower walking
velocity was a more difficult task requiring greater neuromuscular control to achieve
balance during longer single leg support times. Therefore, the reduced coordination
variability of the ACLR involved limb at the first visit compared to the other limbs and
the other visits despite reduced walking velocity had to be a large difference to result in a
statistically significant difference. Another limitation of the study was the number of trials included. It is possible that the range of three to five trials per participant was not enough to represent the variability of the couples between limbs for early and mid-stance. Although this study matched participants for age, sex, and pre-injury activity level it is possible that other characteristics of the participants that were not controlled, such as surgical type, could have contributed to the lack of consistent results in early and mid-stance.

4.5 Conclusions

The results of this study demonstrated that an ACLR population has decreased inter-segment coordination variability of the involved lower extremity during the late stance phase of gait compared to both the contralateral limb and healthy controls at 4 weeks post-surgery. By 12 weeks post-surgery there were improvements in joint function as exemplified by more normal coordination variability. Therefore, coordination variability in the present study is not an indication of the increased risk for ipsilateral graft rupture and contralateral ACL rupture in this population.
4.6 References


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CHAPTER 5

SUMMARY OF RESULTS AND FUTURE STUDIES

5.1 Introduction

The purpose of this study was to classify inter-segment coordination patterns and to quantify inter-segment coordination variability during three portions of the stance phase of gait in individuals post anterior cruciate ligament reconstruction surgery. This was done during walking for healthy age-matched control limbs at one time point and for the ipsilateral and contralateral limbs at three time points post-surgery: 4 weeks, 12 weeks, and when cleared to run. Kinematic data were collected to complete coordination and coordination variability analysis. Results were compared between time points and between limbs. This study used a modified vector coding technique based on the Dynamical Systems Approach to quantify coordination variability. Results may justify: 1) the use of the ACLR contralateral limb as a control limb in this population; 2) improve the understanding of the progression through stages of recovery from surgery; 3) provide insight into the etiology of ipsilateral graft rupture and contralateral ACL rupture following reconstruction; and 4) identify need for improvement of rehabilitation protocol and return to play clearance standards to prevent injury following surgery.

5.2 Summary of Results

Our first hypothesis was that the ACLR involved limb would have significantly reduced coordination variability during all three portions of stance at each of three time points compared to the healthy control limb measured at one time point. For the pelvis-thigh flexion-extension couple, the ACLR involved limb was similar to the healthy
control limb during early stance at all visits. The ACLR involved limb had reduced coordination variability in mid-stance and late-stance at the first visit compared to the controls, and became similar to the control limb for the subsequent visits. For the pelvis-thigh rotation couple during early stance the ACLR involved limb had an increased coordination variability compared to the control limb at visit 1 and became similar to the controls in visits 2 and 3. During mid-stance the ACLR involved limb had reduced coordination variability compared to controls at the second visit; however, there were no statistically significant differences between limbs at visits 1 and 3. During late stance, the hypothesis was supported for visit 1, but the limbs again became similar at the following visits. For the thigh-leg flexion-extension couple, there were no differences between limbs during early and mid-stance at any visit; however, during late-stance the ACLR involved limb had reduced coordination variability compared to controls at the first visit. For the thigh flexion-leg internal rotation couple, there were no differences between these limbs during early and mid-stance at any visit; however, during later stance the ACLR involved limb had reduced coordination variability compared to the control limb at all visits. For the thigh-leg rotation couple, the hypothesis was refuted with the ACLR involved limb having increased coordination variability compared to control limb during early stance at visit 1; however coordination variability was similar between limbs for the subsequent visits. There were no differences between limbs at any visit for this coupling during mid-stance. During late stance, the ACLR involved limb had lower coordination variability compared to control for visit 1 and then became similar to the controls during visits 2 and 3. For the leg-foot flexion-extension couple during early stance the ACLR involved limb had increased coordination variability compared to controls at visit 1, but
became similar in visits 2 and 3; however, during mid and late stance the ACLR involved limb had reduced coordination variability during visit 1. For the leg rotation-foot eversion couple at early stance, the ACLR involved limb had increased coordination variability compared to controls at visit 3, but was similar to controls at the first two visits. During mid-stance, the ACLR involved limb had reduced coordination variability at the first visit compared to controls and became similar at visits 2 and 3. During late stance, hypothesis was supported for all visits.

Our second hypothesis was that the ACLR involved limb would significantly increase coordination variability during all three portions of stance with each progressive time point post-surgery. For the pelvis-thigh flexion-extension couple during early stance, the ACLR involved limb had increased coordination variability at the first visit compared to the second visit, with the third visit being similar to both. At mid-stance there were no differences between visits. During late-stance for this couple, the ACLR involved limb had reduced coordination variability at visit 1 when compared to 2 and 3. For the pelvis-thigh rotation couple during early stance the ACLR involved limb had increased coordination variability at visits 1 and 3 compared to visit 2. During mid-stance, the ACLR involved limb had increased coordination variability at visit 1 compared to visits 2 and 3. During late-stance the ACLR involved limb had increased coordination variability at visit 3. The thigh-leg flexion-extension couple there were no differences between visits during early stance. During mid-stance, there was increased coordination variability at visit 3 compared to visit 1. During late stance the ACLR involved limb had increased coordination variability at visits 2 and 3 compared to visit 1. For the thigh flexion-leg internal rotation couple there were no differences between visits for early or mid-stance,
but visit 1 showed reduced coordination variability compared to visits 2 and 3 during late stance. The thigh-leg rotation couple had increased coordination variability at visit 1 compared to visit 2 during early stance, no differences between visits during mid-stance, and increased coordination variability in visits 2 and 3 compared to visit 1 in late-stance. The leg-foot flexion-extension couple showed no differences between visits for early stance. For mid and late stance, the ACLR involved limb had reduced coordination variability at visit 1 compared to visits 2 and 3. The leg rotation-foot eversion couple showed no differences between visits for early stance, however showed that the ACLR involved limb had reduced coordination variability at visit 1 compared to visits 2 and 3 for mid and late stance.

The third hypothesis was that ACLR involved limb would have significantly reduced coordination variability during all three portions of stance at each progressive time point post-surgery compared to the ACLR contralateral limb. For pelvis-thigh flexion extension the ACLR involved limb was similar to the ACLR contralateral limb during early stance for all visits, but had reduced coordination variability compared to the ACLR contralateral limb during mid and late stance at visit 1 but the limbs were similar at visits 2 and 3. The pelvis-thigh rotation couple during early stance showed no differences between limbs for the first 2 visits, but showed that the ACLR involved limb had greater coordination variability than the ACLR contralateral limb at the third visit. There were no differences for this couple during mid-stance. During late stance, the ACLR involved limb exhibited reduced coordination variability at visit 1, but there were no differences between the limbs at visits 2 and 3. The thigh-leg flexion-extension couple showed no differences between limbs during early stance at any visit, but showed the
ACLR involved limb had reduced coordination variability compared to ACLR contralateral limb during mid and late stance at visit 1 but became similar at visits 2 and 3. The thigh flexion-leg rotation couple showed no differences between limbs during early stance at visits 1 and 2, but showed that the ACLR involved limb had greater coordination variability than the ACLR contralateral limb at the third visit. During mid-stance the ACLR involved limb was reduced at visit 1, but there were no differences at visits 2 and 3. There were no differences between limbs during late stance. The thigh-leg rotation couple showed no differences between limbs for early or mid-stance at any visit. During late stance, the ACLR involved limb had reduced coordination variability compared to the ACLR contralateral limb at visit 1, but became similar at visits 2 and 3. The leg-foot flexion-extension couple had no differences between limbs during early stance at any visit. The ACLR involved limb had reduced coordination variability at visit 1 during mid-stance compared to the ACLR contralateral limb, but became similar at visits 2 and 3. This was also shown during late stance at visits 1 and 2. The leg rotation-foot eversion couple showed that the ACLR involved limb had reduced coordination variability compared to the ACLR contralateral limb during early stance at visits 1 and 2, but became similar at visit 3. During mid-stance this was shown at visit 1 but was similar for visits 2 and 3, while during late-stance this was shown for visit 2 only.

The final hypothesis was that the coordination variability of the ACLR contralateral limb during all three portions of stance at each progressive time point would be similar to the healthy control limb at three portions of stance measured at one time point. The pelvis-thigh flexion-extension couple showed the ACLR contralateral limb had greater coordination variability compared to the control limb during early stance at
visit 1, but the limbs were similar at the later visits. During mid-stance the control limb was greater at visit 2, but similar at visits 1 and 3. During late-stance there were no differences between limbs. For the pelvis-thigh rotation couple during early stance the ACLR contralateral limb had greater coordination variability at visit 1 compared to the control limb at visit 1 but they were similar to the other visits. There were no differences between limbs during mid-stance. During late stance at visit 2 the control limb had significantly greater coordination variability but was similar at the other visits. For the thigh-leg flexion-extension couple the ACLR contralateral limb had increased coordination variability compared to the control limb during early stance at visits 1 and 3, but was similar at visit 2. The ACLR contralateral limb was also greater at visit 1 during both mid and late stance, but similar at the following visits for both portions of stance. For the thigh flexion-leg rotation couple showed no differences between limbs for any visit during early stance, but showed the ACLR contralateral limb had increased coordination variability compared to healthy at all visits during mid-stance. In contrast, the control limb had higher coordination variability during late stance at visits 1 and 3, but was similar at visit 2. The thigh-leg rotation couple showed that the ACLR contralateral limb had higher coordination variability than the control limb during early stance at visit 1, but was similar at the other visits. During mid and late stance there were no differences between limbs at any visit. For the leg-foot flexion-extension couple the ACLR contralateral limb had increased coordination variability at visit 1 compared to the control during early stance, but was similar to control at subsequent visits and there were no other differences between limbs. For the leg rotation- foot eversion couple during early and mid-stance the ACLR contralateral limb had greater coordination variability.
compared to the control limb at visits 1 and 2, but became similar at visit 3. In contrast, during late stance the control limb had increased coordination variability at all visits.

5.3 Conclusions

The results of this study demonstrated that ACLR involved limbs have decreased inter-segment coordination variability of the lower extremity during the late stance phase of gait compared to both the ACLR contralateral and healthy control limbs at 4 weeks post-surgery. This means that the athletes are freezing the use of available degrees of freedom in order to protect their recovering knee. This was in agreement with much of the literature on coordination variability in populations with overuse injury and pathology (Hamill et al., 1999; Seay et al., 2011; Hamill et al., 2012). By 12 weeks post-surgery there were improvements in neuromuscular health and joint function indicated by the ACLR involved limbs becoming similar to healthy controls in terms of coordination variability. This means that the ACLR involved limbs are improving to the level of the control limbs, allowing for the use of more degrees of freedom and allowing the athlete to adjust to potential perturbations. This result opposes the current literature examining coordination variability following ACL reconstruction. Joint coordination variability has been shown to increase following surgery in this population in the literature (Moraiti et al., 2010; Pollard et al., 2015). The results of the present study may differ from these based on the type of variability being measured. There are a number of other limitations to be considered when interpreting the findings of the present study including the assumption that the control limb would not change over time, the difference in preferred walking velocities between visits, and the number of trials used. Contrary to our hypotheses, coordination variability in the present study is not an indication of the
increased risk for ipsilateral graft rupture and contralateral ACL rupture in this population as the ACLR limb was similar to the healthy control limb when athletes were cleared to run. Further work should address the limitations of this study in order to help identify characteristics of this increased risk.

5.4 Future Studies

The current research leads to the following studies that may clarify results and reduce limitations of this study.

- **Inter-segment coordination and coordination variability in a healthy population over time.**
  
  Data for the control group in the present study was collected at one time point. It was assumed that in a healthy population coordination and coordination variability would not change over time. This should be determined in a future study so that comparisons between the data measured at progressive time points for the ACLR group can be made accurately against one time point for the healthy control group without assumption.

- **Impact of variation in number of trials on coordination variability results in a healthy population.**
  
  The current study used a minimum of three walking trials to determine the coordination variability, however increasing the number of trials may produce different and perhaps more accurate variability results. Therefore, future research
should determine the optimal number of walking trials necessary to calculate coordination variability.

- **Effect of walking velocity on coordination variability.**
  Decreased walking velocity has been associated with increased coordination variability as it lower velocities require greater neuromuscular control to maintain balance during longer single leg support times (Chiu & Chou, 2012). However, this relationship is not widely represented in the literature. Therefore, future research should examine how walking at different velocities (both preferred and set) affects coordination variability.

- **Differences in outcomes of inter-segment versus joint coordination variability.**
  Inter-segment variability has been associated with the overall joint function while joint coordination is associated with temporal control of joints to produce a movement. Both types of coordination variability should be determined in the same population in order to determine if coordination variability is the reason for the discrepancy between the inter-segment coordination variability results of the current study and the inter-joint coordination variability presented in the literature.
- **Time between ACL rupture and surgery.**

The time between ACL rupture and surgery may influence the recovery of athletes to post-surgery and therefore contribute to the change in inter-segment coordination variability over the progressive time points in the present study. Future work should address the effect that time between injury and surgery has on recovery and inter-segment coordination variability.
5.5 References


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