12-2020

The Effect of Visual Disruption on Stability After Anterior Cruciate Ligament Reconstruction

Nathan John Robey

UNIVERSITY OF NORTHERN COLORADO

Greeley, Colorado

The Graduate School

THE EFFECT OF VISUAL DISRUPTION ON STABILITY AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

A Dissertation Submitted in Partial Fulfillment
of the Requirements for the Degree of
Doctor of Philosophy

Nathan John Robey

College of Natural and Health Sciences
School of Sport and Exercise Science
Biomechanics Emphasis

December 2020

This Dissertation by: Nathan John Robey

Entitled:
The Effect of Visual Disruption on Stability After Anterior Cruciate Ligament Reconstruction

has been approved as meeting the requirement for the Degree of Philosophy in College of Natural and Health Sciences in School of Sport and Exercise Science, Program Exercise Science.

Accepted by the Doctoral Committee

____
Gary Heise, Ph.D., Research Advisor

____
Jeremy Smith, Ph.D., Committee Member

____
Sara Winges, Ph.D., Committee Member

____
Khalil Shafie, Ph.D., Faculty Representative

Date of Dissertation Defense___________________________________

Accepted by the Graduate School

____
Dr. Jeri-Anne Lyons, Ph.D.
Dean of the Graduate School and
Associate Vice President of Research

ABSTRACT

Robey, Nathan John. *The Effect of Visual Disruption on Stability After Anterior Cruciate Ligament Reconstruction*. Published Doctor of Philosophy dissertation, University of Northern Colorado, 2020.

The overall purpose of this dissertation was to investigate the influence of visual disruption on measures of postural stability, specifically in anterior cruciate ligament reconstruction (ACLR) individuals. Each of the two studies included in this dissertation evaluated postural stability, with the first study evaluating static postural stability and the second study evaluating dynamic postural stability. For the first study, 26 individuals (ACLR group n = 13; control group n =13) were asked to complete both double- and single-limb stances on embedded force platforms while visual information was disrupted using stroboscopic eyewear. Postural stability was assessed using traditional center of pressure (COP) measures. A more recently developed stabilogram diffusion analysis (SDA) was attempted on this group, but data for nearly half of the participants in each group could not be interpreted so this analysis was discarded. Visual information was disrupted using specialized stroboscopic eyewear that cycled through periods of clear and opaque settings. Two visual disruption settings (low and high) along with and eyes-open condition were completed during all stability testing. Group comparisons were performed between individuals with a history of ACLR and healthy, young adults were assessed using standard data analysis. In both double- and single-limb postural stability tasks, demonstrated that ACLR individuals did not rely on visual information to a greater extent than healthy controls. During double-limb stance, ACLR individuals presented with decreased levels of mean COP frequency compared to controls (0.50 ± 0.20 vs 0.69 ± 0.29 Hz). However, no group differences were observed for root mean square distance, mean velocity, and sway area of the COP. No group differences were observed for the single-limb stance condition. Postural stability changes were observed when visual information was disrupted through the use of stroboscopic eyewear, indicating that the glasses were effective at challenging an individual's postural control. For the double-limb stance, the high level of visual disruption resulted in increased mean velocity (14.28 mm/s) compared to the eyes open conditions (13.03 mm/s). All single-limb standard COP measures of postural stability were elevated in the low and high visual disruption conditions when compared to the eyes open condition. The second study's purpose was to evaluate whether ACLR individuals relied on visual information to a greater extent than healthy controls during a dynamic single-limb hopping task. For the dynamic task protocol, 22 participants (ACLR group n = 11; control group n =11) jumped from a two-footed stance and touched an overhead target before landing in a single-limb position on a force platform. The visual conditions utilized three conditions, eyes open, low visual disruption, and high visual disruption. Dynamic postural stability was evaluated using both standard and SDA measures. No group differences were observed, indicating that ACLR individuals did not present with worsened dynamic postural stability compared to healthy controls. There were significant differences between the visual conditions in both the standard and SDA measures. Only the medial-lateral stability index increased with visual disruption for the standard measures. For SDA measures, both the mean critical square displacement and short-term diffusion coefficient increased with visual disruption, and both short- and long-term scaling exponents decreased with visual disruption.

In both studies, the lack of an interaction between the effects of group and vision suggests that ACLR individuals do not rely on visual information to a great extent than control individuals. Additionally, ACLR individuals do not present with worsened postural stability than controls for static or dynamic postural stability tasks. Additionally, this dissertation demonstrated that stroboscopic eyewear perturbed static and dynamic postural stability. The effects of the visual disruption on postural stability had more significant effects during the more challenging single-limb and dynamic postural stability tasks. Based on the current dissertation findings, future research should aim to explore static and dynamic postural stability tasks with activity level matched healthy controls. Future research should also explore the connection between stroboscopic eyewear and sport-like activities to justify their use for laboratory analysis.

ACKNOWLEDGEMENTS

To my friends and family, who showed unwavering amounts of love and support over the years, thank you. This dissertation could not have happened without each and every one of you. To the graduate student cohort at UNC, thank you all for being such great friends throughout this journey. Otto and Shane, we did it! What a ride, my friends. Thanks for all the early morning coffee runs and the late-night brainstorming sessions. I could not have done this without the support from both of you over the years, so thank you. To my committee, thank you all for the time and effort you put into helping me with this project. I would especially like to thank my advisor Dr. Gary Heise. Thank you for being a glowing example of what it means to be a professor in higher education. I hope to one day inspire students the way you have inspired so many before me. To my wife Hillary, thank you for always listening to my seemingly unending list of dissertation ideas. Thank you for always pushing me to be my best self and for making me sit at my desk to get this project finished.

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CHAPTER I

GENERAL INTRODUCTION

Injury to the anterior cruciate ligament (ACL) is a common knee injury that often occurs during sport related activities. Non-contact ACL injuries are estimated to account for 70% of all ACL injuries and occur during sudden landing, cutting, or deceleration tasks (Boden et al., 2000; Hewett et al., 2005a). It is estimated that over 250,000 ACL injuries occur in the U.S. annually, with 175,000 of those individuals electing to undergo ACL reconstruction (Gottlob et al., 1999; Griffin et al., 2006). Surgical reconstruction is performed to restore mechanical stability to the knee, allowing individuals to return to pre-injury sport related activities (Ardern et al., 2011; Barber-Westin & Noyes, 2011; Spindler & Wright, 2008). An estimated cost of ACL treatment, including surgery, rehabilitation, and future pathologies, ranges from $7.6 billion to $17.7 billion per year in the U.S., which places a massive financial burden on our healthcare system (Grooms, Appelbaum, & Onate, 2015a; Mather et al., 2013). After completing the rehabilitation process, research demonstrates that a high number of athletes are able to return to sport (RTS), often reaching similar playing levels as before injury (Brophy et al., 2012; Gans et al., 2018). However, it is hypothesized that while biomechanical measures may return to normalized values and allow for RTS, neurological deficits may remain (Gokeler et al., 2013; McLean, 2008; Needle et al., 2017; Relph et al., 2014).

Complex neuromuscular changes such as those found in ACL reconstructed (ACLR) patients indicate that an ACL injury is not a simple musculoskeletal injury, but rather a more complex injury involving the neurological system (Grooms et al., 2017; Kapreli et al., 2009; Needle et al., 2017). After ACL injury, it has been postulated that neural feedback systems are disrupted, leading to disturbances in the neuromuscular control of the knee (Bonfim et al., 2003; Grooms et al., 2015a; Hasan et al., 2013; Howells et al., 2011; Lehmann et al., 2017; Needle et al., 2017). For example, damage to the native mechanoreceptors present in the ACL may lead to deficits in the somatosensory information received from the knee. Disruption of the somatosensory feedback has been confirmed in ACLR individuals from testing joint position sense and threshold detection of active/passive motion (Relph et al., 2014; San Martín-Mohr et al., 2018; Schultz et al., 1984). These lingering neuromuscular changes may increase an ACLR individual's risk of sustaining a secondary injury (Culvenor et al., 2016; Paterno et al., 2010)

It is estimated that ACL re-injury rates may be as high as 25%, with an increased risk of injury to the contralateral limb once athletes RTS (Hui et al., 2011; Paterno et al., 2012, 2014; Wright et al., 2007). Previous research has demonstrated unresolved neurological adaptations after an ACL injury, reconstructive surgery, and standard rehabilitation (Baumeister et al., 2011; Bonfim et al., 2003; Grooms et al., 2017, 2018; Konishi, 2011; Madhavan & Shields, 2011). These alterations include gamma-motor neuron loop changes, disrupted cortical excitability, altered muscle preactivation times, and slowed long latency reflexes (Grooms et al., 2017; Hasan et al., 2013; Konishi, 2011; Lepley et al., 2020; Madhavan & Shields, 2011; Oliver et al., 2018; Palmieri-Smith et al., 2019; Pietrosimone et al., 2013). Deficiencies or alterations in neuromuscular control may contribute to increased loads on the knee and an increased risk of damage to the reconstructed ligament or contralateral knee (Burland et al., 2020; Palmieri-Smith et al., 2009; Theisen et al., 2016).

Somatosensory deficits experienced by individuals who have undergone ACL reconstruction may cause increased reliance on visual feedback during sport related activities (Bonfim et al., 2008; Negahban et al., 2014; Okuda et al., 2005). Removing visual information in a lab environment allows for insight into the contribution of the visual system; however, it does not replicate sporting scenarios well. The use of stroboscopic glasses has been proposed as a method for replicating neurocognitive demands typically present during sports activities (Grooms et al., 2018). Stroboscopic glasses are designed to disrupt visual input while not completely blocking it (Grooms et al., 2018). These glasses cycle through a series of open and closed conditions that can be manually adjusted to allow for increased or decreased levels of visual input. While the visual system is a crucial feedback system, it is only one aspect of the afferent pathways. ACLR individuals present with a unique problem, as the somatosensory system is affected due to the loss of sensory receptors within the native ACL ligament, and therefore visual feedback is relied on to compensate (Bonfim et al., 2008; Grooms et al., 2015a, 2017; Negahban et al., 2013). Since both somatosensory and visual information are relied upon to maintain appropriate neuromuscular control and postural stability, if one system is impacted, then compensatory movement strategies may be adopted (Grooms et al., 2015a; Nyland et al., 2014; R. J. Peterka, 2002; Peterka & Loughlin, 2004).

Currently, RTS decisions are based upon subjective information (i.e., patient-reported forms), time since surgical intervention, and biomechanical profiles; however, postural stability tests are often neglected (Rambaud et al., 2017). Postural stability examinations allow researchers and clinicians to easily manipulate sensory information received using surface or visual changes (Prieto et al., 1996). Due to ACLR individuals hypothesized increased reliance on visual feedback, assessing postural stability tests may provide additional information to help evaluate an individual's rehabilitation or RTS progress. Traditional static postural stability measures (i.e., center of pressure (COP) excursion and velocity) have demonstrated significant changes in the ACL injured groups once visual feedback has been removed compared to eyes open (Bonfim et al., 2003; Dingenen et al., 2015; Negahban et al., 2013; O'Connell et al., 1998; Okuda et al., 2005).

Deficits in static postural stability measures have been observed in ACLR individuals compared to uninjured, healthy controls (Bonfim et al., 2003, 2008; Dauty et al., 2010; Denti et al., 2000; Howells et al., 2011, 2013; Lehmann et al., 2017; Mohammadi et al., 2012; Zouita Ben Moussa et al., 2009). For example, Dauty et al. (2010), Mohammadi et al. (2012), and Zouita Ben Moussa found larger COP sway areas and COP velocities in ACLR individuals. These static postural stability deficits are commonly observed during single-limb testing as it places a greater challenge on the ACLR limb than in a bilateral testing condition. How exactly bilateral postural stability is impacted after ACLR remains unclear, as previous literature demonstrates conflicting results (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Henriksson et al., 2001; Mattacola et al., 2002). Both Denti et al. (2000) and Henriksson et al. (2001) found larger postural stability scores in ACLR individuals compared to healthy controls. Additionally, Dauty et al. (2010) found increased measures of COP area and total distance in ACLR individuals. In contrast to these findings, Bonfim et al. (2003) and

Mattacola et al. (2002) found no differences in COP sway area, total distance, or stability index score when compared to healthy controls. Static postural stability tests provide insight into an individual's general postural stability but do not reflect the dynamic movements commonly observed during sports activity (Colby et al., 1999; Heinert et al., 2018). Sell (2012) demonstrated a lack of correlation between static and dynamic postural stability measurements in healthy, active populations. In addition, Sell et al. recommended the use of dynamic postural stability tasks when examining athletic populations because of the increased challenge of the task when compared to static tasks.

Dynamic postural assessments have demonstrated lingering postural stability deficits in ACLR individuals that remain impacted years after surgery (Alonso et al., 2009; Dauty et al., 2010; Denti et al., 2000; Heinert et al., 2018; Howells et al., 2011; Lehmann et al., 2017; Mattacola et al., 2002; Mohammadi et al., 2012; Webster & Gribble, 2010). Previous research has implemented both the use of moveable force platforms and single-limb landings to assess dynamic postural stability in ACLR individuals (Dauty et al., 2010; Harrison et al., 1994; Henriksson et al., 2001; Zouita Ben Moussa et al., 2009). However, single-limb landings may be more appropriate to measure in ACLR individuals as it better replicates sports activity (Heinert et al., 2018). Both Heinert et al. (2018) and Webster and Gribble (2010) found dynamic postural stability deficits in ACLR individuals who had been cleared to RTS. While research on visual reliance in ACL individuals during static postural stability has been explored, minimal research exists using dynamic tasks. Recently, Grooms et al. (2018) utilized visual disrupting eyewear in ACLR individuals during drop landings and observed changes in landing mechanics when visual information was reduced. These maladaptive movement strategies observed in ACLR individuals may affect both biomechanical and dynamic postural stability measures, which have been suggested as a potential re-injury risk factor for ACLR individuals (Paterno et al., 2010, 2013).

While it appears that traditional postural stability measures (static and dynamic) may be sensitive enough to capture deficits present in ACLR individuals, their physiological meaningfulness remains in question (Collins & De Luca, 1993; Heise et al., 2012). The Stabilogram Diffusion Analysis (SDA) is a method for gaining more meaningful motor control information from static stabilograms compared to the traditional postural stability assessments (Collins & De Luca, 1993). SDA measures provide information about the interaction of the open-loop and closed-loop neuromuscular mechanisms of postural stability (Collins & De Luca, 1993). This approach uses COP path and time intervals to create a stabilogram-diffusion plot containing two distinct slopes (Collins & De Luca, 1993) (Figure 1.1). The slopes are then used to determine the amount of stochastic activity along the COP path and create two distinct regions associated with open-loop and closed-loop control, and an approximation of when this transition occurs. SDA has demonstrated its ability to detect differences between young and elderly populations, between healthy elderly and idiopathic Parkinson's disease populations, and between vision and no-vision conditions (Collins et al., 1995c; Collins & De Luca, 1995a; Mitchell et al., 1995). Collins and De Luca (Collins et al., 1995c) found that elderly patients utilized open-control mechanisms for longer time intervals than young, healthy individuals. A potential hypothesis for this change in neuromuscular control is that the elderly population experiences reduced proprioception as a result of aging (Collins et al., 1995c). Since ACLR individuals are believed to have reduced proprioception, it can be hypothesized that they may display a similar behavior as the elderly population. Therefore, the additional insights into postural control mechanisms provided by the SDA analysis may improve our understanding of neuromuscular deficits present in ACLR individuals. Understanding this additional information may provide clinicians with more useful information for potentially helping reduce the rate of second ACL injuries. If neuromuscular deficits can be detected during postural stability examinations in the clinic, appropriate rehabilitation efforts may be implemented to direct needed changes.

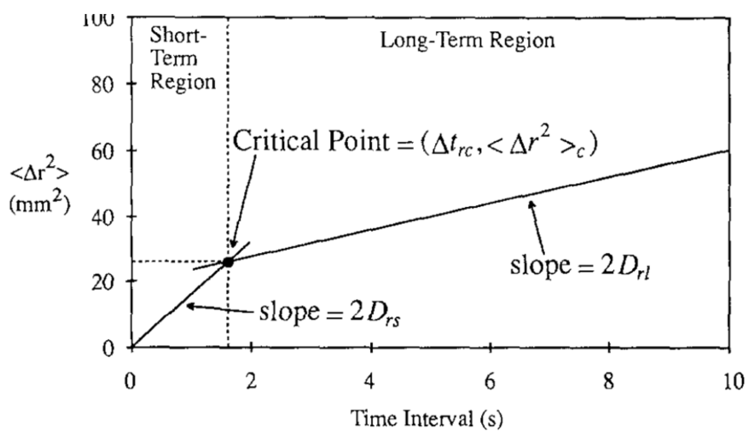

Figure 1.1. Stabilogram Diffusion Analysis Plot. SDA resultant planar plot of Δr^2 and time intervals. Displays both short- and long-term regions used to define open- and closed-loop control. The critical point is the intersection of the two slopes and represents the transition point between open-and closed-loop motor control (adapted from Collins & De Luca, 1993).

In summary, ACL reconstruction and rehabilitation may correct the mechanical stability of the joint, but neuromuscular processes may be compromised, and this may increase an individual's risk of sustaining a second ACL injury (Paterno et al., 2010, 2013). Due to potential deficits in somatosensory information and increased reliance on visual information, it is crucial to understand how ACLR individuals behave with limited visual feedback. By limiting the amount of visual feedback an individual receives rather than entirely blocking it, we can better understand how an individual will perform during athletic scenarios when visual information may be devoted to environmental stimuli (Boden et al., 2009; Brown et al., 2009; Grooms et al., 2015a). Understanding the relationships between visual disruption and postural stability in ACLR individuals can provide clinicians with more information about motor control changes and sensory reweighting due to the loss of somatosensory information from the knee. Given these considerations, the primary purpose of this dissertation was to evaluate static (Study 1) and dynamic stability (Study 2) responses in ACLR individuals and healthy controls under normal and disrupted visual conditions. A secondary purpose was to investigate neuromuscular responses to visual disruption while landing during a dynamic single-leg landing task (Study 3).

Hypotheses

Study One Hypotheses – Static Postural Stability and Anterior Cruciate Ligament Reconstruction

H1 Double-leg static postural stability measures (traditional and SDA) will not be significantly different between the ACL reconstructed group and healthy controls.

H2 Visual disruption conditions (low visual disruption, high visual disruption) will be significantly different from the eyes open condition.

H3 Single-leg static postural stability measures in healthy controls will be more stable in traditional measures compared to the ACL reconstructed group.

H4 ACL reconstructed individuals will have increased short-term diffusion coefficients, shifted critical times, increased short-term scaling exponents, and decreased long-term scaling coefficients compared to healthy controls.

H5 Visual disruption conditions (low visual disruption, high visual disruption) will be significantly different from eyes open condition when analyzed with stabilogram diffusion analysis.

H6 A significant interaction will be present between the ACL reconstruction group and healthy controls over the visual disruption conditions during single-leg postural stability tasks.

Study Two Hypotheses – Dynamic Postural Stability and Anterior Cruciate Ligament Reconstruction

H1 Healthy control participants will present with more stable traditional dynamic stability measures compared to the ACL reconstructed group during single-leg dynamic landings.

H2 As visual feedback is disrupted, dynamic stability measures will increase in both groups compared to the eyes open condition.

H3 ACL reconstructed participants will present with increased short-term diffusion coefficients, right shifted critical times, increased short-term scaling exponents, and decreased long-term scaling coefficients compared to healthy controls.

H4 Visual disruption conditions (low visual disruption, high visual disruption) will be significantly different from eyes open condition when analyzed with stabilogram diffusion analysis.

H5 A significant interaction will be present between the ACL reconstruction and healthy control groups over the visual disruption conditions.

**** Study three was not included in the final dissertation because the data for the study was not accessible due to COVID-19 related campus closures. Study three data was unable to be processed using Visual 3D software and exported as the data collection computer was not accessible.**

Study Three Hypotheses – Visual Disruption and Dynamic Landings

H1 ACL reconstructed participants will present with increased preactivation times in both quadriceps and hamstring musculature during single-leg dynamic landings compared to healthy controls.

H2 As visual disruption increases, muscle preactivation time will increase.

H3 ACL reconstructed participants will have decreased levels of quadriceps:hamstring co-contraction during single-leg dynamic landings compared to healthy controls.

H4 As visual impairment increases, muscle co-contraction will decrease.

CHAPTER II

REVIEW OF LITERATURE

Introduction

Anterior cruciate ligament (ACL) injuries are one of the most common knee injuries occurring in sports today. It is estimated that roughly 250,000 ACL reconstructions occur each year in the United States, with 175,000 of those individuals electing to undergo ACL reconstruction (Gornitzky et al., 2016; Gottlob et al., 1999; Myer et al., 2004; Paterno et al., 2011; Wojtys & Brower, 2010). Beyond the direct costs of the treatment of the injury, indirect costs may be present, including decreased physical activity, loss of financial stability (i.e., college scholarship, professional salary), and increased risk of long-term disability such as osteoarthritis (Freedman et al., 1998; Myer et al., 2004). These indirect costs on our health care system are estimated to range from $7.6 to $17.7 billion per year in the United States (Grooms et al., 2015a; Mather et al., 2013). After sustaining an ACL injury, individuals often elect to undergo a surgical intervention to restore mechanical stability to the knee joint and return to athletic competition (Ardern et al., 2011; Barber-Westin & Noyes, 2011). Once the surgery is completed, individuals undergo an intensive neuromuscular rehabilitation program to restore range of motion (ROM), muscular strength, and postural stability. Before returning to sport (RTS), individuals undergo a variety of tests, performed by clinicians such as Athletic Trainers and Physical Therapists, to determine if any significant asymmetries exist between the surgically repaired limb and uninjured contralateral limb.

The primary goal of anterior cruciate ligament reconstruction (ACLR) and rehabilitation is to restore the mechanical stability of the knee. Athletes who undergo ACL reconstructive surgery plan on returning to similar levels of sports activity as they did prior to their ACL injury (Feucht et al., 2016). However, roughly half of individuals who suffer this type of knee injury return to competitive sports (Ardern et al., 2011, 2014). The problem with the current model of RTS evaluation is that it lacks consistent evidence supporting the ability to reduce the risk of injury, specifically the risk of a second ACL injury (Webster & Hewett, 2019). Previous research has suggested that the risk of re-injury may be as high as 25% (Grooms et al., 2018; Hui et al., 2011; Paterno et al., 2010, 2012; Wright et al., 2007). Passing the RTS test battery leads to a reduction in injury risk of the graft but leads to an increased risk of injury on the contralateral limb (Webster & Hewett, 2019). High injury risk may be due to factors such as reduced lower extremity strength, altered knee proprioception, changes in the biomechanics of landing, decreased neuromuscular control, poor postural stability, and fear-avoidance beliefs (Heinert et al., 2018; Mohammadi et al., 2012; Myer, G.D., Ford, K.R., McLean, S.G. & Hewett, 2006; Paterno et al., 2010, 2011; Wojtys & Huston, 2000). Currently, most RTS protocols used by clinicians only evaluate biomechanical measures associated with injury risk, while neurological information is not assessed with current tests. A task that is often not assessed but yet could provide further insight into an individual's readiness to RTS involves postural stability measures, specifically dynamic postural stability (Heinert et al., 2018; Paterno et al., 2010). Therefore, a deeper understanding of how postural stability measures remain affected after ACLR and RTS will facilitate the development of better clinical RTS screening methods.

The scope of this literature review will examine the following topics: (a) structure and function of the ACL, (b) ACL injury risk factors, (c) ACL re-injury risk factors, (d) postural stability in ACLR individuals, (e) somatosensory deficits and visual reliance, (f) electromyography and muscle function, and (g) return to sport criteria. A rigorous search strategy to find related research began with an intensive database search and review of previously cited literature. Databases used were CINAHL, SPORTDiscus, PubMed, and Google Scholar.

Structure and Function of the Anterior Cruciate Ligament

Structure

To properly understand the mechanisms behind an ACL injury and its recovery, one must understand the anatomy of the ACL. The ACL is a collection of dense connective tissue connecting the distal portion of the femur to the proximal portion of the tibia (Duthon et al., 2006). More specifically, the ACL attaches on the posterior portion of the medial aspect of the lateral femoral condyle and inserts onto a fossa located anterior and medial from the medial intercondylar tubercle (Duthon et al., 2006; Girgis et al., 1975; Moore et al., 2010). The ACL is functionally separated into two distinct bundles, anteromedial and posterolateral bundles (Figure 2.1) (Duthon et al., 2006; Girgis et al., 1975).

The anteromedial bundle originates from the anterior and proximal portion of the femoral insertion and inserts inferiorly on to the anteromedial aspect of the tibial insertion (Amis & Dawkins, 1991; Duthon et al., 2006). The posterolateral bundle attaches to the posterior and distal aspect of the femur and inserts onto the posterolateral aspect of the tibial insertion point (Amis & Dawkins, 1991; Duthon et al., 2006). The

ACL also does not exhibit a constant shape; instead, the ACL has a smaller cross-sectional area at the femoral insertion site (~34 mm^2), and the ligament begins to "fan" out towards the tibial insertion site creating a larger cross-sectional area on the inferior portion of the ligament (~42 mm^2) (Duthon et al., 2006; Harner et al., 1995).

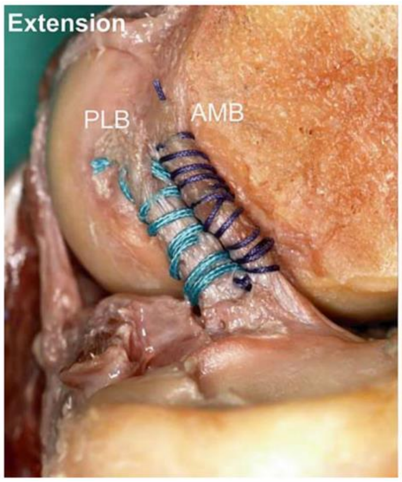

Figure 2.1. Anatomy of the ACL. Anatomical representation of the two distinct bundles of the ACL (adapted from Duthon et al., 2006).

Function

The ACL plays a crucial role in providing knee joint stability, as it is the primary stabilizer against anterior tibial translation (ATT) and also rotational loads (Domnick et al., 2016; Duthon et al., 2006). ATT can be defined as the tibia shifting anteriorly with respect to the femur. The amount of ATT that occurs at the knee joint depends on the angular position of the knee joint itself. Zantop et al. (2007) found that in cadaver limbs, ATT was the greatest at 30° knee flexion compared to 0°, 60°, and 90° positions. A secondary role of the ACL is to resist internal rotation of the tibia when the knee is near full extension (Duthon et al., 2006; Zantop et al., 2007). Duthon et al. (2006) suggested that the ACL may also play a role in restraining knee varus and valgus positioning during weight-bearing tasks. This function of the ACL ligament may be seen during the "pivot shift test" (Duthon et al., 2006). The pivot shift test is an orthopedic clinical test where a valgus force is applied proximal to the knee while the clinician maintains an internal rotation position of the lower limb (Starkey et al., 2011).

Changes in the exact function of the ACL can be seen when the knee position is changed during movement. During knee flexion and extension motions, the tension placed on the anteromedial and posterolateral bundles does not remain constant, instead the tension shifts between the two bundles (Domnick et al., 2016; Duthon et al., 2006; Girgis et al., 1975; Zantop et al., 2006). As the knee begins to move into flexion, the anteromedial bundle starts to tighten and increase in length (Duthon et al., 2006; Hollis et al., 1991; Zantop et al., 2007). Zantop et al. (2007) found that when the posterolateral bundle was removed and an anteriorly directed or rotary (combined knee valgus and internal tibial rotation) load was applied to the knee, ATT significantly increased at 30°, but was not statistically significant at 60° and 90°. These findings correspond with the changes seen in the posterolateral bundle's length from 0° of knee flexion (i.e., full extension) to 90° of knee flexion. Hollis et al. (1991) found that the posterolateral bundle was at its longest length (22.5 mm) at 0°, and when flexed to 30°, its length decreased by 3.2 mm (19.5 mm). Therefore, at lower angles of knee flexion (i.e., < 30°), the posterolateral bundle is responsible for primarily resisting ATT while the anteromedial bundle becomes slack (Hollis et al., 1991). In this same experiment, as the knee was flexed to 90°, the length of the posterolateral bundle decreased again (15.4 mm) (Hollis et al., 1991). Zantop et al. (2007) found that when the anteromedial bundle of the ACL was removed, ATT significantly increased at both 60° and 90°. As the knee increases its knee flexion angle, the length of the anteromedial bundle increases in length, starting at 34.4

mm to 38.8 mm (3.6 mm) (Hollis et al., 1991). The increased ATT at higher degrees of knee flexion indicates the anteromedial bundles increased role at higher degrees of knee flexion when the posterolateral bundle is most lax (Zantop et al., 2007).

Anterior Cruciate Ligament
Injury Risk Factors

Often ACL injuries occur during non-contact sports-related incidents involving dynamic movements such as a landing task, cutting maneuver, and sudden negative acceleration (Yu & Garrett, 2007). While the dynamic motions that may lead to ACL injury are well understood, the exact mechanism behind this catastrophic injury remains unclear. Previous research has suggested that the ACL injury mechanism is multifactorial and is impacted by the following factors: 1) anatomical, 2) hormonal, 3) genetic, 4) neuromuscular, and 5) biomechanical (Hewett et al., 2005a; Shultz et al., 2015). For the purposes of this literature review, only the biomechanical and neuromuscular risk factors will be analyzed as they are the most modifiable and likely to remain impacted after reconstructive surgery.

Biomechanical and Neuromuscular Risk Factors

ACL injury biomechanics have been extensively studied in an effort to better understand the behavior of the lower extremity during sport-like movements such as landing from a jump or a lateral cutting motion. Research involving biomechanical measures allow researchers and clinicians to gain insight into lower extremity kinematics and kinetics that may place an individual at an increased risk of sustaining an ACL injury. Neuromuscular control involves the unconscious activation of dynamic restraints in preparation for, or in response to, forces and this control helps stabilize the joint (Riemann & Lephart, 2002). In order to maintain proper biomechanics during dynamic activities, one needs proper neuromuscular control. Neuromuscular imbalance involving the lower extremity may place an individual at an increased risk of sustaining an initial injury, and also be a risk factor for a second ACL injury (Bryant et al., 2008; Di Stasi et al., 2013; Hewett et al., 2010; Myer et al., 2004).

During sport-specific activities such as drop landings or cutting motions, previous research has demonstrated that increases in knee valgus angle and knee abduction loads are risk factors for sustaining an ACL injury (Carcia et al., 2005; Hewett et al., 2005a, 2010; McLean et al., 2005, 2010; Shultz et al., 2015). Previous research by Quatman et al. (2011) supports the theory of increased knee abduction angles, often referred to as valgus collapse, as a mechanism of ACL injury. Quatman et al. (2011) used articular cartilage pressure distributions to confirm that ACL injuries were the result of a combination of knee valgus, ATT, and external/internal tibial rotation. Hewett et al., (2005a) prospectively screened female athletes and found that those who went on to suffer an ACL injury had increased knee abduction angles and knee abduction moments during drop landings. Along with the increased knee abduction angles and moments, injured participants also demonstrated a 20% increase in vertical ground reaction force (VGRF) during the stance phase of the drop landing (Hewett et al., 2005a).

While aberrant frontal knee motions increase an individual's ACL injury risk, changes in sagittal plane motion at the knee and trunk have also been suggested as injury risk factors (Blackburn & Padua, 2009; Shimokochi et al., 2009; Shultz et al., 2015). Decreases in knee, hip, and trunk flexion have been shown to also contribute to ACL injuries (Blackburn & Padua, 2009; Krosshaug et al., 2007; Shimokochi et al., 2009). Blackburn and Padua (2009) demonstrated that when individuals landed with increased trunk flexion, both vertical ground reaction forces and quadriceps activity were decreased. This decrease in quadriceps activity is essential as inappropriate activation of the quadriceps muscles has been shown to increase ACL injury risk (Palmieri-Smith et al., 2008, 2009).

Several neuromuscular risk factors have been associated with the initial injury, including quadriceps dominance and leg dominance (Myer et al., 2004). Quadriceps dominance is described as an imbalance between the quadriceps and hamstring muscle groups (Hewett et al., 2005b, 2010; Myer et al., 2004). During dynamic tasks, individuals will recruit their quadriceps muscles prior to the hamstring muscle groups (Hewett et al., 2005b; Myer et al., 2004). Increased reliance on the quadriceps musculature is often seen in females when performing dynamic movements (Hewett et al., 2005b; Myer et al., 2004). This activation pattern may place an increased load on the passive structures supporting the knee joint and possibly lead to injury (Hewett et al., 2005b; Silvers & Mandelbaum, 2007). Leg dominance is another proposed neuromuscular risk factor for ACL injuries and occurs when strength or joint kinematics and kinetics differences exist (Myer et al., 2004). These limb differences may increase the risk of ACL injury on both the dominant and non-dominant sides due to differences in muscle strength and control (Myer et al., 2004). Neuromuscular deficits have been well researched for injury prevention and risk factor identification for the initial ACL injury. However, the neuromuscular implications of ACL reconstruction are less understood (Theisen et al., 2016). Previous research has demonstrated conflicting evidence regarding the recruitment and activation of muscles surrounding the knee joint after undergoing ACL reconstruction (Baratta et al., 1988; Bryant et al., 2009; Lustosa et al., 2011; Oliver et al., 2018; Rocchi et al., 2018; Segal et al., 2015; Tsai & Powers, 2013). Oliver et al. (2018) found during single-leg jumps, increased muscle latency in all quadriceps and hamstring musculature, except for the vastus lateralis after ACL reconstruction. However, at the 6-month check-in, there were no significant differences between injured and non-injured limbs (Oliver et al., 2018). The findings of Rocchi et al. (2018) are in contrast to the findings of Oliver et al. (2018). ACLR individuals, regardless of surgical type, employed a protective landing strategy during single-leg landings when compared to healthy controls (Rocchi et al., 2018). Increased pre-impact activation EMG duration was observed in quadriceps and hamstring musculature during landing, hopping, and jumping tasks (Rocchi et al., 2018). These findings of increased quadriceps and hamstring pre-activation times are similar to those observed in the previous literature (Gokeler et al., 2010). Due to conflicting results, further research needs to be performed in order to better understand these neuromuscular changes after ACL reconstruction.

Anterior Cruciate Ligament Reconstruction Injury Risk

While much of the previous research has been focused on the risk factors for initial ACL injury, research examining risk factors associated with a second ACL injury are not as prominent. Secondary ACL injury risks are hypothesized to originate from residual impairments stemming from the surgical intervention and the rehabilitation process (Grooms et al., 2018). Lingering deficits in an individual’s postural stability, quadriceps strength, and decreased hop performance may lead to altered loading patterns placing the passive structures supporting the knee at risk (Heinert et al., 2018; Hewett et al., 2002; Fitzgerald et al., 2001; Kobayashi et al., 2004; Kuenze et al., 2015; Shiraishi et al., 1996; Mattacola et al., 2002).

Research performed by Paterno et al. (2013) demonstrated decreased postural sway measurements in ACLR individuals that remain even after the individual's RTS. ACLR participants presented with less variable postural control measures, assessed with a moving platform (Biodex Balance System SD) (Paterno et al., 2013). Paterno et al. (2013) hypothesized that less variability in the postural sway amplitude may place the individual at an increased risk of injury. This rigid behavior may indicate that an individual is less able to adapt to changing environmental situations, thus making them more susceptible to future injury (Paterno et al., 2013). Paterno et al. (2010) also support the hypothesis that deficits in postural stability may lead to an increased risk of sustaining a second ACL injury. Individuals with single-leg postural stability deficits were twice as likely to sustain a second ACL injury than individuals who did not (Paterno et al., 2010). The mean degree of deflection, representing overall stability scores, were increased in the involved limb of those who went on to sustain a second ACL injury (4.07°±2.06°) when compared to those who did not (3.63°±1.58°) (Paterno et al., 2010).

Beyond deficits in dynamic postural stability measures, abnormal landing mechanics during a drop jump have also demonstrated the ability to predict a secondary ACL risk (Paterno et al., 2010). Multivariate logistic regression revealed that four variables predicted secondary ACL injury risk (Paterno et al., 2010). Decreased hip external rotation moment during the early part of the landing, frontal plane knee ROM during landing, asymmetrical sagittal plane knee position at initial contact, and decreased postural stability measures were the variables associated with a second ACL injury (Paterno et al., 2010). Paterno et al. (2010) used 3D motion analysis to analyze and describe these altered neuromuscular patterns that remain in ACLR individuals. These findings suggest that movement asymmetries during sport-like tasks may contribute to increased risk of injury.

Of the movement asymmetries recorded, hip external rotation moment during the initial loading phase of landings was the strongest predictor of a subsequent ACL injury (Paterno et al., 2010). This increase in frontal plane motion observed in those who sustained a second ACL injury is in agreement with previous findings for initial ACL injury risk (Bryant et al., 2008; Di Stasi et al., 2013; Hewett et al., 2005a, 2010; Myer et al., 2004). Specifically, knee valgus angles and moments are believed to contribute to an individual's initial ACL injury risk (Carcia et al., 2005; Hewett et al., 2005a, 2010; McLean et al., 2005, 2010; Shultz et al., 2015). Paterno et al. (2010) found that the second ACL injury group had significantly higher knee valgus motion during drop landings compared to the first injury group. Frontal knee motion seen during the early phase of the landings is believed to be controlled by neuromuscular factors at the hip, knee, and ankle (Carcia et al., 2005; Geiser et al., 2010; Hewett et al., 2010; McLean et al., 2010; Thomas et al., 2011). Therefore the decreased hip external rotation moment in the second ACL group indicates that neuromuscular deficits at the hip may not be fully resolved by the time of the athlete's RTS (Paterno et al., 2010).

Paterno et al. (2010) also found that asymmetrical sagittal plane knee moments were predictive of second ACL injury risk. The results of their study show that individuals who went on to sustain a second ACL injury had greater asymmetry in knee extensor moments at initial contact compared to the first ACL injury group (Paterno et al., 2010). Paterno et al. (2010) hypothesized that individuals who went on to sustain a second ACL injury had great imbalances in force absorption ability. A prior study demonstrated similar asymmetrical landings as Paterno et al. (2010) suggested and observed increased VGRF and loading rates in ACLR individuals during a drop vertical jump task (Paterno et al., 2007). The study by Paterno et al. (2007) found that ACLR individuals demonstrated increased VGRF and loading rates on the uninvolved limb during the landing phase of a drop jump. These abnormal movement patterns may be linked to an individual's risk of sustaining a second ACL injury (Paterno et al., 2007). More specifically, these findings support previous research demonstrating an increased risk of ACL injury on the contralateral side (Paterno et al., 2012; Wright et al., 2011). While not statistically significant, Paterno et al. (2012) found that ACL re-injury rates were three times greater in the contralateral knee compared to the ipsilateral knee.

Collectively, previous literature supports the hypothesis that deficits in postural stability may contribute to an ACLR individual's re-injury risk (Paterno et al., 2010, 2013). In addition to postural stability deficits, altered neuromuscular landing mechanics may also contribute to ACL re-injury risk (Paterno et al., 2007, 2010). Based on the results of previous literature, it is clear that while mechanical stability may be restored after surgical and rehabilitation interventions, it is not enough to prevent a second ACL injury completely. Therefore, further investigation is required to better understand these lingering postural stability and neuromuscular control deficits in this at-risk population.

Anterior Cruciate Ligament and Postural Stability

Postural stability requires sensory information (i.e., vision, vestibular, and proprioception) to elicit the appropriate motor responses to maintain equilibrium (Sell, 2012). Injury to the ACL may result in sensory deficits due to damage to sensory receptors within the native ACL and may persist after repair due to the new graft (Bonfim et al., 2003; Dauty et al., 2010; Heinert et al., 2018; Howells et al., 2011; Lehmann et al., 2017; Mohammadi et al., 2012; Webster & Gribble, 2010). Damage to the sensory systems may affect motor activities that are involved in maintaining postural control (Grooms et al., 2015a; Kapreli et al., 2009; Kapreli & Athanasopoulos, 2006; Needle et al., 2017).

Static Postural Stability

Postural stability is often assessed using a force platform with individuals attempting to maintain a stable body position. Static postural stability is often assessed using double or single-leg stances with either eyes open or closed conditions. These positions are then evaluated using center of pressure (COP) measurements such as COP excursion, COP velocity, and COP sway area (Prieto et al., 1996). An individual's postural stability may be impacted after sustaining an ACL injury, and remain affected even years after surgical intervention (Bonfim et al., 2003; Dauty et al., 2010; Mohammadi et al., 2012; O'Connell et al., 1998; Soltani et al., 2014). These findings are concerning as deficits in postural stability are related to increased lower extremity injury risk, specifically at the knee and ankle (Hrysomallis, 2007; McGuine et al., 2000; Park et al., 2010).

Assessment of static postural stability may provide valuable insights into the recovery of the proprioception system after ACLR. Researchers often compare the ACLR limb to the uninjured limb, which may not be appropriate as bilateral deficits have been observed in this population (Denti et al., 2000; Hoffman, Schrader, & Koceja, 1999; Howells et al., 2013). Therefore it is recommended that researchers compare ACLR individuals to matched healthy controls due to bilateral deficits (Bonfim et al., 2003;

Denti et al., 2000; Howells et al., 2013). In addition, previous literature has demonstrated conflicting findings for measures examining bilateral postural stability between ACLR and healthy controls (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Henriksson et al., 2001; Mattacola et al., 2002). Both Henriksson et al. (2001) and Mattacola et al. (2002) did not use traditional force platforms. Henriksson et al. (2001) used an Equitest (Neuro-Com Int., Inc., Clackamas, Oregon), which consisted of two small force platforms surrounded by a screen. Mattacola et al. (2002) utilized a Biodex Stability System (Biodex Medical Systems, Shirley, NY), which only consists of a single moveable platform. These studies must be interpreted with caution as previous research utilizing these types of moveable platforms often report a stability score rather than a direct COP measurement (Denti et al., 2000; Mattacola et al., 2002). Therefore it appears that bilateral stance postural stability tests may not be challenging enough to detect differences in ACLR individuals. While bilateral stance tests may not be challenging enough, single-leg postural stability does appear to be affected after ACLR (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Howells et al., 2013; Mohammadi et al., 2012; Zouita Ben Moussa et al., 2009). Based on recent systematic reviews and meta-analysis, single-leg postural stability remains impaired after ACL injury and reconstruction (Howells et al., 2011; Lehmann et al., 2017). However, caution must be used when evaluating these findings since various methodological approaches have been used (Howells et al., 2011).

Double-leg postural stability is often used to evaluate if differences exist between groups. To the author's knowledge, few studies exist that evaluate double-limb postural control in ACLR individuals as most studies are interested in the presence of lingering deficits in the ACLR limb (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Henriksson et al., 2001; Mattacola et al., 2002). Dauty et al. (2010) evaluated double-leg postural stability, both in extended and flexed knee positions, between the ACLR group and control group. The ACLR group had increased sway areas and COP excursion compared to the control population. When vision was removed, these same COP measurements increased again in both knee positions. These findings must be interpreted with caution as the researchers measured the ACLR group's postural stability only 15 days post-surgery (Dauty et al., 2010). Denti et al. (2000) also found significant differences between ACLR individuals and healthy controls. The findings of Denti et al. (2000) are of importance because ACLR individuals were, on average, 6.1 years post-surgery. A limitation of Denti et al. (2000) study is they did not use a traditional force plate to measure postural stability but instead used a moveable platform. Therefore it is difficult to make comparisons to previous literature as the authors did not use a rigid platform during testing (Denti et al., 2000).

Single-leg postural stability can offer an increased amount of insight into the sensory and motor deficits that may remain despite the surgical intervention (i.e., removal of damaged ligament and insertion of new graft). Researchers have found between limb differences both after ACLR and rehabilitation (Alonso et al., 2009; Bonfim et al., 2003; Dauty et al., 2010; Mohammadi et al., 2012; Zouita Ben Moussa et al., 2009). Zouita Ben Moussa et al. (2009) found significant limb differences in sway velocity between the ACLR (0.95 ± 0.2 deg/s) and control limbs (0.79 ± 0.18). No differences in sway velocity were found between the ACLR limb and the uninvolved limb (Zouita Ben Moussa et al., 2009). Dauty et al.(2010) also demonstrated significant differences in postural stability measures (COP sway area and total excursion) between ACLR and control groups. Between limb differences also existed in the ACLR individuals with the involved limb demonstrating increased sway area and total distance compared to the uninvolved limb (Dauty et al., 2010). Mohammadi et al. (2012) evaluated single-leg postural stability on both a rigid force plate and on a compliant surface (i.e., foam pad). The ACLR group had increased postural sway when compared to both the uninvolved limb and the matched limb in the healthy control group (Mohammadi et al., 2012). Overall the previous studies support the hypothesis that ACLR individuals demonstrate decreased single-leg postural stability measures when compared to healthy controls.

While previous research suggests a connection between static postural stability measures and ACLR, several authors have demonstrated contrary findings (Henriksson et al., 2001; Hoffman et al., 1999). Hoffman et al. (1999) found that single-leg static postural stability in ACLR individuals was not significantly different from healthy controls. Researchers found no differences in the total sway path between involved and uninvolved limbs. However, it should be noted that the participants involved in this study had a wide range of time since surgery (3 months-30 months), which may impact the overall findings. Henriksson et al. (2001) also found no differences in static postural stability between groups when testing postural stability on an Equitest, Neuro-Com®. Henriksson et al. (2001) also did not find significant differences between limbs suggesting that static postural stability may return after ACLR. The findings in this study may have been impacted by a specialized rehabilitation program that all participants were enrolled in prior to participation in this study (Henriksson, Ledin, & Good, 2001).

Changes in the central control of postural stability offer a possible explanation as to why some authors find no differences between limbs (Hoffman, Schrader, Applegate, & Koceja, 1998). These central control changes may be a way for the body to reestablish symmetry between the limbs, by reducing function in the uninvolved limb (Hoffman et al., 1999). However, an alternative for these non-existent limb differences is that traditional, static postural stability tasks and measures may not be sensitive enough to detect deficits in postural stability in athletes (Colby et al., 1999).

Dynamic Postural Stability

While static stability is commonly used in the clinical setting, its usefulness when measuring an athletic population has been questioned. Static postural assessments may not be challenging enough for athletic populations and may not be related to dynamic stability measures (Colby et al., 1999; Sell, 2012). Dynamic postural assessments are traditionally evaluated using a hopping task and evaluate an individual's ability to maintain balance when transitioning from dynamic to a static state (Wikstrom et al., 2005). Two dynamic stability measurements, time to stability (TTS) and dynamic postural stability index (DPSI), have been used to evaluate an ACLR individual's dynamic postural stability (Heinert et al., 2018; Webster & Gribble, 2010). Both dynamic stability measures have been shown to remain impacted years after the athlete has RTS (Heinert et al., 2018; Webster & Gribble, 2010). Prolonged deficits in postural control during dynamic activities may lead to increased injury risk, even after the successful completion of a rehabilitation program (Heinert et al., 2018; Paterno et al., 2010).

Time to stability is a measure commonly used to assess dynamic stability and has been shown to be a reliable measure in patients with ACLR during a step-down and hopping task (Colby et al., 1999; Webster & Gribble, 2010). Colby et al. (1999) demonstrated that ACLR individuals had longer stabilization times when compared to the uninjured limb. Webster and Gribble (2010) also found similar findings to Colby et al. (1999), in the ACLR high-level collegiate athletes. ACLR athletes took an average of 0.11 seconds longer to stabilize from a jump landing than the healthy collegiate athletes. These findings are of particular concern as participants involved in this study were, on average, 2.5 years removed from the surgical procedure to repair the torn ACL (Webster & Gribble, 2010).

Dynamic postural stability index is another useful dynamic stability measure that has been used to assess the postural stability in an ACLR population (Heinert et al., 2018). Previous work has suggested that DPSI may be a more comprehensive measure of dynamic postural stability when compared to TTS (Wikstrom et al., 2005). While TTS is focused on the time it takes for an individual to stabilize, DPSI provided information about an individual's overall dynamic stability (Wikstrom et al., 2005) Heinert et al. (2018) compared the injured limb with the uninjured limb during a single-leg hop task. Dynamic postural stability index values were found to be increased in each of the directional components, and composite scores in the ACLR limb compared to the uninvolved limb (Heinert et al., 2018). The most significant difference in DPSI values was in the mediolateral direction (24% greater on ACLR limb) and the overall composite scores (12% greater on ACLR limb) (Heinert et al., 2018). Researchers hypothesized that these greater DPSI scores indicate possible abnormal landing mechanics, thus increasing re-injury risk (Heinert et al., 2018).

These findings of increased TTS and DPSI scores may provide additional insights into the risk of sustaining a second ACL injury. While it is assumed that ACLR restores mechanical stability to the injured limb, it is clear that measures of dynamic postural stability remain affected (Colby et al., 1999; Heinert et al., 2018; Webster & Gribble, 2010). Clinically this indicates that rehabilitation programs may have to be adjusted to help re-establish impacted variables to pre-injury values. Both these studies were performed retrospectively, which brings into question whether or not these deficits were present pre-injury (Heinert et al., 2018; Webster & Gribble, 2010). Hewett et al. (Hewett et al., 2005a) prospectively investigated ACL injury risk in female athletes. Those individuals who went on to suffer a second ACL injury had greater knee valgus angles and knee abduction moments during drop landings. Female participants also demonstrated significantly increased vertical ground reaction forces (VGRF) at lower knee flexion angles and knee valgus angles (Hewett et al., 2005a).

Stabilogram Diffusion Analysis

Traditionally postural stability is assessed using a force platform that measures the ground reaction force between the foot and the force platform. A force vector is created and corresponds to the center of pressure of the individual's body. Researchers evaluate an individual's postural stability by measuring the movement of the COP (Dauty et al., 2010; Prieto et al., 1996). However, the information provided by the traditional method of analyzing stabilograms does not provide any physiological meaningful information (Collins & De Luca, 1993; Heise et al., 2012). Collins and De Luca (1993) proposed a novel method for analyzing traditional stabilograms using statistical mechanics. The stabilogram diffusion analysis (SDA) modeled the "COP of static postural stability as coupled, correlated random walks" (Collins & De Luca, 1993). SDA calculates the mean square displacement of each successive time interval between pairs of COP coordinates (Collins & De Luca, 1993; Heise et al., 2012). After progressing entirely through the COP path, the time interval is then increased, and a mean square displacement is calculated for the new time interval. Both the mean square displacements and their time intervals are then plotted to create the stabilogram diffusion plot (Collins & De Luca, 1993). Two distinct regions (short-term and long-term regions) can be noted on the stabilogram diffusion plot and where these regions intersect is known as the critical point (Collins & De Luca, 1993). Collins and De Luca (1993) suggested that the short-term region of the SDA plot is representative of open-loop control, while the long-term region represents closed-loop motor control. Finally, the critical point is suggested to represent the time interval at which the individual changes from open-loop to closed-loop control (Collins & De Luca, 1993).

Several variables (diffusion coefficients, scaling exponents, critical time point coordinates, and critical mean square displacements) are calculated using the SDA plot in order to evaluate both regions and the critical point of the analysis (Collins & De Luca, 1993). The slopes of resultant linear-linear plots of the mean square COP displacement values versus the time interval curves are then used to calculate the diffusion coefficients (Collins & De Luca, 1993) (Figure 2.2). The diffusion coefficients (Resultant diffusion coefficient (D_r), AP diffusion coefficient (D_x), and ML diffusion coefficient (D_y) are calculated using the slopes of the lines in both the short-term and long-term regions (Collins & De Luca, 1993). Scaling exponents (resultant scaling exponent (H_r), AP scaling exponent (H_x), and ML scaling exponent (H_y) are calculated similarly to diffusion coefficients except using the resultant log-log plots (Collins & De Luca, 1993) (Figure 2.3). Slopes for both diffusion coefficients and scaling exponents are calculated by fitting straight lines using the method of least squares fit (Collins & De Luca, 1993). Critical points are determined as the point at which the short-term and long-term regions intersect (Collins & De Luca, 1993).

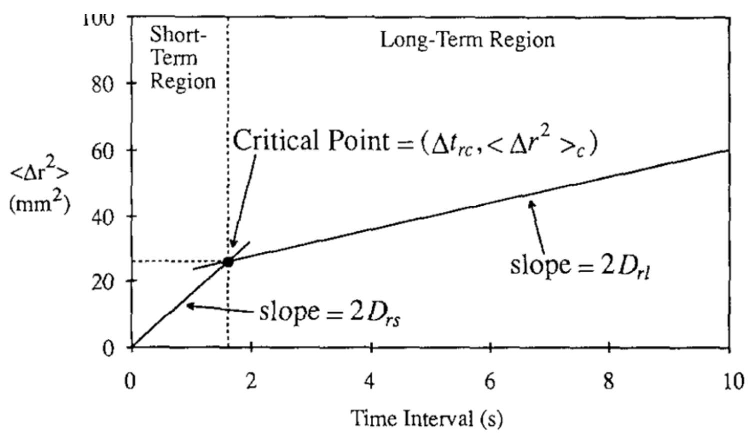

Figure 2.2. Short- and long-term regions of SDA plot. (adapted from Collins & De Luca, 1993).

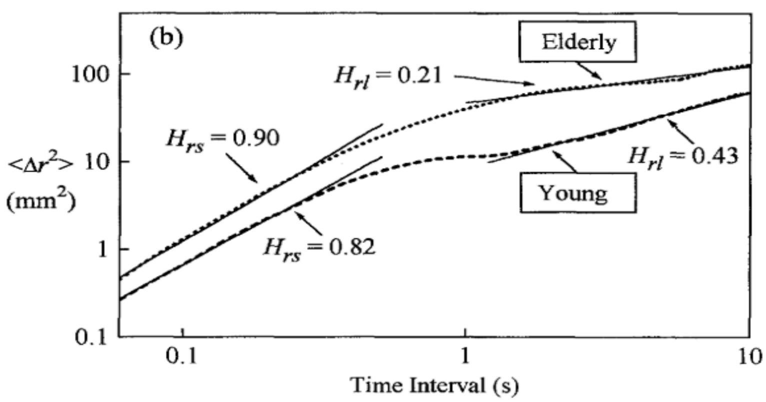

Figure 2.3. Representation of the SDA log-log plot. Comparison of the scaling exponents between young and elderly participants during quiet stance. (adapted from Collins et al., 1995c).

Collectively, the variables associated with the SDA demonstrate unique characteristics that are relatable to motor control characteristics (Collins & De Luca, 1993). Diffusion coefficients (Short-term diffusion coefficient (D_{rs}) and Long-term diffusion coefficient (D_{rl}) are used to demonstrate the level of the stochastic activity of the COP path (Collins & De Luca, 1993; Collins & De Luca., 1995b). Collins and De Luca (1993), found larger diffusion coefficients in the short-term region, and smaller coefficients in the long-term region in young, healthy participants. These findings demonstrate that in open-loop control, there is more stochastic activity than during the more regulated closed-loop control schemes (Collins & De Luca, 1993). Collins et al. (1995c) confirmed their previous findings by demonstrating increased diffusion coefficients in the short-term region in elderly individuals compared to young, healthy individuals. The authors hypothesized that these increased levels of stochastic activity found in the short-term region of the elderly participant may be attributed to a reduction in proprioception (Collins et al., 1995c). These age-related changes may cause the individual to sway over increased mean square displacements and over longer time intervals before corrective feedback mechanisms are utilized (Collins et al., 1995c).

Similar to the diffusion coefficients, scaling exponents also display two distinct regions, short-term and long-term. While the diffusion coefficients represent the level of stochastic activity present in the COP path, the scaling exponents measure the correlation between the growths in displacements over the COP time series (Collins & De Luca, 1993; Collins & De Luca, 1995b). Scaling exponents can represent any real number between zero and one (Collins & De Luca, 1995b; Collins & De Luca, 1993). According to work done by Mandelbrot and Van Ness (1968), if the scaling exponent is greater than 0.5, then past and future increments are positively correlated. This behavior is termed as “persistence” and can be summarized as the trend (increasing or decreasing) of the past increments predicting the same trend (increasing or decreasing) in the future (Collins &

De Luca, 1993). Therefore, persistence may represent open-loop control behavior, which utilizes feedforward mechanisms (Collins & De Luca, 1995b; Collins & De Luca, 1993). Whereas when the scaling component is less than 0.5, the past and future increments are negatively correlated (Collins & De Luca, 1993). This type of behavior is then referred to as “anti-persistence” and indicates that, on average, future trends are the opposite of past trends (Collins & De Luca, 1993). Anti-persistence, therefore, represents a closed-loop control scheme, where feedback is used to make corrections.

During human movement, the central nervous system (CNS) continually receives sensory information from visual, vestibular, and somatosensory sources. Sensory or afferent information is then used by the CNS to modify efferent signaling to muscles. Based on the findings of Collins and De Luca (1993), since the SDA demonstrates both an open and closed-loop control, postural stability utilizes an open-loop control until some threshold is exceeded. Once this threshold (i.e., critical point) is surpassed, the human postural control system then employs a closed-loop control to make the necessary corrections (Collins & De Luca, 1993). Collins and De Luca (1993) hypothesized that the use of the open-loop control strategy may be due to the time delay within the sensory feedback system.

Several studies have examined the SDA approach to different populations and under different conditions (Collins et al., 1995c; Collins & De Luca, 1995a; Mitchell et al., 1995). Collins et al. (1995c) evaluated both traditional postural stability measures (i.e., max AP displacement, max ML displacement, total sway area) versus SDA measures in young and elderly populations. The researchers found diffusion coefficients of the short-term region to be significantly higher in the elderly group compared to the young group (Collins et al., 1995c). While differences were seen in the short-term diffusion coefficients, no significant difference was observed in the long-term diffusion coefficients (Collins et al., 1995c). Elderly individuals also presented with increased critical mean square displacements and critical time intervals than the young group (Collins et al., 1995c). Interestingly in this same study, the elderly group had significantly increased short-term scaling exponents and decreased long-term scaling exponents compared to the young group (Collins et al., 1995c). These findings suggest that while the elderly are considered to be more unstable than young adults in the short-term region, they present as more stable during the long-term. According to Collins et al. (1995c), the decreased scaling exponents in the long-term region may compensate for the unstable behavior observed in the short-term region.

Collectively, the findings from Collins et al. (1995c) demonstrate that elderly populations may utilize open-loop control mechanisms for longer time intervals during quiet standing when compared to young individuals. Elderly populations also have a more significant delay in switching from open-loop control to closed-loop control mechanisms than do the young population. Collins et al. (1995c) speculated that individuals with reduced proprioception might not be able to detect small changes in position. Due to this reduced proprioception, individuals may be allowed to sway over larger displacements before corrective feedback mechanisms can be utilized (Collins et al., 1995c).

Beyond age-related changes, SDA also is affected by the visual system. While age-related differences in SDA are quite apparent, differences in the visual system are much less clear. Collins and De Luca (1995a) used SDA and traditional postural stability measures on healthy young males using two vision conditions (eyes-open vs. eyes-closed). Researchers found when visual input was manipulated, the participants behaved in one of two ways (Collins & De Luca, 1995a). Roughly half of the participants had more stochastic behavior in the short-term region, while the other half displayed increased anteroposterior stochastic behavior and less negatively correlated over the long-term region time intervals (Collins & De Luca, 1995a). Researchers also found no differences between groups or visual conditions when examining the critical points but did find differences in critical mean square displacement values (Collins & De Luca, 1995a). One group displayed increased critical mean square displacements when vision was removed, while the second group showed minimal change (Collins & De Luca, 1995a). Collins and De Luca (1995a) study makes it difficult to interpret how visual impacts the SDA calculation as this study had two distinct adaptations to the absence of visual feedback. Based on the findings of this study, the vision's impact on SDA measurements remains unclear and warrants further investigation.

Somatosensory Deficit and Visual Feedback Reliance

Injury to the ACL may not be a simple musculoskeletal disorder, but rather a more complex injury involving the neurological system (Baumeister et al., 2011; Grooms et al., 2017; Negahban et al., 2014; Okuda et al., 2005). When an ACL injury occurs, the mechanical properties of the ligament are disrupted, but the neural elements present are impacted too (Schultz et al., 1984; Schutte et al., 1987; Zimny et al., 1986). Previous research examining human cadaver ACL's have supported the idea that the ACL contains several different mechanoreceptors (Schultz et al., 1984; Schutte et al., 1987; Zimny et al., 1986). Three mechanoreceptors have been identified in the ACL and are responsible for transmitting afferent information to the CNS about the knee (Relph et al., 2014; Schultz et al., 1984; Schutte et al., 1987; Zimny et al., 1986). While ACLR surgery and rehabilitation are performed to return mechanical stability to the knee, it may not restore the neurological function to the knee (Baumeister et al., 2011; Grooms et al., 2017, 2018; Konishi, 2011).

Lingering neurological deficits, specifically somatosensory feedback dysfunctions, have been reported in ACLR individuals (Bonfim et al., 2003; Relph et al., 2014; San Martín-Mohr et al., 2018). Relph et al. (2014) performed a systematic review of the literature and a meta-analysis that demonstrated that ACLR limb had a higher mean angle of error (i.e., worse joint position sense) compared to the uninjured limb. When compared to healthy controls, ACLR individuals had significantly decreased joint position sense (Relph et al., 2014). Better joint position sense was noted in those who had ACLR compared to those who did not undergo surgery (Relph et al., 2014). A more recent study evaluated joint position sense between groups of ACLR individuals and healthy controls found a decreased joint position in those with ACLR (San Martín-Mohr et al., 2018). However, interestingly there were no differences in joint position sense between graft choice, either bone-patellar tendon-bone or hamstring tendon, used to replace the native ACL ligament (San Martín-Mohr et al., 2018). Relph et al. (2014) also examined a secondary proprioceptive measurement technique called threshold to detect passive motion. The meta-analysis found no differences in mean angle errors between limbs (0.02°) and only a small difference between healthy controls (0.38°) (Relph et al., 2014). It is important to note that while this study found significant differences exist using this measurement technique, the differences were relatively small (Relph et al., 2014). Bonfim et al. (2003) also found similar results as Relph et al. (2014) for the threshold to detect passive motion measure. Bonfim et al. (2003) also found increased latency of hamstring muscles in ACLR individuals in addition to decreased ability to detect passive motion. Longer latency values of the hamstring muscles were observed in both the reconstructed knee compared to the unaffected knee and between ACLR individuals and healthy controls (Bonfim et al., 2003).

Collectively, this information may help explain the increased ACL re-injury risk in ACLR individuals. The increased errors in joint position sense found in San Martín-Mohr et al. (2018) were explicitly between the ranges of 0° and 30°. Decreased joint position sense at these lower levels of knee flexion may be an important finding as ACL injuries are suspected to occur during dynamic tasks in similar knee flexion positions (Yu & Garrett, 2007).

Similarly, the increased latency observed in the hamstring muscles may also contribute to the increased re-injury risk (Coats-Thomas et al., 2013). Coats-Thomas et al. (2013) found later peak activation timing of the hamstring musculature in ACLR individuals versus healthy individuals. Previous research has also demonstrated that individuals who display increased hamstring stiffness experience less anterior tibial translation (Blackburn et al., 2011). Individuals who possess increased hamstring stiffness also decrease ACL loading by limiting the amount of frontal and sagittal plane loading (Blackburn et al., 2013).

As compensation for the compromised somatosensory feedback found in those who have undergone ACL reconstruction, individuals may undergo sensory re-weighting (Grooms et al., 2015b; Kapreli et al., 2009; Ward et al., 2015). Due to the decreased afferent feedback from the knee joint, ACLR individuals may demonstrate increased reliance on visual feedback during dynamic movement tasks (Bonfim et al., 2008; Grooms et al., 2015a; Needle et al., 2017; Negahban et al., 2014; Okuda et al., 2005). Increased reliance on visual feedback may place the ACLR individuals at an increased risk of sustaining a second ACL injury as the result of altered movement strategies (Bjornaraa & Di Fabio, 2011; A. Gokeler et al., 2010; Grooms et al., 2018; Kapreli et al., 2009; Ward et al., 2015).

Grooms et al. (2018) utilized vision disrupting glasses to evaluate drop landings in ACLR individuals compared to healthy controls. Individuals wore stroboscopic glasses to disrupt visual input during a vertical drop jump (Grooms et al., 2018). Stroboscopic vision altered landing mechanics during the drop jump in both ACLR individual and healthy controls (Grooms et al., 2018). Under stroboscopic visual conditions, individuals with ACLR had increased knee flexion excursion compared with healthy controls (Grooms et al., 2018). These findings suggest that ACLR individuals may adopt a more protective landing strategy when visual input is reduced.

Reductions in somatosensory information and increased visual reliance may be necessary for researchers and clinicians to understand as it may directly influence an individual’s re-injury risk. Researchers using cadaver knees have showcased decreased in-situ forces in the ACL at various levels of knee flexion (15°, 30°, and 60°) when hamstring loads were added (Li et al., 1999). In both isolated quadriceps and combined quadriceps and hamstring loads, research found the highest in-situ forces in the ACL at 15° knee flexion (Li et al., 1999). Li et al. (1999) also noted that when an antagonistic hamstring load was added, the highest in-situ forces in the ACL were reduced by 23%.

Therefore if ACLR individuals demonstrate abnormal landing patterns without protective muscular activation, then the surrounding musculature may not offer sufficient protection (Delahunt et al., 2013; Deneweth et al., 2010; Gokeler et al., 2010; Orishimo et al., 2010).

****Electromyographic (EMG) analysis section was included in the final dissertation as it was proposed to the original committee. However, the study that utilized EMG analysis was not included in the final dissertation due to COVID-19 related issues with data availability.**

Electromyographic (EMG) Analysis

It has been estimated that non-contact ACL injuries occur after initial contact with the ground and occur too quickly for the musculature surrounding the knee to protect the ACL (Krosshaug et al., 2007; Olsen et al., 2004; Rocchi et al., 2018). Decreased neuromuscular control of the knee joint may place increased loads on the passive ACL ligament, ultimately exceeding the failure strength of the ligament (Hewett et al., 2005b; Li et al., 1999; Markolf et al., 1978; Myer et al., 2009; Palmieri-Smith et al., 2009). Increased quadriceps activation in relation to hamstring activation, especially at low levels of knee flexion, may lead to an increased shear load being placed on the ACL (Leporace et al., 2016; Myer et al., 2004). Beyond muscle co-contraction, other factors such as muscle pre-activation and muscle recruitment patterns may play a role in abnormal landing patterns often seen in ACL injuries (Brown et al., 2014; Hewett et al., 2013; Palmieri-Smith et al., 2008, 2009; Theisen et al., 2016). Researchers have utilized surface electromyography (EMG) to assess neuromuscular function at the knee to determine risk factors related to the initial ACL injury (Brown et al., 2014; Hewett et al., 2005b; Palmieri-Smith et al., 2008, 2009; Palmieri-Smith & Lepley, 2015).

Surface EMG has also been utilized to evaluate an individual’s neuromuscular function and muscle recruitment patterns after ACLR (Oliver et al., 2018; Rocchi et al., 2018; Theisen et al., 2016). It is vital to examine the muscle function of ACLR individuals in order to help determine the risk factors for sustaining a second ACL injury. Changes in muscle activity after ACLR may represent a protective mechanism to help stabilize the knee during sporting activities (Hewett et al., 2013). However, due to damage to the somatosensory system from the ACL injury and reconstruction, neuromuscular adaptations may develop, thus changing the normal function of the muscles surrounding the knee (Baumeister et al., 2011; Bryant et al., 2009; Grooms et al., 2017, 2018; Konishi, 2011; Madhavan & Shields, 2011; Oliver et al., 2018; Rocchi et al., 2018; Theisen et al., 2016).

It is hypothesized that individuals with ACLR may develop neuromuscular adaptations during dynamic activities such as landing or cutting (Bryant et al., 2009; Oliver et al., 2018; Rocchi et al., 2018). However, the results of previous research offer conflicting findings. Oliver et al. (2018), examined muscle activity of the quadriceps and hamstring musculature during a single-leg drop landing from a 25 cm box. The results of this study showed a delayed muscle latency time in the vastus medialis but demonstrated improvements in the other quadriceps and hamstring muscle (Oliver et al., 2018). Improvements in muscle latency time were found over the course of the rehabilitation process until no muscle differences existed at the six-month check-in (Oliver et al., 2018). In a similar study, Rocchi et al. (2018) found that ACLR individuals experienced increased pre-activation when compared to healthy controls. Increased pre-activation times were found in both graft types used in ACLR when compared to healthy controls in both the quadriceps and hamstring muscles (Rocchi et al., 2018). Interestingly during a single-leg hopping task, ACLR individuals activated the hamstring muscles at an earlier time prior to contact than their quadriceps muscles (Rocchi et al., 2018). An earlier muscle onset timing in the hamstring muscles is an important strategy that serves as a protective mechanism during dynamic landings. These findings are in contrast to Bryant et al. (2009), who found no differences in muscle onset times between ACLR individuals and healthy controls during single-leg hops. While no differences in onset times were found between groups, a similar trend of earlier hamstring activation, compared to quadriceps, was noted (Bryant et al., 2009).

During dynamic tasks, the body may utilize a feed-forward motor control (i.e., muscle pre-activation before ground contact) to help protect the knee joint (Bryant et al., 2009; Rocchi et al., 2018). Another muscle strategy employed to protect the ACL, a passive stabilizer of the knee, is increased muscle quadriceps and hamstring co-activation (Baratta et al., 1988; Hewett et al., 2005b; Segal et al., 2015). Previous research has demonstrated that ACLR individuals demonstrated significantly lower levels of co-contraction in the involved limb when compared to the uninvolved limb (Lustosa et al., 2011). A lower level of co-contraction may place individuals at an increased risk of re-injury during dynamic tasks. In contrast to the findings of Lustosa et al. (2011), Bryant et al. (2009) found no statistical differences in co-contraction levels between ACLR, ACL deficient, and healthy control groups. A possible explanation for these contrasting results is the task performed in each study. Bryant et al. (2009) used a series of dynamic tasks, while Lustosa et al. (2011) examined walking gait with perturbations. Another possible limitation between Bryant et al. (2009) and Lustosa et al. (2011) could be the differences in co-contraction calculations used.

Increases in co-contraction may theoretically create a more stable joint and protect the ACL; however, increased co-activation may lead to joint damage (Tsai & Powers, 2013). Avoiding excessive joint compression during activities of daily living may protect the knee long term and may prolong the onset of osteoarthritis development. Tsai and Powers (2013) found reduced tibiofemoral compressive forces after undergoing training to create a more compliant landing strategy. Decreased tibiofemoral compressive forces were found with decreased co-activation levels at the knee during walking (Tsai & Powers, 2013). A similar study also found decreased levels of co-activation during a dynamic landing task after receiving landing instructions (Elias et al., 2015). Collectively, these findings demonstrate while increased muscle co-activation may help protect the repaired ligament, it may also increase detrimental joint compression loads that may lead to the development of knee osteoarthritis (Hall et al., 2012).

Return to Sport Criteria

Despite surgical and rehabilitation interventions and the utilization of RTS testing ACLR injury risk remains high, suggesting a level of inadequacy in testing methods (Grooms et al., 2018; Hui et al., 2011; Paterno et al., 2010, 2012; Webster & Hewett, 2019; Wellsandt et al., 2018; Wright et al., 2007). Clinicians typically use a battery of testing to help determine an individual’s readiness to return to unrestricted sports activities (Rambaud et al., 2017; Undheim et al., 2015). Beyond time since the surgical intervention, clinical testing consists of a variety of strength, hopping, knee laxity, and self-reported questionnaires (Novaretti et al., 2018; Rambaud et al., 2017). Yet despite the widespread use of these clinical examinations, no validated criteria exist for safe RTS in ACLR individuals (Rambaud et al., 2017). What is concerning is that while RTS testing exists, and 90% of patients attain normal or nearly normal knee function, only 44% returned to competitive sports activity (Ardern et al., 2011). In a more recent systematic review and meta-analysis, Webster and Hewett (2019) found that only 23% of individuals passed RTS testing. Interestingly those who passed the RTS testing did show a significant reduction in risk of a second graft injury (~60%), but also increased the risk of a contralateral ACL injury by 235% (Webster & Hewett, 2019). Therefore, a clear need exists to further evaluate these clinical tests in ACLR individuals in an effort to better understand how this specific population performs.

Clinical Postural Stability

While postural stability is easily collected and assessed in the research laboratory, it is often performed using expensive force platforms and analysis software. Due to this limitation, clinical researchers have developed tools to allow for a more cost-effective evaluation of postural stability (Clagg et al., 2015; Hertel et al., 2000; Kinzey & Armstrong, 1998). One such tool that has been developed to evaluate an individual's dynamic postural stability is the Star Excursion Balance Test (SEBT) and the modified Star Excursion Balance Test (Y-Balance test). Both the SEBT and Y-Balance tests involve having an individual maintain a stable base of support using a single-leg stance, while the other limb performs a reaching task (Hertel et al., 2000; Kinzey & Armstrong, 1998).

The SEBT has been found to be a reliable test, with a high test-retest reliability, and has been used to evaluate the dynamic postural stability and neuromuscular control (Clagg et al., 2015; Hertel et al., 2000; Kinzey & Armstrong, 1998; Leavey et al., 2010; McLeod et al., 2009; Plisky et al., 2006). Previous research has indicated that the SEBT is able to detect dynamic postural stability deficits in a variety of musculoskeletal injuries and also predict lower extremity injury (Butler et al., 2013; Herrington et al., 2009; Plisky et al., 2006; Smith et al., 2015).

Previous investigators have sought to use the SEBT to evaluate dynamic postural stability in ACLR individuals (Clagg et al., 2015; Delahunt et al., 2013). Reported deficits in SEBT performance are not consistent in the literature as conflicting results exist (Clagg et al., 2015; Delahunt et al., 2013). Clagg et al. (2015) found only deficits in the anterior reach direction in ACLR individuals vs. healthy controls. Anterior reach asymmetries found during Y-balance testing have been associated with increased risk of non-contact injuries (Smith et al., 2015). In contrast, Delahunt et al. (2013) found deficits in posterior-medial and posterior-lateral reach directions, but not anterior reach direction. While the studies by Clagg et al. (2015) and Delahunt et al. (2013) demonstrated conflicting results in SEBT reach direction deficits, it is important to note that each study examined participants at different times in the recovery process. Clagg et al. (2015) examined individuals who ranged from 4-11 months since surgery, while Delahunt et al. (2013) participants ranged from 10 months to 6 years since surgery. Therefore, anterior reach deficits recorded using the Y-balance test may recover with increased time since surgery.

Interestingly, Clagg et al. (2015) compared isokinetic strength testing and found that hip abductor strength was related to all SEBT reach directions, while quadriceps strength was related to posterior-lateral reach directions. These findings support the idea that hip musculature should be a priority for clinicians during the rehabilitation process. While hip abductor strength is vital for postural stability as measured by the SEBT, quadriceps strength has been associated with the development of future pathologies such as osteoarthritis (Blackburn et al., 2016; Mikesky et al., 2000).

Beyond muscle strength, lower limb kinematics remain impacted during clinical assessments such as the SEBT (Delahunt et al., 2013). Delahunt et al. (2013) examined the kinematics of the hip, knee, and ankle during the modified SEBT and found clinically meaningful differences at the hip and knee. In all three directions (anterior, posterior-medial, and posterior-lateral) measured, the ACLR group demonstrate decreased knee flexion (Delahunt et al., 2013). As previously mentioned, changes in sagittal plane motions (i.e., decreased knee flexion) are associated with increased risk of ACL injury (Yu & Garrett, 2007). In addition to sagittal plane deficits, abnormal frontal plane motions remained as well during the SEBT (Delahunt et al., 2013). ACLR individuals displayed abnormal hip motion, in all planes of motion, during all reach directions of the modified SEBT (Delahunt et al., 2013). Aberrant motion at the hip may also be an indicator of decreased neuromuscular control of the limb and place greater amounts of rotatory loads on the knee (Delahunt et al., 2013; Hollman et al., 2013; McLean et al., 2005; Paterno et al., 2010). Therefore, the abnormal motions at both the hip and knee during clinical dynamic postural stability should be examined prior to RTS.

Clinical Hopping Tasks

In an effort to assess an athlete's readiness to RTS and reduce an athlete's ACL re-injury risk, a series of functional tasks have been proposed to evaluate lingering limb asymmetries (Rambaud et al., 2017). One suggested functional test is a series of single-leg hop tasks (Noyes et al., 1991; Rambaud et al., 2017). Single-leg hopping tasks currently used in RTS testing are 1) single-leg hop for distance, 2) single-leg triple hop for distance, 3) timed distance hop, and 4) cross-over hop for distance (Noyes et al., 1991; Rambaud et al., 2017). Currently the standards for RTS range from 80-90% limb symmetry index (LSI) ([involved limb/uninvolved limb] x 100%) (Barber-Westin & Noyes, 2011; Wellsandt et al., 2018).

Single-leg hopping tasks have demonstrated the ability to detect differences between ACLR and healthy individuals, as well as differences in quadriceps strength (Myer et al., 2011; Schmitt et al., 2012). Myer et al. (2011) found group differences in three of the four single-leg hopping tasks. ACLR individuals demonstrated a significantly lower LSI of 92% while healthy controls had an LSI of 100% during the single-leg hop for distance task (Myer et al., 2011). During the single-leg triple hop task ACLR participants presented with a significantly lower LSI compared to the healthy control participants, 91% and 100%, respectively (Myer et al., 2011). The cross-over hopping tasks also presented with significant LSI deficits in the ACLR group compared to the healthy controls, 92% and 97%, respectively (Myer et al., 2011). However, no significant group differences were found during the timed hop task (Myer et al., 2011). The findings presented in Myer et al. (2011) study indicated that single-leg deficits exist in ACLR individuals within one year since surgery.

Single-leg hopping tasks have demonstrated not only the ability to detect differences among healthy and ACLR individuals, but also the ability to detect strength deficits (Schmitt et al., 2012; Xergia et al., 2015). Schmitt et al. (2012) found that single-leg hop scores detected differences in quadriceps strength in ACLR individuals. Researchers examined groups based on ACLR and quadriceps (low quadriceps strength and high quadriceps strength) function (Schmitt et al., 2012). Individuals classified as low quadriceps strength performed worse on both the single-leg hop for distance and triple-hop for distance tasks when compared to high quadriceps strength group and healthy controls (Schmitt et al., 2012). The low quadriceps function group also performed significantly worse on the cross-over and timed-hop tasks when compared to the healthy group, but were not significantly different when compared to the high quadriceps strength group (Schmitt et al., 2012). Single-leg hop tasks have also been found to be moderately correlated with isokinetic knee extensor function (Xergia et al., 2015). The findings of Xergia et al. (2015) offer another potential method for clinicians to evaluate muscle strength using a clinical test.

Clinical single-leg hop tasks have demonstrated promise in detecting lingering limb differences in ACLR individuals but also have been used in a predictive fashion. Several studies have investigated the predictive nature of these single-leg hopping tasks as it related to self-reported knee function after surgery, as well as future ACL injury risk (Logerstedt et al., 2012; Nawasreh et al., 2018; Wellsandt et al., 2018). However, these findings must be interpreted with caution as several studies demonstrated that despite achieving a high level of limb symmetry (i.e., > 90% LSI), individuals may not achieve pre-injury function levels (Logerstedt et al., 2012; Wellsandt et al., 2018). Wellsandt et al. (2018) found that despite passing both quadriceps strength and single-leg hop LSI requirements, eight of 11 ACLR individuals suffered a second ACL injury. Based on the current level of research presented, the inclusion of single-leg hop tasks should be utilized by clinicians for RTS decisions. These same tests may also be used during the rehabilitation process to evaluate patient progress prior to RTS (Logerstedt et al., 2012).

Isokinetic Testing

Strength measurements are often utilized by clinicians during RTS testing to assess an athlete's readiness to return to high levels of activity (Rambaud et al., 2017; Undheim et al., 2015; Webster & Hewett, 2019). These strength tests are important to measure prior to RTS, as muscular strength deficits are often seen in ACLR individuals both at RTS and years after (Andrade et al., 2002; Hiemstra et al., 2000; Ingersoll et al., 2008; Larsen et al., 2015; Lautamies et al., 2008; Osterǎs et al., 2011; Otzel et al., 2015; Wilk et al., 1994; Wojtys & Huston, 2000). Both quadriceps and hamstring strength measures are important to evaluate prior to RTS as any loss of muscular strength may reduce the dynamic stability of the knee and place increased reliance on the passive structures at the knee (Järvelä et al., 2002; Strauss et al., 1998). Quadriceps and hamstring strength assessments are often performed using an isokinetic dynamometer. A recent systematic review found the two most common testing velocities for quadriceps and hamstring strength to be 60°/s and 180°/s (Undheim et al., 2015). However, the slower angular velocity of 60°/s may be more appropriate to detect strength deficits in ACLR individuals, as higher velocities may not highlight deficiencies (Undheim et al., 2015).

While strength measures are often assessed prior to RTS, the clinical criteria for passing these tests remain unclear (Undheim et al., 2015). Previous work has used a variety of limb symmetry cut-off values ranging from ≥70% to ≥90% (LSI), yet there remains no recommend symmetry values for RTS (Hartigan et al., 2010; Järvelä et al., 2002; Schmitt et al., 2012; Thomeé et al., 2011; Undheim et al., 2015). It is of concern that individuals who meet or exceed these limb symmetry cut-offs may still be at an increased risk of sustaining a second injury (Wellsandt et al., 2018). Wellsandt et al. (2018) found that of the 11 individuals who passed the quadriceps strength with a 90% symmetry value, eight suffered a second injury. The authors also proposed and examined a new limb symmetry measure that sought to create more stringent criteria than the current levels. Wellsandt et al. (2018) created what they referred to as "EPIC level" of quadriceps asymmetry. When compared to a more traditional way of assessing limb symmetry *([Involved Limb /Uninvolved Limb] x 100%*), the EPIC level creates a symmetry index using a participant's involved limb strength level (i.e., 6 months, 9 months, etc.) to the uninvolved limb at initial evaluation (Wellsandt et al., 2018). While this measure creates a more demanding pass/fail criteria, it has yet to be determined if it is a valid measure of safe RTS.

Obtaining appropriate muscular strength should be an essential rehabilitation goal prior to RTS as these muscles serve as active stabilizers for the knee joint (Osterăs et al., 2011; Strauss et al., 1998). Impaired quadriceps strength is often observed in ACLR individuals, both at RTS and can remain even years after (Andrade et al., 2002; Hiemstra et al., 2000; Ingersoll et al., 2008; Larsen et al., 2015; Lautamies et al., 2008; Osterăs et al., 2011; Otzel et al., 2015; Wilk et al., 1994; Wojtys & Huston, 2000). The findings of Lautamies et al. (2008) support the hypothesis that muscle strength can remain impaired years after surgical intervention. ACLR, independent of surgical graft, showed decreased isokinetic peak muscle torques when compared to the unaffected limb (Lautamies et al., 2008). Decreased isokinetic peak muscle torques were observed at both testing velocities, 60°/s and 180°/s, regardless of ACL graft choice (bone-patellar tendon-bone or combined semitendinosus and gracilis) (Lautamies et al., 2008). The findings of Wojtys and Huston

(2000) also support the hypothesis of prolonged quadriceps strength deficits in ACLR patients. Only 40% of patients who completed a standardized rehabilitation protocol achieved strength levels similar to the uninjured limb at the 12-month evaluation (Wojtys & Huston, 2000). At the 18-month evaluation, the number of patients who achieved equal quadriceps peak torque values increased to 72% (Wojtys & Huston, 2000). Andrade et al. (2002) also found quadriceps deficits remaining in ACLR individuals but found that these deficits decreased over time. Natri et al. (1996) experienced decreased quadriceps peak torque compared to the uninvolved limb in individuals with bone-patellar tendon-bone graft. Quadriceps strength deficits, specifically bone-patellar tendon-bone, were observed after ACLR in patients who were a mean of five years post-operative. Collectively these findings demonstrate the importance of focused quadriceps rehabilitation in ACLR patients, specifically those who have had a patellar tendon graft.

Contrary to previous work, the findings of Moisala et al. (2007) found no significant differences between surgical graft type in peak quadriceps torque at either 60°/s and 180°/s in patients with a mean postoperative time of 5 years and 9 months. The authors hypothesized that these lack of differences in quadriceps strength may be due to the differing rehabilitation protocols used between studies (Moisala et al., 2007). In addition to these, non-significant findings have been more recently supported by Novaretti et al. (2018), who retrospectively found that quadriceps deficits at six months post-surgical intervention were not predictive of RTS.

Surprisingly, Lautamies et al. (2008) reported no statistically significant differences between graft type and peak muscle torque; however, significant differences did exist between ACL graft and quadriceps isokinetic strength ratios. Decreased quadriceps strength ratios were observed in the bone-patellar tendon-bone group compared to the semitendinosus and gracilis group (Lautamies et al., 2008). A relatively small quadriceps strength difference existed between surgical groups with the bone-patella tendon-bone graft types having roughly 3-4% less quadriceps strength ratios (Lautamies et al., 2008).

Quadriceps impairments have demonstrated a negative association with sagittal plane mechanics during dynamic tasks. Specifically, Palmieri-Smith and Lepley (2015) found that individuals with lower quadriceps strength landed from a hopping task with decreased knee flexion angles decreased knee extensor moments. These findings are important has deficits in sagittal plane motion have been related to an increased ACL injury (Blackburn & Padua, 2009; Krosshaug et al., 2007; Shimokochi et al., 2009).

Quadriceps strength may be an important factor for clinicians to consider when rehabilitating an ACL injury, but hamstrings muscle function may also be important for focused rehabilitation as it is a dynamic restraint to ATT (Blackburn et al., 2011; Järvelä et al., 2002). Hamstring muscle function is of particular interest when examining muscle function in individuals who elect to use a hamstring graft to replace the damaged native ACL. Kobayashi et al. (2004) also found hamstring strength deficits at 12 months post-surgery in bone-patellar tendon-bone grafts. However, these strength deficits were not as significant as quadriceps strength insufficiencies. In contrast, Lautamies et al. (2008) found no significant differences in hamstring strength peak torques between surgical graft groups. These findings demonstrate that while hamstring deficits may exist early on in the rehabilitation process, they do not last as long as the quadriceps deficits (Lautamies et al., 2008; Wojtys & Huston, 2000).

Beyond limb symmetry measures, a ratio between hamstring and quadriceps muscles have also been suggested as an RTS criterion (Moisala et al., 2007; Undheim et al., 2015; Webster & Hewett, 2019). The increased hamstring-to-quadriceps ratio has been hypothesized to create a more stable joint and possibly protect the ACL from injury (Rosene et al., 2001). Moisala et al. (2007) found no differences in hamstring-to-quadriceps ratios when comparing surgical graft types. Andrade et al. (2002) found increased hamstring to quadriceps ratios in the repaired limb vs. the uninjured limb. Webster and Hewett (2019) found that the hamstring-to-quadriceps ratio in the ACLR limb was highly associated with graft injury. Previous work has also demonstrated that the hamstring-to-quadriceps strength ratio may be related to the primary ACL injury (Hewett et al., 2010). The hamstring-to-quadriceps ratio may be important to evaluate prior to RTS; however, the lack of consistent findings in previous research indicates a need for further analysis.

This review of literature showcases the need to continue researching the impact of ACLR on postural stability and muscle function measures. Proprioception may remain impacted after ACLR, and the resultant increased reliance on visual input may contribute to an individual's risk of sustaining a second ACL injury. The effect of decreased visual input will be examined in hopes of providing more information about the adaptations ACLR individuals experience after RTS. This information will help expand the current literature on RTS testing in an effort to improve our current testing methods, with the potential of decreasing injury risk.

CHAPTER III

METHODOLOGY

General Methodology

The overall purpose of the studies contained in this dissertation was to investigate the influence of visual disruption on both static and dynamic measures of postural stability in a joint pathology population, specifically anterior cruciate ligament reconstruction (ACLR). The first study of this dissertation was designed to examine differences in static postural stability measures between ACLR and control individuals. A novel aspect of this study was the implementation of the Stabilogram Diffusion Analysis (SDA) to investigate how motor control during a static postural stability task was affected in a joint pathology population. Additionally, this first study sought to examine the impact of visual disrupting eyewear on static postural stability measures. The second study of this dissertation sought to examine the influence of visual disruption on dynamic stability measures from a single-limb forward hopping maneuver. SDA has not been applied to a joint pathology population, specifically ACLR, for dynamic testing. Specifically, the SDA was applied after individuals landed from a normalized (i.e., height and distance) forward hop onto a force platform. During the hopping tasks, participants wore visual disrupting eyewear that reduced the amount of visual information for the duration of the task.

Participants

Twenty-six recreationally active individuals with a history of ACLR (n = 13) and healthy control (n = 13) individuals were recruited from the student populations at the University of Northern Colorado and Western Washington University. Inclusion criteria required all individuals to be recreationally active based on the guidelines of the American College of Sports Medicine, no history of lower extremity pain or injury within the past six months, no history of concussion within the last year, have normal or corrected to normal vision, and no known vestibular dysfunction or history of epilepsy. ACLR individuals specifically had to have undergone surgery within the past four years and must have received full clearance to resume athletic activities from their physician.

The study was approved by the University of Northern Colorado and Western Washington University Institutional Review Boards, and each participant provided consent before participation.

Data Collection

Data collection for this dissertation consisted of two visits to the Biomechanics Lab at the University of Northern Colorado and the Motion Analysis Lab at Western Washington University. During the first visit, each volunteer completed two self-reported questionnaires, the Tegner Activity Scale and the International Knee Documentation Committee (IKDC). Additionally, the primary researcher collected each participant’s demographic information and brief health history to gather information about their respective ACL surgery. Participants started each visit to the lab with a 5-minute warm-up on a motorized treadmill at a 1.3 m/s pace (Sloot et al., 2014). Next, participants were then asked to perform three maximum countermovement jumps, with jump height recorded using a Vertec device (JUMPUSA, Sunnyvale, CA). A mean of the three maximum countermovement jumps was calculated and used to determine each individual's jump height for the dynamic hop task. Following the countermovement jump, participants were asked to perform a 5-minute accommodation period for the stroboscopic glasses (Senaptec, Beaverton, OR) (Grooms et al., 2018). The accommodation period consisted of a ball-tossing activity where the level of visual disruption increased after five successful catches (Grooms et al., 2018).

For the first study, participants stood barefoot in a double-limb stance on two force platforms (AMTI, Watertown, MA) (1000 Hz) for 30-second trials. Each participant complete three randomized trials for each level of visual disruption. The three levels of visual disruption were eyes-open (EO), low visual disruption (LVD), and high visual disruption (HVD). These levels of visual disruption were selected based on the previous work of Grooms et al. (2018), who utilized similar stroboscopic eyewear during a drop jump landing task. For the LVD condition, the stroboscopic glasses cycled through periods of 100 milliseconds opaque and 100 milliseconds of clear settings (Grooms et al., 2018). During the HVD condition, the opaque lens was increased to 250 milliseconds, but the clear lens duration remained unchanged (Grooms et al., 2018). After completing the three double-limb stances, participants were provided a 5-minute rest period before completing six randomized single-limb postural stability tasks. Participants were instructed to stand on one of two available force platforms using either their dominant or non-dominant limbs for 30-seconds. Similar to the double-limb task, participants completed each level of vision for both dominant and non-dominant limbs.

For the second study, each participant arrived at the lab for their second visit (minimum of 48 hours between visits) and completed both the 5-minute treadmill warm-up and 5-minute stroboscopic glasses accommodation period. Participants then completed a forward hop protocol consisting of a barefoot forward hop from a two-footed starting positioned set at a distance of 40% of the participant body height (Sell, 2012). Normalization of jump distance to 40% of the participant's height was selected to allow for better comparisons to previous literature assessing the dynamic postural stability of individuals with a history of ACLR (Head et al., 2019; Heinert et al., 2018). During the forward hopping task, participants were instructed to touch an overhead target set at 50% of the participants maximum jump height and land on a single-limb on a force platform (AMTI, Watertown, MA) (1000 Hz) (Heinert et al., 2018; Webster & Gribble, 2010). After landing, participants were asked to stabilize as quickly as possible and remain balanced for 30-seconds. If the participant missed either the overhead target or force platform, the data collection was stopped, and the participant was asked to repeat the trial. Each participant was asked to complete three repetitions on both dominant and non-dominant limbs for each level of vision. To help prevent lower extremity fatigue, rest periods were provided after the completion of the second and fourth sets of forward hops. The same levels of vision that were used in study one were also used in study two (i.e., EO, LVD, and HVD). Prior to any recorded hops, all participants received the same verbal instructions for completing the task and were allowed to practice until they felt comfortable. The verbal instructions included directions on how to touch the overhead target, where to land on the force platform, and to place their hands on their hips after stabilizing from the landing. Participants were also given at least the same amount of time for viewing the target before initiating the forward hop. This was accomplished through a countdown provided by the primary researcher.

Data Analysis

For the first study, the full 30-seconds of force platform(s) COP data was used to calculate traditional (Prieto et al., 1996) and SDA (Collins & De Luca, 1993) measures of postural stability. For the traditional analysis, COP data were filtered using a 4^{th} order low-pass Butterworth filter with a cutoff frequency of 10 Hz. For the SDA calculations, COP data were filtered using a 4^{th} order low-pass Butterworth filter with a cutoff frequency of 20 Hz. Cutoff frequencies were selected based on the recommendations of Collins and De Luca (1993) and Prieto et al. (1996). Between-group comparisons (ACLR vs. control) were conducted using the operated limb of the ACLR group and the dominant limb of the control group.

All data for the second study were filtered using a 4^{th} order low-pass Butterworth filter with a cutoff frequency of 20 Hz (Head et al., 2019; Heinert et al., 2018). The outcome variables used for this study were derived from the following DPSI (Wikstrom et al., 2005), TTS (Colby et al., 1999), and SDA (Collins & De Luca, 1993). All outcome measures were averaged across three trials to provide a representation of the individual's performance. The injured limb for the ACLR group was matched with the corresponding limb of the control group (Lehmann et al., 2017).

Study One Specific Methodology

Participants

Thirteen recreationally active individuals with a history of ACLR volunteered for this study and were age (± 4 years) and sex-matched with thirteen recreationally active healthy controls (Howells et al., 2013). For the purposes of this study, recreationally active was operationally defined, based on the American College of Sports Medicine guidelines, as an individual who participates in physical activity for at least 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity per week. ACLR individuals were included if they had suffered a unilateral ACL injury, undergone reconstructive surgery within the past four years, and had received full clearance to resume athletic activities from their physician. ACLR group exclusion criteria were; 1) suffered a second ACL injury in either the contralateral or ipsilateral limb, 2) experienced any lower extremity pain or injury within six months of the testing session, 3) had a head injury (i.e., concussion) within the last year, 4) did not have normal or corrected to normal vision, 5) a known vestibular dysfunction, or 6) had a history of epilepsy. The control group had no history of ACL injury. All other exclusion criteria for the control group was the same as the ACLR group. The study was approved by the University of Northern Colorado and Western Washington University Institutional Review Boards, and each participant provided consent before participation.

Data Collection

Participants began the testing session by completing two self-reported questionnaires, the Tegner Activity Scale, and the International Knee Documentation Committee (IKDC) (Rambaud et al., 2018). The Tegnar Activity Scale is a self-reported questionnaire that provides clinicians and researchers with a self-reported level of activity for the patient (Collins et al., 2011). Scores from the Tegnar Activity Scale indicate the patient's pre-injury and post-injury level of activity, allowing clinicians to gain insight into the patient's perceived level of physical activity (Collins et al., 2011). The IKDC is a subjective questionnaire that provides insight into a patient's self-reported function for activities of daily living (Collins et al., 2011). The questionnaire is an assessment that provides a score from 0-100 with a score of 100, indicating no limitations in daily activities of living and no symptoms (Collins et al., 2011). Limb dominance was determined by asking each participant, "Which leg would you prefer to kick a soccer ball with?". Each participant then completed a 5-minute walk on a motorized treadmill, at a 1.3 m s^{-1} pace, as a warm-up (Sloot et al., 2014). Before postural stability testing, each participant completed a 5-minute accommodation period for the stroboscopic glasses (Senaptec, Beaverton, OR) that were worn for the duration of the testing session. The accommodation period has been previously described in detail by Grooms et al. (2018).

The stroboscopic glasses did not block the participant's vision completely, instead obstructed the participant's vision for only small periods as the glasses cycled through pre-defined phases of transparent and opaque settings. The stroboscopic visual settings selected for this study were based on previous research investigating visual disruption during a drop jump movement (Grooms et al., 2018). After completing the accommodation period, each participant performed three randomized double-limb and six randomized single-limb (dominant and non-dominant limb) static postural stability tasks. Three visual settings were used during the double- and single-leg stances; 1) eyes open (EO), 2) low visual disruption (LVD), and 3) high visual disruption (HVD) (Grooms et al., 2018). For the LVD condition, the stroboscopic glasses cycled through periods of 100 milliseconds opaque and 100 milliseconds of clear settings (Grooms et al., 2018). During the HVD condition, the opaque lens was modified to 250 milliseconds, but the clear lens duration remained unchanged (Grooms et al., 2018).

For double-limb tasks, each participant was asked to stand barefoot on two force platforms (AMTI, Watertown, MA). After completing all three double-limb static postural stability tasks, participants received a 5-minute rest period. For each single-limb postural stability task, participants were asked to stand barefoot on one of two force platforms with either their dominant or non-dominant limb. Participants were directed to maintain an extended knee position on the test limb while the contralateral knee was flexed to 90°, and hip flexed to approximately 45°. For all testing conditions, participants were asked to place their hands on their hips and focus on a fixed point on the wall in front of them. For double-limb testing, conditions were randomized for each participants by the visual conditions using a custom MATLAB script (MathWorks, Natick, MA). For the single-limb stance, the conditions were randomized for both limb and vision conditions using a specialized programming script in MATLAB. All postural stability testing was collected for 30 seconds, and force platform data were sampled at 1000 Hz. If the participant lost their balance or touched the floor with the non-testing limb, the trial was discarded, and another was performed.

Data Analysis

From the 30 seconds of recorded force platform(s) COP data, static postural stability calculations were performed using a custom MATLAB script. The COP data for the traditional measures of postural stability (Prieto et al., 1996) were filtered using a 4th order low-pass Butterworth filter with a cutoff frequency of 10 Hz. The outcome variables selected for this study were; 1) root mean square distance, 2) mean velocity, 3) sway area, and 4) mean frequency. The outcome measures used in this study were selected based on the findings of previous work (Prieto et al., 1996). For the SDA calculations, COP data were filtered using a 4th order low-pass Butterworth filter with a cutoff frequency of 20 Hz. Both the SDA calculations and descriptions of the outcome variables have previously been described in detail (Collins & De Luca, 1993). Additionally, representative figures of the outcome variables (mean critical displacement (Δr^2), mean critical time interval (Δt), short- and long-term diffusion coefficients (D_S and D_L), and short- and long-term scaling exponents (H_S and H_L) can be found in chapter two of this dissertation (Figure 2.2 and 2.3). For between-group comparisons, the injured limb for the ACLR group was matched with the corresponding limb of the control group (Lehmann et al., 2017).

Statistical Analysis

Independent t-tests were performed to compare the demographic data between the ACLR and control groups. As Prieto et al. (1996) did, multiple 2x3 repeated measures ANOVA's were used to assess the relationship between groups (ACLR vs. controls) and within vision (EO, LVD, HVD) for both the traditional and SDA outcome measures. An α level was set a priori at .05 for all statistical testing. Bonferroni post-hoc testing was performed to evaluate the effect of vision when appropriate. All statistical testing and analysis was performed using SPSS (Version 26.0, IBM Inc. Chicago, IL).

Study Two Specific Methodology

Participants

Twelve recreationally active individuals with a history of ACLR volunteered for participation in this study and were age (± 4 years) and sex-matched with twelve recreationally active healthy controls (Howells et al., 2013). The term "recreationally" active was operationally defined for this study using the guidelines set by the American

College of Sports Medicine (ACSM) guidelines as an individual who participants in physical activity for at least 150 minutes of moderate-intensity or 75 minutes of vigorous activity per week. ACLR individuals were included in this study if they had suffered a unilateral ACL injury, had reconstructive surgery within the past four years, and had received full clearance to resume athletic activities from their physician. The exclusion criteria for the ACLR group included; 1) suffered a second ACL injury in either the contralateral or ipsilateral limb, 2) experienced any lower extremity pain or injury within six months of the testing session, 3) history of head injury (i.e., concussion) within the last year, 4) uncorrected vision, 5) a known vestibular dysfunction, or 6) had a history of epilepsy. Individuals included in the control group had no history of ACL injury in either limb. All other exclusion criteria for the control group was the same as the ACLR group. This study was approved by the University of Northern Colorado and Western Washington University Institutional Review Boards, and each participant provided written informed consent before participation.

Experimental Protocol

The current study was day two of a multi-day data collection. All participants in the current study completed two self-reported questionnaires, the Tegner Activity Scale, and the International Knee Documentation Committee (IKDC), during day one of the data collection protocol (Rambaud et al., 2018). These self-reported questionnaires are used to gain insight into how the ACLR patient would rate their physical activity level and determine their level of function during activities of daily living (Collins et al., 2011). In order to determine limb dominance, each participant was asked, “Which leg would you prefer to kick a soccer ball with?”. A 5-minute warm-up was completed on a motorized treadmill at a 1.3 m s^{-1} pace (Sloot et al., 2014). After completing the warm-up, each participant's vertical jump height was recorded using a Vertec device (JUMPUSA, Sunnyvale, CA). Reach height was assessed by asking the participant to stand beneath the Vertec and reach the highest vane possible, displacing the vane forward. Each participant then completed three repetitions of a counter movement jump, jumping vertically and moving the highest vane possible. Maximum vertical height was calculated as the difference between the average of the three vertical jump trials and the standing reach height.

Before beginning the dynamic postural stability task, each participant completed a 5-minute accommodation period for the stroboscopic glasses (Senaptec, Beaverton, OR) that were worn for the duration of the testing session. The accommodation period has been previously described in detail by Grooms et al. (2018). These specialized glasses do not block the participant's vision completely, instead only obstructed the participant's vision for small increments as the glasses cycle through pre-determined phases of transparent and opaque settings. After completing the accommodation period, each participant performed six randomized single-limb (dominant and non-dominant limb) dynamic postural stability tasks. Three visual settings were used during the double- and single-leg stances; 1) EO, 2) LVD, and 3) high visual disruption (HVD). The stroboscopic visual settings selected for this study were based on previous research investigating visual disruption during a drop jump movement (Grooms et al., 2018). For the LVD condition, the stroboscopic glasses cycled through periods of 100 milliseconds opaque and 100 milliseconds of clear settings (Grooms et al., 2018). During the HVD condition, the opaque lens was modified to 250 milliseconds, but the clear lens duration remained at 100 milliseconds (Grooms et al., 2018).

The forward hop protocol required participants to jump barefoot from a two-footed starting position set at a distance of 40% of the participant's height, touch an overhead target set at 50% of the participants maximum jump height, and land on the force platform on a single-limb (Heinert et al., 2018; Ross & Guskiewicz, 2003; Sell, 2012). Upon landing, participants were instructed to stabilize as quickly as possible, looking straight forward at a fixed target on the wall, and balance for 30 seconds. Additionally, participants were instructed to place their hands on their hips after stabilizing from the jump landing. However, participants were allowed to remove their hands from their hips to help stabilize themselves from falling, but asked to return their hands to their hips once they were stable again. Participants were allowed to touch the overhead target with a single arm of their choosing before landing on the force platform (Ross & Guskiewicz, 2003; Wikstrom et al., 2005). Practice trials were permitted for the forward hopping task while wearing the stroboscopic glasses; however, the glasses were not on and, therefore, could not obstruct vision. Participants were allowed to practice the forward hop procedure, on each limb, until they felt comfortable completing the task. All participants were provided the same verbal instructions for completing the hopping movement and given at least the same amount of time for viewing the target before initiating the forward hop. This was accomplished through a countdown provided by the primary researcher. The verbal instructions included directions on how to touch the overhead target, where to land on the force platform and to place their hands on their hips after stabilizing from the landing.

All hopping tasks and visual conditions were randomized using a custom MATLAB (Mathworks, Natick, MA, USA) script. Each participant completed three repetitions of the following forward hop tasks: 1) forward single-leg hop, EO, dominant limb, 2) forward single-leg hop, EO, non-dominant limb, 3) forward single-leg hop, LVD, dominant limb, 4) forward single-leg hop, LVD, non-dominant limb, 5) forward single-leg hop, HVD, dominant limb, 6) forward single-leg hop, HVD, non-dominant limb. To help prevent lower extremity fatigue, participants received a 5-minute break after completing the second and fourth hopping task. All ground reaction force (GRF) data were collected using a force platform (AMTI, Watertown, MA) using a sampling frequency of 1000 Hz.

Data Analysis

Force platform data were used to calculate the dynamic postural stability outcome measures using a custom MATLAB script (MathWorks, Natick, MA). All data were filtered using a 4th order low-pass Butterworth filter with a cutoff frequency of 20 Hz (Head et al., 2019; Heinert et al., 2018). The outcome variables used for this study were derived from the following DPSI (Wikstrom et al., 2005), TTS (Colby et al., 1999), and SDA (Collins & De Luca, 1993). All outcome measures were averaged across three trials to provide a representation of the individual's performance. The injured limb for the ACLR group was matched with the corresponding limb of the control group (Lehmann et al., 2017).

DPSI calculations were analyzed using methods described by Wikstrom et al. (2005). This method provided both directional (anterior-posterior, medial-lateral, and vertical) stability indices and the composite DPSI. These dynamic stability indexes were calculated using the first three seconds of the GRF data after landing on the force platform, as the small timeframe closely resembles athletic activity (Wikstrom et al., 2005). The single-limb landing was defined as the point where the GRF signal exceeded 10 N. The vertical stability index (VSI) was normalized to body weight to allow for between-group comparisons. DPSI is a composite value which includes the anterior-posterior stability index (APSI), medial-lateral stability index (MLSI), and VSI (Wikstrom et al., 2005). TTS outcome measures were calculated using a sequential average method used in previous research analyzing dynamic stability during a forward hopping task (Colby et al., 1999; Liu & Heise, 2013). TTS was determined when force values remained within a one-quarter standard deviation of the overall mean (Colby et al., 1999; Liu & Heise, 2013). For all SDA outcome variables, calculations were made using the methods previously described in detail by Collins and De Luca (1993). To create the SDA plot (refer to Figure 2.1 and 2.2), the distance between COP data points were averaged over increasing time intervals. The mean square displacements (Δr^2) were then plotted at each respective time interval (Δt). The critical point was then established by obtaining the intersection point of the SDA plot's short and long-term regions (Figure 2.2). Both the critical mean square displacement (Δr^2) and critical time interval (Δt) at the critical point represent the approximate transition between the open- and closed-loop control strategies (Collins & De Luca, 1993). The short- and long-term diffusion coefficients (D_S and D_L) were then calculated based on the line of best fit for each region and indicated the level of stochastic activity present in the system. Additionally, the short- and long-term scaling exponents (H_S and H_L) were calculated similarly on the line of best fit from the log-log plot of the SDA (Figure 2.3). The scaling exponents represent the correlation between past and future COP data points, and physiologically represent open- (positively correlated past and future COP, $H > 0.5$) and closed-loop (negatively correlated past and future COP, $H < 0.5$) behaviors (Collins & De Luca, 1993).

Statistical Analysis

Independent t-tests were performed to compare the group demographic data. Multiple 2x3 repeated measures ANOVA's were used to assess the relationship between groups (ACLR vs. controls) and within vision (EO, LVD, HVD) for the DPSI, TTS, and SDA outcome measures. An α level was set a priori at .05 for all statistical testing. Bonferroni post-hoc testing was performed to evaluate the effect of vision when appropriate. All statistical testing and analysis were performed using SPSS (Version 26.0, IBM Inc. Chicago, IL).

CHAPTER IV

STUDY ONE: THE EFFECT OF VISUAL DISRUPTION ON STATIC STABILITY MEASURES IN ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTED INDIVIDUALS

Introduction

Anterior cruciate ligament (ACL) injuries are one of the most common knee injuries occurring in sports today. An estimated 250,000 ACL injuries occur each year in the United States, with 175,000 of those individuals electing to undergo ACL reconstruction (ACLR) surgery (Gornitzky et al., 2016; Gottlob et al., 1999; Myer et al., 2004; Paterno et al., 2011; Wojtys & Brower, 2010). Beyond the direct costs of injury treatment, indirect costs may also be present, including decreased physical activity, loss of financial stability (i.e., scholarship, salary), and increased risk of long-term disability such as osteoarthritis (Freedman et al., 1998; Myer et al., 2004). Surgical reconstruction of the ACL is performed to restore mechanical stability to the knee and allow individuals to return to athletic competition (Ardern et al., 2011; Barber-Westin & Noyes, 2011). However, despite surgical and rehabilitative efforts to return these ACLR individuals to athletic competition, the risk of re-injury remains elevated (Paterno et al., 2014; Wiggins et al., 2016).

A majority of second ACL injuries occur through non-contact mechanisms, indicating appropriate neuromuscular patterns may not be fully restored when athletes return to sport (RTS) (Wright et al., 2010). In addition to this non-contact mechanism, there is an increased risk of injury to the contralateral (intact ACL) limb (Paterno et al., 2012, 2014). Collectively, the non-contact mechanism and higher injury rates in the contralateral limb support the hypothesis that an ACL injury may not be a simple musculoskeletal injury, but rather a more complex injury involving neurological adaptions (Grooms et al., 2017; Kapreli et al., 2009; Needle et al., 2017). Lingering neurological deficits, specifically somatosensory dysfunctions have been reported in patients with a history of ACLR (Bonfim et al., 2003; Relph et al., 2014; San Martín-Mohr et al., 2018). These somatosensory dysfunctions may result in an increased reliance on visual information as a compensation strategy during tasks such as quiet stance (Bonfim et al., 2003; Dingenen et al., 2015; Grooms et al., 2015a; Negahban et al., 2013; O'Connell et al., 1998). This process of sensory reweighting may allow ACLR individuals to successfully maintain postural stability when visual information is available but becomes problematic during athletic activities which require the visual system to be diverted to other tasks (i.e., managing external environmental factors) (Grooms et al., 2015a; Kim et al., 2017). Postural stability assessments can provide valuable insight into how the sensory (i.e., vision, vestibular, and somatosensory) systems are functioning.

Deficits in these traditional postural stability measures have been observed in ACLR individuals and may remain impacted even years after surgery (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Mohammadi et al., 2012; Shiraishi et al., 1996). These traditional measures of static postural stability provide information about the COP movement during the task but provided limited physiological meaning (Collins & De Luca, 1993; Heise et al., 2012). The Stabilogram diffusion analysis (SDA) is a proposed method for analyzing COP data that offers a unique insight into the neuromuscular control (i.e., open-loop and closed-loop control) system during postural stability tasks (Collins & De Luca, 1993) (Figure 4.1).

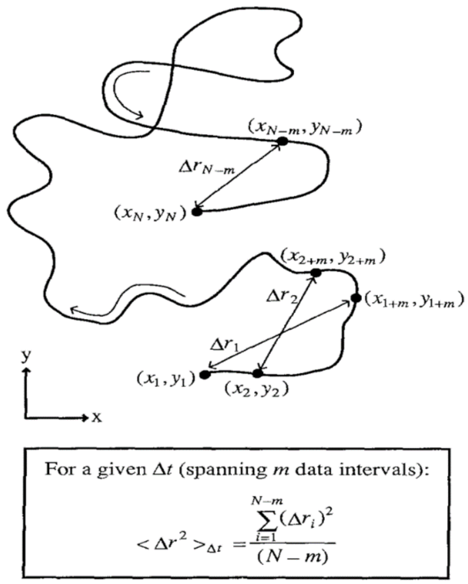

Figure 4.1. Method for calculation of stabilogram diffusion analysis as described by Collins and De Luca (adapted from Collins & De Luca, 1993).

Application of the SDA method may allow for a deeper understanding of potential motor control strategies utilized by individuals with a history of ACLR. Therefore, the first purpose of this study was to explore the use of SDA to evaluate postural stability in both ACLR and healthy individuals. A secondary purpose was to evaluate the effect of visual perturbations on double- and single-limb postural stability measures in both ACLR and healthy controls.

Methods

Participants

Thirteen recreationally active individuals with a history of ACLR volunteered for this study and were age (± 4 years) and sex-matched with thirteen recreationally active healthy controls (Howells et al., 2013). For the purposes of this study, recreationally active was operationally defined, based on the American College of Sports Medicine guidelines, as an individual who participates in physical activity for at least 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity per week. ACLR individuals were included if they had suffered a unilateral ACL injury, undergone reconstructive surgery within the past four years, and had received full clearance to resume athletic activities from their physician. ACLR group exclusion criteria were; 1) suffered a second ACL injury in either the contralateral or ipsilateral limb, 2) experienced any lower extremity pain or injury within six months of the testing session, 3) had a head injury (i.e., concussion) within the last year, 4) did not have normal or corrected to normal vision, 5) a known vestibular dysfunction, or 6) had a history of epilepsy. The control group had no history of ACL injury. All other exclusion criteria for the control group was the same as the ACLR group. The study was approved by the University of Northern Colorado and Western Washington University Institutional Review Boards, and each participant provided consent before participation.

Data Collection

Participants began the testing session by completing two self-reported questionnaires, the Tegner Activity Scale, and the International Knee Documentation Committee (IKDC) (Rambaud et al., 2018). The Tegnar Activity Scale is a self-reported questionnaire that provides clinicians and researchers with a self-reported level of activity for the patient (Collins et al., 2011). Scores from the Tegnar Activity Scale indicate the patient's pre-injury and post-injury level of activity, allowing clinicians to gain insight into the patient's perceived level of physical activity (Collins et al., 2011). The IKDC is a subjective questionnaire that provides insight into a patient’s self-reported function for activities of daily living (Collins et al., 2011). The questionnaire is an assessment that provides a score from 0-100 with a score of 100, indicating no limitations in daily activities of living and no symptoms (Collins et al., 2011). Limb dominance was determined by asking each participant, “Which leg would you prefer to kick a soccer ball with?”. Each participant then completed a 5-minute walk on a motorized treadmill, at a 1.3 m s^{-1} pace, as a warm-up (Sloot et al., 2014). Before postural stability testing, each participant completed a 5-minute accommodation period for the stroboscopic glasses (Senaptec, Beaverton, OR) that were worn for the duration of the testing session. The accommodation period has been previously described in detail by Grooms et al. (2018).

The stroboscopic glasses did not block the participant's vision completely, instead obstructed the participant's vision for only small periods as the glasses cycled through pre-defined phases of transparent and opaque settings. The stroboscopic visual settings selected for this study were based on previous research investigating visual disruption during a drop jump movement (Grooms et al., 2018). After completing the accommodation period, each participant performed three randomized double-limb and six randomized single-limb (dominant and non-dominant limb) static postural stability tasks. Three visual settings were used during the double- and single-leg stances; 1) eyes open (EO), 2) low visual disruption (LVD), and 3) high visual disruption (HVD) (Grooms et al., 2018). For the LVD condition, the stroboscopic glasses cycled through periods of 100 milliseconds opaque and 100 milliseconds of clear settings (Grooms et al., 2018). During the HVD condition, the opaque lens was modified to 250 milliseconds, but the clear lens duration remained unchanged (Grooms et al., 2018).

For double-limb tasks, each participant was asked to stand barefoot on two force platforms (AMTI, Watertown, MA). After completing all three double-limb static postural stability tasks, participants received a 5-minute rest period. For each single-limb postural stability task, participants were asked to stand barefoot on one of two force platforms with either their dominant or non-dominant limb. Participants were directed to maintain an extended knee position on the test limb while the contralateral knee was flexed to 90°, and hip flexed to approximately 45°. For all testing conditions, participants were asked to place their hands on their hips and focus on a fixed point on the wall in front of them. For double-limb testing, conditions were randomized for each participants by the visual conditions using a custom MATLAB script (MathWorks, Natick, MA). For the single-limb stance, the conditions were randomized for both limb and vision conditions using a specialized programming script in MATLAB. All postural stability testing was collected for 30 seconds, and force platform data were sampled at 1000 Hz. If the participant lost their balance or touched the floor with the non-testing limb, the trial was discarded, and another was performed.

Data Analysis

From the 30 seconds of recorded force platform(s) COP data, static postural stability calculations were performed using a custom MATLAB script. The COP data for the traditional measures of postural stability (Prieto et al., 1996) were filtered using a 4^{th} order low-pass Butterworth filter with a cutoff frequency of 10 Hz. The outcome variables selected for this study were; 1) root mean square distance, 2) mean velocity, 3) sway area, and 4) mean frequency. The outcome measures used in this study were selected based on the findings of previous work (Prieto et al., 1996). For the SDA calculations, COP data were filtered using a 4th order low-pass Butterworth filter with a cutoff frequency of 20 Hz. Both the SDA calculations and descriptions of the outcome variables have previously been described in detail (Collins & De Luca, 1993). Additionally, representative figures of the outcome variables (mean critical displacement (Δr^2), mean critical time interval (Δt), short- and long-term diffusion coefficients (D_S and D_L), and short- and long-term scaling exponents (H_S and H_L) can be found in chapter two of this dissertation (Figure 2.2 and 2.3). For between-group comparisons, the injured limb for the ACLR group was matched with the corresponding limb of the control group (Lehmann et al., 2017).

Statistical Analysis

Independent t-tests were performed to compare the demographic data between the ACLR and control groups. As Prieto et al. (1996) did, multiple 2x3 repeated measures ANOVA's were used to assess the relationship between groups (ACLR vs. controls) and within vision (EO, LVD, HVD) for both the traditional and SDA outcome measures. An α level was set a priori at .05 for all statistical testing. Bonferroni post-hoc testing was performed to evaluate the effect of vision when appropriate. All statistical testing and analysis was performed using SPSS (Version 26.0, IBM Inc. Chicago, IL).

Results

Demographic data for both ACLR and control groups are shown in Table 4.1. No significant differences were found between the groups for age, mass, height, and current level Tegnar activity scale. There was a statistically significant difference in IKDC scores between ACLR and control group ($t(24) = -3.536$, $p = .002$). All 26 participants were able to complete both double- and single-limb testing.

Double-Limb Postural Stability

In the present study, when analyzing double-limb traditional static stability measures, a significant main effect between groups was observed for the mean frequency (MFREQ) outcome variable ($F(1, 24) = 4.87$, $p = .037$). ACLR individuals demonstrated decreased MFREQ values compared to the control group. No significant main effect for group was observed for the rest of the traditional static postural stability outcome variables.

Table 4.1

Demographic and self-reported questionnaires data for ACLR and control groups.

	ACLR (n = 13)	Control (n = 13)	*p-value* -
Age (years), mean ± SD	20.0 ± 1.3	21.2 ± 2.1	.106
Mass (kg), mean ± SD	76.1 ± 8.1	69.5 ± 11.6	.105
Height (m), mean ± SD	1.7 ± .09	1.7 ± .10	.934
Graft type	HS: 4	-	-
	BPTB: 9	-	-
Time since surgery (months), mean ± SD	28.0 ± 9.7	-	-
Pre-injury Tegner activity scale, mean ± SD	8.6 ± .9	-	-
Current level Tegner activity scale, mean ± SD	7.8 ± 1.3	6.7 ± 1.4	.052
IKDC, mean ± SD	86.1 ± 12.3	98.5 ± 2.9	.002*

Note. *indicates a significant group difference ($p < .05$). HS = hamstring tendon graft. BPTB = bone-patellar tendon-bone graft.

Table 4.2.

Double-limb stability outcome measures for ACLR and control groups.

Traditional outcome measures	ACLR n = 13	Control n = 13	*p-value* -
RDIST (mm), mean ± SD	5.15 ± .38	4.78 ± .39	.583
MVELO (mm/s), mean ± SD	12.25 ± .64	15.02 ± .64	.059
Sway Area (mm^2/s), mean ± SD	18.21 ± 2.45	20.88 ± 3.19	.543
MFREQ (Hz), mean ± SD	0.50 ± .04	0.69 ± .04	.037*

Note.*indicates a significant group difference ($p < .05$).

A main effect of vision showed a statistically significant difference between the levels of vision for mean velocity (MVELO) ($F(2, 48) = 5.599$, $p = .007$). These results are shown in Figure 4.2. No significant main effect for vision was observed for root mean square distance (RDIST), sway area, or MFREQ.

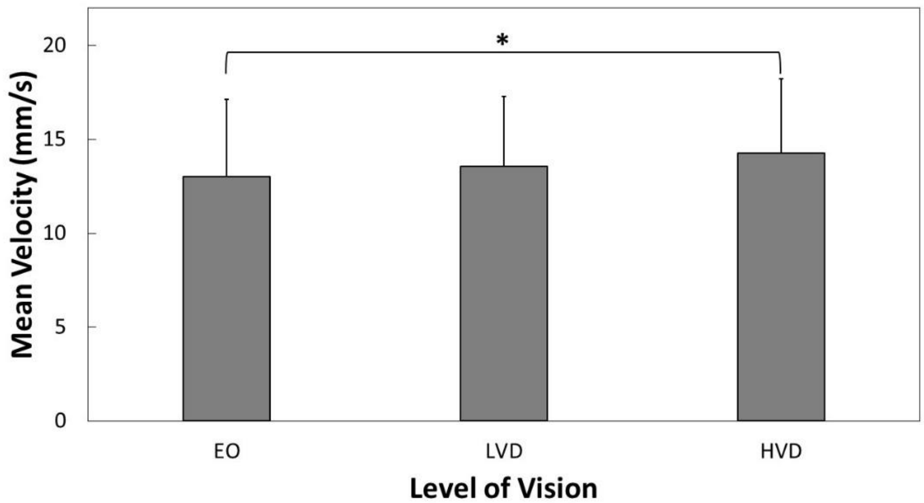

Figure 4.2. Double-limb mean velocity calculated based on the work of Prieto et al. (1996). * indicates a significant difference ($p < .05$) in mean velocity between the levels of vision.

Single-Limb Postural Stability

No significant interaction was observed for any traditional outcome measure. No significant main effect for group was observed for RDIST, MVELO, sway area, or MFREQ in single-limb static postural stability measures (Table 4.3).

As shown in Figures 4.3-4.6, significant main effects for vision were demonstrated in traditional postural stability measures RDIST ($F(2, 48) = 21.315$, $p < .001$), MVELO ($F(2, 48) = 70.47$, $p < .001$), sway area ($F(2, 48) = 45.226$, $p < .001$), and MFREQ ($F(2, 48) = 11.691$, $p < .001$).

Table 4.3.

Single-limb stability outcome measures for ACLR and control groups.

Traditional outcome measures	ACLR n = 13	Control n = 13	*p-value* -
RDIST (mm), mean ± SD	13.79 ± 1.20	12.98 ± .2.10	.160
MVELO (mm/s), mean ± SD	65.49 ± 15.05	56.11 ± 12.64	.080
Sway Area (mm^2/s), mean ± SD	281.26 ± 97.44	225.51 ± 79.13	.056
MFREQ (Hz), mean ± SD	0.86 ± .08	0.79 ± .07	.242

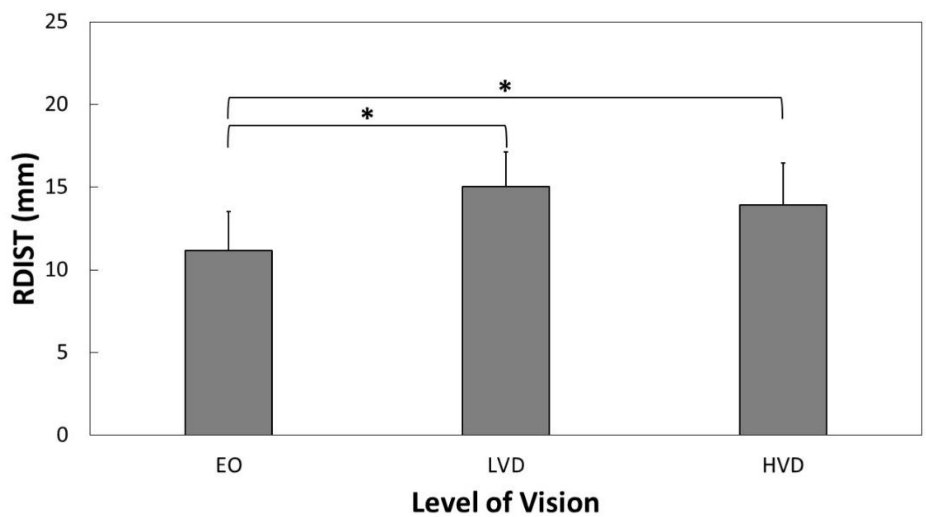

Figure 4.3. Single-limb root mean square distance calculated based on the work of Prieto et al. (1996). * indicates a significant difference (p < .05) in mean root mean square distance between the levels of vision.

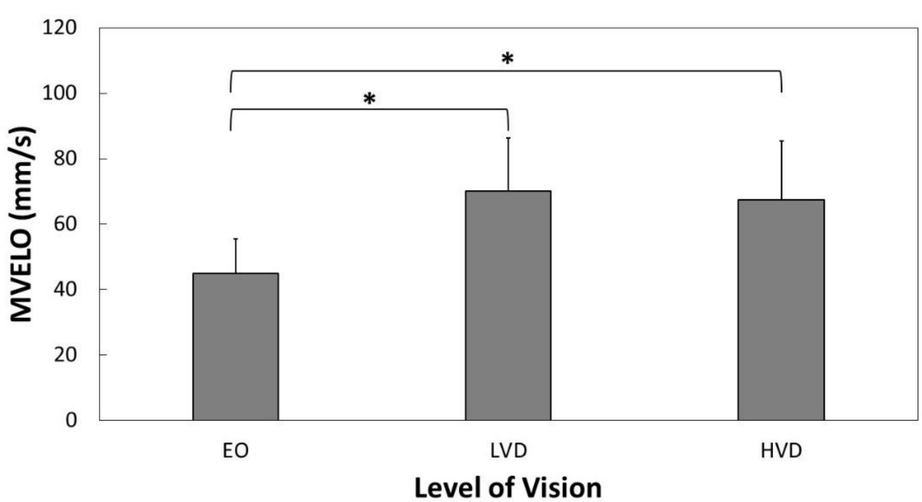

Figure 4.4. Single-limb mean velocity calculated based on the work of Prieto et al. (1996). * indicates a significant difference (p < .05) in mean velocity between the levels of vision.

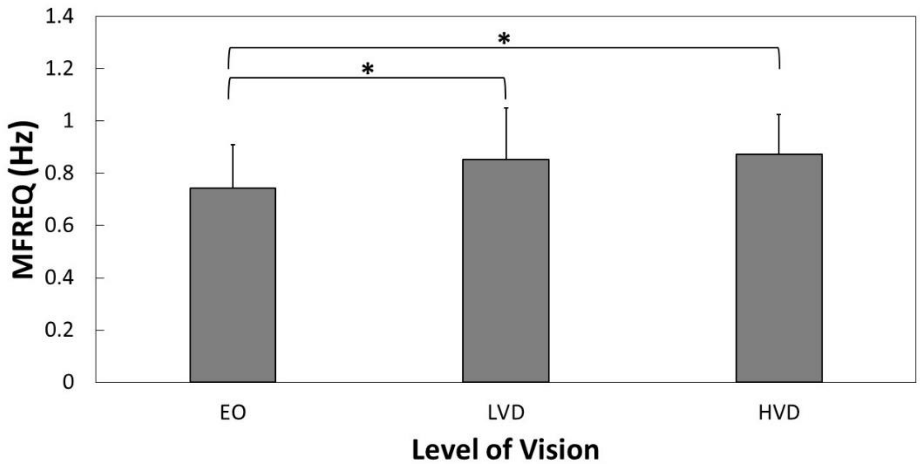

Figure 4.5. Single-limb mean frequency calculated based on the work of Prieto et al. (1996). * indicates a significant difference ($p < .05$) in mean frequency between the levels of vision.

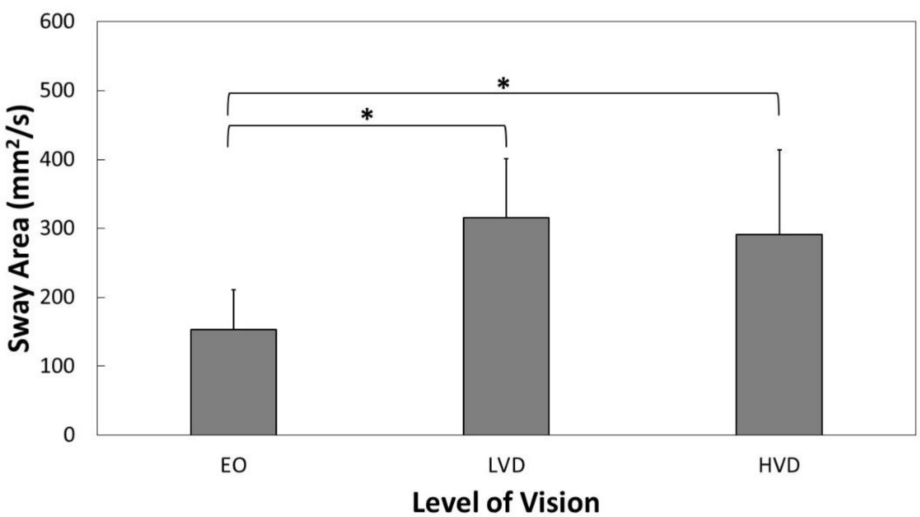

Figure 4.6. Single-limb sway area calculated based on the work of Prieto et al. (1996). * indicates a significant difference ($p < .05$) in sway area between the levels of vision.

Stabilogram Diffusion Analysis (SDA)

Data from SDA are not included in this study because long-term diffusion coefficients or scaling exponents for many participants were negative. This situation is uninterpretable based on the original work of Collins and De Luca (1993). In particular, when analyzing SDA results for double- and single-limb stances, the usable data associated with participants decreased substantially when visual disruption was added to the static task. Appendix B details these results. To perform the repeated measures analysis, participants needed to have interpretable SDA values for each level of vision (EO, LVD, and HVD). This requirement led to low participant numbers for statistical analysis (Tables B.1 and B.2 in Appendix B). An example of an uninterpretable SDA result is presented in appendix B (Figure B.1). In an effort to salvage the SDA, post hoc adjustments to SDA time intervals were investigated. However, changes to the time intervals did not result in additional positive diffusion coefficients or scaling exponents, which would lead to an increase in sample size (Tables B.3-B.5).

Discussion

The overall purpose of this study was to evaluate whether ACLR individuals had worse static postural stability measures at different levels of visual disruption compared to controls. This approach was taken as previous research suggested that ACLR individuals rely on visual information to compensate for decreased proprioception information from the knee (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Konishi et al., 2002; Mohammadi et al., 2012; Shiraishi et al., 1996). This study's primary purpose was to explore SDA between groups; however, these data were insufficient for statistical analysis and interpretation. Therefore, this study's primary purpose was to explore the use of traditional COP measures to evaluate postural stability in both ACLR and healthy individuals. The secondary purpose of this study was to evaluate the effect of visual perturbations on double- and single-limb postural stability measures on both ACLR and healthy controls.

Double-Limb Postural Stability

For double-limb postural stability, ACLR individuals did not present with worse postural stability measures as visual disruption increased. It was expected that as levels of visual disruption increased, ACLR individual's postural stability would be negatively affected to a greater extent than the control participants. Previous work has supported the theory that individuals with a history of ACLR may rely more on visual information to compensate for decreased proprioception information for the knee (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Konishi et al., 2002; Mohammadi et al., 2012; Shiraishi et al., 1996). The rationale for why this study's results did not show similar adverse effects of removing vision, might be explained by a couple of potential reasons.

First, the present study utilized a more traditional method of collecting and analyzing static postural stability. A rigid force platform was used to collect all static postural stability trials, whereas previous research has used a combination of rigid and moveable platforms (i.e., Biodex Stability System, Equitest). Another potential reason is that a certain level of sensory function has returned to the knee (Ochi et al., 1999). Individuals included in the current study's ACLR group were, on average, two years removed from surgery, compared to previous work which measured ACLR individuals at much earlier time frames (i.e., < 9 months after surgery) (Dauty et al., 2010; Denti et al., 2000; Mohammadi et al., 2012). Ochi et al. (1999) observed similar cortical somatosensory evoked potentials (SEP) in ACLR patients at 18 months after surgery when compared to the control group. Ochi et al. (1999) observed no differences in voltage levels of SEP when the ACL was directly stimulated between the ACLR and control groups. However, the authors did find significant voltage differences between the

ACL deficient group and healthy controls (Ochi et al., 1999). Based on the results of Ochi et al. (1999), the participants included in the current study may have some level of sensory function return to the reconstructed ACL ligament, providing some level of afferent information about the knee joint. However, there is still much research to be done in this area of ACLR research, as conflicting results do exist (Young et al., 2016). Young et al. (2016) observed a reduction in neural tissue sampled from ACL grafts compared to the remains of an initial ACL injury. The lack of mechanoreceptor reinnervation in ACLR patients may contribute to the lingering proprioceptive deficits (Bonfim et al., 2003; Relph et al., 2014; San Martín-Mohr et al., 2018). Additionally, it may be that a double-limb testing position may not be challenging enough to detect differences between ACLR and healthy controls.

When examining the traditional double-limb postural stability outcome measures, only a single outcome measure (MFREQ) had a significant group effect. Mean frequency (MFREQ) is an indicator of directional changes or corrective actions (Prieto et al., 1996). A greater mean frequency score would be indicative of a greater number of directional changes or decreased levels of postural stability. Surprisingly, the study showed that the ACLR group was considered to be more stable (i.e., lower mean frequency) during the 30-second postural examination compared to the control group. To the author's knowledge, this outcome variable has not been previously reported in the ACLR literature, and therefore it is difficult to make direct comparisons to our work. This improved postural stability behavior may be the result of previous experience with balance training in ACLR individuals. Additionally, the examination of the traditional outcome measures as a whole instead of as individual components leads to a different interpretation of postural stability. When analyzed collectively, the results of this study are in line with previous work demonstrating no significant differences between the ACLR and control groups (Bonfim et al., 2003; Denti et al., 2000; Henriksson et al., 2001; Mattacola et al., 2002).

The visual disruption caused by the varying levels of stroboscopic vision from the glasses resulted in an increase in double-limb MVELO. As expected, MVELO increased from the EO condition (13.03 mm/s) to the HVD condition (14.28 mm/s) when visual disruption was at its highest (Figure 4.2). These findings are similar to those of previous research, which found increased velocities in both the anterior-posterior and medial-lateral directions when utilizing stroboscopic glasses (Kim et al., 2017). However, in contrast to Kim et al. (2017), the results from this study did not find a significant difference at the LVD level. A significant difference in MVELO was only present when cycling through periods of 250 milliseconds opaque and 100 milliseconds clear in this study's sample. However, this study included both ACLR and control participants, whereas Kim et al. (2017), only evaluated healthy young adults. The results reported in the current study are similar to the findings of Prieto et al. (1996), who found that MVELO was more sensitive at detecting visual differences than other standard outcome measures in both young and elderly individuals.

Single-Limb Postural Stability

For the single-limb quiet stance task, it was anticipated that the ACLR group would present with increased postural stability deficits as this stance position would challenge the reconstructed limb to a greater extent than the double-limb stance. Contrary to the study hypothesis, we found no differences between the ACLR and control groups using the traditional measures to evaluate postural stability. Similar findings have been observed in previous research, suggesting that ACLR individuals do not exhibit worse traditional postural stability measures than controls (Bodkin et al., 2018; Bonfim et al., 2003; Chmielewski et al., 2002; Henriksson et al., 2001; Hoffman et al., 1999). In contrast to this study's findings, several studies have found significant group differences between ACLR and control individuals (Dauty et al., 2010; Mohammadi et al., 2012; Shiraishi et al., 1996; Zouita Ben Moussa et al., 2009). Both Zouita Ben Moussa et al. (2009) and Mohammadi et al. (2012) found significant increases in single-limb sway velocity in ACLR patients when compared to healthy controls. The ACLR group in the present study did have a higher mean MVELO during single-limb testing compared to controls but was not statistically significant. Increased postural sway has also been reported in ACLR individuals compared to healthy controls during single-limb stance (Mohammadi et al., 2012). Similar to mean velocity, the mean sway area was also non-significant, but the ACLR group did have a higher mean value when compared to controls, 281.26 mm/s vs. 225.51 mm/s, respectively. Beyond sample size differences, Mohammadi et al. (2012) utilized a flexed knee position during testing, which may exacerbate measures of postural stability due to the reliance on knee extensor muscles in this position and the known quadriceps dysfunction in ACLR participants (Otzel et al., 2015).

Changes to the level of visual disruption did not impact the postural stability of ACLR participants to a greater extent as originally hypothesized; however, visual disruption did negatively impact postural stability measures. Examination of the traditional variables demonstrated significant increases in all measures from EO to the

LVD condition (Figures 4.3-4.6). These findings are similar to findings in previous work, demonstrating significant increases in traditional measures of postural stability (Kim et al., 2017). It is difficult to make direct comparisons to the work of Kim et al. (2017) as the only common variable was MVELO. However, similar to Kim et al. (2017), the results of this study demonstrate that postural stability worsened with the LVD condition versus the EO conditions. As hypothesized, there were significant increases in all traditional outcome variables when comparing EO to HVD. Surprisingly no significant differences were found between the LVD and HVD levels of visual disruptions, suggesting that future research may only need to test one level of disruption to understand the effects of stroboscopic vision.

In the present study, ACLR individuals had lower levels of self-reported function compared to healthy controls, as observed in IKDC scores. IDKC scores are used by clinicians to detect changes in the patient's self-reported symptoms, function, and physical activity (Collins et al., 2011). ACLR individuals had lower mean values of self-reported IKDC scores of 86.1, compared to 98.5 for healthy controls. The lower levels of self-reported knee function observed in ACLR individuals may have contributed to the group differences in postural stability measures observed in this present study.

An unexpected outcome of the SDA was the calculation of negative long-term diffusion coefficients (D_L) or scaling exponents (H_L). Because this occurred for multiple participants, these data were not included in the present study but are included in Appendix B of this dissertation. The SDA offers no interpretation for these negative slopes (Collins & De Luca, 1993). As shown in Appendix B, this led to a significant loss of available data for statistical analysis. Examination of the data presented in Appendix

B, showcases that the SDA calculation may have been impacted by the visual disruption conditions used for this study. In most of the static postural stability tasks and time intervals, the EO condition had the most usable data, whereas the participant numbers decreased as the visual disruption increased. Previous research studying the effects of visual input on SDA demonstrated mixed results as two distinct behaviors were found in a group of young, healthy individuals (Collins & De Luca 1995a). In conjunction with the findings of the current study, these previous findings suggest that the SDA may not be appropriate when analyzing different visual conditions. Furthermore, SDA has been used to assess static postural stability of different pathologies, such as phobic postural vertigo and Parkinson’s disease, so it is reasonable to believe that joint pathologies could be examined using SDA methods.

This study is not without limitations. First, the sample size was smaller than previous work that examined measures of postural stability between ACLR and control groups. In both double- and single-limb stability, several outcome measures were trending towards significance and may have been significant with a larger sample size. This study did not account for any rehabilitation protocol or individual compliance differences in our study, as participants were not followed long-term. This study’s baseline activity cutoff may also be considered a limitation. The participants were asked to self-report their level of engagement in regular physical activity based on the minimum guidelines provided by the American College of Sports Medicine. Although not directly measured, many of our ACLR participants indicated regular involvement in club sports compared to our control group. Future studies should seek to have a higher activity threshold to ensure the groups are competing at a similar level of sport recreation.

Conclusion

In conclusion, the results of this study suggest that ACLR individuals do not rely more on visual information to complete static postural stability tasks. This finding is similar to a recent systematic review and meta-analysis that concluded that ACLR individuals do not demonstrate increased reliance on visual information during postural stability testing (Wikstrom et al., 2017). Collectively the results of the study demonstrate that traditional measures of postural stability may not be sensitive enough to detect differences in ACLR individuals as they demonstrate similar behaviors to healthy controls. Due to the effect of stroboscopic vision on postural stability measures, clinicians may utilize these cost-effective glasses as an alternative to the traditional binary (EO vs. EC) rehabilitation approaches for postural stability. Future research should aim to investigate non-linear methods of analyzing postural stability due to the non-significant findings using traditional measures in the current study.

CHAPTER V

STUDY TWO: THE IMPACT OF VISUAL DISRUPTION ON DYNAMIC STABILITY MEASURES IN ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTED INDIVIDUALS

Introduction

Injury to the anterior cruciate ligament (ACL) is one of the most common knee injuries that occur during athletic participation (Majewski et al., 2006). In the United States, it is estimated that approximately 250,000 ACL injuries occur each year, with roughly 175,000 of the injured electing to undergo surgical reconstruction (Gottlob et al., 1999; Griffin et al., 2006; Myer et al., 2004; Paterno et al., 2011; Wojtys & Brower, 2010). ACL reconstruction (ACLR) is typically performed for athletes who wish to return to sport (RTS) and involves replacing the native ligament with an autograft (i.e., bone-patellar-bone or hamstring tendon) or allograft (Myklebust, 2005). The surgical and rehabilitative interventions are believed to restore mechanical stability to the knee and allow individuals to successfully RTS (Ardern et al., 2014; Barber-Westin & Noyes, 2011).

Consequently, individuals whom RTS after ACLR are at an increased risk of experiencing a second ACLR injury to either the ipsilateral or contralateral limb (Hui et al., 2011; Paterno et al., 2012, 2014; Salmon et al., 2005; Wright et al., 2007). Similar to the first ACL injury, non-contact mechanisms of injury are often reported for the second ACL injury indicating possible unresolved neuromuscular deficits during dynamic movements commonly seen in sports participation (Paterno et al., 2012; Wright et al., 2010; Yu & Garrett, 2007). The lingering neuromuscular deficits may be the result of neurological adaptations that occur after an ACL injury, indicating that it may not be a simple musculoskeletal injury (Kapreli & Athanasopoulos, 2006; Kapreli et al., 2009; Needle et al., 2017). Previous research has demonstrated lingering somatosensory dysfunctions, which may remain for years after surgical intervention and rehabilitation (Bonfim et al., 2003; Relph et al., 2014; San Martín-Mohr et al., 2018). These somatosensory deficits may encourage sensory reweighting, forcing the central nervous system to rely more on visual feedback to maintain appropriate motor control (Grooms et al., 2015a). The potential sensory reweighting has been observed using brain scans (i.e., functional MRI) which show increased activation in areas responsible for visual processing during simple movements (Criss et al., 2020; Grooms et al., 2015b). Increased reliance on visual feedback has been observed in ACLR patients as they present with greater postural stability deficits measures when vision is removed (Bonfim et al., 2003; Dingenen et al., 2015; Grooms et al., 2015a; Negahban et al., 2013; O'Connell et al., 1998).

Static postural stability tasks are often utilized by clinicians and researchers to assess ACLR individual lower extremity neuromuscular function (Alonso et al., 2009; Bodkin et al., 2018; Chmielewski et al., 2002; Dauty et al., 2010; Denti et al., 2000; Harrison et al., 1994; Henriksson et al., 2001; Hoffman et al., 1999; Mohammadi et al., 2012; Shiraishi et al., 1996; Zouita Ben Moussa et al., 2009). However, static positions may not replicate sport like maneuvers or be challenging enough for physically active individuals (Colby et al., 1999; Riemann, Caggiano, & Lephart, 1999; Sell, 2012).

Previous research has demonstrated increased dynamic postural stability indices (DPSI) and time to stability (TTS) in ACLR individuals when using a single-limb landing (Heinert et al., 2018; Webster & Gribble, 2010). In addition to decreased performance during dynamic postural stability testing, Paterno et al. (2010) identified deficits in dynamic postural stability as a potential risk factor for sustaining a second ACL injury. Therefore the purpose of this study was to determine if ACLR individuals display worsened traditional and SDA dynamic postural stability measures compared to controls. A secondary purpose was to explore how different levels of visual disruption impact dynamic postural stability measures.

Methods

Participants

Twelve recreationally active individuals with a history of ACLR volunteered for participation in this study and were age (± 4 years) and sex-matched with twelve recreationally active healthy controls (Howells et al., 2013). The term "recreationally" active was operationally defined for this study using the guidelines set by the American College of Sports Medicine (ACSM) guidelines as an individual who participants in physical activity for at least 150 minutes of moderate-intensity or 75 minutes of vigorous activity per week. ACLR individuals were included in this study if they had suffered a unilateral ACL injury, had reconstructive surgery within the past four years, and had received full clearance to resume athletic activities from their physician. The exclusion criteria for the ACLR group included; 1) suffered a second ACL injury in either the contralateral or ipsilateral limb, 2) experienced any lower extremity pain or injury within six months of the testing session, 3) history of head injury (i.e., concussion) within the last year, 4) uncorrected vision, 5) a known vestibular dysfunction, or 6) had a history of epilepsy. Individuals included in the control group had no history of ACL injury in either limb. All other exclusion criteria for the control group was the same as the ACLR group. This study was approved by the University of Northern Colorado and Western Washington University Institutional Review Boards, and each participant provided written informed consent before participation.

Experimental Protocol

The current study was day two of a multi-day data collection. All participants in the current study completed two self-reported questionnaires, the Tegner Activity Scale, and the International Knee Documentation Committee (IKDC), during day one of the data collection protocol (Rambaud et al., 2018). These self-reported questionnaires are used to gain insight into how the ACLR patient would rate their physical activity level and determine their level of function during activities of daily living (Collins et al., 2011). In order to determine limb dominance, each participant was asked, “Which leg would you prefer to kick a soccer ball with?”. A 5-minute warm-up was completed on a motorized treadmill at a 1.3 m s^{-1} pace (Sloot et al., 2014). After completing the warm-up, each participant’s vertical jump height was recorded using a Vertec device (JUMPUSA, Sunnyvale, CA). Reach height was assessed by asking the participant to stand beneath the Vertec and reach the highest vane possible, displacing the vane forward. Each participant then completed three repetitions of a counter movement jump, jumping vertically and moving the highest vane possible. Maximum vertical height was calculated as the difference between the average of the three vertical jump trials and the standing reach height.

Before beginning the dynamic postural stability task, each participant completed a 5-minute accommodation period for the stroboscopic glasses (Senaptec, Beaverton, OR) that were worn for the duration of the testing session. The accommodation period has been previously described in detail by Grooms et al. (2018). These specialized glasses do not block the participant's vision completely, instead only obstructed the participant's vision for small increments as the glasses cycle through pre-determined phases of transparent and opaque settings. After completing the accommodation period, each participant performed six randomized single-limb (dominant and non-dominant limb) dynamic postural stability tasks. Three visual settings were used during the double- and single-leg stances; 1) EO, 2) LVD, and 3) high visual disruption (HVD). The stroboscopic visual settings selected for this study were based on previous research investigating visual disruption during a drop jump movement (Grooms et al., 2018). For the LVD condition, the stroboscopic glasses cycled through periods of 100 milliseconds opaque and 100 milliseconds of clear settings (Grooms et al., 2018). During the HVD condition, the opaque lens was modified to 250 milliseconds, but the clear lens duration remained at 100 milliseconds (Grooms et al., 2018).

The forward hop protocol required participants to jump barefoot from a two-footed starting position set at a distance of 40% of the participant's height, touch an overhead target set at 50% of the participants maximum jump height, and land on the force platform on a single-limb (Heinert et al., 2018; Ross & Guskiewicz, 2003; Sell, 2012). Upon landing, participants were instructed to stabilize as quickly as possible, looking straight forward at a fixed target on the wall, and balance for 30 seconds. Additionally, participants were instructed to place their hands on their hips after stabilizing from the jump landing. However, participants were allowed to remove their hands from their hips to help stabilize themselves from falling, but asked to return their hands to their hips once they were stable again. Participants were allowed to touch the overhead target with a single arm of their choosing before landing on the force platform (Ross & Guskiewicz, 2003; Wikstrom et al., 2005). Practice trials were permitted for the forward hopping task while wearing the stroboscopic glasses; however, the glasses were not on and, therefore, could not obstruct vision. Participants were allowed to practice the forward hop procedure, on each limb, until they felt comfortable completing the task. All participants were provided the same verbal instructions for completing the hopping movement and given at least the same amount of time for viewing the target before initiating the forward hop. This was accomplished through a countdown provided by the primary researcher. The verbal instructions included directions on how to touch the overhead target, where to land on the force platform and to place their hands on their hips after stabilizing from the landing.

All hopping tasks and visual conditions were randomized using a custom MATLAB (Mathworks, Natick, MA, USA) script. Each participant completed three repetitions of the following forward hop tasks: 1) forward single-leg hop, EO, dominant limb, 2) forward single-leg hop, EO, non-dominant limb, 3) forward single-leg hop, LVD, dominant limb, 4) forward single-leg hop, LVD, non-dominant limb, 5) forward single-leg hop, HVD, dominant limb, 6) forward single-leg hop, HVD, non-dominant limb. To help prevent lower extremity fatigue, participants received a 5-minute break after completing the second and fourth hopping task. All ground reaction force (GRF) data were collected using a force platform (AMTI, Watertown, MA) using a sampling frequency of 1000 Hz.

Data Analysis

Force platform data were used to calculate the dynamic postural stability outcome measures using a custom MATLAB script (MathWorks, Natick, MA). All data were filtered using a 4th order low-pass Butterworth filter with a cutoff frequency of 20 Hz (Head et al., 2019; Heinert et al., 2018). The outcome variables used for this study were derived from the following DPSI (Wikstrom et al., 2005), TTS (Colby et al., 1999), and SDA (Collins & De Luca, 1993). All outcome measures were averaged across three trials to provide a representation of the individual's performance. The injured limb for the ACLR group was matched with the corresponding limb of the control group (Lehmann et al., 2017).

DPSI calculations were analyzed using methods described by Wikstrom et al. (2005). This method provided both directional (anterior-posterior, medial-lateral, and vertical) stability indices and the composite DPSI. These dynamic stability indexes were calculated using the first three seconds of the GRF data after landing on the force platform, as the small timeframe closely resembles athletic activity (Wikstrom et al., 2005). The single-limb landing was defined as the point where the GRF signal exceeded 10 N. The vertical stability index (VSI) was normalized to body weight to allow for between-group comparisons. DPSI is a composite value which includes the anterior-posterior stability index (APSI), medial-lateral stability index (MLSI), and VSI (Wikstrom et al., 2005). TTS outcome measures were calculated using a sequential average method used in previous research analyzing dynamic stability during a forward hopping task (Colby et al., 1999; Liu & Heise, 2013). TTS was determined when force values remained within a one-quarter standard deviation of the overall mean (Colby et al., 1999; Liu & Heise, 2013). For all SDA outcome variables, calculations were made using the methods previously described in detail by Collins and De Luca (1993). To create the SDA plot (refer to Figure 2.1 and 2.2), the distance between COP data points were averaged over increasing time intervals. The mean square displacements (Δr^2) were then plotted at each respective time interval (Δt). The critical point was then established by obtaining the intersection point of the SDA plot's short and long-term regions (Figure 2.2). Both the critical mean square displacement (Δr^2) and critical time interval (Δt) at the critical point represent the approximate transition between the open- and closed-loop control strategies (Collins & De Luca, 1993). The short- and long-term diffusion coefficients (D_S and D_L) were then calculated based on the line of best fit for each region and indicated the level of stochastic activity present in the system. Additionally, the short- and long-term scaling exponents (H_S and H_L) were calculated similarly on the line of best fit from the log-log plot of the SDA (Figure 2.3). The scaling exponents represent the correlation between past and future COP data points, and physiologically represent open- (positively correlated past and future COP, $H > 0.5$) and closed-loop (negatively correlated past and future COP, $H < 0.5$) behaviors (Collins & De Luca, 1993).

Statistical Analysis

Independent t-tests were performed to compare the group demographic data. Multiple 2x3 repeated measures ANOVA's were used to assess the relationship between groups (ACLR vs. controls) and within vision (EO, LVD, HVD) for the DPSI, TTS, and SDA outcome measures. An α level was set a priori at .05 for all statistical testing.

Bonferroni post-hoc testing was performed to evaluate the effect of vision when appropriate. All statistical testing and analysis were performed using SPSS (Version 26.0, IBM Inc. Chicago, IL).

Results

All 24 participants were able to complete all three visual conditions on both dominant and non-dominant limbs. However, due to limitations within the SDA calculations (i.e., a negative slope), one participant of the ACLR group had uninterpretable outcome measures for the SDA calculations for all three visual conditions. Therefore, the ACLR participant, along with the matched control, were removed from further analysis. Demographic data for both ACLR and control groups are shown in Table 5.1. There was a statistically significant difference in the current level Tegner activity level scale ($t(20) = 2.911$, $p < .01$), IKDC scores ($t(20) = 3.574$, $p < .01$), and age ($t(20) = 2.324$, $p < .05$).

In the present study, when analyzing the single-limb dynamic postural stability, no significant interaction was present for the stability indices related to DPSI, TTS, or SDA outcome measures. Additionally, no significant group differences were found for any of the outcome measures (stability indices, TTS, and SDA). These results are shown in Table 5.2.

Significant main effects for vision were found for MLSI ($F(2, 40) = 4.086$, $p < .05$), mean critical square displacement ($F(2, 40) = 4.264$, $p < .05$) (Δr^2), short-term diffusion coefficient ($F(2, 40) = 11.154$, $p < .001$) (D_S), short-term scaling exponent ($F(2, 40) = 6.182$, $p < .01$) (H_S), and long-term scaling exponent ($F(2, 40) = 4.877$, $p < .05$) (H_L). These results are shown in Figures 5.1 through 5.5.

Table 5.1

Demographic and self-reported questionnaires data for ACLR and control groups.

	ACLR (n = 11)	Control (n = 11)	*p-value* -
Age (years), mean ± SD	20.0 ± 1.3	21.6 ± 1.9	0.03*
Mass (kg), mean ± SD	75.2 ± 8.1	68.1 ± 12.2	0.13
Height (m), mean ± SD	1.7 ± .08	1.7 ± .09	0.94
Graft type	HS: 5	-	-
	BPTB: 6	-	-
Time since surgery (months), mean ± SD	29.7 ± 9.1	-	-
Pre-injury Tegner activity scale, mean ± SD	9.0 ± .0	-	-
Current level Tegner activity scale, mean ± SD	8.1 ± 1.1	6.6 ± 1.2	0.009*
IKDC, mean ± SD	84.8 ± 12.5	98.6 ± 2.9	0.002*

Note. *indicates a significant group difference ($p < .05$). HS = hamstring tendon graft. BPTB = bone-patellar tendon-bone graft.

Table 5.2

Dynamic postural stability outcome measures.

Traditional measures	ACLR (n = 11)	Control (n = 11)	*p-value* -
DPSI, mean ± SD	0.34 ± .03	0.34 ± .03	0.56
APSI, mean ± SD	0.09 ± .01	0.09 ± .01	0.51
MLSI, mean ± SD	0.04 ± .01	0.04 ± .01	0.35
VSI, mean ± SD	0.33 ± .03	0.32 ± .03	0.53
TTS AP	1.69 ± .09	1.71 ± .08	0.66
TTS ML	0.88 ± .26	0.73 ± .17	0.06
TTS Vert	1.15 ± .14	1.13 ± .15	0.72
SDA outcome measures	(n = 11)	(n = 11)	-
Δr^2 (mm^2), mean ± SD	983.59 ± 505.62	1079.23 ± 443.46	0.54
Δt (s), mean ± SD	1.67 ± .69	1.94 ± .71	0.25
$D_{S,}$ mean ± SD	300.31 ± 98.35	281.88 ± 87.10	0.44
$D_{L,}$ mean ± SD	25.08 ± 14.35	23.07 ± 15.26	0.66
$H_{S,}$ mean ± SD	0.47 ± .06	0.45 ± .06	0.24
$H_{L,}$ mean ± SD	0.12 ± .06	0.09 ± .04	0.10

Note. TTS AP = time to stability in the anterior-posterior direction. TTS ML = time to stability in the medial-lateral directions. TTS Vert = time to stability in the vertical direction.

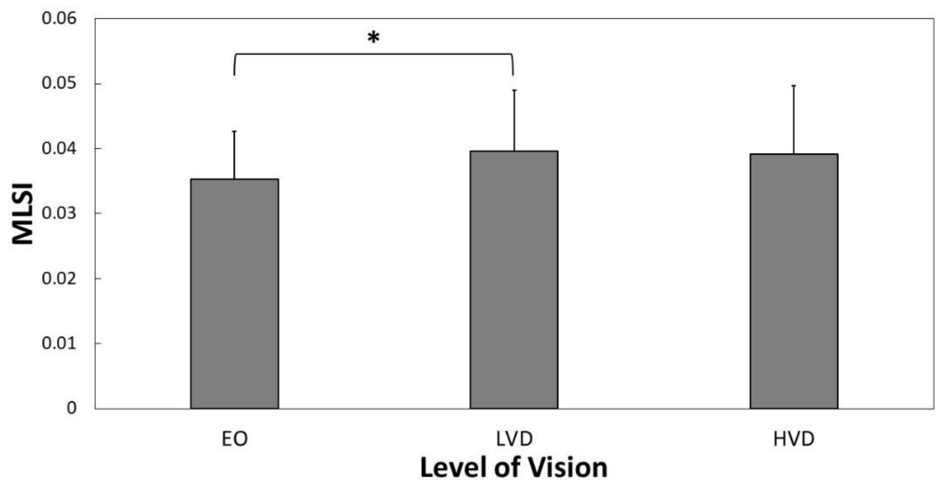

Figure 5.1. Mean values of medial-lateral stability index using the DPSI calculation. * indicates a significant difference ($p < .05$) in mean medial-lateral stability indexes between the levels of vision.

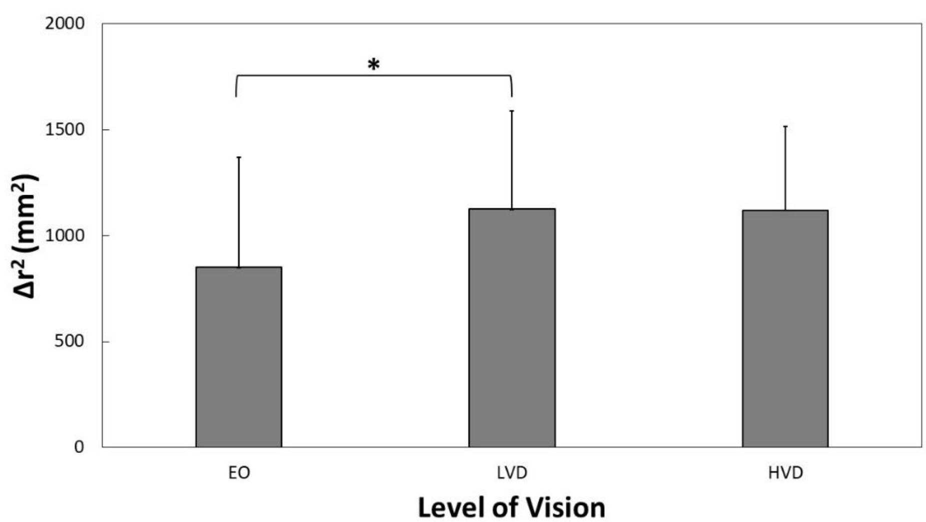

Figure 5.2. Mean critical square displacement calculated using the SDA method. * indicates a significant difference ($p < .05$) in mean critical square displacement between the levels of vision.

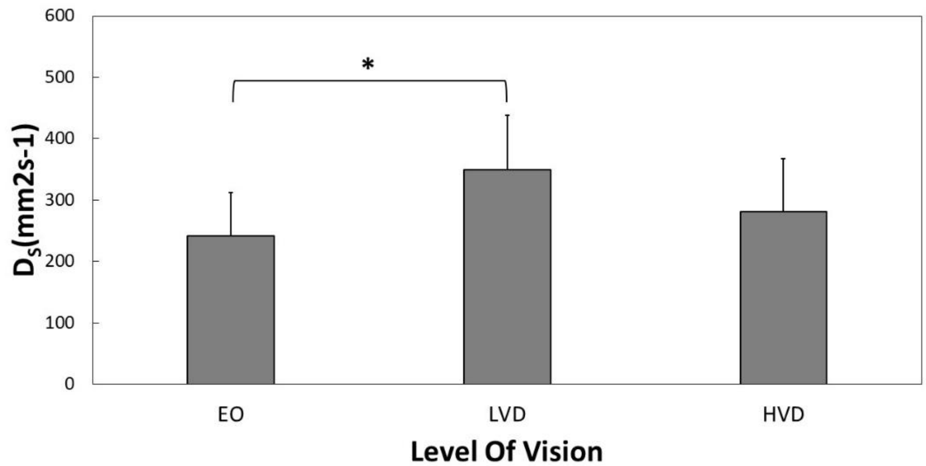

Figure 5.3. Mean short-term diffusion coefficients (D_S) calculated using the SDA method. * indicates a significant difference (p < .05) in short-term diffusion coefficients between the levels of vision.

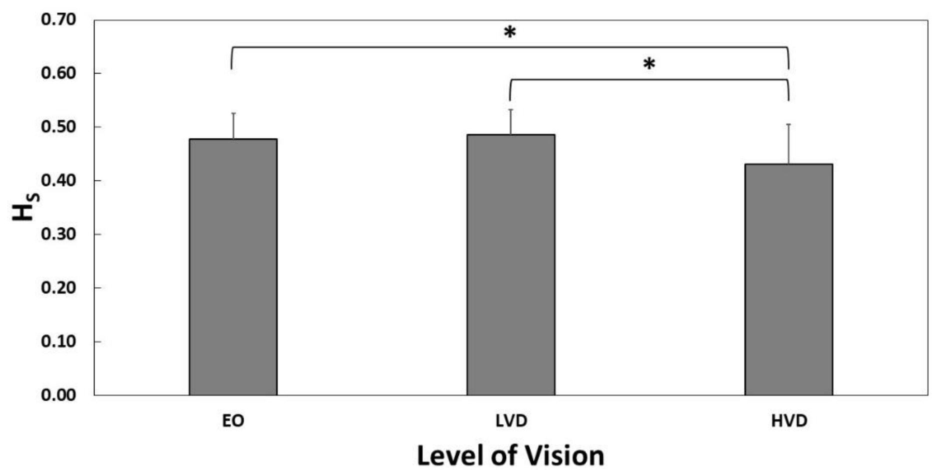

Figure 5.4. Mean short-term scaling exponent (H_S) calculated using the SDA method. * indicates a significant difference (p < .05) in short-term scaling exponents between the levels of vision.

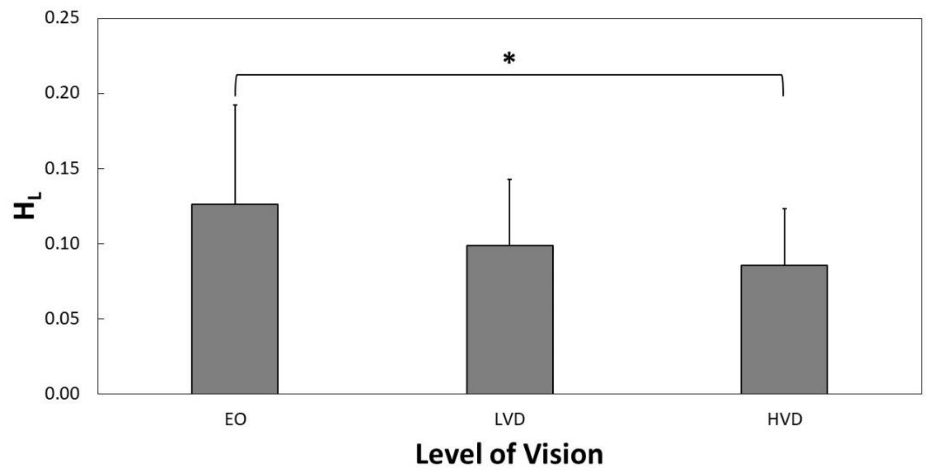

Figure 5.5. Mean long-term scaling exponent (H_L) calculated using the SDA method. * indicates a significant difference ($p < .05$) in long-term scaling exponents between the levels of vision.

Discussion

The overall purpose of the present study was to evaluate whether ACLR individuals presented with worse dynamic postural stability measures at different levels of visual disruption compared to controls. Previous work by Paterno et al. (2010) noted that deficits in dynamic postural stability may contribute to the increased risk of sustaining a second ACL injury. It was hypothesized that ACLR individuals would present with worsened dynamic postural stability measures as previous research has demonstrated that ACLR individuals rely on visual information to compensate for decreased proprioceptive information for the knee (Bonfim et al., 2003; Dauty et al., 2010; Denti et al., 2000; Konishi et al., 2002; Mohammadi et al., 2012; Shiraishi et al., 1996). The secondary purpose was to explore how varying levels of visual disruption impacted dynamic postural stability measures.

In the present study, ACLR participants did not present with statistically different dynamic postural stability measures compared to healthy controls. The findings of the current study are in agreement with Head et al. (2019), which reported no group differences for DPSI. The ACLR group mean DPSI value reported by Head et al. (2019) was identical to the mean value for ACLR participants in the current study, 0.34 ± 0.143 vs. 0.34 ± 0.003, respectively. These findings suggest that dynamic postural stability may be successfully recovered in ACLR individuals who are cleared to return or near returning to sports activities.

However, the findings of both Head et al. (2019) and the current study are in contrast to previous work demonstrating worsened postural stability in ACLR individuals compared to healthy controls during single-limb landings (Colby et al., 1999; Heinert et al., 2018; Webster & Gribble, 2010). During single-limb landings used in Webster and Gribble (2010), ACLR individuals took an average of 0.11 seconds longer to stabilize than healthy controls. While the longer TTS found in Webster and Gribble (2010), may not seem significant, ACL injuries are estimated to occur at time frames less than 50 milliseconds (Krosshaug et al., 2007; Webster & Gribble, 2010). Therefore the longer TTS observed in ACLR individuals in Webster and Gribble (2010) may impact the individual's capability to avoid future knee injuries (Webster & Gribble, 2010).

Additionally, Heinert et al., (2018) found deficits in dynamic postural stability measures (stability indices) in the involved limb at two years post-surgery compared to the non-involved limb. Heinert et al. (2018), found increased values of the dynamic postural stability indices in the surgical limb compared to the non-surgical limb. Compared to the results of the current study, which found no group differences for any directional stability indices, ACLR participants enrolled in the Heinert et al. (2018) study presented with increased stability indices in all directions. All directional stability indices in Heinert et al. (2018) were higher (DPSI = 0.49 ± 0.05; APSI = 0.18 ± 0.01; VSI = 0.46 ± 0.05) than the values observed in the current study (DPSI = 0.34 ± 0.03; APSI = 0.09 ± 0.01; VSI = 0.33 ± 0.03) except for MLSI. Heinert et al. (2018), reported mean MLSI values of 0.03 ± 0.06, whereas the current investigation found mean MLSI values of 0.04 ± 0.01.

Several factors may attribute to the group differences in dynamic postural stability measures observed in previous work when compared to the non-significant group findings in the current study. First, the examination of the patient-reported time since surgery revealed several differences between the current study and previous work. The ACLR group involved in the current study were, on average, 29 months post-surgical intervention, whereas ACLR individuals involved in Heinert et al. (2018) were only 14 months from surgical intervention. The lower time since surgery reported in Heinert et al. (2018) may explain the higher stability indexes when compared to the current study. In other words, it may be that ACLR individuals with longer times since surgery have improved muscle strength, proprioception, and muscle activation patterns that are similar to pre-surgery levels. These lower extremity improvements in neuromuscular function may lead to improved dynamic postural stability scores. However, the impact of time since surgery must be interpreted with caution, as Head et al. (2019) found no differences in DPSI measures between ACLR and controls. ACLR individuals enrolled in Head et al. (2019) were, on average, 7.6 months post-surgical intervention. Participants included in Webster and Gribble (2010) had similar times since surgery as the current study with a mean value of 30 months. The current study found no group differences in any of the dynamic postural stability measures, while Webster and Gribble (2010) did find longer

TTS times in ACLR participants. These conflicting findings highlight the need for future research to examine how dynamic postural stability measures change throughout the rehabilitation process and after return to sport.

Another significant difference between the current study and previous research is that ACLR participants reported higher levels of activity. ACLR participants in the current study reported higher mean Tegner activity scores than those participating in Heinert et al. (2018) study, 8.81 vs. 6.64, respectively. Similar to the ACLR participants enrolled in the current study, the ACLR volunteers involved in Head et al. (2019) study also had high levels of Tegner activity scores, 8.81 vs. 8.7. While a significant difference in Tegner activity levels did exist in the current study, the ACLR and control groups in Head et al. (2019) were not significantly different. As previously stated, Heinert et al. (2018) found increased mean values of DPSI (0.49) in ACLR individuals when compared to the equal values (0.34) found in the current study and Head et al. (2019). The higher DPSI mean values observed in Heinert et al. (2018) may be the result of the decreased self-reported Tegner activity levels (6.64).

Dynamic postural stability for the present study was defined as the ability to maintain stability while transitioning from a dynamic movement to a static position (Gribble & Robinson, 2009; Liu et al., 2013). Previous research investigating ACLR individuals dynamic postural stability have used different research paradigms to assess stability ranging from the maintenance of static postural stability on moveable platforms to single-limb squats (Alonso et al., 2009; Culvenor et al., 2016; Denti et al., 2000; Henriksson et al., 2001; Mattacola et al., 2002). Examination of the moveable platform literature reveals equivocal outcomes when comparing ACLR individuals with healthy controls (Alonso et al., 2009; Denti et al., 2000; Henriksson et al., 2001; Mattacola et al., 2002). In contrast to the current study, Denti et al. (2000) reported worsened dynamic postural stability scores in ACLR compared to healthy controls. However, similar to the current study Mattacola et al. (2002) and Henriksson et al. (2001) found no significant differences between the ACLR and control groups. In addition to moveable platforms, previous research has utilized full-body movements (i.e., single-limb squat) to assess dynamic postural stability (Culvenor et al., 2016). Contrary to the current study's findings, Culvenor et al. (2016), found degraded measures of dynamic postural stability in ACLR individuals compared to healthy controls. Culvenor et al. (2016) reported increased center of pressure (COP) path velocity, COP excursion (AP and ML), and COP standard deviations (AP and ML) in ACLR individuals.

While traditional dynamic postural stability measures have been explored using an ACLR population, SDA has not been applied to this population during a dynamic task. While no significant group differences were found in the present study, it is important to recognize a few key differences. The slightly higher value of D_S may indicate that the ACLR group had higher levels of stochastic activity within the short-term region. This difference further suggests that ACLR individuals used greater exploratory behavior during short-term time intervals. This results in larger COP sway that indicates less stability. The decreased stability in the short-term region may help explain the quicker transition (decreased Δr^2 and Δt) from open- to closed-loop control to compensate for sensory deficits associated with ACLR.

When compared to previous work using the SDA method on dynamic stability, there were some notable differences. The mean critical time point for the present study was shifted to the right for both ACLR and controls (1.67 s, 983.59 mm^2 and 1.94 s, 1079.23 mm^2, respectively) compared to Heise et al. (2012) (0.72 s, 587 mm^2) and Buchholz (2017) (1.12 s, 173.8 mm^2). These mean critical time points occurred much earlier in both Heise et al., (2012) and Buchholz (2017), suggesting an earlier transition to closed-loop control compared to the current study. A potential reason for the earlier transition times in the previous work may be attributed to the hopping task itself. In the current study, the hopping task contained both vertical and horizontal minimum thresholds that participants had to achieve in order for the hop to be successful. The addition of a vertical threshold, 50% of max vertical jump, may have created larger GRF's for which the participant had to overcome to achieve stability.

ACLR individuals demonstrated significant differences in both the current level of Tegner activity scales and IKDC scores compared to controls (Table 5.1). ACLR individuals self-reported higher levels of activity than controls but had lower levels of self-reported function. Healthy controls enrolled in this study reported a lower level of activity than ACLR individuals (6.6 vs. 8.1), which may influence the results of the postural stability outcome measures (Alonso et al., 2009). While this study did not explicitly compare the physical activity level on postural stability measures, it is possible the outcome measures were influenced by comparing highly active ACLR participants to lower physically active healthy individuals. From a clinical perspective, it could be hypothesized that individuals who participate in lower levels of physical activity would display worsened postural stability than those with higher levels of physical activity. The lower levels of self-reported physical activity could, therefore, mask any postural stability deficits ACLR individuals would display if compared to healthy individuals with higher levels of self-reported activity. The IKDC is used by clinicians to detect changes in patient symptoms, function, or physical activity (Collins et al., 2011). In the current study, ACLR participants presented with decreased ratings in overall knee function when compared to healthy controls, 84.8 vs. 98.6, respectively. These values are similar to self-reported IKDC values reported in previous research examining postural stability (Bodkin et al., 2018; Culvenor et al., 2016). The present study's findings indicate that ACLR individuals report that their injured limb prohibits full, unencumbered activities of daily living.

No group differences were observed for any outcome variable used in the current study; however, the level of visual disruption had an impact on dynamic postural stability. For the traditional measures of dynamic postural stability, only MLSI was statistically significant. As visual disruption was introduced, MLSI increased, indicating decreased postural stability in the medial-lateral direction. While minimal research has explored the use of the DPSI and postural stability with knee pathologies, Wikstrom et al. (2010) suggested increased MLSI may be a compensation pattern for ankle instability. A similar compensation pattern could be present in ACLR to maintain stability during dynamic landings. The levels of visual disruption had a greater impact on outcome measures for the SDA methods. When visual disruption increased from EO to LVD, the Δr2 increased from 850.02 mm2 to 1124.76 mm2, suggesting increased sway during open-loop control. Similarly, increased levels of D_S were found between EO (241.33 mm^2s^{-1}) and LVD (350.22 $mm^2 \cdot s^{-1}$) during single-limb landing. This finding indicates increased stochastic activity when the low level of visual disruption was implemented. Interestingly, H_S did not demonstrate changes to visual input until the highest level of visual disruption. For H_S, there was a decrease from EO (0.48 ± 0.05) to HVD (0.43 ± 0.07) and from LVD (0.49 ± 0.05) to HVD. This decrease in H_S suggests that during the highest level of visual disruption, participants moved away from purely random movements during short-term intervals. Heise et al. (2012) found similar H_S during their dynamic hopping task suggesting that during the open-loop control phase during single-limb landings may display purely random movements ($H_S = 0.5$) instead of the traditional persistent ($H_S > 0.5$) behavior observed in static tasks (Collins & De Luca, 1993, 1995b). However, these must be interpreted with caution as results from a study utilizing a shorter hop distance found more persistent behavior during the short-term region (Buchholz, 2017). Lastly, H_L decreased from the EO (0.13 ± 0.07) condition to the HVD (0.09 ± 0.04), indicating a more tightly controlled posture as visual information decreased. Similarly, Collins and De Luca (1995a) reported lower H_L values when participants closed their eyes, indicating a more anti-persistent behavior. This behavior could represent an attempt of the body to create a more generally rigid control in order to maintain postural stability though more research is needed to confirm this hypothesis.

There are several limitations involved in the present study. First, the sample size was smaller than previous work examining dynamic postural stability measures. This smaller sample size may have contributed to the lack of statistical power observed in the current study. Additionally, because the ACLR participants enrolled in this study were, on average, 29 months removed from their surgery, the results are not generalizable to individuals closer to the RTS timeline (i.e., less than one year). In addition, due to the increased time since surgery, researchers were also unable to account for any rehabilitation differences (i.e., balance training) that may have influenced postural stability measures. Participants were asked to self-report their physical activity levels and were enrolled based on meeting a minimum threshold of physical activity based on the ACSM guidelines. The healthy individuals included in the present study had lower levels of self-reported physical activity when compared to the ACLR group. While not directly measured, many of the ACLR individuals indicated participation in club sports, whereas healthy controls reported general physical activity. The significant difference in Tegnar activity level may have limited the current findings as ACLR individuals may have more experience participating in sports with single-limb demands (i.e., cutting or pivoting activities). Participation in organized sports may provide opportunities for further rehabilitation of the injured knee through exposure to dynamic movements that are more similar to ACL injury mechanisms. Future research should consider matching participants based on their participation in sports activities. For example, participants involved in activities involving more dynamic movements (i.e., involving cutting, jumping, and change of directions) should be matched with similar level participants to limit additional variability. Matching a dynamic sport with a more endurance type of sport (i.e., running, cycling) may add unwanted individuals differences to analysis.

Another limitation is the differences in the dynamic hopping task seen in this study and previous work analyzing ACLR individuals. The lack of hop standardization (i.e., hop distance and height) in dynamic tasks used to evaluate ACLR participants makes it difficult to directly compare results between studies. Work done by Liu and Heise (2013), found higher TTS measures in the medial-lateral, anterior-posterior, and vertical directions compared to the current study. The speculation for the higher values observed in Liu and Heise (2013) is the longer jump distance (full leg length) vs.

normalized to body height. Liu and Heise (2013) also found that TTS measures were influenced by jump direction, which clinicians and researchers should be aware of during testing. It is important to note that both the current study and previous research examining dynamic postural stability only tested the forward hopping direction. It is hypothesized that the forward direction has been used exclusively when analyzing ACLR individuals as it would stress the ACL graft and supporting musculature (i.e., quadriceps muscle group) the most. Additionally, there are only a few studies that have evaluated dynamic postural stability as defined in this current study (Heinert et al., 2018; Webster & Gribble, 2010). Additional research is also needed to determine the relationship between different dynamic postural stability testing tasks (i.e., non-rigid force platforms vs. forward hopping tasks).

Conclusion

In conclusion, the results of this study suggest that ACLR individuals do not rely more on visual information when performing dynamic postural stability tasks. No group differences were found using either the traditional or SDA methods. The results of this study suggest that while no group differences were found, visual disruption did change the COP behavior during this challenging single-limb landing task. Future research is needed to examine ACLR individuals at different stages in the rehabilitation process to examine how dynamic postural stability changes over time. In addition, more research is needed to determine the clinical significance of dynamic postural stability measures in ACLR patients.

CHAPTER VI

GENERAL RESULTS

Overview

The purpose of this dissertation was to investigate the influence of visual disruption on measures of postural stability in a joint pathology population, specifically ACLR. The study was based on the theory that individuals with an ACL injury undergo neurological changes, resulting in greater reliance on visual information due to deficits in proprioception (Criss et al., 2020; Grooms et al., 2015a; Kapreli et al., 2009; Needle et al., 2017). Therefore, it is necessary to understand if individuals with a history of ACLR prioritize visual feedback when performing athletic tasks, as it may relate to increased ACL injury risk (Grooms et al., 2015a). Previous research often measures the influence of vision using two extremes, full vision and complete vision removal (i.e., eyes-closed). The current study sought to measure the influence of vision on postural stability tasks using a commercially available device (stroboscopic glasses) that would not block vision completely. Disrupting visual information through the use of stroboscopic vision may allow researchers, in a controlled laboratory space, to replicate conditions that athletes would experience during sports activities (Grooms et al., 2018). Only recently have these visual disrupting eyewear been used to affect visual feedback during static postural stability testing and drop-jump testing, but have not been used to analyze dynamic postural stability in single-limb landings (Grooms et al., 2018; Kim et al., 2017).

The first study of this dissertation investigated how ACLR individuals differed during static postural stability measures when compared to healthy controls using both traditional and non-linear methods. However, due to low available participant numbers, the non-linear portion of the study was unable to be completed. As seen in Appendix B, the addition of the visual disruption conditions resulted in negative long-term diffusion coefficients or scaling exponents from the SDA for many participants and thus the inability to statistically test the visual conditions. The author of this dissertation hypothesizes that the SDA is unable to assess disruptions to vision, between the extremes of eyes-open and eyes-closed. One traditional outcome measure demonstrated significant group differences and suggested that ACLR individuals were more stable than healthy controls. However, if the traditional measures are analyzed collectively, rather than focusing on a single significant outcome measure, ACLR individuals did not display worsened postural stability. This finding suggests that the use of traditional methods to analyze postural stability in an individual with a history of ACLR may not be sensitive enough to detect differences when compared to an uninjured population. Consequently, the results give the impression that ACLR individuals do not have any lingering neuromuscular deficits as initially suspected (Dauty et al., 2010; Denti et al., 2000; Howells et al., 2011; Mohammadi et al., 2012; Shiraishi et al., 1996; Zouita Ben Moussa et al., 2009). In addition, the stroboscopic glasses did result in worsened static postural stability compared to the eyes-open condition.

The second study of this dissertation examined a more demanding single-limb landing task that resembled a sport like hopping maneuver. The primary purpose of this study was to determine if ACLR individuals displayed worsened traditional and SDA dynamic postural stability measures compared to healthy controls. The use of the stroboscopic vision during a dynamic hopping task was used to challenge the participant and create a sport-like maneuver that was safely applied in a laboratory space. Using stroboscopic glasses and the use of an overhead target allowed the individual to be tested in a manner that may be more representative of the neurocognitive demands during sports activities (Grooms et al., 2018). The results of this study demonstrate that ACLR individuals who were on average two years post-reconstructive surgery did not rely on visual information more than healthy controls. This finding is in agreement with recent research that suggests ACLR individuals do not rely on visual information during static postural stability tasks (Wikstrom et al., 2017). However, the implementation of stroboscopic vision did significantly impact dynamic postural stability measures in ACLR and control individuals. The SDA method demonstrated significant changes in the neuromuscular control between levels of vision. This study's findings suggest that individuals displayed larger COP sway during the short-term region and more tightly regulated COP during the long-term region when additional sensory information was unavailable.

Stabilogram Diffusion Analysis

This dissertation demonstrates that ACLR individuals do not present with lingering deficits in double- or single-limb postural stability as measured using traditional methods. SDA methodology was only able to be applied to the second study of this dissertation due to limitations within the SDA calculation that led to low participants numbers in study one. For the second study of this dissertation, according to the SDA, ACLR individuals did not present with lingering neuromuscular deficits during a single-limb landing task compared to healthy controls. No statistically significant group differences were observed for any of the SDA outcome measures examining dynamic postural stability.

Effect of Vision on Static and Dynamic Stability

This dissertation's second focus was to examine the effects of stroboscopic vision on both static and dynamic postural stability measures. The use of stroboscopic vision had minimal impact on double-limb static postural stability tests but a much more significant effect during a more challenging single-limb testing position. During single-limb testing, all traditional measures of postural stability increased from the eyes-open condition to each visual disruption condition. These findings suggest that an individual's postural stability worsens with the addition of stroboscopic glasses as visual information is reduced. Additionally, the stroboscopic glasses resulted in worsened measures of dynamic postural stability during single-limb landings. Interestingly, only one traditional variable was impacted by stroboscopic visual disruption. Several SDA variables were affected by the visual perturbations leading to an unstable behavior in the short-term region and a more rigid behavior during the long-term region.

This present dissertation adds to the current literature on ACLR and visual reliance. Overall, the studies presented contribute to the body of literature by applying a new method of analyzing dynamic postural stability in ACLR individuals. The SDA method was implemented in the current dissertation to add physiological meaning to the postural stability examination in ACLR and healthy control individuals. It is important to note that the SDA analysis for study one was unable to be completed due to issues previously described in study one and Appendix B. Based on the results presented in

Appendix B (Tables B.3-B.5), the amount of usable data generally decreased as visual disruption increased. Collins and De Luca (1995a) found two distinctly different behaviors when analyzing two visual conditions (eyes-open and eyes-closed). Therefore, it is plausible that the SDA may not be appropriate for analyzing more subtle differences in vision. The SDA has been used to analyze different pathologies (i.e., phobic postural vertigo, Parkinson's disease), so it is reasonable to believe that joint pathologies could be examined using this specific technique (Mitchell et al. 1995, Wuehr et al., 2013).

Additionally, this dissertation adds to the knowledge of the use of stroboscopic vision on postural stability measures during both static and dynamic tasks. Stroboscopic eyewear offers clinicians a unique approach to challenge the patient's postural stability in a safe and controlled environment. Currently, little research exists on stroboscopic vision in clinical populations such as ACLR (Grooms et al., 2018), or in general postural stability tasks (Kim et al., 2017). This current dissertation showcases the ability of stroboscopic vision to impact both static and dynamic postural stability assessments. Furthermore, the two studies presented in this dissertation demonstrate an alternative approach to the traditional eyes-open and eyes-closed conditions for challenging the visual system during postural stability tasks.

Conclusions

This dissertation's first study sought to examine double- and single-limb postural stability measures using traditional measures in ACLR and healthy control individuals. Partially supporting the current dissertation's initial hypotheses, group differences were observed in both double- and single-limb static postural stability tasks. No group differences were hypothesized for the double-limb postural stability task. However, the traditional analysis revealed that ACLR individuals made less frequent adjustments than healthy controls. Due to the challenging nature of a single-limb postural stability task, it was hypothesized that ACLR individuals would present with worsened postural stability compared to healthy controls. The results of study one did not support the initial hypothesis as no traditional variables demonstrated significant group differences. The dissertation was unable to answer the SDA hypothesis for static postural stability due to low participant numbers. Therefore, only the traditional outcome measures were reported for the first study in this dissertation. The stroboscopic visual disruption utilized during this dissertation impacted single-limb quiet stance outcome measures but had little to no effect on the double-limb task. These findings partially support the initial hypotheses, which stated that both double- and single-limb postural stability measures would be affected. This finding suggests that commercially available stroboscopic eyewear may be useful for clinicians and researchers looking to challenge the visual system in a unique way outside of the traditional binary eyes-open and eyes-closed approach. Contrary to the original dissertation hypothesis, no interaction effects were observed.

For the second study, the findings only support one of the three proposed hypotheses. The current study’s findings do not support the group differences and interaction hypotheses initially proposed. Therefore, ACLR individuals do not present with increased visual reliance during dynamic postural stability as initially hypothesized. However, the findings do suggest that stroboscopic visual disruptions did result in worsened dynamic postural control when compared to the eyes-open condition. Therefore, the stroboscopic eyewear is sufficient enough to challenge the user's visual systems during dynamic postural stability testing.

Future Directions

Based on the findings of the current dissertation, future research is necessary in order to explore the use of non-linear measures to evaluate ACLR individuals in both static and dynamic tasks. Additionally, the current dissertation and previous research (Wikstrom et al., 2017) found that ACLR individuals did not rely on visual feedback to a greater extent than controls. This dissertation's findings prompt the need for further investigation to determine what measures are potentially related to postural control deficits believed to contribute to the increased ACL injury risk (Paterno et al., 2010). It is important to note that while not explored in this dissertation, future research is needed to investigate differences in dynamic postural stability task normalization approaches. The current dissertation normalized both hop height (50% of maximum vertical jump) and distance (40% of body height) to each individual. Previous research investigating dynamic postural stability tasks in ACLR individuals have implemented variations in hopping tasks such as standardized hop heights (i.e., 12-inch hurdle) and distances (i.e., 70 cm) (Heinert et al., 2018; Webster & Gribble, 2010). The modification of jump heights and distances have led to both kinetic and kinematic changes and should be considered when assessing clinical populations such as ACLR individuals (Dickin et al., 2015; Heebner et al., 2017).

Clinicians and researchers should be aware of the task demands and how they might change postural stability outcome measures due to limitations related to specific injuries. For example, ACLR individuals may not modulate anterior-posterior or vertical forces as well as healthy controls (Lepley & Kuenze, 2018). Therefore, deviations in task demands between studies will limit their generalizability. Beyond methods associated with dynamic postural stability, it is clear that the research remains mixed on the appropriate knee testing position in ACLR individuals during single-limb static postural stability tasks. While the current dissertation did find significant differences in static postural stability measures with a knee extended position, a knee flexed testing position may be more appropriate in ACLR individuals. A flexed knee position may exacerbate postural stability measures due to the reliance on knee extensor muscles to remain in an upright stance, and ACLR individuals known quadriceps dysfunction.

Additionally, future research should examine both static and dynamic postural stability measures using participants with appropriately matched activity levels. In both studies contained in this dissertation, ACLR individuals presented with higher levels of self-reported physical activity compared to healthy controls. The lower self-reported activity levels observed in the healthy control group may have masked postural stability deficits in individuals with a history of ACLR. Therefore future research should match healthy controls with ACLR individuals based on self-reported activity levels to determine if postural stability measures are recovered at the time of RTS. Future research should also consider participant matching based on the type of sports activities. For example, ACLR individuals who regularly participate in dynamic sports (i.e., soccer, basketball) should be matched with controls who engage in similar activities. Through appropriate activity-based matching, researchers could help reduce the variability within their study's sample. Furthermore, the current dissertation found that cost-effective stroboscopic eyewear did impact postural stability measures. However, little research has been done to examine how well these stroboscopic glasses mimic sport-like activities in a controlled laboratory manner. Future research should explore how well these commercially available glasses mimic the visual-motor demands observed in sports activities. Also, to improve the understanding of the use of stroboscopic vision on postural stability tasks, future research should explore the full range of visual settings of the glasses compared to the standard eyes-open and eyes-closed tasks to help determine future vision settings.

To the author's knowledge, this dissertation is the first application of the SDA methodology to postural stability measures of individuals with a history of ACLR. The findings of this dissertation demonstrated no group differences in SDA outcome measures during postural stability. However, this dissertation was unable to apply the SDA methods to static postural stability measures due to a low number of usable data associated with nearly half of all participants. Therefore, future research should aim to investigate the SDA with a larger sample size to determine if these methods provide more physiological meaningful information for individuals with a history of ACLR. Specifically, future research should implement the SDA to determine if ACLR individuals present with lingering neuromuscular deficits during static postural stability. Finally, this dissertation found no group differences during either static or dynamic stability tasks. The increased time since surgery observed in this dissertation may have influenced the findings when compared to previous work that found lingering postural stability deficits (Alonso et al., 2009; Dauty et al., 2010; Denti et al., 2000; Heinert et al., 2018; Mohammadi et al., 2012; Webster & Gribble, 2010). Therefore, future research should aim to test ACLR individuals throughout the recovery process and at the point of RTS to understand how postural stability measures are impacted.

In conclusion, future research is needed to explore static and dynamic testing protocols in relation to joint pathologies such as ACL injury. Research should also explore the use of activity matched healthy controls to ACLR individuals to determine if postural stability deficits exist. Additionally, future research is needed to explore SDA's use in an ACLR population to assess its usefulness to clinicians and researchers. Finally, additional research is required to help determine the reasoning behind the postural control deficits observed in previous work if visual reliance is not the reasoning.

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APPENDIX A

INSTITUTIONAL REVIEW BOARD DOCUMENTATION

UNIVERSITY of NORTHERN COLORADO

CONSENT FORM FOR HUMAN PARTICIPANTS IN RESEARCH
UNIVERSITY OF NORTHERN COLORADO

Project Title: **The Effect of Visual Disruption on Stability after ACL Reconstruction**
Researchers: Nathan Robey M.S., School of Sport and Exercise Science
nathan.robey@unco.edu
Phone: 970-351-1597
Research Advisor: Dr. Gary Heise 970-351-1738, School of Sport & Exercise Science

Purpose and Description:
This project is interested in studying how differences in visual inputs (eyes open and visual disruption) influence an individual's postural stability. We are asking you to participate as part of our anterior cruciate ligament injured population as you meet our inclusion criteria. Our inclusion criteria states that you are a healthy, non-smoking, physically-active adult, 18-30 years old, who is free of any lower extremity injury or pain for 6 months prior to testing, had anterior cruciate ligament reconstruction on one limb within the last 4 years, have full or corrected vision, were cleared by a physician to return to sport, have no neurological or vestibular disorders, and no history of epilepsy. The duration of the data collection will be approximately 2.5-3 hours (~1.5 hours per testing session) if you agree to participate.

Preparation for Data Collection
To begin each testing session, you will walk on a motorized treadmill at 1.3 m/s for 5-minutes to accommodate to the treadmill and warm-up. If you have never walked on a treadmill before you will be asked to walk on the treadmill for 30-minutes before data collection. After completing the warm-up session, we will place reflective markers on your lower body. Infrared cameras will be used to capture these markers. Your identity will be protected as the cameras do not actually capture regular video, only the location of the markers. Electrodes, which measure the electrical activity (EMG) of your muscles, will be attached to the surface of your skin over various leg muscles. It is necessary to shave your hair, lightly abrade your skin, and clean your skin with alcohol in the small areas where these electrodes will be attached to improve the quality of the signal. You will complete two separate data collections for this research.

Data Collection
Your balance will be assessed using a force platform secured to the laboratory floor. For one testing session, you will be asked to maintain balance on using both legs and on a single leg, while force data is collected. During these tasks you will wear strobe glasses that will flash and slightly obstruct your vision. Two levels of flashing will be used

during the testing, low-level flashing and high-level flashing. A spotter will be nearby to prevent you from falling during all postural stability tests. Once you have completed all balance tests you will perform a series of lower extremity strength tests on a computerized strength testing device. Specifically, we will test your ability to bend and straighten your knee (quadriceps and hamstring strength) as you push and pull against the resistance offered by the machine. For the second testing session, you will be asked to perform several forward hopping activities, while hitting an overhead target with your hand, landing on one leg, while motion, force, and EMG data are collected. During the hopping tasks you will be asked to wear strobe glasses that will flash and slightly obstruct your vision. Two levels of flashing will be used during the testing, low-level flashing and high-level flashing. A spotter will be nearby to prevent you from falling during all testing. Once you have completed these landing tasks on the force platform, you will be asked to do a series of clinical hopping and balance tests. The first test, you will complete a series of hopping tasks for maximum distance. Your distance will be recorded for each of these jumps. Next, you will perform a clinical balance test where you will be standing on a single-leg and will reach out maximally with your foot in multiple directions. Your reach distance will be recorded by the researcher.

What are the possible discomforts or risks?

Potential risks in this study are minimal. As with any exercise, risks include fatigue, localized muscle soreness, and the potential for strains and sprains. The balance and hopping tasks that you will be asked to perform will be similar to activities you encounter during normal exercise routines. You may also experience a minimal risk of falling as a result of tripping during the jumping assessment, this may result in you sustaining a sprain or possibly a contusion. While you perform the jumping tasks on a force platform, a spotter will be near the force plate to help minimize any falls or stumbles. In the unlikely event of injury, we will contact the appropriate medical authorities. While performing the strength testing there is a minimal risk that you may sustain a muscle strain. To decrease the likelihood of this happening, you will perform a five-minute walk as a warm-up to prepare your muscles for strength testing. This warm-up will increase your muscle temperature helping make you less susceptible to muscle strain. Practice repetitions will also be used to familiarize you with the testing procedures and also help reduce your risk of sustaining a muscle strain. The computerized strength testing device also has a controlled range of motion that you will only be allowed to move through, limiting excessive motions during exercise. An emergency button is available on the computerized strength testing device that will immediately stop the testing session if you ever experience increased muscle discomfort or pain.

What are the possible benefits of the study?

There are no direct benefits to you for participating in this study. However, by participating in this study you will help contribute to the existing literature on anterior cruciate ligament injuries and postural control under different visual conditions. This information will help determine if deficits remain in postural stability and muscular control in individuals who have returned to sport after an anterior cruciate ligament injury.

Privacy Protections.
All data collected will be housed in a restricted card-swipe access room (Gunter Hall 1750). Only the principal investigator, research advisor, and research assistants will be present during data collection. You will be assigned an individual identification number that will be used for all tests and data collection. This document will be kept separately from other documents that do not contain identifying information in a locked file cabinet in the UNC Biomechanics Laboratory. The locked file cabinet will only be accessible by the project researchers. Electronic data will only contain your assigned identification number and will be located on a password protected computer. Any identifiable information will be kept for a period of five years in a locked cabinet. After five years it will be removed and destroyed. All non-identifiable information will be kept indefinitely.

Participation in this study is voluntary.
You may decide not to participate in this study and if you begin participation you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. Having read the above and having had an opportunity to ask any questions, please sign below if you would like to participate in this research. A copy of this form will be given to you to retain for future reference. If you have any concerns about your selection or treatment as a research participant, please contact Nicole Morse, Office of Research, Kepner Hall, University of Northern Colorado Greeley, CO 80639; 970- 351-1910.

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Subject’s Signature   Date

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Researcher’s Signature   Date

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Purpose and Description:
This project is interested in studying how differences in visual disruption (eyes open and stroboscopic glasses) influence an individual's postural stability and motor control. We are asking you to participate as a healthy control because you meet our inclusion criteria, healthy, non-smoking, physically-active adults, 18-30 years old, who is free of any lower extremity injury or pain for 6 months prior to testing, no history of anterior cruciate ligament injury, have full or corrected vision, no neurological or vestibular disorders, and no history of epilepsy. The total duration of the data collection (two sessions) will be approximately 2.5 – 3 hours (~1.5 hours per testing session) if you agree to participate.

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Subject's Signature Date

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Researcher's Signature Date

A. Purpose

Injury to the anterior cruciate ligament (ACL) is a common knee injury that often occurs during sport related activities, with an incidence rate of 68.6 per 100,000 person-years (Sanders et al., 2016). Non-contact ACL injuries are estimated to account for 70% of all ACL injuries and occur during sudden landing, cutting, or deceleration tasks (Boden, Dean, Feagin, & Garrett, 2000; Hewett et al., 2005). An estimated cost of ACL treatment, including surgery, rehabilitation, and future pathologies, ranges from $7.6 billion to $17.7 billion per year in the U.S., which places a massive financial burden on our healthcare system (D. Grooms, Appelbaum, & Onate, 2015; Mather et al., 2013). After completing the rehabilitation process, research demonstrates that a high number of athletes are able to return to sport (RTS), often reaching similar playing levels as before injury (Brophy et al., 2012; Gans, Retzky, Jones, & Tanaka, 2018). However, it is hypothesized that while biomechanical measures may return to normalized values and allow for RTS, neurological deficits may remain (Gokeler et al., 2013; McLean, 2008; Needle, Lepley, & Grooms, 2017; Relph, Herrington, & Tyson, 2014).

Complex neuromuscular changes such as those found in ACL reconstructed patients indicate that an ACL injury is not a simple musculoskeletal injury, but rather a more complex injury involving the neurological system (D. R. Grooms et al., 2017). Due to these neuromuscular changes, individuals may experience decreased joint stability during unanticipated activities, such as those seen in sporting activities (Brown, Palmieri-Smith, & McLean, 2009; Needle et al., 2017). After ACL injury it has been postulated that neural feedback systems are disrupted leading to disturbances in the motor control of the knee (Thátia R Bonfim, Antonio Jansen Paccola, & Barela, 2003; D. Grooms et al., 2015; Hasan et al., 2013; Howells, Ardern, & Webster, 2011; Lehmann, Paschen, & Baumeister, 2017; Needle et al., 2017). For example, damage to the sensory receptors present in the ACL may lead to deficits in the somatosensory information received from the knee. Disruption of the somatosensory feedback has been confirmed in ACL reconstructed individuals from testing joint position sense and threshold detection of active/passive motion (Relph et al., 2014; San Martin-Mohr et al., 2018; Schultz, Miller, Kerr, & Micheli, 1984).

Somatosensory deficits experienced by individuals who have undergone ACL reconstruction may cause increased reliance on visual feedback during sport related activities (Thatia Regina Bonfim, Grossi, Paccola, & Barela, 2008; Negahban, Mazaheri, Kingma, & van Dieën, 2014; Okuda et al., 2005). Removing visual information in a lab environment allows for insight into the contribution of the visual system; however, it does not replicate sporting scenarios well. The use of stroboscopic glasses has been proposed as a method for replicating neurocognitive demands typically present during sports activities (D. R. Grooms et al., 2018). Stroboscopic glasses are designed to disrupt visual input, while not completely blocking it (D. R. Grooms et al., 2018). These glasses cycle through a series of open and closed conditions that can be manually adjusted to allow for increased or decreased levels of visual input. While the visual system is a crucial feedback system, it is only one aspect of the afferent pathways. ACL reconstructed individuals present with a unique problem, as the somatosensory system is affected and visual feedback is relied on more after injury. Since both feedback systems are relied upon to maintain appropriate neuromuscular stability if one feedback system is impacted, then athletic performance may suffer (D. Grooms et al., 2015).

Static postural stability tests provide insight into an individual's general postural stability, but may not be challenging enough to detect differences in an athletic population (Colby, Hintermeister, Torry, & Steadman, 1999; Heinert et al., 2018). While static and dynamic stability measures remain impacted years after ACL injury and reconstruction, dynamic tasks may be more appropriate to assess prior to RTS (Baumeister et al., 2011; Thátia R Bonfim et al., 2003; Dauty, Collon, & Dubois, 2010; Heinert, Willett, & Kernozek, 2018; Howells et al., 2011; Lehmann et al., 2017; Lepley et al., 2015; Mohammadi et al., 2012; Webster & Gribble, 2010). Drop jump landings, which is a similar task to some dynamic postural assessments, exhibit changes in mechanics when visual feedback is manipulated (D. R. Grooms et al., 2018).

In summary, ACL reconstruction and rehabilitation may correct the mechanical stability of the joint, but neuromuscular processes may be compromised and this may increase an individual’s risk of sustaining a second ACL injury (M. V Paterno et al., 2013). Due to potential deficits in somatosensory information and increased reliance on visual information, it is important to understand how ACL reconstructed individuals behave with limited visual feedback. By limiting the amount of visual feedback an individual receives rather than entirely blocking it, through the use of stroboscopic glasses, we can better understand how an individual will perform during athletic scenarios when visual information is required. Understanding the relationships between visual disruption and postural stability in ACL reconstructed individuals can provide clinicians more precise information about RTS. Given these considerations, the primary purpose of this dissertation is to evaluate static and dynamic stability responses in ACL reconstructed individuals and healthy controls. A secondary purpose is to investigate neuromuscular responses to visual disruption, while landing during a dynamic single-leg landing task.

B. Methods

1. Participants

Healthy, physically-active adults, 18-30 years of age will be recruited for this study from graduate and undergraduate courses at UNC, UNC athletics, and the surrounding community. Specifically, we will recruit individuals who have undergone ACL surgery (n = 30) within the past four years and have received full clearance for athletic activities from their physician and are physically active. Healthy physically active controls (n = 30) will also be recruited for this study. For the purposes of this study, a “physically-active person” will be operationally defined, based on the American College of Sports Medicine guidelines, as an individual who participates in physical activity for at least 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity exercises per week. Before participation in this study, volunteers will meet with the principal investigator or research assistants where they will be given a written informed consent form. The inclusion and exclusion criteria for both the ACL reconstructed and healthy control groups are listed below. Healthy controls will be matched with ACL reconstructed individuals using the following variables: 1) age, 2) gender, 3) body mass, and 4) leg dominance.

	ACL Reconstructed	Health Control
Inclusion criteria	• Physically active male or female (n = 30) • Between ages of 18-30 • No lower extremity injury in the past 6 months • Unilateral ACL reconstruction within the last 4 years • Received full clearance for return to sport from physician • Have full or corrected vision (contacts or glasses)	• Physically active male or female (n = 30) • Between ages of 18-30 • No lower extremity injury in the past 6 months • No history of ACL injury • Have full or corrected vision (contacts or glasses)
Exclusion criteria	• Suffered a second ACL injury in reconstructed limb or previously uninjured limb • Lower extremity injury in the past 6 months • Head injury (i.e. concussion) within the last year • History of epilepsy • Known vestibular dysfunction • Uncorrected visual impairment	• Lower extremity injury in the past 6 months • Head injury (i.e. concussion) within the last year • History of epilepsy • Known vestibular dysfunction • Uncorrected visual impairment

The study's purpose and all procedures will be verbally explained, and then the volunteer will have as much time as needed to read the form. Each volunteer's level of understanding will be assessed before being asked to sign the IRB-approved consent form. In cases in which English is not the volunteer's first language, additional time will be provided to ask questions to ensure that the potential participant fully understands all of the elements of the study. Participation in the study will not begin until a signed consent form is returned to the principal investigator or researcher assistants. A copy of the informed consent will also be provided to the participant.

2. Data Collection Procedures

Participants will perform all research testing involved with this study in Gunter Hall on the campus of the University of Northern Colorado. Testing will occur in the Biomechanics Laboratory (1750) over two separate testing days. The two testing sessions will occur no earlier than 48 hours apart.

The first testing day will begin with completing the Tegner Activity Scale score and International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC) questionnaires. Once the subjective questionnaires have been completed, individuals will be provided with tight-fitting clothing to wear throughout the testing session. Anthropometric measurements (height and body mass) will be recorded by researchers prior to beginning the testing session. Leg dominance will be determined by asking the participant, "Which leg would you prefer to kick a soccer ball with?". Navicular height will be also be measured by having the participant in a seated non-weight bearing position and then again, once they have transitioned to a standing weight-bearing position. An embedded force treadmill will be used to record the force during all static and dynamic postural stability testing. After completing anthropometric measurements and clinical navicular height test, participants will begin the testing session walking on the treadmill at a 1.3 m/s pace for 5 minutes to accommodate to the treadmill and warm-up (Sloot et al., 2014a)(Sloot et al., 2014a)(Sloot et al., 2014a). Vertical jump height will be measured using a Vertec (JUMPUSA, Sunnyvale, CA). First, reach height will be measured by having the participant reach straight up with their dominant arm and push the highest plastic tab forward. After the reach height is recorded, the participant will perform three vertical jumps for maximum height using the Vertec. Both reach height and average vertical jump height will be recorded.

Prior to performing postural stability tasks, participants will complete a 5-minute stroboscopic glasses accommodation. During the accommodation period individuals will wear the stroboscopic glasses while playing catch with the researcher. These stroboscopic glasses (Senaptec, Beaverton, OR) are securely strapped to the individuals head using an adjustable strap. The glasses do not block an individual's vision consistently, but instead block vision for a minor period. Participants will then perform a series of static postural assessment tasks. Individuals will be asked to perform the quiet standing tasks in both double and single-leg stances under three visual conditions (eyes open, low visual disruption, high visual disruption). Participants will wear the stroboscopic glasses during all static postural stability tasks. For the low visual impairment condition, the glasses will be set to be clear for 100-

milliseconds and 100-milliseconds dark. The high visual impairment condition will be set to be clear for 100-milliseconds and 250-milliseconds dark. Based on research by Grooms et al. (2018), levels greater than 250-milliseconds of visual impairment resulted in complete loss of vision during a jumping task. Each participant will complete a single 30-second static stability trial for the following double and single-leg tasks: 1) double-leg, eyes open, 2) double-leg, low visual disruption, 3) double-leg, high visual disruption 4) single-leg, dominant limb, eyes open, 5) single-leg, non-dominant limb, eyes open, 6) single-leg, dominant limb, low visual disruption, 7) single-leg, non-dominant limb, low visual disruption, 8) single-leg, dominant limb, high visual disruption, 9) single-leg, non-dominant limb, high visual disruption. The order of the vision conditions will be randomized for double and single-leg tasks. All participants will receive 5-minute rest periods after completing the double-leg conditions and again after each single-leg testing condition. During double-leg postural stability each foot will be placed on a separate force platform (**Figure 1**). For single-leg postural stability participants will stand on a single force platform (**Figures 2 & 3**).

Figure 1

Figure 2

Figure 3

Figures 1-3. Double and single-leg static postural stability tasks wearing stroboscopic glasses.

After completing the static postural stability conditions, participants will complete a lower extremity strength assessment. All strength testing will be performed using a computerized strength testing device known as a dynamometer. Strength will be assessed using a knee flexion (bending of the knee) and knee extension (straightening the leg) exercise while in a seated position on the dynamometer (see ***Figure 1***). Participants will be given time to practice and learn the techniques used for the lower extremity strength tests. After completing the practice trials, participants will perform a total of five repetitions, giving maximum effort, to determine peak torque of knee flexion and extension. The total time for this testing session (static postural stability and strength assessments) will approximately take one hour and 30 minutes.

Figure 1. *Isokinetic Dynamometer*

For the second testing day, participants will be given tight-fitting clothing to wear for the duration of the testing session. Participants will begin the testing session by completing a 5-minute warm-up on a treadmill at a 1.3 m/s pace. Retroreflective markers will then be placed on various anatomical landmarks using double-sided tape. A 3D motion capture system will be used to record each participants movement during the single-leg landings. Muscle activity of the quadriceps, hamstrings, gastrocnemius, and tibialis anterior will be measured using surface electromyography (EMG) electrodes. Before any measurements are taken, the skin will be well cleaned and lightly abraded to reduce skin resistance. Adhesive tape will be applied to hold the surface EMG electrodes in place while testing occurs, but will not impede the individual's movement. Participants will perform the same 5-minute stroboscopic glasses accommodation as day one before performing the dynamic stability tasks.

Once the reflective markers and EMG electrodes have been securely attached to the participant, they will be the dynamic postural stability assessment. For the dynamic testing session, individuals will perform a series of forward single-legged hops in a randomized order. Single-legged hops will be performed on both the dominant and non-dominant limbs of both the ACL reconstructed group and the healthy control group. For the forward hop task, individuals will start in a standing position at 40 percent of the body height from the center of the force place (Heinert et al., 2018a; Wikstrom et al., 2005). Participants will be required to jump with both legs and touch an overhead marker (Vertec plastic tabs) that is equivalent to 50 percent of their maximum vertical height, with a single arm of his or her choosing before landing on the force plate (Wikstrom et al., 2005). Upon landing, individuals will place their hands on their hips as quickly as possible and maintain stability for 30 seconds. Participants will wear the stroboscopic glasses during all dynamic postural stability tasks. For the low visual impairment condition, the glasses will be set to be clear for 100-milliseconds and 100-milliseconds dark. The high visual impairment condition will be set to be clear for 100-milliseconds and 250-milliseconds dark. Participants will get three repetitions to practice the forward hops before data is collected. All visual disruption conditions will be randomized prior to testing. Each participant will complete one repetition of the following forward hop tasks: 1) forward single-legged hop, eyes open, dominant limb, 2) forward single-legged hop, eyes open, non-dominant limb, 3) forward single-legged hop, low visual disruption, dominant limb, 4) forward single-legged hop, low visual disruption, non-dominant limb, 5) forward single-legged hop, high visual disruption, dominant limb, 6) forward single-legged hop, high visual disruption, non-dominant limb. Participants will receive a 5-minute break after completing the second jumping task and again after completing the fourth jumping task.

After completing the forward hop tasks, each participant will complete a 5-minute rest period. Maximal voluntary isometric contractions (MVIC) will be completed using the Biodex isokinetic dynamometer system. A maximal test will be performed for the quadriceps, hamstrings, gastrocnemius, and tibialis anterior. Once maximal testing has been completed for EMG testing, EMG surface electrodes and reflective markers will be removed. Participants will then perform a series of clinical hopping tasks to use as a criterion to assess limb symmetry during a dynamic hopping task (**Figure 2**). The distance of each jump will be recorded using a standard tape measure and will be measured from the toe at push-off to the heel where the participant landed (Zult et al., 2017).

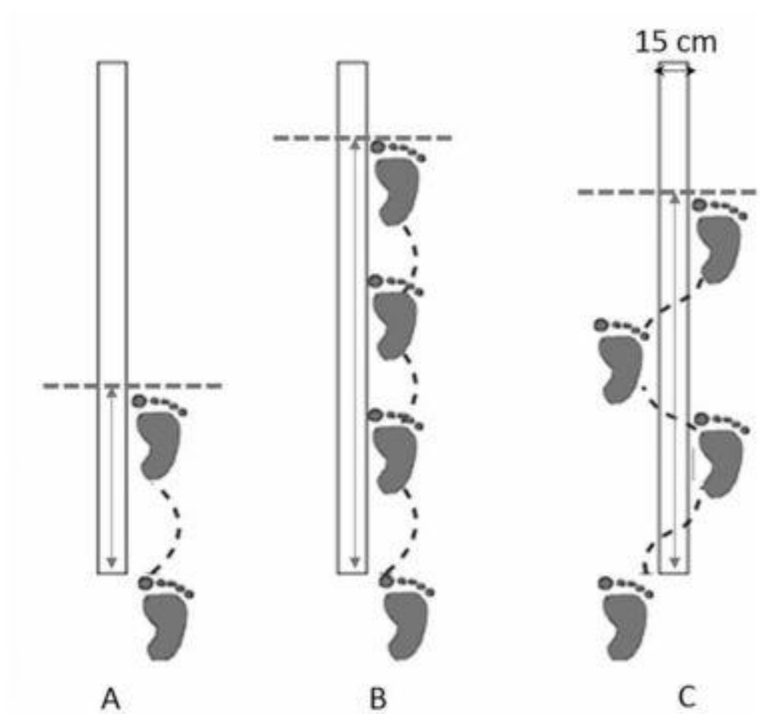

Figure 2. *Hop Tests from Noyes et al.* (1991)*: (A) single-leg one hop test, (B) single-leg triple hop test, (C) single-leg cross-over hop test.*

Each individual will complete three repetitions of the following hopping tasks: 1) single-leg one hop test (dominant limb), 2) single-leg one hop test (non-dominant limb), 3) single-leg triple hop test (dominant limb), 4) single-leg triple hop test (non-dominant limb), 5) single-leg cross-over hop test (dominant limb), 6) single-leg cross-over hop test (non-dominant limb). For each task, the hop with the greatest distance will be recorded for data analysis (Rambaud et al., 2017). Next participants will complete the modified Star Excursion Balance Test (SEBT) (Clagg et al., 2015; Rambaud et al., 2017). During this task, participants will be asked to balance on a single leg and reach out maximally with their foot, touching a point as far as possible in each direction. In accordance with the modified SEBT, the following directions will be used (**Figure 3**): 1) anteroposterior axis, 2) the posterolateral axis, and 3) posteromedial axis. The total time for this testing session (dynamic stability, hopping tasks, and SEBT) will approximately be one hour and 30 minutes.

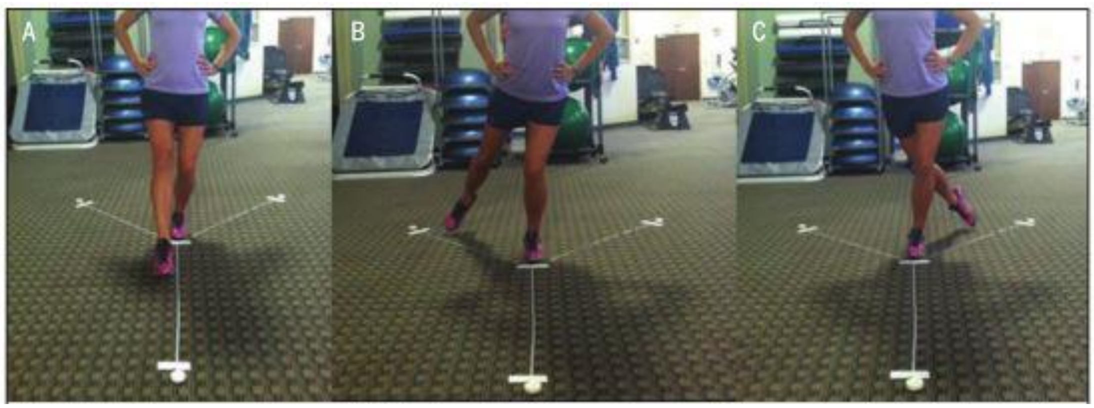

Figure 3. *Modified Star Excursion Balance Test (SEBT). Participant balance on the test limb and performs maximal reaches with the nonstance limb in the following directions: (A) anterior, (B) posteromedial, and (C) posterolateral. Picture from Clagg et al.* (2015).

3. **Data Analysis Procedures**

From the recorded force platform data, static assessment calculations will be performed over the 30 seconds of data, which is consistent with traditional linear and nonlinear analysis (Cavanaugh et al., 2006; J. J. Collins & De Luca, 1993; Thomas E. Prieto et al., 1996b). For dynamic landing tasks, an individual's time to stability (TTS) will be calculated using methods proposed by Ross et al., and the Dynamic Postural Stability Index (DPSI) will be calculated using the first 3 seconds of data (Ross & Guskiewicz 2003; Wikstrom et al., 2005). All data will be filtered using a 4th order low-pass Butterworth filter. All postural stability calculations will be completed using a custom written MATLAB script. The data collected from the questionnaires, static and dynamic postural stability, EMG muscle activity, hop distances, SEBT, and strength measurements will be averaged to represent performance at testing. The dependent variables will be the calculated scores from each test type. The independent variables will be group (ACL and healthy control) and vision condition.

Statistical Analysis. All data will be numerically coded so that no personally identifiable information will be associated with any data. The mean score for each calculation for each group and vision condition will be evaluated for differences.

Repeated measures (eyes open, low visual disruption, and high visual disruption) MANOVAs will be used on all dependent measures for static, dynamic postural stability, and EMG recordings. All statistical analysis will be conducted at an $\alpha \leq 0.5$. Bonferroni post-hoc testing will be used to evaluate the direction of significant pairwise comparisons when appropriate.

4. **Data Handling Procedures.**

The data will be collected privately within the UNC Biomechanics Laboratory (Gunter Hall 1750, restricted card-swipe access), without any outside observers beyond the principal investigator, research advisor, and research assistants. Participants will be assigned an individual identification number that will be used for all tests and data collection. The informed consent forms will be kept separate from other data that do not have identifying information. Consent forms will be kept in a locked file cabinet in the UNC Biomechanics Laboratory and will only be accessible by the researchers. Electronic data will only contain the participant's assigned an identification number and will be located on a password protected computer. Any identifiable information will be stored for a period of five years in a locked cabinet. After five years it will be removed and destroyed. Any non-identifiable information will be kept indefinitely.

C. Risks, Discomforts, and Benefits

The following are possible risks associated with the study and the precautions that will be taken to minimize them:

5. Self-consciousness during data collection (a psychological risk)
   a. Only the primary investigator, researcher advisor, and research assistant(s) will be allowed in the data collection area.
   b. A participant may withdraw at any time without penalty.
   c. All data will be numerically coded so that no names will be associated with the data.
   d. All data will be kept in a locked cabinet in the locked Biomechanics Laboratory.
   e. All personally identifiable data will be destroyed after five years.

2. Localized muscle soreness, and the potential for strains and sprains from the test during data collection (a physical risk)
   a. All participants will be free of any current lower extremity and head injury for 6 months prior.
   b. ACL reconstructed participants will be at least one year and a max of 4 years after ACL reconstruction and have been cleared by a physician.
   c. All participants will perform a warm-up on the treadmill.

d. All participants who have the diagnosis of epilepsy, or head injury (i.e. concussion) within the last year will be excluded from the study, due to the use of stroboscopic glasses.
e. Participants with any vestibular dysfunction will be excluded from this study.
f. Physically active individuals will be recruited for participation. These individuals workout on a regular basis and will be familiar with the type of muscles soreness they may develop.
g. Any muscle soreness should be minor and will dissipate without special care within a few days.
h. The warm-up used for the treadmill test will serve as the warm-up for the strength testing as well. This physical activity will increase the muscle temperature to help decrease the risk of muscle damage.
i. Individuals will be allowed to practice knee flexion and extension on the computerized strength testing machine to allow for accommodation to the machine.
j. Participants full available range of motion will be set in the computerized strength testing machine which limits how far the leg can be flexed and extended during the testing session.
k. Participants will be instructed on the use of the emergency stop button located on the computerized strength testing machine and educated to hit the button if they feel any discomfort during the testing.

3. Trip of fall during data collection (a physical risk)
a. The probability for a trip or fall is low. The targeted participant population is not prone to falls. Injury potential from a trip or fall might include skin abrasion, contusion, or broken bone.
b. An investigator will act as a spotter during both static and dynamic activities.
c. During dynamic testing, participants will wear stroboscopic glasses. Participants will be allowed to adjust them to ensure fit and comfort.
d. An accommodation period will be given during both days of testing to reduce the novelty of the stroboscopic glasses.
e. The stroboscopic glasses have been used during dynamic tasks before with little to no risk as the glasses do not completely obstruct the participant's vision (D. R. Grooms et al., 2018a).

D. Cost and Consumptions

There will be no direct costs to the participants involved in this study other than their time commitment (approximately two 1.5 hour sessions). No compensation of any kind will be awarded to the participants for their involvement in the study. If a participant elects to withdraw from the study, at any point, there will be no penalty against them.

E. **Grant Information**

The stroboscopic glasses used in this study were purchased with a grant provided through the University of Northern Colorado Graduate Student Association.

Attached Relevant Material

The Informed Consent form, Recruitment flier, and Email Script example are attached to this document.

UNIVERSITY OF
NORTHERN COLORADO

Institutional Review Board

DATE:	March 15, 2019
TO:	Nathan Robey, M.S.
FROM:	University of Northern Colorado (UNCO) IRB
PROJECT TITLE:	[1403888-1] The Effect of Visual Disruption on Stability after ACL Reconstruction
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	March 15, 2019
EXPIRATION DATE:	*see note in bold below*
REVIEW TYPE:	Expedited Review

Thank you for your submission of New Project materials for this project. The University of Northern Colorado (UNCO) IRB has APPROVED your submission. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on applicable federal regulations.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this committee prior to initiation. Please use the appropriate revision forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office.

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

Under the recently revised Common Rule, this project will not require annual continuing review by the committee. Your project has been assigned a "Next Report Due" date of March 15, 2022. Just prior to that date, the IRB will check in with you to get a current status of your project. This will help us determine if your project needs to be extended or if your study is ready to be closed. If you have completed your project prior to that date, please contact the Office of Research & Sponsored Programs to complete a closing report.

Please note that all research records must be retained for a minimum of three years after the completion of the project.

If you have any questions, please contact Nicole Morse at 970-351-1910 or nicole.morse@unco.edu. Please include your project title and reference number in all correspondence with this committee.

Nathan -

Thank you for your patience with the UNC IRB process. Your materials and protocols have been approved by both reviewers with no requests for any amendments/modifications or additions. You may proceed with participant recruitment and data collection using these materials and protocols.

Best wishes with your research and please don't hesitate to contact me with any IRB-related questions or concerns.

Sincerely,

Dr. Megan Stellino, UNC IRB Co-Chair

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB's records.

IRB Authorization Agreement

Institution or Organization Providing IRB Review:

Name (Institution/Organization A): University of Northern Colorado
IRB Registration #: IRB00001254
Federalwide Assurance(FWA)#, if any: FWA00000784

Institution Relying on the Designated IRB (Institution B):

Name (Institution/Organization A): Western Washington University
Federalwide Assurance(FWA)#, if any: FWA00001207

The Officials signing below agree that **Western Washington University** may rely on the designated IRB for review and continuing oversight of its human subjects research described below:

☐ This agreement applies to all human subjects research covered by Institution B's FWA.
☒ This agreement is limited to the following specific protocol(s):

Name of Research Project: The Effect of Visual Disruption on Stability after ACL Reconstruction
Name of Principal Investigator: Nathan Robey
WWU Investigator: Nathan Robey
Sponsor or Funding Agency: N/A
Award Number, if any: N/A
Other (describe):

The review performed by the designated IRB will meet the human subject protection requirements of Institution B's OHRP-approved FWA. The IRB at Institution/Organization A will follow written procedures for reporting its findings and actions to appropriate officials at Institution B. Relevant minutes of IRB meetings will be made available to Institution B upon request. Institution B remains responsible for ensuring compliance with the IRB's determinations and with the Terms of its OHRP-approved FWA. This document must be kept on file by both parties and provided to OHRP upon request.

Signature of Signatory Official (Institution/Organization A):

Signature: Linda R. Black Date: 5/17/19

Print Full Name: Dr. Linda Black Institutional Title: Associate Provost, Dean, Office of Research & Sponsored Programs

Signature of Signatory Official (Institution B):

Signature: Kathleen L. Kitto Date: 5/20/19

Print Full Name: KATHLEEN L. KITTO Institutional Title: Acting Vice Provost for Research.

APPENDIX B

STABILOGRAM DIFFUSION ANALYSIS DATA

Tables B.1 and B.2 show mean results from stabilogram diffusion analysis for participants that displayed positive diffusion coefficients (D_S, D_L) and scaling exponents (H_S, H_L). As shown in the tables, only 6 participants in the double-limb tests and 7 participants in the single-limb tests displayed these outcomes.

Table B.1

Raw data for double-limb SDA outcome measures for ACLR and control groups.

SDA outcome measures	ACLR n = 6	Control n = 6
Δr^2 (mm^2), mean ± SD	25.57 ± 3.31	12.11 ± .55
Δt (s), mean ± SD	2.10 ± .07	1.15 ± .24
$D_{S,}$ mean ± SD	6.52 ± .87	10.24 ± 1.12
$D_{L,}$ mean ± SD	1.17 ± .47	0.75 ± .55
$H_{S,}$ mean ± SD	0.51± .00	0.56 ± 0.01
$H_{L,}$ mean ± SD	0.20 ± .05	0.18 ± .06

Table B.2

Raw data for single-limb SDA outcome measures for ACLR and control groups.

SDA outcome measures	ACLR n = 7	Control n = 7
Δr^2 (mm^2), mean ± SD	341.55 ± 166.51	309.97 ± 104.13
Δt (s), mean ± SD	0.80 ± .21	1.07 ± .10
$D_{S,}$ mean ± SD	213.97 ± 68.04	160.69 ± 59.30
$D_{L,}$ mean ± SD	3.11 ± .34	7.85 ± 6.43
$H_{S,}$ mean ± SD	0.59 ± .07	0.55 ± 0.06
$H_{L,}$ mean ± SD	0.07 ± .04	0.12 ± .02

The reason that many participants could not be included in this analysis is shown in Figure B.1. For many participants, the long term diffusion coefficient was negative; this result is uninterpretable.

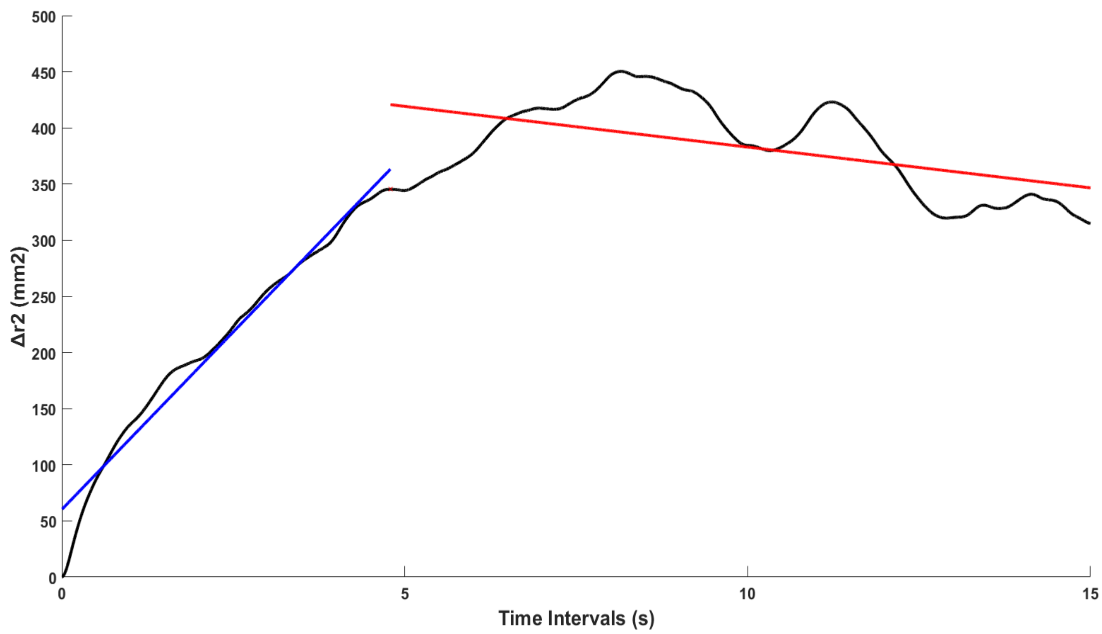

Figure B.1. An example of a negative long-term diffusion coefficient (D_L) which is not interpretable using the SDA methodology.

After this initial analysis was performed, the time interval was adjusted for additional SDA analyses to see if more participants displayed positive diffusion coefficients and scaling exponents. The results of these additional post hoc analyses are shown in Tables B.3 through B.5.

Table B.3

Number of interpretable participants for double-limb postural stability

Vision conditions	ACLR	Control
15 second time interval		
EO	8	12
LVD	12	12
HVD	11	10
Total	6	10
10 second time interval		
EO	8	13
LVD	12	12
HVD	11	11
Total	6	10
5 second time interval		
EO	6	9
LVD	6	12
HVD	9	7
Total	2	6

EO – eyes open; LVD – low visual disruption; HVD – high visual disruption. Total represents the number of participants with interpretable SDA measures for all three visual conditions.

Table B.4

Number of interpretable participants for single-limb (dominant) postural stability

Vision conditions	ACLR	Control
15 second time interval		
EO	13	13
LVD	12	11
HVD	10	11
Total	9	9
10 second time interval		
EO	11	13
LVD	10	11
HVD	8	11
Total	6	8
5 second time interval		
EO	11	12
LVD	12	11
HVD	10	10
Total	8	7

EO – eyes open; LVD – low visual disruption; HVD – high visual disruption. Total represents the number of participants with interpretable SDA measures for all three visual conditions.

Table B.5

Number of interpretable participants for single-limb (non-dominant) postural stability

Vision conditions	ACLR	Control
15 second time interval		
EO	10	9
LVD	9	8
HVD	10	11
Total	7	3
10 second time interval		
EO	11	9
LVD	9	10
HVD	7	11
Total	6	7
5 second time interval		
EO	13	12
LVD	7	9
HVD	6	11
Total	5	7

EO – eyes open; LVD – low visual disruption; HVD – high visual disruption. Total represents the number of participants with interpretable SDA measures for all three visual conditions.

Tables B.3-B.5 represents the post hoc analysis performed in an attempt to salvage the double- and single-limb (dominant and non-dominant limbs) SDA data for use in Study 1. The 15 second time interval has been used in previous work from the UNCO Biomechanics lab. This specific time interval is the maximum available time interval for the 30 second trials for the static stances. The next time interval analyzed was a 10 second time interval. Collins and De Luca (1995c) suggested that a 10 second time interval was enough to capture the COP behavior during the postural stability assessment. Finally, a 5 second interval was analyzed in an attempt to decrease the number of negative long-term slopes. However, this resulted in even less interpretable data for use in the current dissertation.